Determining and Alerting Risk of ACL Injury in Female Horizontal Jumps Due to Changes in Athletic Performance

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Abstract

Increase in muscle fatigue and improper biomechanics can lead to certain injuries in athletes. In track and field, anterior cruciate ligament (ACL) injuries can be seen in female long and triple jumpers. The changes in muscle activation as well as other changes in biomechanics are key indicators of potential risk of this injury. Our team worked with the WPI Women's Track and Field team in order to develop a MATLAB code that detects and determines changes that are related to the cause of ACL injuries which then recommends the athlete to stop activity. Indicators of fatigue that the team analyzed were knee valgus positioning, knee flexion angle, hip vertical velocity, and average angular velocity. Based on the data collected, our device alerts when an athlete's hip vertical velocity reaches above 3 m/s or if the knee angular velocity is above -1000 degrees/s after halfway through the jump and if the knees are in valgus positioning, as this could potentially indicate fatigue.

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1. Introduction

1.1 Long and Triple Jump

The sport of track and field encompasses events which test a variety of athletic skills. These events are typically separated into sprints, distance, jumps, and throws, with each enlisting a distinct set of skills from an athlete. Within each of these event groups, there is further separation by the distinct event. Some of the most biomechanically complex event groups are jumps and throws. Horizontal jumps are of interest due to the complexity combined with the high impact endured by the jumper, which creates an increased risk of injury. The term “horizontal jumps” encompasses two jumping events which have the goal of reaching the longest horizontal distance into a sand pit: long jump and triple jump.

Long jump consists of an approach, take-off, flight, and landing. The athlete sprints along the runway during the approach, takes off from a designated line known as the “board,” is in the air during flight, and lands in a pit of sand at the end. The overall process of the long jump is shown in Fig. 1.1.

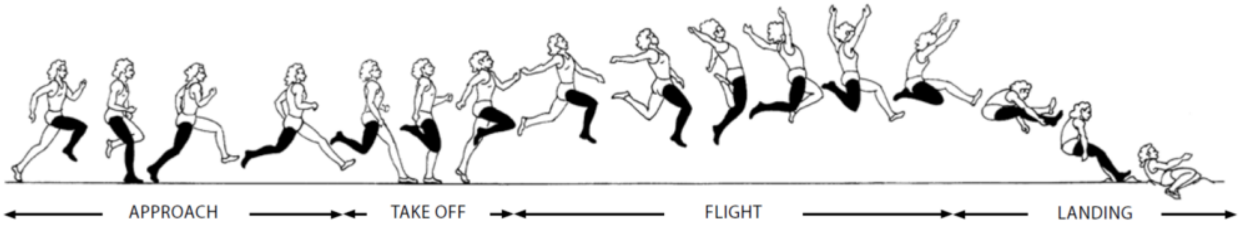


Fig. 1.1 Overview of phases within long jump (*Long Jump - The Technical Model — Aths.coach Athletics Coach*, 2021).

Triple jump holds many similarities to long jump but has some added complexity due to the inclusion of three phases after the approach instead of taking off. These three phases are typically referred to as a hop, step, and jump, and are performed with two steps on one leg, and one step on the other. Fig. 1.2 below demonstrates the intended form of each of the phases.

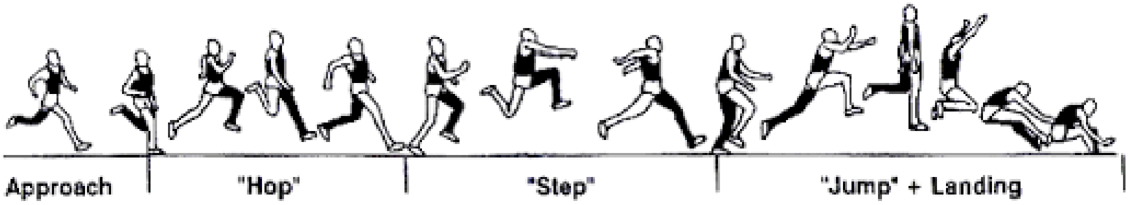


Fig. 1.2 Overview of phases within triple jump (Stander, 2022).

1.2 ACL Injury Mechanism

While each type of horizontal jump holds some differences, the increased risk of injury is not unique to just one jump or the other. A common injury in jumping and pivotal sports is an anterior cruciate ligament (ACL) tear as shown in Fig. 1.3. Seventy percent of ACL injuries involve minimal to no contact and occur during landing or deceleration maneuvers (Boden & Sheehan, 2022). In collegiate athletes, ACL injury occurrence has increased overtime, where women are four times as likely to sustain an ACL injury than male athletes (Smith et al., 2016). This is suspected to be the result of differences in pelvis and lower extremity anatomy, increased looseness in ligaments, and the hormonal effects of estrogen on ligament properties (Slauterbeck et al., 2002).

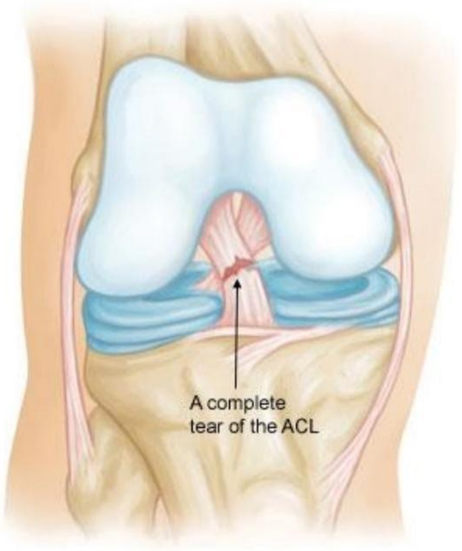


Fig. 1.3 Anterior view of an ACL tear in the knee joint (OrthoInfo).

In the knee joint, the femur, tibia, and patella meet and are supported by ligaments. The ACL runs diagonally across the middle of the joint, preventing the tibia from sliding forward and provides rotational stability to the knee. Increased knee abduction angle, internal hip rotation, increased knee and hip flexion, and high ground reaction forces are all indicators of ACL strain. ACL tears are costly for athletes with its expensive surgery and extensive rehabilitation period, affecting quality of future performances and poses places the athlete at high risk for other health issues, such as osteoarthritis. Currently, there is no commercial device to monitor ACL strain during athletic activity.

1.3 Project Scope

The goal of the project is to design a device that can detect biomechanical risk indicators of athletes to prevent ACL injuries in women. To complete its function, the device will: (i) detect the biomechanics of the jump, (ii) determine harmful changes in the biomechanics, and (iii) be functional in a practice setting.

For the device to perform at precise and accurate levels, it must also have design specifications that aid in its function, as well as maintain the user's comfort. These specifications include:

- Materials used should have good elasticity and flexibility to support the motions of the athlete's leg
- Materials that come into contact with the athlete should not cause irritation to the user, even in the presence of sweat
- Feedback should be returned within 8 minutes
- Device should measure angles with a maximum error of 0.05 (5%)

2. Literature Review

2.1 Biomechanics of Long and Triple Jump

Long jump and triple jump are the two track and field events aimed at reaching the greatest horizontal distance with a jump. Some obvious similarities lie in the way an athlete approaches with a sprint and ends with jumping into a sandpit. While long jump is the measurement of a single jump, triple jump consists of a series of three jumps, as the name implies. In the triple jump, the athlete performs what is called a “hop,” “step,” and “jump” phase as seen in Fig. 2.1.

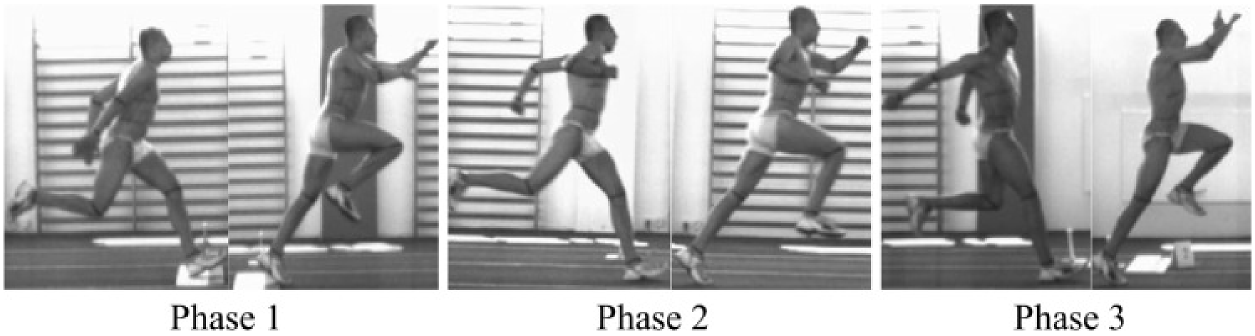


Fig. 2.1 The three phases of the triple jump (Dziewiecki K., et. al, 2013)

The jump phase of the triple jump holds the most similarity with the long jump due to the technique but does consist of some differences in forces and transition into the jump due to coming out of the “step” phase. An additional similarity is the lowering of the athlete’s center of gravity in the last phases of the approach to generate vertical velocity during take-off. The addition of phases in the triple jump requires the jumper to focus on minimizing the loss of horizontal velocity, even while tolerating high impact forces (Perttunen et al., 2000). A long jumper must tolerate a high impact force on the last step, and the focus is on generating vertical velocity to increase distance. While considering these types of jumps, it is important to analyze all three phases in the triple jump and focus on the final phase of the long jump.

2.1.1 Triple Jump Biomechanics

During triple jump, an athlete performs a sprint and then jumps twice on one leg, and then once on the other for their last jump which is when they jump into the sand pit. In each phase, the athlete attempts to maintain horizontal velocity while still gaining a large amount of distance. Professional female triple jumpers can limit their ground contact time, which usually is the main contributor to horizontal velocity loss (Eissa, 2014, see Table 2.1). Another factor that contributes to maintaining a high horizontal velocity is an inclination of the braking angle of the average resultant force during a phase close to 90 degrees (Perttunen et al. 2000). This allows the muscle actions and timing to be well-coordinated.

Table 2.1 Professional Female Triple Jumper Statistics (Eissa, 2014).

Phase	Horizontal Velocity (m/s)	Horizontal Velocity Loss (m/s)	Vertical Velocity (m/s)	Contact Time (s)	Pushing Time (s)	Braking Time (s)	Take-off Angle (degrees)
Hop	8.4 - 8.86	0.69 - 0.95	2.09 - 2.49	0.103 - 0.110	0.059	0.079	15.02 - 16
Step	7.58 - 8.22	0.38 - 0.52	1.24 - 1.76	0.133 - 0.150	0.075	0.087	9 - 12.7
Jump	6.46 - 7.34	0.85 - 1.05	2.41 - 2.76	0.11 - 0.14	0.064	0.113	N/A

A study which analyzed a female triple jumper for the Egyptian national team in 2014 identified the main limiting factor for the athlete's performance as being her loss in horizontal velocity during the three phases of the jump (Eissa, 2014). In this study, the triple jumper's phases were recorded using cameras placed laterally to each take-off phase. These videos were then analyzed using a 2D motion analysis known as DARTFISH 4.5.

Take-off technique is important to the maintenance of velocity, and the biomechanical loading during triple jump. There are large ground reaction forces in each phase, with the largest being in the step take-off (Perttunen et al. 2000), and the distribution of forces throughout the body are critical to jump performance and injury prevention. The forces experienced also lead to a high amount of stress within the joints, with a finite element analysis estimating a maximum Von Mises stress and shear stress of 385.12 MPa and 44.51 MPa, respectively, at the medial sides of the articular cartilage in the knee (Huang et al., 2019). The ground reaction forces experienced by the jumper are much larger than those experienced while walking, with average vertical force being about four times higher than during walking, and the maximal peak vertical forces being almost ten times higher (Perttunen et al. 2000). With higher ground reaction forces comes greater peak pressures. In a study that measured the peak pressures throughout the foot for national triple jumpers, the highest peak pressures were experienced under the heel and forefoot, and these were about four times higher than those experienced during walking (Perttunen et al. 2000). While forces are important to examine for mechanical loading, they also can be utilized as a way of predicting jump distance. The plantar pressure of the lateral side of the forefoot is highly related to the length of jump, and the maximal vertical force in the braking phase and maximal horizontal force in the push-off face were shown to be the best ground reaction forces for predicting final jump distance (Perttunen et al. 2000).

Another important thing to consider amongst triple jump athletes is the phase ratio. The phase ratio is the amount of time spent in each phase over the course of a jump. The step is typically the shortest phase, yet this seems to be the only consistent trend (Hay, 1993). There is not an optimal phase ratio for distance, as each phase is an important contributor to the overall jump distance. The ratios of these phases may also be a contributor to how forces are experienced by the athlete since it affects velocity and force from one phase to the next.

2.1.2 Long Jump Biomechanics

While triple jump has three separate jumps to consider, the long jump holds its own complexities, specifically during the touch-down to take-off period of the jump, often referred to as the critical phase. Additionally, some analyses of the long jump may be utilized when evaluating the last phase of the triple jump due to the parallels between the two. The critical phase of the long jump can be broken up even further into touch-down, compression, maximum knee flexion, extension, then take-off as seen in Fig. 2.2 below. Each of these phases is important for maximizing the distance achieved by the jump.

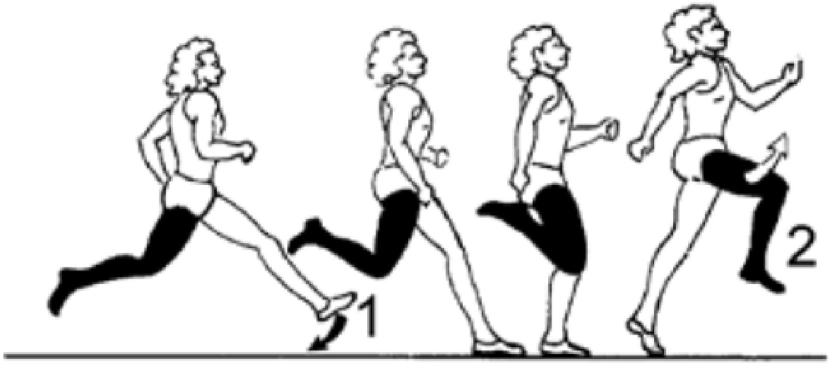
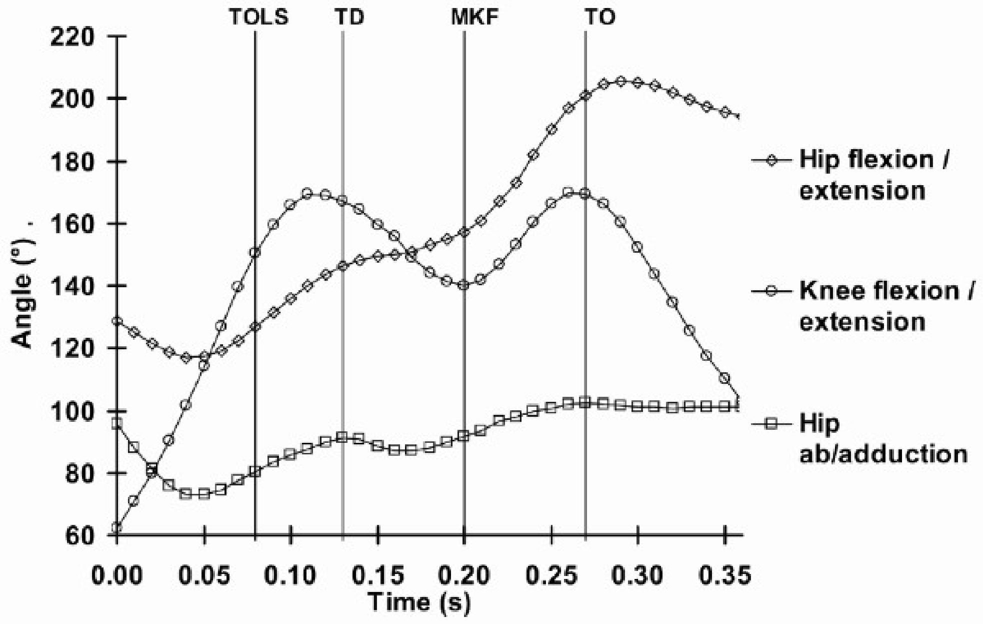


Fig. 2.2: In order from 1 to 2, the touch-down, compression, maximum knee flexion, and extension form within the long jump critical phase (*Long Jump - The Technical Model — Aths.coach Athletics Coach*, 2021).

While it may seem counterintuitive since the aim of the event is to reach the greatest horizontal distance, during the take-off, the athlete hopes to achieve a high vertical velocity. This velocity gain occurs during the compression phase, where 69.8% of the vertical velocity is typically gained (Graham-Smith & Lees, 2005). This increase can be attributed to the pivot action, in which the body moves over the planting foot and is forced upward. This vertical impulse can be conceptualized by thinking about the muscle-tendon system of the knee as a spring that stores energy during compression and releases it from the tendon during extension.

Throughout the long jump, the hip and knee joints shift. The movements of these joints were quantified during a study of fourteen male long jumpers as shown in Fig. 2.3 below. For these athletes, the hip extended through an average of 11.0 degrees with a minimum extension angular velocity of 1.6 rad/s during compression, and 43.6 degrees with a peak extension velocity of 12.7 rad/s during extension. The hip also abducted an average of 3.9 degrees during compression, then through a range of 15.4 degrees during extension. For the knee, it extends throughout the last stride before touch-down to 167.0 degrees. There is then 26.5 degrees of flexion at a peak velocity of 10.1 rad/s, followed by 29.1 degrees of extension at a peak velocity of 11.2 rad/s (Graham-Smith & Lees, 2005).



TOLS = ***take-off last stride***, **TD** = ***touch-down***, **MKF** = ***maximum knee flexion***, **TO** = ***take-off***

Fig. 2.3 Quantified movement of joints during long jump (Graham-Smith & Lees, 2005).

Several factors contribute to the result of the long jump, and it is important to recognize patterns which are consistent. Analyzing the joints, jumper velocity, and phases are just some ways to begin to understand the way the athlete performs this event.

2.2 Common Injuries

Long jump and triple jump have heavy neuromuscular and biomechanical activity, especially in the lower region of the body (thighs, calves, ankles, feet, and toes). During the various phases of both jumps, there is a generation of high forces in short periods of time, similar to short bursts of energy (Zemper et. al, 2005). This is a result of the high impulse generated through the leg muscles. High strain rates and supramaximal forces are applied to the contracting muscles and ligaments involved in the lower extremity movements (Lambert et. al, 2020). When these forces and strains are applied in repetitive patterns, it exceeds the loading capability of the body structure, and if there are poor recovery practices the athlete is more likely to sustain an injury. It is this cycling pattern that leads to fatigue and acute injuries sustained during competition or training.

An athlete's risk of injury is heavily dependent on these factors: biomechanics employed in their motions, technical movements, training workload, and activity duration (Springer, 2022). Disparity in any of these areas can lead to an increased risk of injury. Biomechanics refers to the neuromuscular activity that occurs during each movement and the different forces being applied to the muscle and bones. This goes hand in hand with the technical movements used by the athlete to achieve optimum success when participating in their event. It is important that an athlete uses techniques that do not apply too much strain to their body and provide the most support. Alongside techniques, the greater the duration of practice, the more likely an athlete will reach a point of fatigue.

As stated earlier, most injuries in the jump events are within the lower region of the body. A major injury is anterior cruciate ligament (ACL) tears or rupture, specifically non-contact. Non-contact ACL injuries are usually caused by valgus rotation where the foot is planted on the ground, there is external rotation of the tibia, the knee is near full extension, and there is a sudden twisting moment about the knee. This is more common during the takeoff and landing phases of the jumps since this is where the largest forces are applied. At least two-thirds of ACL injuries occur when an athlete is planting their feet, accelerating, or landing from a jump (Barber-Westin & Noyes, 2017). According to a study focused on the effects of fatigue on lower neuromuscular movements in jumping, it was found that there is a higher percentage and risk of women sustaining this acute injury (Barber-Westin & Noyes, 2017). Women are four times more likely to sustain an ACL injury than their male counterparts (Arendt & Dick, 1999).

Injury to these regions reduces athletic performance. Once a muscle or ligament is torn or ruptured, the muscle begins to heal itself through the application of stem cells to the rupture site which aids in the regeneration of muscle fibers (Leong et al., 2020). However, after this repair process is completed, there is still a significant amount of scar tissue that remains. As time progresses, the scar tissue will remodel itself, but the muscle is never fully healed (Leong et al., 2020). This remaining scar tissue has a negative impact on the elasticity and movement of this muscle/ligament. This reduced functionality results in reduced athletic performance during training and competitive events.

2.3 Biomechanical Indicators to Predict the Risk of ACL Injury

Multiple biomechanical risk factors have been identified that can lead to an ACL injury. These include knee abduction angle, internal hip rotation, knee and hip flexion and ground reaction forces.

When these factors are addressed during training, with augmented feedback, there are improvements in the athletes form that improve their resilience to an ACL injury (Neilson et al., 2019). For women, landing with an extended hip and knee is a common form that results in ACL injury. Landing in this position can cause the knee to be in valgus, with an internal rotation of the tibia, and a pronated foot (Acevedo et al., 2014).

Knee abduction angles were greater in female landings that resulted in ACL injuries than those that did not. Hewett et al (2005) found the initial contact of the landing had an average of 8.4 degrees greater knee abduction angles for landings that resulted in injury compared to uninjured. The peak external, knee abduction moment was greater in the injured subjects, – 45.3 ± 28.5 N.m, than the uninjured, –18.4 ± 15.6 N.m (Hewett et al., 2005). Since knee abduction moments contribute to lower extremity dynamic valgus and knee joint load, this is a clear indicator of ACL injury risk (Hewett & Bates, 2017). Landings that experienced increased valgus loading can lead to injury since valgus loading can increase ACL force (Lloyd & Buchanan, 2001). Therefore, knee valgus angles and moments can be indicators of risk.

Imbalances in muscle recruitment and control is another contributor to ACL injury. Leg dominance occurs when one leg demonstrates more dynamic control than the other, adding more stress onto one leg (Pappas et al., 2016). Additionally, there can be imbalances between muscle recruitment from the knee flexors and extensors. The quadriceps muscle induces anterior tibial translation and ACL strain when contracted while the hamstring counteracts this force, providing dynamic control (Di Stasi et al., 2013). Therefore, when the quadriceps-hamstring activation ratio is below 60% there is an increased risk of ACL injury (Hewett & Bates, 2017).

Trunk dominance is another indicator of risk. When there is poor control of the trunk during the jump, the center of mass can move outside of the base support of the body. This occurs more frequently and with greater motion in women than with men (Hewett et al., 2010). Poor core stability is a common contributor of the valgus positioning of the knee and indicator for knee injuries (Zazulak et al., 2007).

2.4 Biological Predictors of Athlete Fatigue

Neuromuscular fatigue is described as a decrease in exercise-induced, maximal voluntary force which comes from the repetition or continuation of muscular contractions (Alba-Jimenez et al., 2022). There are multiple physiological explanations as to why muscles fatigue. Muscle fatigue could be caused by differences in metabolic factors, changes in the central nervous system, and oxygen levels. These increased levels in muscle fatigue can also lead to many different health conditions and numerous muscular-related injuries. Some metabolic factors that increase muscle fatigue are hydrogen ion concentration, lactate levels, inorganic phosphate concentration, reactive oxygen species, heart shock protein levels, and orosomucoid levels (Wan et al., 2017). The central nervous system also plays an important role in exercise and muscle fatigue. Certain neurotransmitters such as 5-hydroxytryptamine (5-HT), dopamine (DA), and noradrenaline (NA) all produce some effect during whole body exercise (Wan et al., 2017). Lastly, the amount of oxygen that reaches the muscles can affect metabolic homeostasis leading to fatigue (Wan et al., 2017).

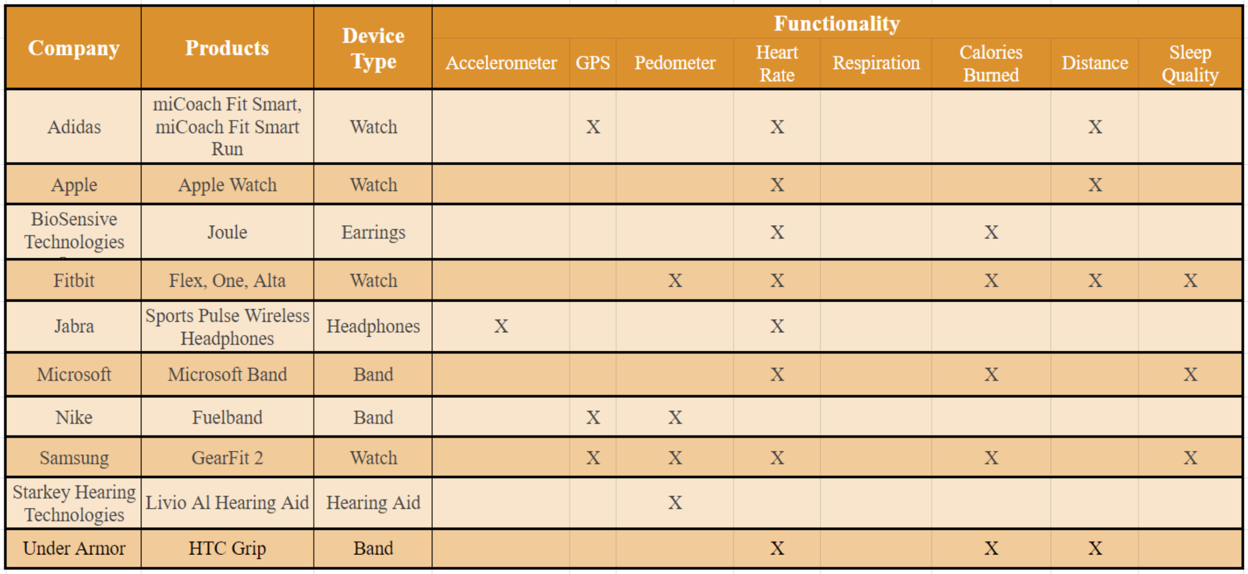
Muscle fatigue originates from two different motor pathways: central and peripheral. Central fatigue is seen in the central nervous system and decreases the neural drive to the muscle (Wan et al., 2017). Peripheral fatigue comes from changes around the neuromuscular junction (Wan et al., 2017). During peripheral fatigue, disruptions in the excitation-contraction coupling process may be present. During this process of excitation-contraction coupling, the activation of myofilaments eventually leads to muscular relaxation which is mediated by calcium ions that are taken through ATPase sarcoplasmic reticulum pumps (Giannesini et al., 2003). With the limitation of ATP, the ionic pumps used in action potential propagation will not function correctly. This could cause a decrease in the rate of muscular relaxation (Giannesini et al., 2003). Muscle fatigue is seen less frequently in children, which could be a result of differences in the muscle characteristics. As children are able to remove more metabolic by-products, their muscles are able to have a faster recovery than seen in adults (Ratel et al., 2012).

Another explanation of muscle fatigue comes from the changes in oxygen levels. According to Wan et al., there is a direct relationship between enhanced oxygen levels and a decrease in muscle fatigue as well as an increase in muscle efficiency (2017). However, when peak maximum oxygen uptake is reached, ATP utilization and oxygen levels no longer can increase (Wan et al., 2017). This is seen in high-intensity activity and as there is an imbalance of metabolic homeostasis, muscle fatigue occurs. Oxygen plays a key role in muscle activity because it discards the buildup of lactic acid produced by muscular activity (Yamada 2016). In children, muscle fatigue is easier to resist because of their oxidative capacity and regulation of acid-base concentrations (Ratel et al., 2012).

2.5 Current Devices and Methods

Most common wearable technology used by athletes and non-athletes to analyze physical and physiological performance are wrist-based devices and other accessories. An overview of common wearable devices is depicted in Table 2.2 below. Movement-based sensors in these products often combine accelerometers, pedometers, global positioning satellite (GPS) devices to determine energy expenditure, position, movement, and balance control. Optical sensors photoplethysmography (PPG) are also utilized to measure heart rate, which is a key indicator of exercise intensity and physiological fatigue (Seshadri et al., 2019).

Table 2.2 A summary of wearable devices and their monitoring functions (Seshadri et al., 2019).



Company	Products	Device Type	Functionality							
			Accelerometer	GPS	Pedometer	Heart Rate	Respiration	Calories Burned	Distance	Sleep Quality
Adidas	miCoach Fit Smart, miCoach Fit Smart Run	Watch		X		X			X	
Apple	Apple Watch	Watch				X			X	
BioSensive Technologies	Joule	Earrings				X		X		
Fitbit	Flex, One, Alta	Watch			X	X		X	X	X
Jabra	Sports Pulse Wireless Headphones	Headphones	X			X				
Microsoft	Microsoft Band	Band				X		X		X
Nike	Fuelband	Band		X	X					
Samsung	GearFit 2	Watch		X	X	X		X		X
Starkey Hearing Technologies	Livio AI Hearing Aid	Hearing Aid			X					
Under Armor	HTC Grip	Band				X		X	X	

Epidermal wearable sensors have great potential to quantify movement during performance and monitor joint activity to prevent injuries (Seshadri et al., 2019). They are ideal to use on the ulnar collateral ligament (UCL), anterior cruciate ligament (ACL), medial collateral ligament (MCL), and posterior cruciate ligament (PCL) since they have high stretchability, durability, and robustness (Seshadri et al., 2019). Currently, there is no commercial device to determine ACL strain and assess fatigue during physical performance.

A common injury among pitchers in baseball is a torn UCL. To analyze pitcher's elbow activity and prevent UCL injuries, the U.S. Major League Baseball (MLB) approved the first wearable technology for in-game use, motusBASEBALL^{TM} as shown in Fig. 2.4. This monitoring device is an arm sleeve over the elbow containing five accelerometers and sensors that measure joint angles, velocity, stress, and strain exerted by a pitcher. A sensor near the elbow specifically measures stress exerted on the UCL (Motus Global, n.d.). In a study conducted by Motus Global, the device sensors were proven to be successful in calculating torque when compared to mocap calculation of torque with minor differences in final quantities. The device also includes software to be used by coaches to view the biomechanical data collected by the sensors during athletic performance and aid in future training personalized to previous activity (Laughlin et al., 2016).

Fig. 2.4 motusBASEBALL™ sleeve; sensor inserted in blue pocket (Motus Global, n.d.).

Motus Global produces a range of other monitoring devices in athletic activities such as baseball batting, football throwing, cricket bowling, and volleyball spiking/serving. Using two sensors located on the pelvis and wrist, the motusVB™ measures total number of spikes and serves with their respective speeds in addition to measuring and tracking vertical jump height and total count over a period of athletic activity (Motus Global, n.d.). To quantify a jump, the pelvis sensor measures the takeoff velocity of the athlete and calculates the jump height (Hansen et al., 2016). Even though volleyball athletes are highly susceptible to ACL injuries, there is no feature within motusVB™ that analyzes the knee during athletic performance.

Recently, a patent has been filed for a knee brace shown in Fig. 2.5 that features various types of sensors at different locations to actively measure ACL injury indicators during physical activity (Tesnow, 2020). Four flexion sensors (904, 906) located around the knee measure joint angle. Two gyroscopes at the knee (910) and at the ankle measure relative angle between the foot and knee to calculate and alert for excessive torque. An accelerometer (908) measures knee joint downward acceleration. From these sensors, the tibial shear force (TSF) value is calculated. If the TSF level becomes unsafe, the system warns the user that they are at risk for an ACL injury. A processing unit (910) is also included to process the output data from the flexion sensors and accelerometer and create feedback pertaining to ACL injury prone form, posture, or movement (Tesnow, 2020). This device and feedback system is ideal for ACL monitoring and injury prevention; however, it does not address nor monitor key indicators identified in female athletes, the patient population most at-risk for noncontact ACL injuries.

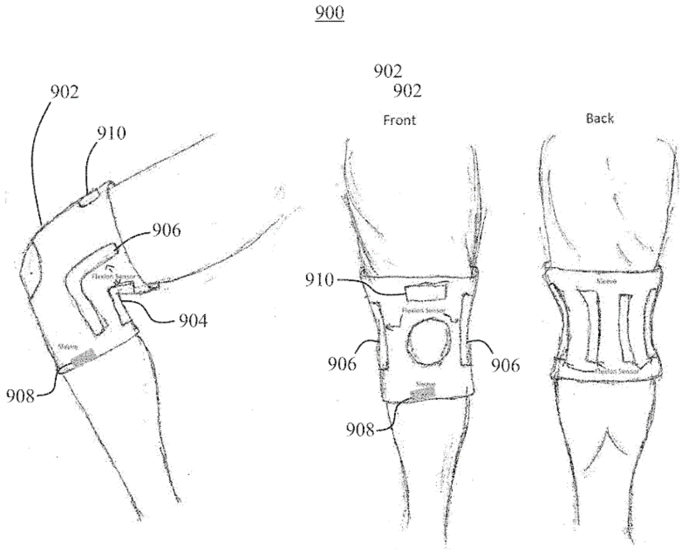


Fig. 2.5 Patent drawing of Wearable Knee Injury Prevention System (Tesnow, 2020)**.**

These current devices are useful to detect fatigue and injury, however there is no current device specific to detect ACL injuries in horizontal jumpers. A device is needed to monitor indicators that predict ACL injury, especially in female horizontal jump athletes, without interfering with their jump performance.

3. Project Strategy

3.1 Initial Client Statement

The initial client statement was developed by faculty advisor Professor Funmi Ayobami. The scope of the project is as followed:

Athlete fatigue during track and field training often leads to an increased risk of injury. This is especially true for high impact, biomechanically-complex activities such as throwing or jumping. The goals of this project are to:

- Determine the kinematics and kinetics associated with the selected athletic activity during peak performance
- Determine and quantify changes in the kinematics and kinetics associated with the athletic activity during fatigue
- Design a device/system to alert coaches about athlete fatigue based on altered biomechanical performance during training

3.2 Technical Design Requirements

3.2.1 Objectives

The overall aim of our project is to design a device that is able to identify risk indicators within the legs in order to reduce ACL injuries. Since there is a heavy disproportion of women who suffer from ACL injuries more than men, the research team has decided to focus on ACL injuries specifically in women and how they may be monitored. To achieve this goal, the design needs to include the following objectives: detect the biomechanics of the jump, determine harmful changes in the biomechanics, and be functional in a practice setting, see Fig 3.1.

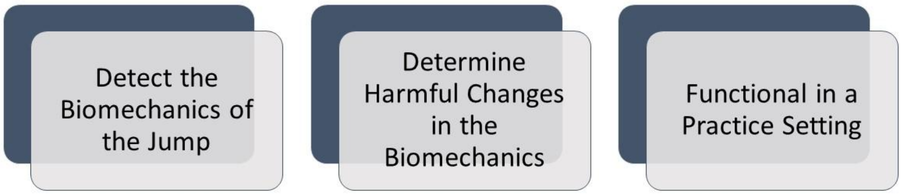


Fig. 3.1 Objectives to be met by final design**.**

Objective 1: Detect the Biomechanics of the Jump

To be able to determine harmful motion, we first need to quantify the normal motion of a jump. Since this device focuses on ACL injury, the biomechanics surrounding the knee are most relevant. This includes knee abduction/adduction, knee flexion/extension, and valgus positioning of the knees. This information provides quantifiable data on the biomechanics during the jump.

Objective 2: Determine Harmful Changes in the Biomechanics

Once we are able to detect the biomechanics of the jump, it is important to determine when there are changes from the normal biomechanics that may be harmful and lead to increased risk of injury. When looking at knee abduction/adduction, it will be important to determine if the knee is in valgus during landing, as this is often a risk for ACL injury. Additionally, with less knee flexion, the knee has more shear forces applied to it which increases risk as well. With reduced symmetry, more forces are applied to one leg compared to the other. It will be important to determine benchmarks for each of these biomechanics through values in literature, as well as observed values from practice videos.

Objective 3: Functional in a Practice Setting

Our device is intended to be used during track and field training, so it is important that it will be functional in a practice setting. The device or system should be user friendly since it is intended to be used by athletes and coaches. Without being user friendly, it is unlikely to be used. Another part of usability is setup. There is limited time during practice and the setup of the device should not take up much of this time, which would negatively affect training. The setup should be able to be performed by athletes and coaches as well so that it can be done without the MQP team present in the future. Additionally, the design should not impede the athlete's ability to perform their jump or distract them. When considering this, if it is a physical device, it should not be physically restraining in a way that will negatively affect performance. Any materials used should have enough elasticity and flexibility to support the motions of the athlete's leg without being restrictive. It also should not distract from practice. Finally, there should be quick feedback. The design should be able to give feedback in between jumps so if an athlete is displaying harmful biomechanics, they can stop before injury. The typical recommended time taken between jumps from the WPI track and field coach is about 8 minutes, so feedback should be given in this range of time ideally. Any further delay in feedback would delay practice. The feedback that is given should be clear and concise as well, so it will be useful to the athletes and coaches.

3.2.2 Constraints

The design of this device is limited by a few constraints. The first constraint is the budget provided to the design team. Each member of the project is entitled to only $250 each. With a total of five team members, the budget total cost is $1250. This limits the types of materials that can be bought, the forms of testing that can be deformed, as well as the manufacturing tools available for use. With this in mind, the design team has to construct a device made of specific materials, while still performing its primary function.

Next is time given for the end-product of this project. The design team was provided a window from August 24, 2022 to April 27, 2023 to complete the design of the device. This adds up to 246 days, which is approximately 8 months. Within this time period, the team must complete their report, full cycle of the design process and have a functional final product.

The number of human test subjects participating in the study is also a limiting factor. The team has decided to only focus on the long and triple jump events within the women's track and field competitions due to the prevalence of injury. Since the team is working with the women's track and field long and triple jumpers from Worcester Polytechnic Institute there are only 6 members. The subject group is not representative of men and women collegiate track and field jumpers on the regional, national or international level.

Additionally, our device would be limited to use only in jump practice sessions. The NCAA sets specific guidelines for Track & Field meets, including rules on equipment used by athletes and coaches. Any device developed within this project will most likely not be permitted to use in these meets under such guidelines.

Lastly, is the manner in which testing is executed. Due to the nature of our device and its intimate interactions with the human body, testing techniques have to follow certain ethical guidelines. Additionally, since the research is focused on the anterior cruciate ligament (ACL) found deep within the knee joint, we also have to utilize non-invasive testing techniques when verifying the functionality of the device.

3.2.3 Specifications

In addition to the general design objectives, there are technical specifications for the device. These specifications validate the precision, accuracy and functionality of the device.

- Any materials that come into contact with the athlete should not cause irritation to the user, even in the presence of sweat
- Feedback should be returned within 8 minutes
- Device should measure angles with a maximum error of 0.05 (5%)

3.3 Design Standards

Standards are requirements, specifications, guidelines, or characteristics that set regulations during the device development and production process. They are crucial to understand and execute to ensure consistency in materials, products, processes, and services to achieve the intended use of the device. General standards to follow include FDA device classification and the universal medical device standard set by the International Standards Organization (ISO). The device is intended to have low risk associated with use, therefore it would most likely be categorized by the FDA under device Class I. The FDA regulates general controls with Class I devices which include current "Good Manufacturing Practices" (cGMP), labeling, registration, and listing. Virtually all medical devices are subject to adhere to ISO 13485, the internationally recognized standard details a quality management system to be followed through all stages of device development, including design. Other specific technical standards that may be applicable to the final device are summarized in Table 3.1.

Table 3.1 Summarized Technical Standards and Compliance Methods.

Standard	Description	Application to Our Device	Actions for Compliance
IEEE 2700-2017 Sensor Performance	Establishes guidelines for sensor performance specifications.	We plan to use sensors to measure knee abduction angle.	We will need to check that the sensor performance specifications we provide meet this standard.
ISO 14155 Clinical Investigation of Medical Devices for Human Subjects	Establishes good clinical practices for design, conduct, recording and reporting of clinical investigations.	Our device prototype will be tested on human subjects	We will ensure the well-being of participants testing our device and follow applicable IRB processes.
IEC 60601-1 Medical Electrical Equipment	Establishes basic safety and performance specifications for medical electrical equipment.	Our device will include electrical components to take measurements.	We will ensure the electrical components of our device meet this standard with any necessary testing and supplemental research.
ISO 10993-10:2021 Biological evaluation of medical devices	Establishes safe procedures in regards to skin sensitization	We will be providing a pair of leggings to the users.	We will use leggings that are already on the market so we will be exempt from further testing.

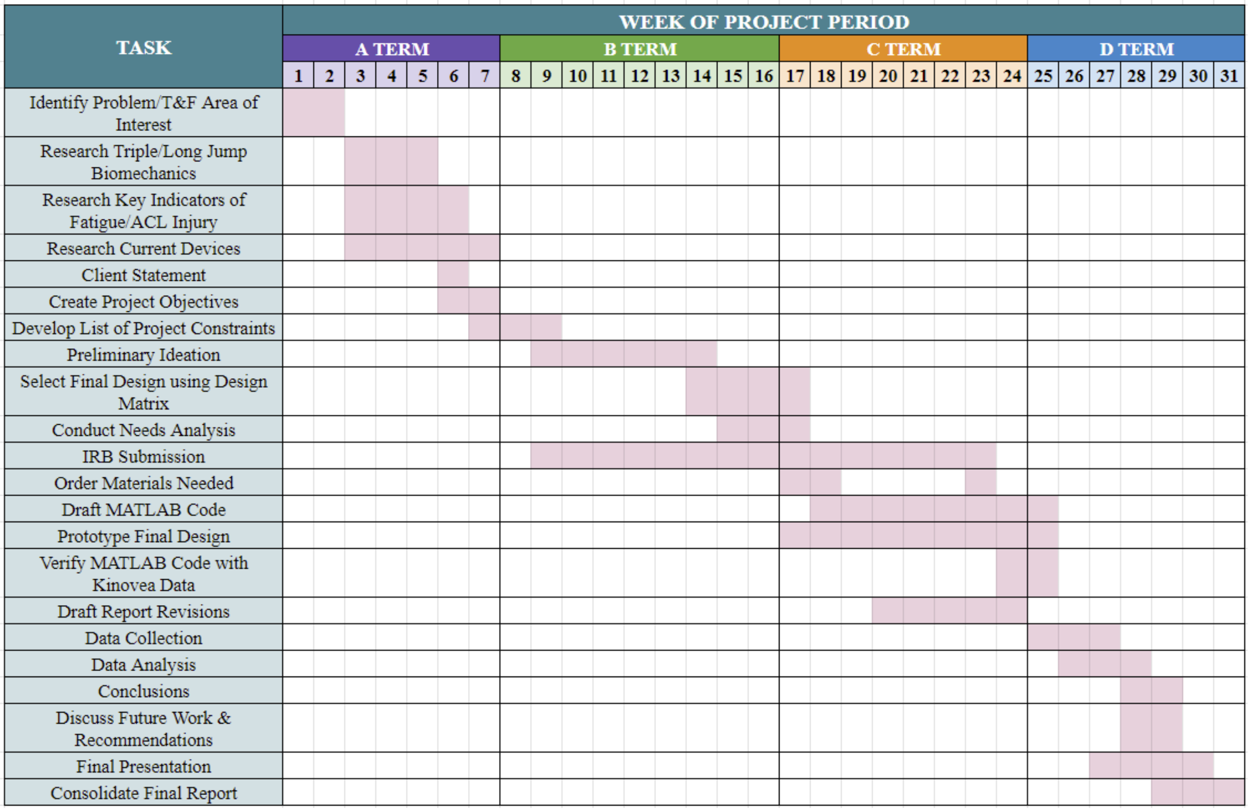
In addition to technical standards within device design, there are also ethical standards to consider. Since the final device will collect personal health information, there must be compliance with HIPAA, especially regarding security of health data storage and maintaining anonymity of human test subjects. All team members completed research ethics training and complied with the IRB process when conducting surveys and/or device tests.

3.4 Revised Client Statement

ACL injury is a common injury for women long and triple jumpers. A device that monitors a female athlete's long/triple jump to identify risk indicators is needed to reduce ACL injury. It must be noninvasive and minimal to ensure the athlete can regularly perform their jump. This device should include biomechanical monitoring to detect fatigue and harmful motion.

3.5 Management Approach

This project is being conducted over a course of four academic terms, lasting from August 2022 until May 2023. This project is being completed by use of the engineering design process, a continuous cycle starting with identifying the needs of the consumer, researching the problem, coming up with possible solutions, planning the design, creating the prototype, testing the prototype and then making improvements before going through the cycle again. As shown in Fig. 3.2, a Gantt Chart was created to dedicate durations to project tasks. This project may be extended into future years to continue the engineering design process and improve the final product following the conclusion of this project period.



TASK	WEEK OF PROJECT PERIOD																														
	A TERM							B TERM									C TERM								D TERM						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Identify Problem/T&F Area of Interest	■	■																													
Research Triple/Long Jump Biomechanics			■	■	■																										
Research Key Indicators of Fatigue/ACL Injury			■	■	■	■																									
Research Current Devices			■	■	■	■	■																								
Client Statement						■																									
Create Project Objectives						■	■																								
Develop List of Project Constraints							■	■	■																						
Preliminary Ideation									■	■	■	■	■	■																	
Select Final Design using Design Matrix														■	■	■	■														
Conduct Needs Analysis															■	■	■														
IRB Submission									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■								
Order Materials Needed																	■	■					■								
Draft MATLAB Code																		■	■	■	■	■	■	■	■						
Prototype Final Design																	■	■	■	■	■	■	■	■	■						
Verify MATLAB Code with Kinovea Data																								■	■						
Draft Report Revisions																				■	■	■	■	■							
Data Collection																									■	■	■				
Data Analysis																										■	■	■			
Conclusions																												■	■		
Discuss Future Work & Recommendations																												■	■		
Final Presentation																											■	■	■	■	
Consolidate Final Report																													■	■	■

Fig. 3.2 Gantt Chart of task durations throughout the project period.

4. Design Process

4.1 Needs Analysis

When thinking about the needs for our design, specific functional blocks emerge. These functional blocks, as shown in Fig. 4.1, are based on the original needs statement, and factors of the analysis that we have identified throughout the preliminary steps of our project.

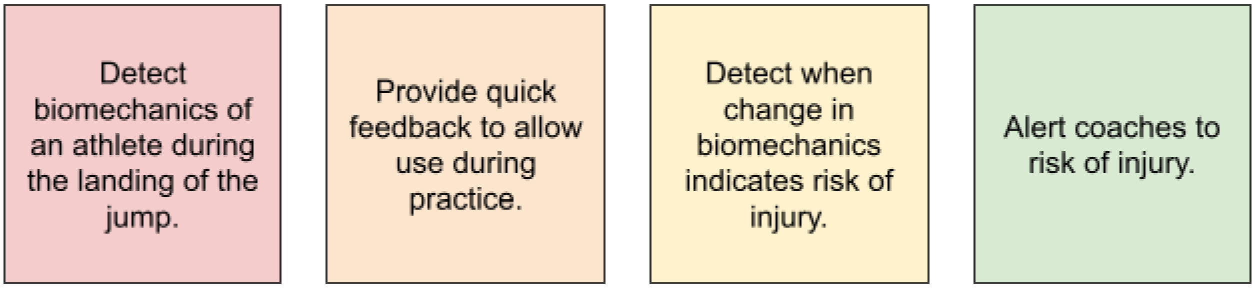


Fig. 4.1 Functional blocks of final design.

The design needs to be able to capture the biomechanics of the athlete during their jump. As discussed in the literature review, the abduction/adduction and flexion/extension angles of the knee can indicate harmful biomechanics. When both knees have an adduction angle during landing, rather than abduction angles, then the knees are in valgus positioning. Additionally, the quad-hamstring activation ratio is a good indicator of potential ACL injury. This can be indirectly determined by the flexion of the knee when landing from a jump. The more bent the knee is upon landing, the more quad force is used. This results in less shear force on the knee and therefore, less force on the ACL as compared to a landing with a larger flexion angle which would put more force on the hamstring. Additionally, the positioning and motion of the trunk can be used to locate the center of mass (COM), and if it is outside the core support of the body.

The design needs to detect when the athlete is beginning to show signs that indicate risk of injury. This is a combination of factors including: an increase in the knee flexion angle, increasing knee adduction causing the knees to be in valgus, the trunk positioning moving forward, and decreasing symmetry in landing. These factors increase the strain on the ACL which can cause a tear. When these factors begin to pass a threshold, the design should detect the motion and provide an alert.

The design must provide quick feedback so it can be utilized during practice. This project should be designed to be easily integrated into the current practice routine. While feedback does not need to be immediate, it should work quickly enough to not hinder the flow of practice, and to deliver a result quickly enough to actually mitigate injury. In order to do this, jumps should be analyzed and feedback should ideally be given before the next jump. In a typical jumps practice, the recommended wait time between attempts is 8 minutes. With this in mind, feedback on biomechanics should be given in this amount of time or less.

To prevent injury, the coach needs to be alerted of the harmful motion quickly and clearly to instruct the athlete. This means the data needs to be analyzed in less than 8 min to provide feedback before the next jump. The design also needs to indicate what motion the athlete is beginning to demonstrate, such as landings with larger flexion angles, so the coach can inform the athlete. This would allow the coach and athlete to try and correct the motion to reduce the strain on the ACL.

4.2 Concept Mapping

During the development of the project, the team created concept maps to determine the course of the production of the design. Fig. 4.2 shows how the team got from the brainstormed ideas to completing the final product while Fig. 4.3 shows how the team decided on the final design. These tasks that were performed were set in order to fulfill the stated objectives of detecting the biomechanics of the jump, determine harmful changes in the biomechanics of the jump, as well as making our design functional in a practice setting. The group began by brainstorming ideas collectively as a group. From previous courses taken at WPI, the team was able to come up with feasible design ideas that were influenced by other projects that were completed previously. The feasibility of these designs were then evaluated by design matrices. After determining the final design idea, the motion capture video analysis, the group was able to test theories based on previously recorded videos. Once the MATLAB code was written to analyze the angles of the knee from the video the data that was collected was then compared to a previously used program called Kinovea. Although Kinovea does not meet all of the design objectives, it does help locate angles of certain joints, allowing for verification of the MATLAB code. Once the accuracy of the code was tested, the addition of the final objective was completed by adding the element of alerting the coach of when an athlete is at risk of injury.

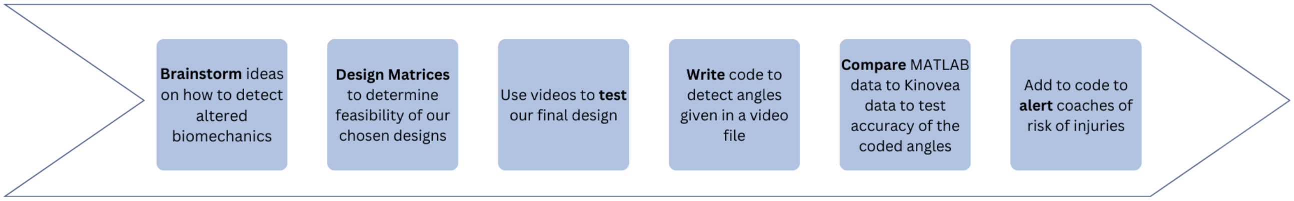


Fig. 4.2 Tasks performed to develop the final product

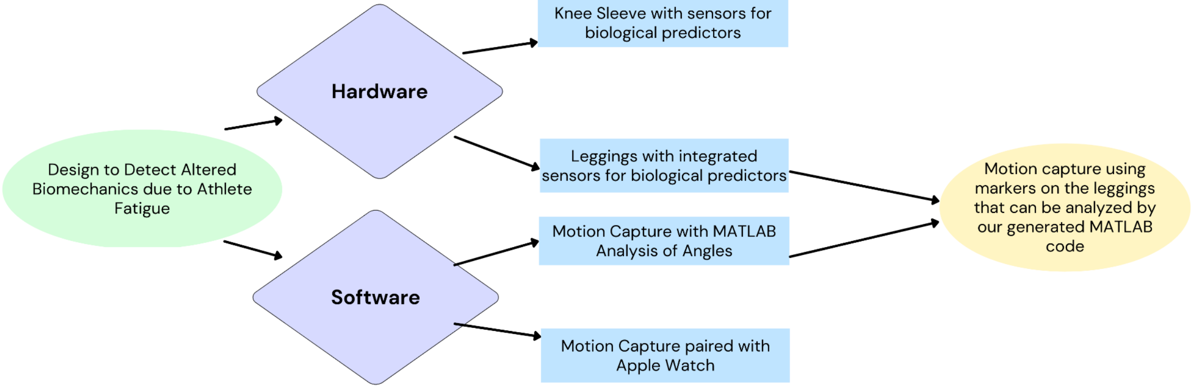


Fig. 4.3 Concept Map of how the team got to the final design

4.3 Alternative Designs

To achieve our needs for the design, three different designs were created to analyze biomechanics. The first, a video design, focuses on using motion capture analysis, the second, a knee sleeve design, uses integrated sensors, and the third, a legging design, uses integrated sensors. These three designs had advantages and disadvantages when trying to determine the biomechanics involved in a jump.

4.3.1 Motion Capture System

The video design captures the frontal and sagittal view of a jump as shown in Fig. 4.4 and 4.5. Motion capture analysis can accomplish some of the biomechanical analysis desired within our design. By pairing this motion capture with an Apple Watch or equivalent device, we can incorporate biological indicators into our analysis as well. The plan for this design is to use a camera to capture the front view, frontal, of the motion, as well as a camera, or multiple in the case of triple jump, to capture the side view, sagittal. A high-contrast tape such as kinesiology tape will be placed on joint markers to allow for the analysis of biomechanics in the videos. One software that can be utilized to analyze the videos is called Kinovea. This can track fiducial markers that are identified by the user, and measure the angles between them. It also allows frame-by-frame adjustments to ensure the software's tracking is accurate and does not move off of the markers. By tracking the angles by these markers, we could identify if or when the athlete is in risk of injury. However, this requires the videos to be uploaded into a software for analysis which adds a requirement for the user and increases the time between the jump and receiving feedback. Additionally, it would require multiple markers to be placed correctly on each athlete, which could introduce an area for user error.

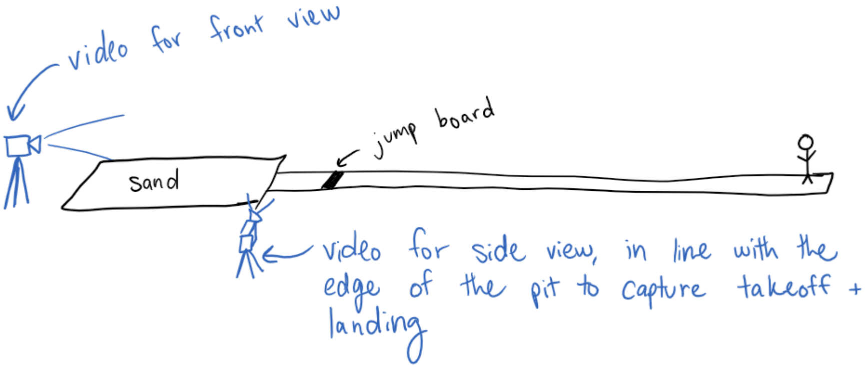


Fig. 4.4 Motion capture setup for long jump

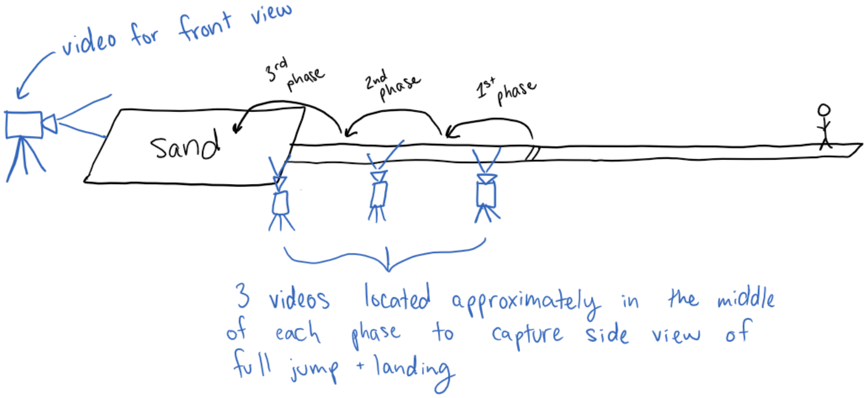


Fig. 4.5 Motion capture setup for triple jump

4.3.2 Knee Sleeve

Another design that is less software-based and more hardware-based is a knee sleeve as shown in Fig. 4.6. In this design, biological sensors could be integrated, or at least have a place for them to be attached. The biological sensors would detect the oxygen levels, body temperature, and sweat levels in order to determine if the leg is experiencing fatigue. Additionally, a battery pack or wireless transducer will allow the electrical components of the sleeve to run. Integrated sensors could also be used to analyze the biomechanics of the knee during the jump. However, this design limits the biomechanical data collected to just the knee. Since there are other factors such as trunk positioning that can affect ACL injuries, this design is limiting.

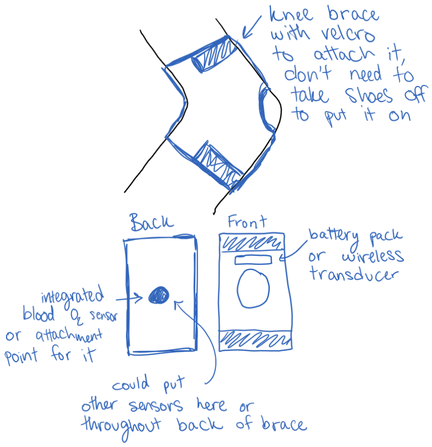


Fig. 4.6 Knee sleeve design

4.3.3 IMU Sensor Leggings

A third design would be an adaptation of the previous design of the leg sleeve, however, we would be using a pair of leggings as shown in Fig. 4.7. By doing this, we can get a more complete view of the leg and the biomechanics involved instead of just looking at the knee. Additionally, biological sensors can be integrated into the leggings to prevent the requirement of an additional device, such as with video monitoring. Another advantage to leggings is that it is unlikely to negatively affect performance, since many athletes are already accustomed to wearing them.

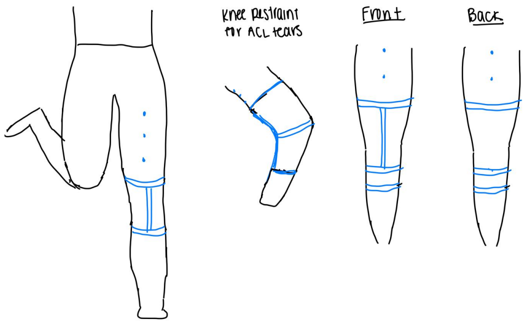
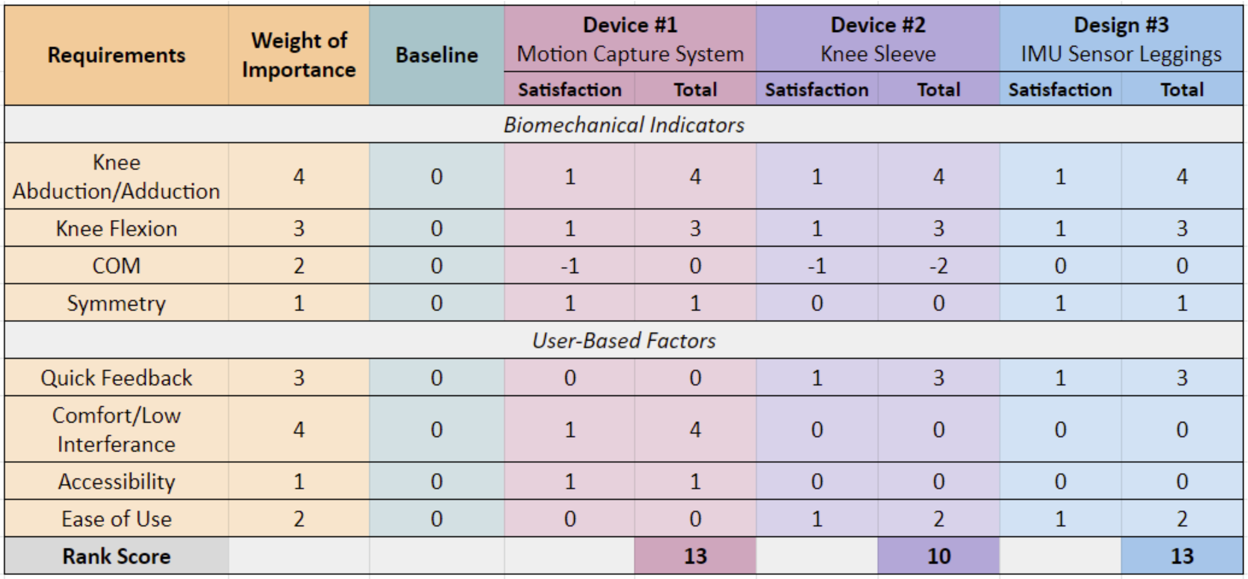


Fig. 4.7 IMU Sensor legging design

4.4 Final Design Selection

When determining a final design, the alternative designs must be analyzed both individually and comparatively. While all three designs aimed at addressing the same issue, there is a final design that will meet the design objectives most efficiently. To determine which of the preliminary designs to develop further, a Pugh Concept Selection Matrix was utilized as shown in Fig. 4.8. Each objective was given a weight based on its relative importance to analyze ACL biomechanical fatigue. If the conceptual design satisfied the requirement more effectively and efficiently than the baseline, it received a score of 1. On the other hand, if the conceptual design did not meet the requirement, it received a -1. If the requirement was met equally by the conceptual design and the baseline, it received a 0. A final score was determined for each device concept by calculating the sum of each objective's weight multiplied by the score assigned (-1, 0, 1). Based on the matrix, the Motion Capture Video Analysis System device was calculated to most effectively meet the design requirement with a score of 15.



Requirements	**Weight of Importance**	**Baseline**	**Device #1** Motion Capture System		**Device #2** Knee Sleeve		**Design #3** IMU Sensor Leggings	
			Satisfaction	**Total**	**Satisfaction**	**Total**	**Satisfaction**	**Total**
Biomechanical Indicators								
Knee Abduction/Adduction	4	0	1	4	1	4	1	4
Knee Flexion	3	0	1	3	1	3	1	3
COM	2	0	-1	0	-1	-2	0	0
Symmetry	1	0	1	1	0	0	1	1
User-Based Factors								
Quick Feedback	3	0	0	0	1	3	1	3
Comfort/Low Interferance	4	0	1	4	0	0	0	0
Accessibility	1	0	1	1	0	0	0	0
Ease of Use	2	0	0	0	1	2	1	2
Rank Score				**13**		**10**		**13**

Fig. 4.8 Pugh Concept Selection Matrix to quantitatively analyze and compare how each conceptual design fulfills requirements.

One thing we were quick to point out was the potential drawbacks of the knee sleeve design. While it could be useful for assessing the biomechanics of the knee, it is limited to only that part of the body. As we continued our research it became apparent that a design limited to such a small area of the knee would not be sufficient for assessing fatigue. One of the main biomechanical changes that leads to an ACL tear is the knee being in valgus. With a knee sleeve, it would be difficult to look at the knee placement in relation to the feet and hips, which is necessary to determine if a knee is valgus. Another drawback from this design was the effect for it to actually alter the athlete's biomechanics. By using a knee sleeve, it may add constraints to the joint which could cause injury or cause the joint to weaken. With all of these things in mind, we chose to remove the knee sleeve from consideration and take a closer look at our other two designs.

The two designs left to consider were a pair of leggings and video analysis. One thing that was important to consider was how our project was going to be integrated into the current practice routine. Videos are typically taken during practice to assess jump form already, so the athletes are already familiar with that procedure and would not have to make any changes in regards to that aspect of it. The main change would be requiring specific placement of the videos, and using a tripod to stabilize the video and allow for replication. Athletes typically wear shorts or leggings to practice, so asking them to wear a specific pair of leggings would likely not negatively affect performance. However, some athletes do prefer to wear shorts over leggings, so this could have an impact on willingness to wear the device. Creating a pair of leggings to be worn by every athlete would also be expensive, especially if they are going to have integrated sensors. The sensors that seemed most promising to use are inertial measurement unit (IMU) sensors. These would each be around $40, and multiple would be needed per pair of legging to fit athletes of various sizes and accurately record biomechanics.

While comparing the two designs, we wanted to consider the efficacy of each design and the limitations. One benefit to video analysis is that it can look at the whole body, which is beneficial if we choose to utilize trunk stability as a parameter, and the videos can still be used as current videos are, to analyze jumping form. A benefit to the leggings is that the quality of the results is less likely to be user-dependent. With leggings, sensors would be integrated and then used for analysis. With videos, athletes need to set up the cameras each time, and it is likely they may need to do some manipulation of the video so it can be analyzed. After revisiting our design matrix and thinking about the cost-benefit to each design, we decided to move forward with preliminary designs for video analysis.

After shifting our focus to video analysis, we considered how we could achieve what we wanted. We initially explored the software Kinovea as a reliable way of tracking fiducial markers and joint angles over time. While it is a great software, we had to think about feedback time and ease of use. We determined Kinovea could be leveraged for analyzing previous videos to assess the biomechanics we would be monitoring. By doing this, we could get an idea of the general trends for each parameter. Additionally, we could use Kinovea to test against the software we developed to validate our results. Members of our team have experience with MATLAB, so we chose to look into that software for our design. Another benefit of MATLAB is there are several packages that will help read and analyze videos, so we felt this to be an appropriate approach.

4.5 Final Design

Our final design, largely based on the video design, is a motion tracking video setup with leggings with designated iron-on vinyl markers on key anatomical locations worn by the jump athlete.

The markers are used to determine knee flexion angles and knee valgus positioning. This design uses the same concept of motion tracking from markers in the frontal and sagittal view, but instead of having the athlete or coach place tape, the markers will be ironed onto a pair or legging for the athlete to wear. This provides an inexpensive solution that removes the time and effort needed to place multiple markers on each athlete. Additionally, it would keep the placement consistent, reducing opportunity for user error. This design has the same benefits of the preliminary video design: minimal interference, full leg view, and easy application for multiple athletes, and additionally further improves the ease of use by reducing action needed from the athlete or coach.

5. Design Verification

5.1 Camera Alignment

Initially, the cameras were to be aligned with each phase of the triple jump. Since most ACL injuries occur during the landing of a jump rather than the phases leading up to it, the cameras were positioned to capture the landing biomechanics. As a result, the three cameras were changed to focus on the sagittal and frontal planes of the landing in the pit as shown in Fig. 5.1 below.

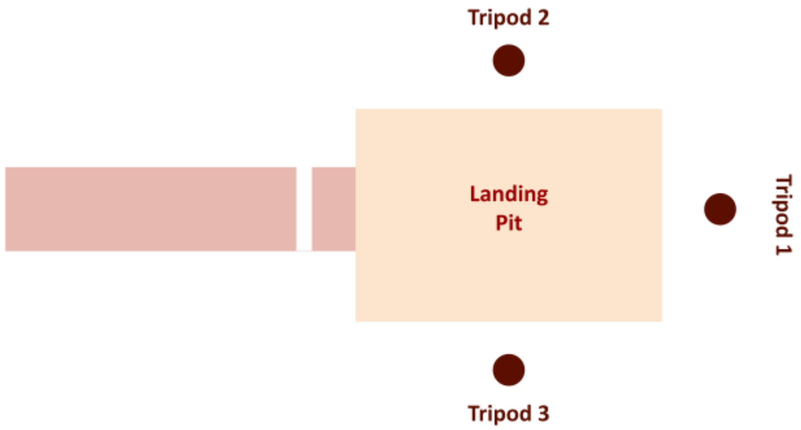


Fig. 5.1 Tripod set-up for new recordings of long and triple jump athletes.

A factor that was not previously considered was the location of the landing pit and the available space surrounding it. When initially testing the motion capture system set-up, the WPI Recreation Center indoor jump landing pit was used. This landing pit is very close to the gym wall, without enough space to place the tripod to record the right sagittal plane of the jump athlete limiting analysis to only the frontal and left sagittal planes, as seen in Fig. 5.2 and 5.3. Thus, the right knee flexion angle and velocities cannot be determined to alert potential risk factors for an ACL injury in the right knee. However, the WPI outdoor jump landing pit has plenty of surrounding space so all three tripods can be utilized, which would allow full analysis of both left and right sagittal planes of the athlete and provide more alerts for an athlete's risk of injury. The camera is placed so the athlete lands in roughly the center of the frame.

Fig. 5.2 Tripod set-up for recordings of long and triple jump athletes on the WPI Recreation Center indoor jump landing pit: left sagittal view.

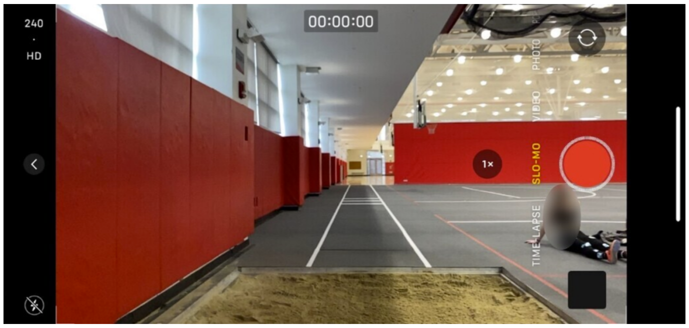
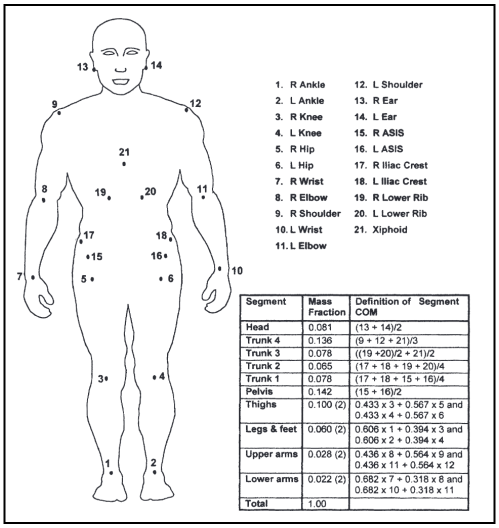


Fig. 5.3 Tripod set-up for recordings of long and triple jump athletes on the WPI Track and Field outdoor jump landing pit: frontal view

5.2 Marker Placement

In our final design, anatomical markers as shown in Fig. 5.4 (Winter, 2009) are used with the video capture in which the team-written code reads and locates specific areas of the lower body to calculate the angles produced. To determine the knee angles, a marker needs to be placed on the frontal and sagittal planes of the femoral head and lateral distal tibiofibular joint, as well as the lateral knee joint and patella. This means six markers on each leg, three on each plane. However, when the left and right knees reached above the hips, the markers in the frontal plane were covered and unable to be seen. The same issue was presented when the foot became flexed and the tibiofibular joint was no longer visible in the frontal view. As shown in Fig. 5.5, the markers were then moved to the femoral shaft and tibial shaft in order to be visible in videos while in line with the frontal view of the femoral head and tibiofibular joint.



Segment	Mass Fraction	Definition of Segment COM
Head	0.081	(13 + 14)/2
Trunk 4	0.136	(9 + 12 + 21)/3
Trunk 3	0.078	((19 +20)/2 + 21)/2
Trunk 2	0.065	(17 + 18 + 19 + 20)/4
Trunk 1	0.078	(17 + 18 + 15 + 16)/4
Pelvis	0.142	(15 + 16)/2
Thighs	0.100 (2)	0.433 x 3 + 0.567 x 5 and 0.433 x 4 + 0.567 x 6
Legs & feet	0.060 (2)	0.606 x 1 + 0.394 x 3 and 0.606 x 2 + 0.394 x 4
Upper arms	0.028 (2)	0.436 x 8 + 0.564 x 9 and 0.436 x 11 + 0.564 x 12
Lower arms	0.022 (2)	0.682 x 7 + 0.318 x 8 and 0.682 x 10 + 0.318 x 11
Total	1.00	

Fig. 5.4 Anatomical locations for biomechanical analysis (Winters, 2009).

Fig. 5.5 Frontal (left image) and sagittal (right image) view of marker placement with athletic tape.

Originally, these anatomical markers were placed on the athlete with athletic tape for highest location accuracy to the joints. However, users who are not familiar with anatomical positions may misplace markers, contributing to human error, and disrupt practice time. A design that would be able to mark general locations of each joint without the user individually placing markers was needed. As shown in Fig. 5.6, this design developed into leggings with larger markers made of iron-on vinyl that athletes could easily reuse and take on and off. The placement of the joint markers replicated the previous athletic tape positions from Fig. 5.5. The bright white and blue vinyl 2 ¼" squares contrasted with the black leggings and made it easier for the video to recognize the anatomical locations of the hip, knee, and ankle joints to track coordinates, and thus calculate angles produced in the jump. The sagittal knee joint markers were made smaller than the rest, 1 ⅛" blue squares bordered with white, due to its close proximity to the frontal knee joint markers.

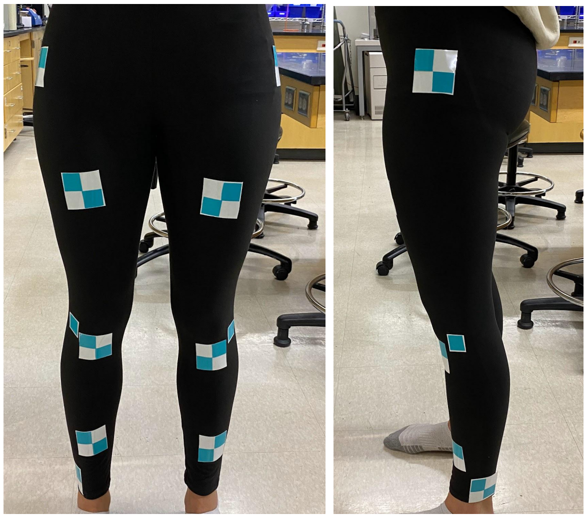


Fig. 5.6 Frontal (left image) and sagittal (right image) view of marker placement on initial legging design.

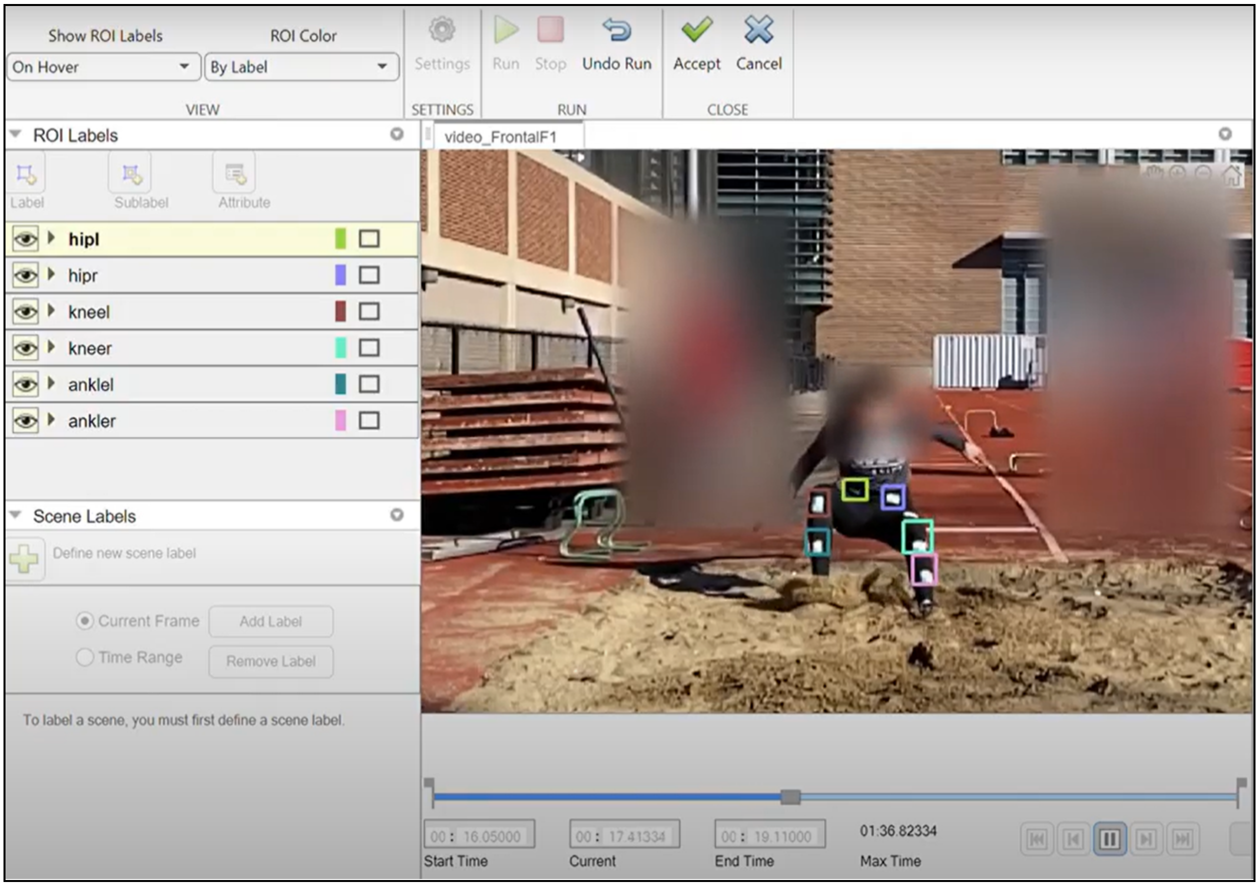
With further testing, the sagittal knee joint markers were too small to be detected when the knees flexed at landing. In the final legging design shown in Fig. 5.7, all joint markers were 2 ¼" vinyl squares as there was no issue with the sagittal knee marker's relation to the frontal knee marker. In order to also capture the trunk, two additional markers were added at the left and right ilium superior to the hip joint in the frontal plane of the leggings. The ilium and femoral shaft markers are proxy to the hip joint and the tibial shaft markers are proxy to the ankle joint. These are not common anatomical locations for biomechanics, but due to the athlete's movement during landing, the markers would not be seen in the frontal view if directly placed on the hip and ankle joints.

Fig. 5.7 Frontal (left image) and sagittal (right image) view of marker placement on final legging design.

The final legging design includes 14 total markers, 7 on each leg. In the frontal view, the coordinates of markers at the left and right ilium, femoral shaft, patella, and tibial shaft are used to determine when the knees are about to or have become valgus. In the sagittal view, the markers at the femoral head (hip joint), lateral knee joint, and the lateral distal tibiofibular joint (ankle joint) are utilized to calculate knee flexion angle during landing.

5.3 Preliminary Code

To be able to determine the biomechanics of the knee, coordinates of key markers need to be extracted from a video file of a jump. The code (Appendix D) analyzes a video file using videoLabeler in MATLAB as shown in Fig. 5.8. This prompts the user to identify markers in a video, and will track the location for the duration of the video. The data for these markers are then exported as coordinates. The coordinate values can then be used with the angle code below to determine the angle between the marker coordinate at any frame in the video.



Show ROI Labels: On Hover

ROI Color: By Label

To label a scene, you must first define a scene label.

Start Time: 00 : 16.05000

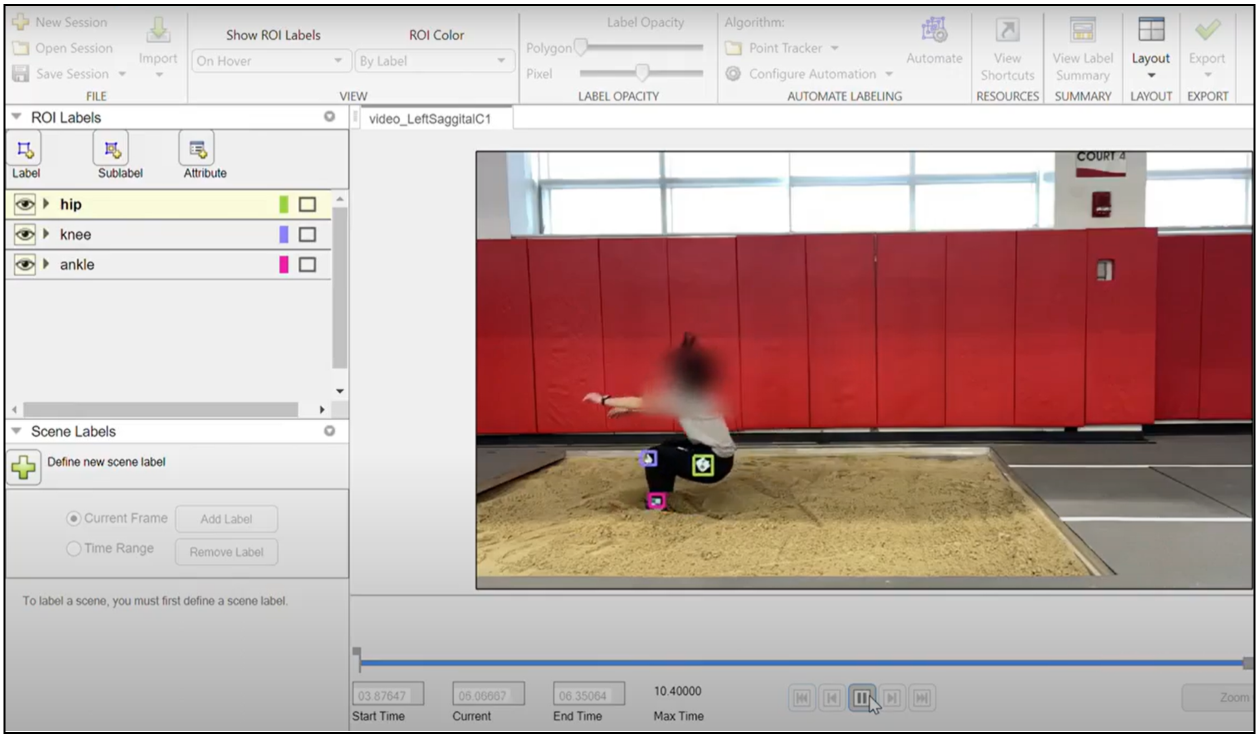
Current: 00 : 17.41334

End Time: 00 : 19.11000

Max Time: 01:36.82334

Fig. 5.8 Example of MATLAB videoLabeler command window with frontal marker labels.

To begin analysis on jumps, data on the biomechanics needs to be collected from the coordinate data calculated from the video. To do this, the knee flexion/extension angles have to be determined from a marker coordinates. The code (Appendix D) is used to determine the angle between three marker coordinates over the course of a video, as shown in Fig. 5.9, and then can be used for further calculations and analysis.



To label a scene, you must first define a scene label.

Start Time 03.87647

Current 06.06667

End Time 06.35064

Max Time 10.40000

Fig. 5.9 Example of MATLAB videoLabeler command window with sagittal marker labels.

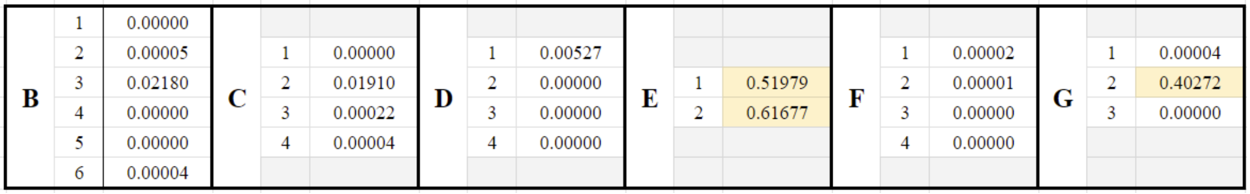
5.4 MATLAB Accuracy Verification

To verify the accuracy of the MATLAB code in tracking the markers over the landing period, the same videos were analyzed through another software, Kinovea. Similar to MATLAB, Kinovea allows the user to automate marker trackers and measure angles as shown in Fig. 5.10, but the automated points can be easily adjusted frame by frame for highest accuracy.

Fig. 5.10 Tracked angle measurement of jumper within Kinovea.

The knee flexion angles generated by Kinovea and MATLAB were analyzed in a two-tailed, paired t-test to determine if there is a statistical significance between data sets. In this statistical test, the null hypothesis would be that there is a significant difference between the automated MATLAB tracking data and the Kinovea data, therefore MATLAB would not produce reliable data. If the resultant p-value equaled less than 0.05, then the data between softwares was statistically significant and the MATLAB automation produces accurate measurements and analysis. If the resultant p-value equaled greater than 0.05 and less than 0.95, then the data between softwares was not statistically significant and the null hypothesis would be accepted.

Table 5.1 P-values from two-tailed, paired t-test of each jumps' knee flexion angles on MATLAB and Kinovea during landing period.



B	1	0.00000	**C**			**D**			**E**			**F**			**G**		
	2	0.00005		1	0.00000		1	0.00527					1	0.00002		1	0.00004
	3	0.02180		2	0.01910		2	0.00000		1	0.51979		2	0.00001		2	0.40272
	4	0.00000		3	0.00022		3	0.00000		2	0.61677		3	0.00000		3	0.00000
	5	0.00000		4	0.00004		4	0.00000					4	0.00000			
	6	0.00004															

As shown in Table 5.1, most of the jumps were statistically significant - almost 70% of jumps had a p-value below 0.0001 meaning MATLAB and Kinovea data sets are the same. There were three jumps (highlighted in yellow) where the p-value exceeded 0.05: E1, E2, and G2. Most likely, these three MATLAB data sets were not statistically significant due to periods of time within the landing where at least one marker was blocked in the video. As shown in Fig. 5.11, E1 had the sagittal ankle joint marker blocked from the sand depth while sliding to land, E2 blocked the sagittal hip marker with their left arm, and G2 blocked their sagittal knee joint marker with their hand. This non-statistical significance within these three jumps means that the data produced by MATLAB is not as reliable if one or more markers are obstructed from the camera's view. However, it can be concluded that if all markers are visible in the video then MATLAB's data is accurate.

Fig. 5.11 Moments markers were blocked in jumps E1 (left), E2 (middle), and G2 (right).

5.5 Rigid Body Error in Leggings

This project analyzes the rigid body biomechanics associated with horizontal jump landing. The markers that provide coordinate data for analysis are not directly placed on the rigid body, but rather on a pair of stretchy leggings. Therefore, it is expected that the markers will move as the athlete moves. To determine how much percent error the leggings produce as a non-rigid body, the average deviations of the hip to knee and knee to ankle distances were calculated for each jump and then divided by the mean distance. The percent error for each jump is shown in Table 5.2 below. From these values, the average percent error for all jumps is 4.95% - a relatively small error that should minimally impact data collected. This error is slight, but still important to consider in the final data output as the markers may deviate slightly from the original anatomical location.

Table 5.2 Average percent error of hip to knee and knee to ankle distances in each jump.

		Hip-Knee Percent Error	Knee-Ankle Percent Error			Hip-Knee Percent Error	Knee-Ankle Percent Error			Hip-Knee Percent Error	Knee-Ankle Percent Error
B	1	3.73%	5.88%	**C**				**D**			
	2	2.53%	2.37%		1	7.03%	3.46%		1	4.25%	4.32%
	3	3.17%	2.77%		2	7.80%	1.61%		2	1.41%	4.13%
	4	2.47%	2.90%		3	8.99%	1.70%		3	2.27%	4.09%
	5	1.37%	3.09%		4	6.07%	1.40%		4	3.18%	5.61%
	6	5.46%	4.25%								

		Hip-Knee Percent Error	Knee-Ankle Percent Error			Hip-Knee Percent Error	Knee-Ankle Percent Error			Hip-Knee Percent Error	Knee-Ankle Percent Error
E				**F**				**G**			
					1	5.97%	1.44%		1	2.16%	6.29%
	1	1.49%	27.17%		2	12.79%	2.45%		2	4.20%	4.88%
	2	1.79%	4.94%		3	20.39%	2.59%		3	6.44%	12.62%
					4	2.02%	0.72%				

6. Final Design and Validation

6.1 Experimental Methods

6.1.1 Code Development Methods

To create the code, the team utilized MATLAB, and specifically the Video Labeler package in MATLAB. In this software package, you are able to mark various regions of interests (ROI) in an image or video frame, keep these ROIs consistent across video frames, and then export this labeled data into an external file. One important aspect of developing the program was figuring out how to keep track of each athlete's data separately. The program is designed to utilize maps with each athlete's name being used as a key to store the data under. The values currently stored under each athletes' name is the number jump they are on, as well as all previous jump data including sagittal and frontal video data. To keep track of jump numbers, once a new video is added for a specific athlete, their jump number is incremented by one.

Once the coordinate data has been exported from the Video Labeler, the code performs analysis and stores values such as the average angular velocity and hip average vertical velocity over the course of the landing (for the sagittal view), and if both knees are in valgus (for the frontal view). The average velocity values are each calculated over a time period of 0.1 seconds. To check for valgus positioning, the x-values of the knees are compared to the x-values of the hip and ankle. All collected video data is then exported into an Excel workbook, with a new sheet labeled with each jumper's name and jump number. There is one Excel workbook for each camera view, and they are each opened for the user to view.

6.1.2 Data Collection Methods

Before conducting human subject based research, the team received IRB approval (Appendix B) for all research activities. Prior to participation, all participants were informed of project details and signed a consent form (Appendix A). All identifying features were not associated with data collection - each jumper was assigned a letter for confidentiality and faces were blurred in any publicized images. The team kept all data related to participants confidential and confined to project work.

The code that the team developed was used to collect data on the landings of jumps. To do this, the tripods with cameras needed to be set up around the sand pit. The cameras were placed according to Fig. 5.1, with the third camera only being used when the jumps were taking place outside. The indoor sand pit was a wall, preventing the placement of a third camera to capture the right sagittal plane.

The jumpers, wearing the leggings described in Section 5.2, performed multiple jumps. The cameras on the tripods were set to slow-motion video (240 frames per second) and were started when the jumper began to run towards the sand pit and stopped when the jumper walked out of the pit. The jumpers waited briefly between jumps based on the regular activity of practice or personal preference.

Once the videos were collected, the videos were uploaded to generated MATLAB code and the markers were tracked for the duration of the landing. The landing is defined as the moment their feet hit the sand to when the hip stops moving down. The code produces the coordinate data for the markers which was used to calculate various measures. From the sagittal view, the knee flexion angles, angular velocity, and hip vertical velocity for the duration of the landing was calculated. From the frontal view, the x-coordinate of the knee and hip marker was used to determine if the knees were in valgus during the landing. Knee valgus positioning was determined if both the knee x-coordinates are between the hip and ankle x-coordinates. This data was exported into a spreadsheet for further analysis. Each jumper was labeled with a letter and number indicating which jump. For example, A1 and A2 are the same jumper but two different sequential jumps.

Since the videos were taken in slow-motion, the time data needed to be converted to real-time. One real-time second is equivalent to eight slow-motion seconds. Therefore, the time data was divided by eight before performing analysis to be representative of the correct time range of the landing.

6.2 Data Analysis

Once the data was exported to a spreadsheet, flexion angle, angular velocity, and hip vertical velocity were determined for the sagittal view. First, the flexion angle over the course of the landing was plotted. Of all the jumpers observed, the flexion angle did not exceed 155 degrees with the greatest angle occurring at the initial part of the landing. The smallest angle observed was 25 degrees, and always occurred at the end of the landing. The curve of the data appeared to vary between jumpers. Some jumpers displayed a fairly linear curve such as jumper B in Fig. 6.1 below while some jumpers displayed a logarithmic curve such as jumpers C and D, Fig. 6.2 and Fig. 6.3. This could be the result of jumper B landing in a sitting position, with the exception of jump 1, while jumper C and D remained standing. While the curves appeared to differ between jumpers, the curves were fairly consistent between jumps, indicating that if a jumper displays a constant decrease in knee flexion angle, then the proceeding jumps will likely display a similar linear decrease.

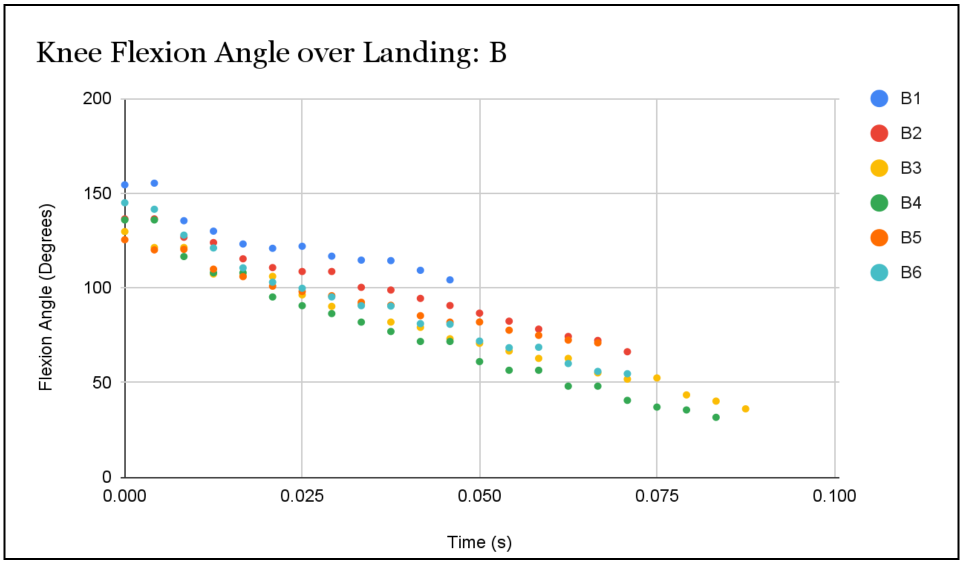


Fig. 6.1 Knee flexion angle over landing for jumper B for jumps 1 through 6.

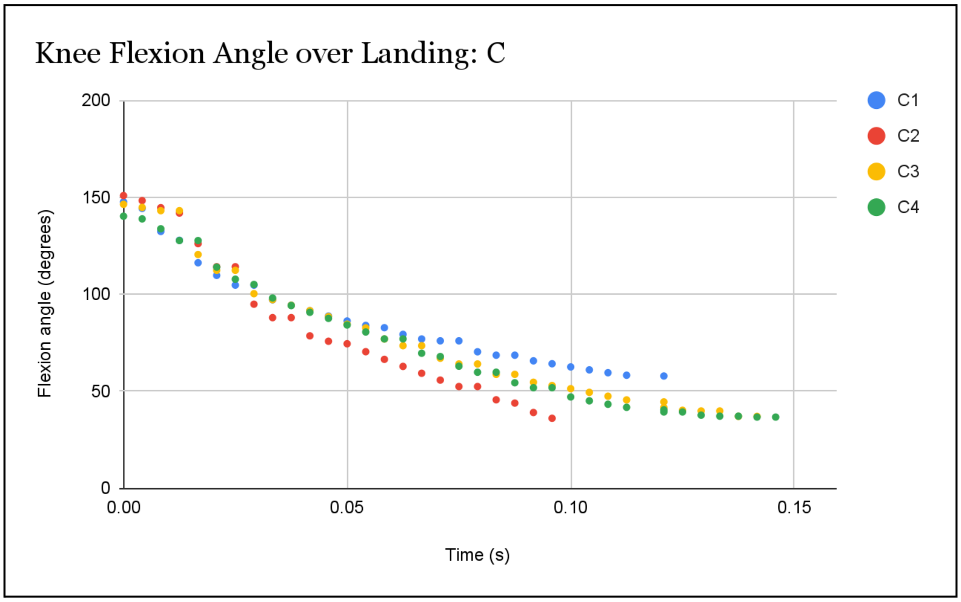


Fig. 6.2 Knee flexion angles over landing for jumper C in jumps 1 through 4.

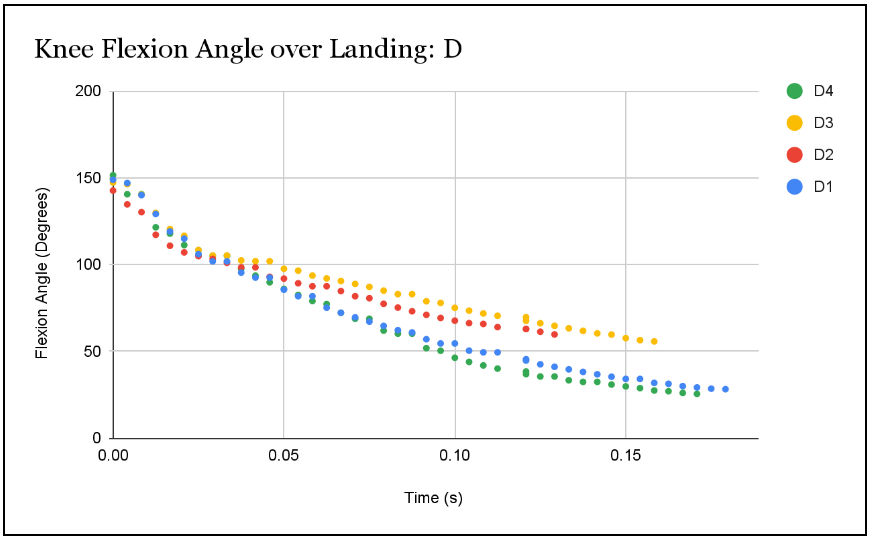


Fig. 6.3 Knee flexion angles over landing for jumper D in jumps 1 through 4.

If an athlete is becoming fatigued, they would have less control of their landing which results in a faster vertical decline and therefore angular velocity. The average angular velocity of the knee flexion angles were calculated from the change in knee flexion angle over a 0.1 second time interval. The angular velocity generally peaked at roughly 300 degrees/sec with the highest angular velocity determined was 321 degrees/sec, and declined to 0 degrees/sec. However, some jumpers begin the landing at the peak angular velocity, Fig. 6.4 and Fig. 6.6, while others begin at a low angular velocity and have a steep increase to the peak, Fig. 6.5. This could indicate that some jumpers land with more muscle activation than others. While there were different trends between jumpers, the curve was consistent between the same jumpers multiple jumps.

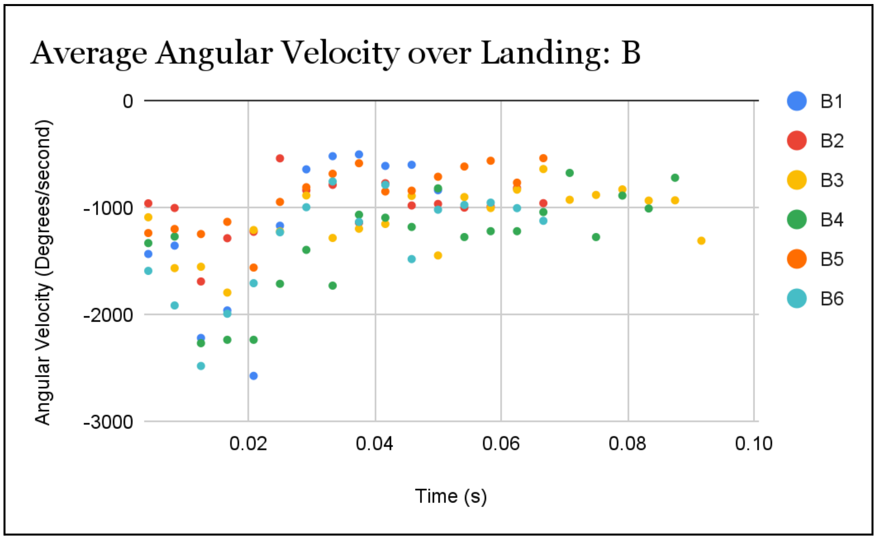


Fig. 6.4 Average angular velocity of the knee flexion angle for jumper B in jumps 1 through 6.

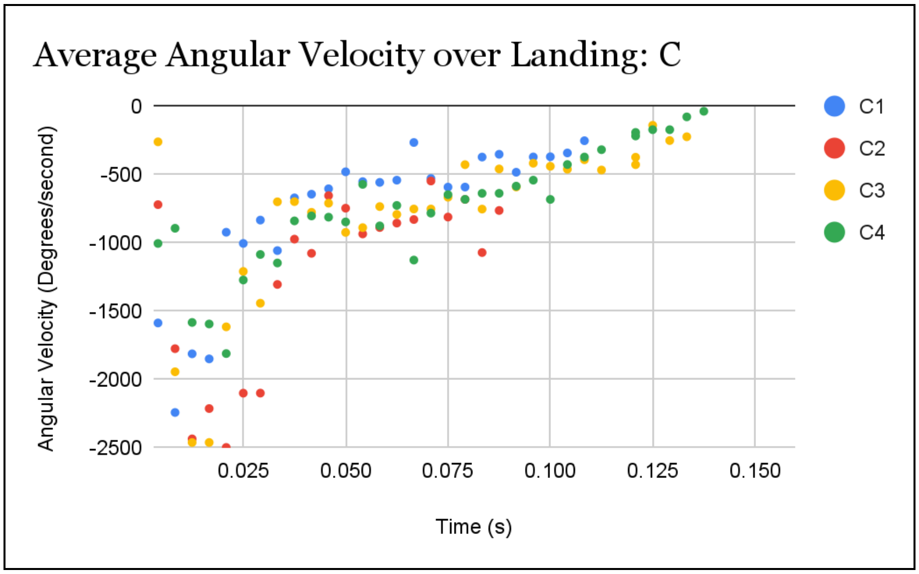


Fig. 6.5 Average angular velocity of the knee flexion angle for jumper C in jumps 1 through 4.

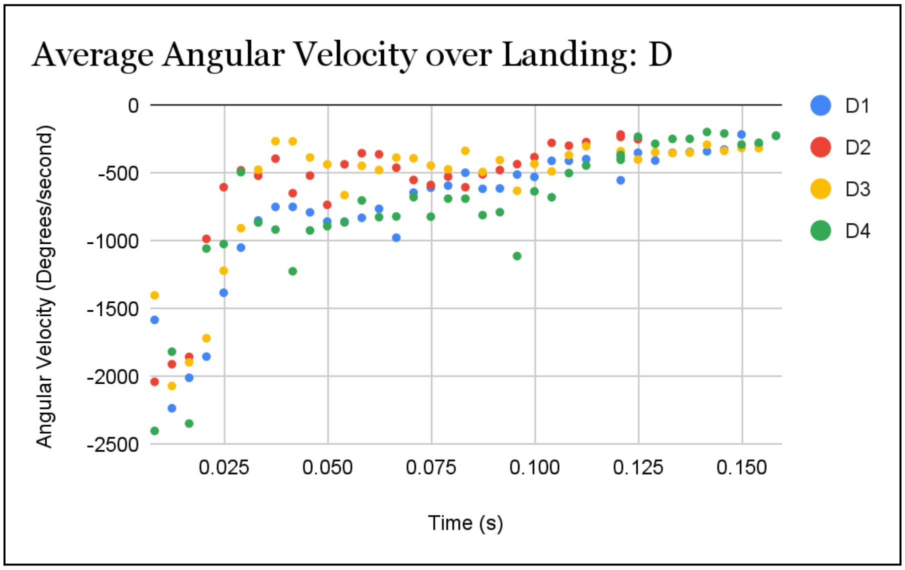


Fig. 6.6 Average angular velocity of the knee flexion angle for jumper D in jumps 1 through 4.

A similar measure to angular velocity that was determined was average hip vertical velocity. This measured the change in the y coordinate of the hip marker over the course of the landing. Both of these measures can indicate the amount of muscle activation. If a jumper is becoming fatigued, they would use less muscle activation resulting in changes in the angular and hip velocity. These changes could be an increased peak velocity, or a delayed peak velocity. Generally, the average hip vertical velocity began at roughly 0.85 m/s and declined to 0 m/s. Fig. 6.7 displays a peak in velocity at 0.7 seconds for jump D4, the last jump. This is a deviation from the trends of the previous jumps for jumper D, and the trends displayed by other jumpers, such as Fig. 6.8. This second peak in velocity could be the result of the jumper becoming fatigued.

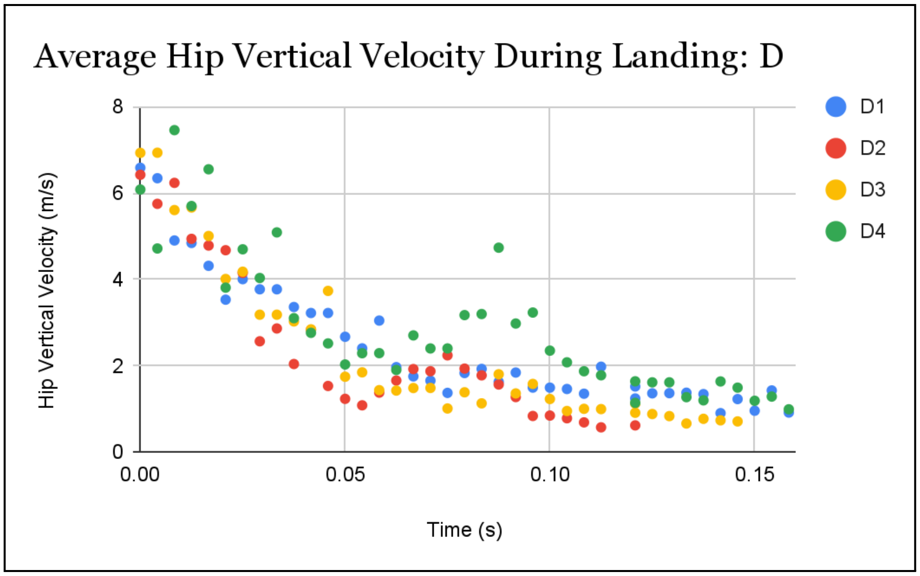


Fig. 6.7 Average hip vertical velocity during landing for jumper D in jumps 1 through 4.

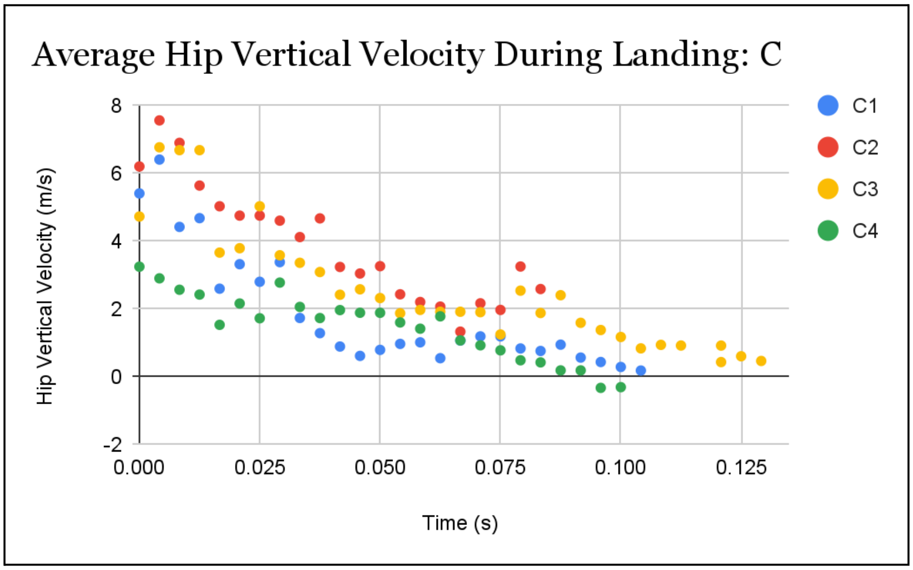


Fig. 6.8 Average hip vertical velocity during landing for jumper C in jumps 1 through 4.

While the angular velocity and hip vertical velocity are similar measures, if the knee marker was obscured or the jumper twists out of frame, the hip vertical velocity is a clearer measure. For example, jumper F had a series of jumps that resulted in a different biomechanical pattern. The first jump, F1, the foot that was being tracked slid forward to be fully extended while the other foot did not. The second and third jump, F2 and F3, the jumper twisted away from the camera as they fell. This resulted in skewed knee flexion angles as the jumper ended facing the camera. As a result the knee flexion angle, Fig. 6.9, and the average angular velocity, Fig. 6.10, does not accurately display the flexion angles that occurred and had a large spread in the data. However, the average hip vertical velocity, Fig. 6.11, still displayed consistent trends in line with the rest of the data as this measure does not depend on all three markers remaining in the same plane.

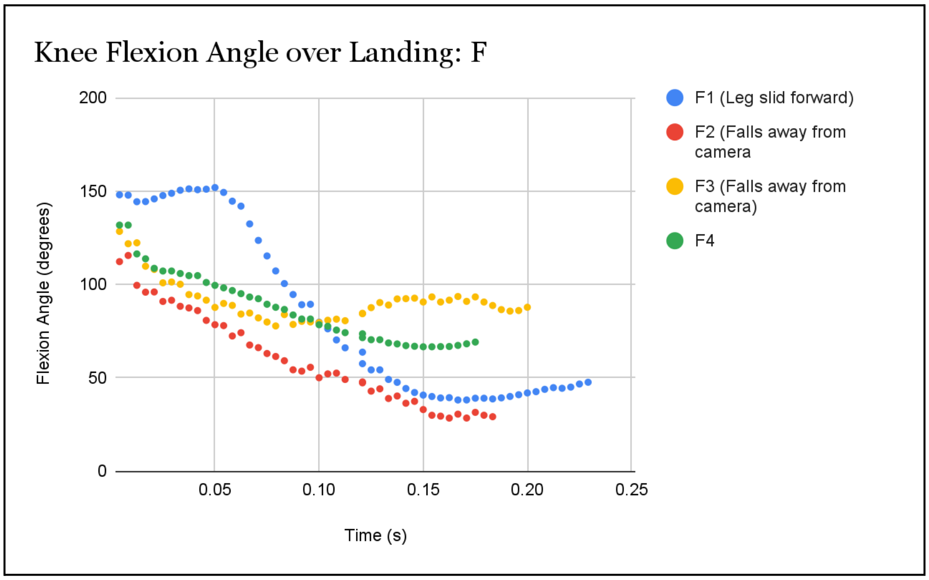


Fig. 6.9 Knee flexion angle over landing for jumper F in jumps 1 through 4.

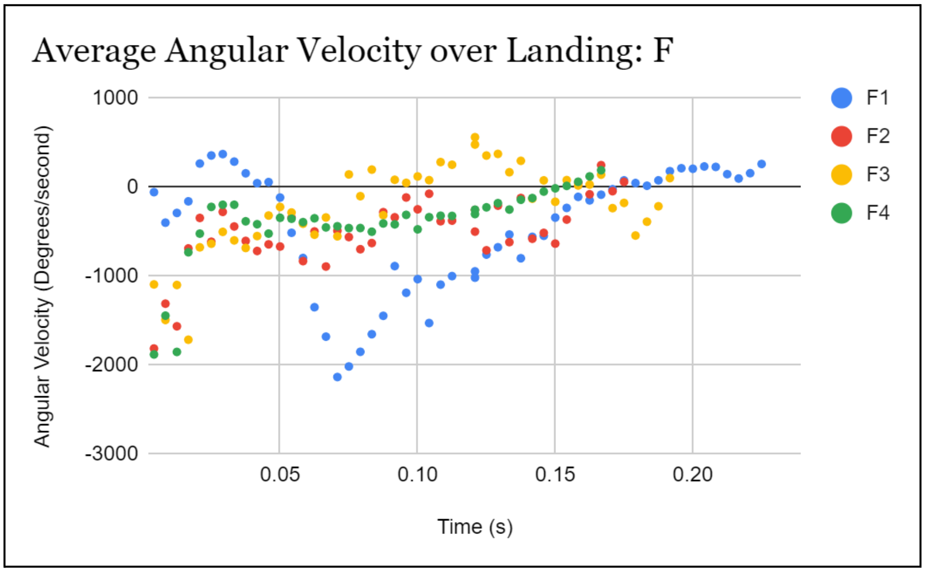


Fig. 6.10 Average angular velocity of knee flexion angle over landing for jumper F in jumps 1 through 4.

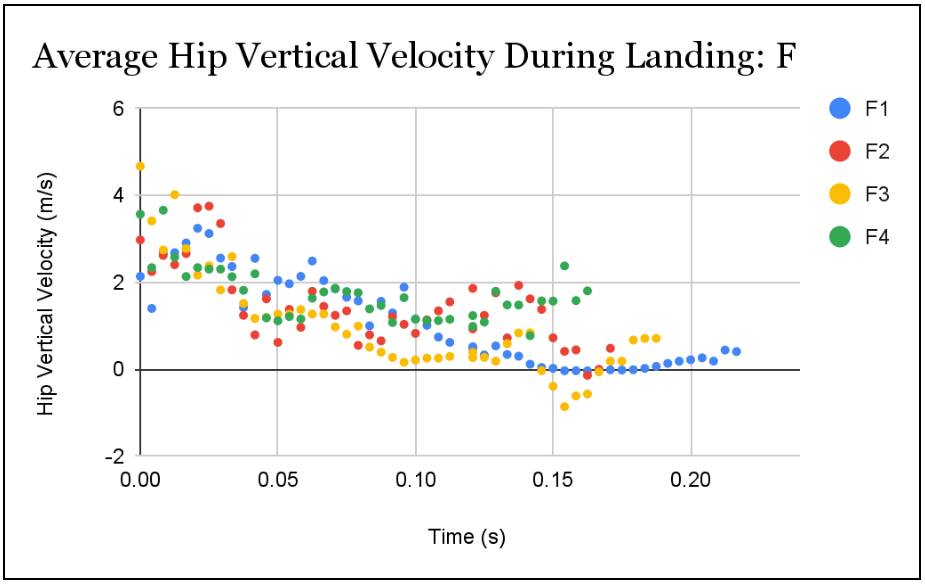


Fig. 6.11 Average hip vertical velocity during landing for jumper F in jumps 1 through 4.

This data collected determine the average normal ranges for knee flexion angles, angular velocity, and hip vertical velocity. Additionally we determined trends for jumps of the same athlete and between different athletes. These values and trends were used to incorporate alerts into the MATLAB code.

6.3 Project Impacts

6.3.1 Economics

As stated earlier, anterior cruciate ligament (ACL) injuries are one of the most common lower extremity injuries sustained during long and triple jump. This injury not only has a physical impact, but a financial impact on the athlete. ACL injuries are treated in one of two ways, the surgical and non-surgical method. The non-surgical method entails a brace for increased stability in the knee joint, coupled with physiotherapy to strengthen the surrounding muscles and ligaments. This is often used in cases where the injury is more minor, i.e there is a small tear in the ligament. Surgical treatment is the next viable option for injury. This is used in more severe cases, such as a complete tear or rupture of the ligament. Once completed, there is usually an extensive rehabilitation and recovery period. Both treatments are quite expensive and require a lot of medical attention. According to New Choice Health databases, the average national cost of ACL reconstruction surgery is $15,445 and the average price for Boston, MA is $21,950, both pre-insurance deductions (New Choice Health, 2023). Sometimes these expenses put the person, and sometimes medical facilities, in debt.

This final project design is aimed at early detection of athlete fatigue in order to reduce ACL injury occurrence. By increasing the chances of detection and reducing the amount of injuries, fewer athletes will have to pay for these expensive medical procedures, save money and keep some financial stability. Another benefit is increased participation in competition which increases team morale and an athletic team's ranking in competition. This also improves the mental well-being of athletes by lessening injury concerns, feelings of isolation due to missing training sessions, and disappointment from lower athletic performance.

On the other hand, there can be some economic ramifications. In reducing the number of ACL repair surgeries and treatments, the market price for these procedures may drastically change. It may either increase due to resource costs, or decrease to encourage market sales. With this design as the cheaper option, there may also be a shift in market focus to creating various injury detection devices to be used. The team's final design may then suffer due to more advanced, efficient and specialized systems being designed. Additionally, it is important to note that this design, while being a cheaper option, is still costly. This puts lower funded athletic teams and athletes of a lower socioeconomic status at a disadvantage of not being able to purchase this product. Even if some were able to simply buy the product, they may not be able to afford any maintenance fees applied in the future.

Overall, this device has significant benefits to the athlete's and athletic staff's finances. It may also cause a positive change within the sports medical devices and promote the growth of a new sector within the field.

6.3.2 Environmental Impact

Sustainability is a major consideration being taken into account with engineering design. Global warming and climate change are rapidly altering the environment and faster than people can fix the issue. In 2020, the industry sector (manufacturing of goods from raw materials) contributed 24% of the greenhouse gas emissions which is equivalent to 1435.44 million metric tons of CO_2 (carbon dioxide) (United States Environmental Protection Agency, 2023). In order to counteract this, more sustainable and environment-friendly manufacturing processes and materials are being implemented into more engineering companies and factories.

This final design mainly consists of a team-written MATLAB code that collects, stores and analyzes the respective athlete's data. Due to its digital format, this portion of the design requires no physical manufacturing. It eliminates the need for a physical storage space, high resource and manufacturing costs and multi-production.

The other half of this design are the marked leggings used to track various joint and muscle movements of the athlete in the motion-capture algorithm. These leggings are standard athletic gear made from cotton and polyester. They have iron-on blue and white vinyl stickers used as markers in the software. Even though this does require manufacturing varying sizes to suit each athlete, these may be recycled within teams. They can be a one time purchase that may only need to be replaced if they get damaged, which makes it more sustainable for the environment. However, the vinyl stickers pose a threat to environment safety. Once an athletic team is done with a pair of leggings, they are going to dispose of them. Donation to a clothing drive or homeless shelter would be highly encouraged as this saves on waste production. The downfall in this scenario is that people may not want to wear them because of their aesthetic. They will then end up in the landfill. This would have negative environmental impact for two reasons: (i) this contributes to non-biodegradable waste in landfills, and (ii) if sent to an incineration facility would result in the release of toxins into the air from the materials, leading to air pollution.

6.3.3 Societal Influence

Within final design testing and analysis, not all demographics could be represented. Since testing was conducted in collaboration with the WPI female long and triple jump athletes, test subjects came from a limited pool; most participants who tested the device were white cisgender women ages 18-22 with lean physiques. Therefore, our device may produce different outcomes and may not be reliable for athletes of various demographics. For example, a transgender woman may not have the same ligament elasticity because of differences in estrogen levels in development resulting in the indicators of fatigue or potential injury being less relevant for her. . Additionally, the markers on athletes with larger builds and body sizes may not be visible initially and placement may need to be adjusted. The device may have a racial bias since it has not yet been tested on people of color. With further testing and development on these types of participants, the device can become more reliable for all female athletes.

6.3.4 Political Ramifications

Track and field is not a very expensive activity, so athletes from any financial background compete in this sport. Most athletes will only need to purchase a pair of sneakers and/or spikes in order to compete. Our design requires one to have at least two electronics that can record video and a computer to upload the videos to and run the MATLAB code on. This can become very pricey, especially for those who come from lower income backgrounds.

As mentioned earlier, this design has been tested and used by WPI female jumpers with similar demographics. Although this has been tested on a smaller scale, it is not uncommon to suggest this will work for those in other countries. Hopefully, adaptations to our designs will encourage testing on a larger scale with people from all demographics.

Our design is again, partially MATLAB code, which is currently used worldwide, so our code can be used in many different countries around the world if they have access to MATLAB. The other part of our design is the leggings with vinyl squares ironed on which should be available for use in other countries as well. Ultimately, this can be used universally, however, there may be some people who may not be able to afford the necessary tools for our design.

The design and development of this device expands the growing number of athletic monitoring technologies available for uses ranging from tracking performance to monitoring injury risk. Most of these technologies are not currently permitted for use in professional and collegiate regulated meets/games. As monitoring systems continue to expand, these leagues may reconsider their current regulations, especially if they are proven effective to prevent injuries.

6.3.5 Ethical Concerns

This project design involves human testing and high interaction between athletes and the device. The team took certain considerations to address the ethical concerns this design may have. When testing on humans, WPI requires a group to go through the Institutional Review Board (IRB). Although our project is non-invasive, we still needed to make sure the athletes were okay with being video recorded while wearing a pair of leggings we provided. After finishing our IRB training, the team drafted and submitted our IRB application as well as a consent form for the athletes to sign if they were willing to participate in our study. The consent form provided can be found in Appendix A. Athletes were given complete autonomy when asked whether or not they wanted to be recorded for our project while we also clarified their rights to say no to participation before performing any jumps.

Our design is to be expected to be used by coaches at practice. Therefore, the coaches will have access to the data being collected from their athletes. Although our design is not intended to allow coaches to favor one athlete over another, there could be bias shown by the coach because of our design. Ultimately, our goal is to prevent ACL injuries, without causing any bias towards any athlete.

6.3.6 Health and Safety Issues

The athlete’s safety is most important when producing the initial concept and final design of this project. ACL injuries are one of the most common injuries in long and triple jumpers. This specific injury can affect an athlete in various ways. By promoting the use of an early injury risk detection, one is able to reduce injury and improve the overall health and well-being of their athlete. This includes their emotional, physical and psychological health.

This device, however, does show some safety issue concerns. One such concern is data collection. While collecting data from current track and field athletes, we asked each jumper to perform a set number of jumps. In any activity, accidents can happen and there is always a chance of injury. Inevitably, the jumpers' legs will fatigue once their muscles have performed to their capacity, making them more at risk of injuring themselves. In order to minimize the risk of injury, when taking videos outside of practice, we limited each jumper to 4 jumps with the exception of one jumper, who performed 6. On an average day at practice, these jumpers are taking upwards of 8 full jumps as well as jumping drills which is significantly more activity than we are asking from the jumpers during our data collection.

Another aspect we have to take into consideration is the video storage. While obtaining the videos, the team made sure to protect the identity of these athletes by storing them in a secure and private OneDrive folder that could only be accessed by the members and advisors of this team. While presenting the data to those outside of our team, there were no identifying features or names to ensure the privacy of the athletes who participated in the development of this design. We achieved this by assigning letters to each athlete and blurring the faces in example images and videos during our presentation.

All man-made devices are prone to error, whether that is due to the user or the device malfunctioning. In the case that this device malfunctions, less accurate data is collected and produced. This would then lead to inaccurate risk detection and false alerts being made. In the case that the device malfunctions and a present risk is not alerted to the coach, the athlete may injure themselves. This puts the athlete’s health and safety at risk whilst using this device. In order to prevent that, routine monthly maintenance and technical check-ins should be made on the device.

Another source of error may be ignorance of alerts made. Sometimes coaches push their athletes’ limits. They may do this by ignoring the alerts made by the device which can result in the athlete injuring themselves, putting the athlete’s health at risk. To prevent this, athletic trainers and coaches should be informed of the proper use of the device and undergo ethical training sessions.

6.3.7 Manufacturability

A key factor to consider in product design is its manufacturability and reproducibility. Our final design has some benefits and faults in this area. A majority of our design consists of a MATLAB code and slow-motion captured videos on 2-3 phones. Digital software has high reproducibility since multiple copies can be shared and downloaded online. However, a laptop or computer is required for access. In lower income areas, this may require the team to provide computers to the customers who fall into this category.

The only component of our design that requires external manufacturing is the leggings used for motion tracking. These can be manufactured on a small scale for two reasons: (i) each buying customer may only need one legging for each size since they are reusable amongst athletes, and (ii) the blue and white markers are iron vinyl stickers that require minimum heat (around 270 ºF) and less than a minute per application.

6.3.8 Sustainability

As previously stated, the design includes leggings and a computer generated MATLAB code. When a team is using our design, they will most likely need multiple pairs of leggings to fit the sizes of each athlete. However, athletes with the same size can share the same pair and be used and washed multiple times. After sufficient usage, leggings may need to be replaced after two or three years. Overtime, computers and certain programs update and change, which could affect the code we developed through MATLAB. As technology updates, certain changes to our code may also need to be updated.

7. Discussion

This device successfully tracks the anatomical markers for the duration of landing and produces the corresponding coordinates. The code then calculates the knee flexion angles, angular velocity, vertical velocity, and valgus positioning. This fulfills our first objective: to detect the biomechanics of the jump.

To meet our second objective, determine harmful biomechanics, we collected data from jumps performed by multiple athletes. This device incorporates multiple risk indicators based on research and the data collected. The sagittal data collected was used to determine baseline values for knee flexion angle, angular velocity, and hip vertical velocity. There are clear ranges of values for these three factors based on the data collected. If an athlete performs a jump with data outside these ranges, the device provides an alert for this change. Additionally, for angular velocity and hip vertical velocity, there is generally an initial steep decrease in velocity followed by a more gradual decline to 0. This change occurs roughly halfway through the landing. Therefore, the device provides an alert if the jump displays velocities above 3 m/s (hip vertical velocity) or -1000 degrees/s (knee angular velocity) after halfway through the jump. If a jumper displays an increased velocity after halfway through the landing, this could indicate that they are becoming fatigued since they are using less muscle activation to slow their descent.

The device will provide a graph of the three factors, overlaying the sequential jumps of the same jumper. This will allow the coach to visualize the progression of the data and identify if there are changes in the trends. If an athlete is becoming fatigued, this could be identified in the latest jump data displaying a different curve than the previous jumps.

In the frontal view, valgus positioning of the knees is the predominant risk factor for jump landings based on the literature. The x-coordinates of the hip, ankle, and knee marker data is used to determine if the knees are in valgus. If the knee values are in between the range of hip and ankle values, the knees are determined to be in valgus and the device provides an alert.

These alerts are displayed to the user, likely the coach, for consideration. The coach can use their judgment to recommend if the athlete should jump again. The coach should consider if the markers remained in frame for the videos and the progression of the data based on the graphs. If the markers were accurately tracked and the data prompted multiple alerts, then the jimper should be recommended to discontinue their practice.

This device is intended to be used during practice, meaning that it should be able to provide quick feedback, as referenced in our functional blocks. This device takes roughly 4 min to upload the videos and run the code. The time varies depending on how comfortable the user is with the process. This is within the 8 min benchmark previously described in Chapter 4.1, the average wait time between jumps.

7.1 Limitations

This device is limited by the visibility of the markers. In the jumps where the markers became obscured, the code was unable to track the markers. Additionally, when the jumpers twisted their legs away from the camera the knee flexion angle and angular velocity became skewed. This can be circumvented by focusing on the hip vertical velocity instead of the angular velocity when this occurs. Similarly, the video capture method limits the data collected to visual factors. This excludes any biological monitoring such as heart rate and EMG. These factors could be helpful in identifying fatigue, but the video method helps not impede the athlete in their jump and can be easily used by multiple jumpers.

These data are limited by the small sample size used to collect the baseline data. There were six sets of jumps collected from 5 different athletes, all of which are of a similar demographic of 18-22 athletic build white women. A larger data set would likely provide a clearer consensus on trends and outliers. Since the sample size was small, the device can export the coordinate data, knee flexion angles, angular velocity, and hip vertical velocity in a labeled spreadsheet if the coach or further researchers wanted to collect more data.

Additionally, the device requires that the jumpers wear leggings. This limits the device to athletes that are willing to wear the leggings. During an outdoor practice on a warm day some of the athletes declined to participate in the data collection since they wanted to wear shorts instead. However, indoor practices do not not have this limitation since it is in a climate controlled environment.

This device is assuming the leggings are acting as a rigid body. The markers are placed on bony landmarks that should not change, however the leggings are a flexible fabric that allows for some movement. As explained in chapter 5.5, the distance between markers had an average error of 4.95%. However, the calculations were performed assuming the markers were consistently accurate on the bony landmarks and thus the leggings moved as a rigid body.

8. Conclusions & Recommendations

8.1 Final Conclusions

Track and field long and triple jumps have a clear risk of injury for the athletes notably during the landing of the jump. ACL injury is a common injury for jumping sports and women experience notable higher rates of ACL injury. Research suggests that more injuries occur when the athlete becomes fatigued as they begin to alter their form of their landing and use less muscle activation. The overall goal of this project was to develop a device that monitors the biomechanics of the jump and detects harmful changes in their biomechanics to prevent injury by altering the coach with quick feedback.

The motion capture device tracks anatomical markers for the duration of the landing and produces respective coordinate data. Then, these coordinates are used to determine key biomechanical factors, such as knee flexion angle and valgus positioning of the knees, and provide an alert to any notable changes from normal values. Data collection from multiple athletes determined average normal values for knee flexion angels, angular velocity, and hip vertical velocity. Additionally, the device stores the data for each jump to be able to compare the progression of the jumps for each athlete. This allows the user, such as the coach, to be notified of harmful biomechanics and assess the changes over the course of several jumps. The coach can receive these alerts and advise the athlete to stop their jumps due to signs of fatigue. By suspending practice once the athlete begins to display harmful biomechanics indicative of fatigue, the athlete will be less likely to injure themselves.

This device is intended to be used during practice to minimize the risk of injury. Current injury prevention methods include visual assessment of fatigue by observers and the athlete's personal fatigue tolerance. Using the device's monitoring in conjunction with the current methods should reduce the occurrence of injury and harmful biomechanics during the landing of the jump. With further development, this motion capture system can become a more effective method of monitoring fatigue and preventing ACL injury.

8.2 Future Work & Recommendations

This project has set a foundation for various expansions and further development. As with any engineering design process, further iterations, prototyping and testing helps to improve the overall design of the finished product. To start this process, the team has curated a list of suggestions and recommendations for future work in this project.

The first suggestion is to have a more integrated system between the motion capture system, altered biomechanical detection, and alert mechanism. At the moment, the videos have to be uploaded to a computer to be used by the matlab code. This slows down the data callback time between the athlete's jump and the device's injury risk analysis. Developing an automated mobile user interface would be beneficial so the videos could be taken and analyzed on the same mobile device instead of using a computer. This would also make the device easier to use, especially for those who may not have much coding/data analytical tool experience. Overall this integrated system would be automated and provide a faster response time for athletic data collected.

In adjusting the system to be more integrated, it is also proposed to make the motion capture system three-dimensional (3D) instead of two dimensional (2D). By expanding the analysis space, the device is able to better capture most if not all changing biomechanics of the jumper as they perform their jump. 3D analysis could also allow for the analysis of more biomechanical indicators, such as trunk positioning, that could not be included in the previous design due to dimensional restrictions. This would yield more verification data and improve the device's precision and accuracy in identifying and alerting risk of injury in the athlete. While this may require more video capture devices, a new tripod alignment, and additional anatomical markers, 3D motion capture is able to provide a more realistic and holistic view.

As stated earlier, trunk (upper body) positioning is one of the biomechanical indicators not analyzed in the current device. During latent stages of fatigue, the body may tend to lose control over certain muscles including the abdomen (Hewett et al., 2010). This will cause the jumper to lose form and position their trunk outside of its normal stable position, and throw off their balance. Trunk positioning can also influence valgus positioning of the knees. This would aid in the current frontal analysis and help improve the precision of valgus detection.

Another recommendation is to collect more data. For our current data collection, it is a representative sample of five women's long and triple jumpers on the WPI track and field team. While this group did provide valuable data for analysis, it is not indicative of all female track and field jumpers on WPI's track and field team. It is also not illustrative of all female collegiate long and triple jumpers across the United States. To better verify and improve the accuracy of the device, more jumpers from WPI, as well as across the country, would need to be involved in the study.

The final recommendation the team has is to incorporate biological indicators into the design. As mentioned in previous chapters, biological factors such as oxygen levels, certain metabolic factors and changes in the central nervous system can all lead to an increase in muscle fatigue. It is important to recognize that there are other indicators of fatigue rather than the physical changes in the biomechanics. As there is muscle fatigue due to changes in the peripheral nervous system, there is limited ATP which can hinder the rate of muscular relaxation (Giannesini et al., 2003). If there are sensors detecting electromyography (EMG) levels that monitor muscle contraction and relaxation, we can recognize and alert when there is an increase in muscle fatigue. Also, by having an oxygen level monitor, we would be able to detect how much oxygen is reaching the muscles. As muscular activity increases, there is a build up of lactic acid which would be discarded by oxygen (Yamada, 2016). By monitoring the oxygen, we would be able to predict when there is a build up of lactic acid and increase in muscle fatigue. The monitoring of these levels will help us predict when there is an increase in muscle fatigue leading to muscle-related injuries. By incorporating these recommendations, the device could more effectively identify fatigue, and be used by a larger population.

References

Acevedo, R. J., Rivera-Vega, A., Miranda, G., & Micheo, W. (2014, May). Anterior cruciate ligament injury: identification of risk factors and prevention strategies. *Current Sports medicine Reports*, *13*(3), 186-191. 10.1249/JSR.0000000000000053

ACL Reconstruction Surgery Cost and Procedure Information. (n.d.). *New Choice Health, Inc.,* Retrieved April 2023, from https://www.newchoicehealth.com/procedures/acl-reconstruction-surgery

Alba-Jiménez, C., Moreno-Doutres, D., & Peña, J. (2022). Trends Assessing Neuromuscular Fatigue in Team Sports: A Narrative Review. *National Library of Medicine*, *10*(3), 33.

Anterior cruciate ligament (ACL) injuries - orthoinfo - aaos. OrthoInfo. (n.d.). Retrieved April 21, 2023, from https://orthoinfo.aaos.org/en/diseases--conditions/anterior-cruciate-ligament-acl-injuries/

Arendt, E. A., Agel, J., & Dick, R. (1999). Anterior cruciate ligament injury patterns among collegiate men and women. *Journal of athletic training*, *34*(2), 86.

Barber-Westin, S. D., & Noyes, F. R. (2017). Effect of fatigue protocols on lower limb neuromuscular function and implications for anterior cruciate ligament injury prevention training: a systematic review. The American journal of sports medicine, 45(14), 3388-3396.

Boden, Barry P., Sheehan, Frances T. (2022, Mar). Mechanism of non-contact ACL injury: OREF Clinical Research Award 2021. *Journal of Orthopaedic Research*. 40(3):531-540. doi: 10.1002/jor.25257

Chaisomphob, T., Silsirivanit, A., & Boonyong, S. (2021). Principal component analysis identifies major muscles recruited during vertical jump. Physical Therapy, Faculty of Allied Health Sciences, Southwestern University, Thailand. Retrieved from https://physicaltherapy.swu.ac.th/sites/default/files/2021-04/Principal%20component%20analysis%20identifies%20major%20muscles%20recruited%20during%20vertical%20jump.pdf

Di Stasi, S., Myer, G. D., & Hewett, T. E. (2013, Nov). Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. *Journal of orthopedic & sports physical therapy*, *43*(11), 777-A11. https://www.jospt.org/doi/10.2519/jospt.2013.4693

Dziewiecki K., Mazur Z., Blajer W. (2013). ASSESSMENT OF EXTERNAL AND INTERNAL LOADS IN THE TRIPLE JUMP VIA INVERSE DYNAMICS SIMULATION. *Journal of Biology of Sport*, *Vol. 30* No. 2, 103-109. 10.5604/20831862.1044225

Eissa, A. (2014). Biomechanical evaluation of the phases of the triple jump take-off in a top female athlete. *Journal of human kinetics*, *40*, 29.

Enoki, S., Nagao, M., Ishimatsu, S., Shimizu, T., & Kuramochi, R. (2021). Injuries in collegiate track and field jumping: a 2-year prospective surveillance study. *Orthopaedic journal of sports medicine*, *9*(1), 2325967120973397.

Giannesini, B., Cozzone, P. J., & Bendahan, D. (2003). Non-invasive investigations of muscular fatigue: metabolic and electromyographic components. Biochimie, 85(9), 873–883. https://doi.org/10.1016/s0300-9084(03)00124-x

Graham-Smith, P., & Lees, A. (2005, Sep). A three-dimensional kinematic analysis of the long jump take-off. *Journal of sports sciences*, *23*(9), 891-903. 10.1080/02640410400022169

Hansen, B., Laughlin, W., Dowling, B., Owen, C., & Fleisig, G. (2016). VALIDATION OF A TWO-SENSOR IMU SYSTEM FOR MEASURING JUMP HEIGHT AND WRIST SPEED IN VOLLEYBALL PLAYERS.

Hay, J. G. (1993). Citius, altius, longius (faster, higher, longer): the biomechanics of jumping for distance. *Journal of biomechanics*, *26*, 7-21.

Hewett, T. E., & Bates, N. A. (2017, Sep). Preventive biomechanics: a paradigm shift with a translational approach to injury prevention. *The American journal of sports medicine*, *45*(11), 2654-2664. 10.1177/0363546516686080

Hewett, T. E., Ford, K. R., Hoogenboom, B. J., & Myer, G. D. (2010, Dec). Understanding and preventing acl injuries: current biomechanical and epidemiologic considerations. *North American journal of sports physical therapy*, *5*(4), 234-251.

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., Van den Bogert, A. J., Paterno, M. V., & Succop, P. (2005, Apr). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *The American journal of sports medicine*, *33*(4), 492-501. 10.1177/0363546504269591

Hospital for Special Surgery. (n.d.). Muscle Strain. Retrieved April 26, 2023, from https://www.hss.edu/conditions_muscle-strain.asp#:~:text=After%20this%20inflammatory%20phase%2C%20the,muscle%20tissue%20never%20fully%20regenerates.

Huang, S.-J., Wei, M., Zhu, L., Zhang, J.-W., Ding, Z.-Y., Luo, F., & Liu, T.-Z. (2019, Jan). Mechanical function of the human knee joint region during triple jump by combined multi-body dynamics and finite element analysis. *Procedia Manufacturing*, *35*, 956-961. 10.1016/j.promfg.2019.06.041

Lambert, C., Reinert, N., Stahl, L., Pfeiffer, T., Wolfarth, B., Lachmann, D., ... & Ritzmann, R. (2022). Epidemiology of injuries in track and field athletes: a cross-sectional study of specific injuries based on time loss and reduction in sporting level. *The Physician and Sportsmedicine*, *50*(1), 20-29.

Laughlin, W., Geronimo, A., Close, K., Holstad, R., & Hansen, B. (2016). A CASE STUDY TO EXAMINE THE RELATIONSHIP BETWEEN ELBOW VALGUS TORQUE IN FOOTBALL THROWING AND BASEBALL PITCHING.

Leong, N. L., Kator, J. L., Clemens, T. L., James, A., Enamoto‐Iwamoto, M., & Jiang, J. (2020). Tendon and ligament healing and current approaches to tendon and ligament regeneration. *Journal of Orthopaedic Research®*, *38*(1), 7-12.

Lloyd, D. G., & Buchanan, T. S. (2001, Oct). Strategies of muscular support of varus and valgus isometric loads at the human knee. *Journal of Biomechanics*, *34*(10), 1257-1267. 10.1016/S0021-9290(01)00095-1

Long Jump - The Technical Model — aths.coach Athletics Coach. (2021, February 9). aths.coach Athletics Coach. Retrieved October 12, 2022, from https://www.aths.coach/resources/long-jump-the-technical-model

Motus Global. (n.d.). *motusBASEBALL*. Motus. https://motusglobal.com/motusbaseball.html

Motus Global. (n.d.). *motusVB*. Motus. https://motusglobal.com/volleyball/

Neilson, V., Ward, S., Hume, P., Lewis, G., & McDaid, A. (2019, September). Effects of augmented feedback on training jump landing tasks for ACL injury prevention: A systematic review and meta-analysis. *Physical Therapy in Sport*, *39*. https://doi.org/10.1016/j.ptsp.2019.07.004

Nicolò, A., Paoli, A., & Palma, A. (2020). Drop jumping I: The influence of jumping height and sex on ground reaction forces, shock attenuation, and lower limb stiffness. Osteosports, 12(2), 6-15. Retrieved from https://osteosports.com/wp-content/uploads/2020/05/Drop_jumping__I__The_influence_of_jumping.3.pdf

Pappas, E., Shiyko, M. P., Ford, K. R., Myer, G. D., & Hewett, T. E. (2016, Jan). Biomechanical deficit profiles associated with ACL injury risk in female athletes. *Medicine and science in sports and exercise*, *48*(1), 107-113. 10.1249/MSS.0000000000000750

Perttunen, J., Kyrolainen, H., Komi, P. V., & Heinonen, A. (2000). Biomechanical loading in the triple jump. *Journal of sports sciences*, *18*(5), 363-370.

Ratel, S., Duché, P., & Williams, C. A. (2006). Muscle Fatigue during High-Intensity Exercise in Children. *Sports Med*, 1031–1065.

Sérgio Rocha Piedade, Philippe Neyret, João Espregueira-Mendes, Moises Cohen, Mark R. Hutchinson. (2021). *Specific Sports-Related Injuries. International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine*. ISBN 978-3-030-66321-6 https://doi.org/10.1007/978-3-030-66321-6

Seshadri, D. R., Li, R. T., Voos, J. E., Rowbottom, J. R., Alfes, C. M., Zorman, C. A., & Drummond, C. K. (2019, July 29). Wearable sensors for monitoring the internal and external workload of the athlete. *NPJ Digit Medicine*, *2*(71). PubMed Central. https://doi.org/10.1038/s41746-019-0149-2

Slauterbeck, J. R., Fuzie, S. F., Smith, M. P., Clark, R. J., Xu, K., Starch, D. W., & Hardy, D. M. (2002). The Menstrual Cycle, Sex Hormones, and Anterior Cruciate Ligament Injury. Journal of athletic training, 37(3), 275–278.

Smith, H. C., Vacek, P., Johnson, R. J., Slauterbeck, J. R., & Hashemi, J. (2016). Collegiate ACL Injury Rates Across 15 Sports: National Collegiate Athletic Association Injury Surveillance System Data Update (2004-2005 Through 2012-2013). Clinical Journal of Sport Medicine, 26(6), 518-523. doi: 10.1097/JSM.0000000000000315

SPRINGER. (2022). *Specific sports-related injuries*.

Stander, R. (2022, Oct 12). *Athletics Omnibus - Triple Jump*. Athletics Omnibus South Africa. https://athleticssa.org.za/SportsInfo/Coaching-Triple-Jump.pdf

Takahashi, S., Nagano, Y., Ito, W., Kido, Y., & Okuwaki, T. (2019, June). A retrospective study of mechanisms of anterior cruciate ligament injuries in high school basketball, handball, judo, soccer, and volleyball. *Medicine (Baltimore)*, *98*(26). PubMed Central. https://doi.org/10.1097/MD.0000000000016030

Tesnow, A. (2020, October 8). *SYSTEM AND METHOD FOR A WEARABLE KNEE INJURY PREVENTION* [US-20200315523-A1] [Patent]. USPTO.

United States Environmental Protection Agency. (2021, January 28). Sources of Greenhouse Gas Emissions. Retrieved from https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

Wan, J., Qin, Z., Wang, P., Sun, Y., & Liu, X. (2017). Muscle fatigue: general understanding and treatment. *National Library of Medicine*, 49(10), 384.

Winter, D. A. (2009). *Biomechanics and motor control of human movement*. Wiley.

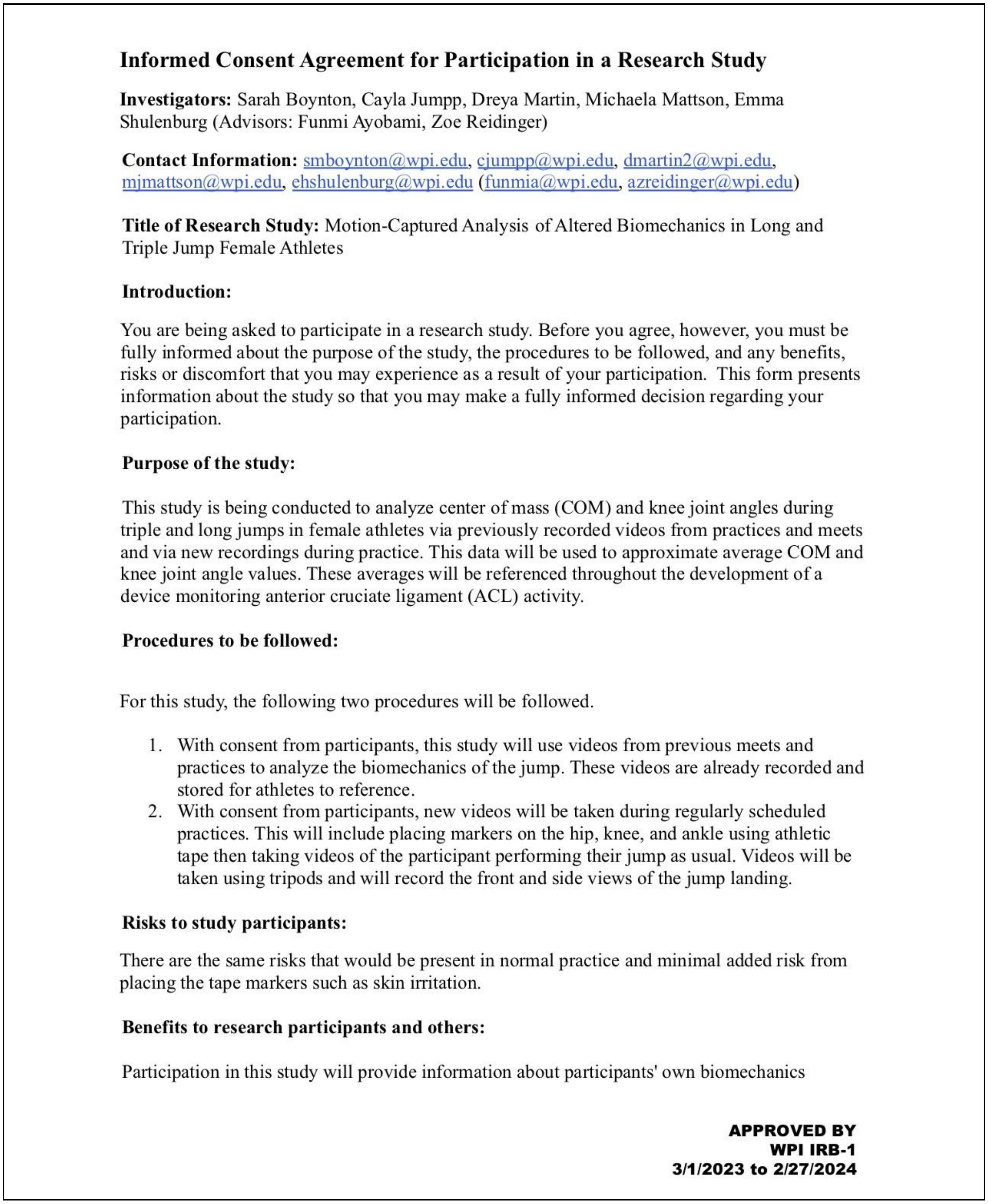
Yamada, K. (2016). Energetics of muscle contraction: further trials. *The Journal of Physiological Sciences*, 67(1), 19–43.

Zazulak, B. T., Hewett, T. E., Reeves, P. N., Goldberg, B., & Cholewicki, J. (2007, Mar). The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *The American journal of sports medicine*, *35*(3), 368-373. 10.1177/0363546506297909

Zemper, E. D. (2005). Track and field injuries. *Epidemiology of pediatric sports injuries: individual sports*, *48*, 138-151.

Appendix

Appendix A: IRB Consent Form



Informed Consent Agreement for Participation in a Research Study

Investigators: Sarah Boynton, Cayla Jumpp, Dreya Martin, Michaela Mattson, Emma Shulenburg (Advisors: Funmi Ayobami, Zoe Reidinger)

Contact Information: smboynton@wpi.edu, cjumpp@wpi.edu, dmartin2@wpi.edu, mjmattson@wpi.edu, ehshulenburg@wpi.edu (funmia@wpi.edu, azreidinger@wpi.edu)

Title of Research Study: Motion-Captured Analysis of Altered Biomechanics in Long and Triple Jump Female Athletes

Introduction:

You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

Purpose of the study:

This study is being conducted to analyze center of mass (COM) and knee joint angles during triple and long jumps in female athletes via previously recorded videos from practices and meets and via new recordings during practice. This data will be used to approximate average COM and knee joint angle values. These averages will be referenced throughout the development of a device monitoring anterior cruciate ligament (ACL) activity.

Procedures to be followed:

For this study, the following two procedures will be followed.

1. With consent from participants, this study will use videos from previous meets and practices to analyze the biomechanics of the jump. These videos are already recorded and stored for athletes to reference.
2. With consent from participants, new videos will be taken during regularly scheduled practices. This will include placing markers on the hip, knee, and ankle using athletic tape then taking videos of the participant performing their jump as usual. Videos will be taken using tripods and will record the front and side views of the jump landing.

Risks to study participants:

There are the same risks that would be present in normal practice and minimal added risk from placing the tape markers such as skin irritation.

Benefits to research participants and others:

Participation in this study will provide information about participants' own biomechanics

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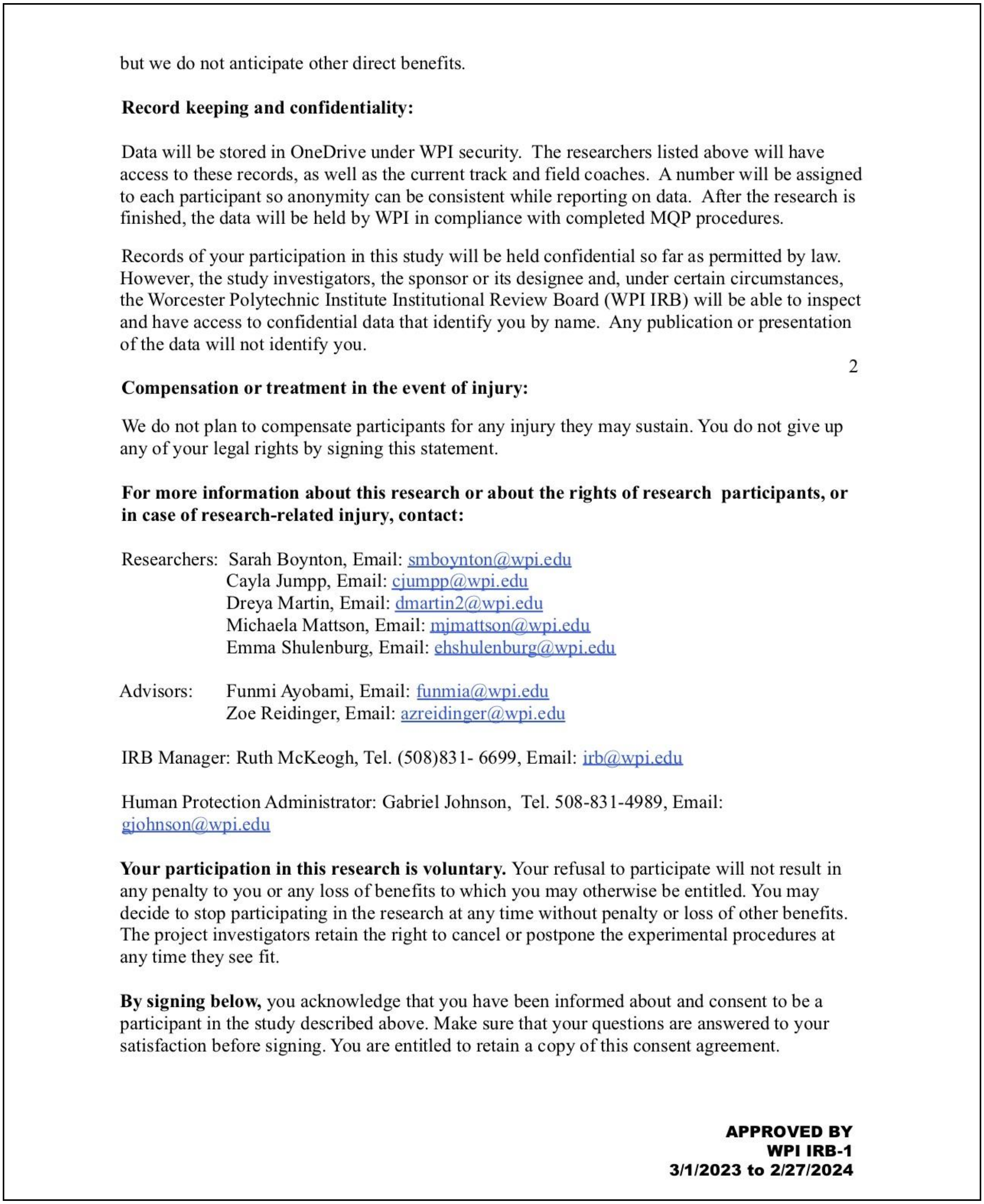
WPI IRB-1
3/1/2023 to 2/27/2024



but we do not anticipate other direct benefits.

Record keeping and confidentiality:

Data will be stored in OneDrive under WPI security. The researchers listed above will have access to these records, as well as the current track and field coaches. A number will be assigned to each participant so anonymity can be consistent while reporting on data. After the research is finished, the data will be held by WPI in compliance with completed MQP procedures.

Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or its designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you.

Compensation or treatment in the event of injury:

We do not plan to compensate participants for any injury they may sustain. You do not give up any of your legal rights by signing this statement.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact:

Researchers: Sarah Boynton, Email: smboynton@wpi.edu
Cayla Jumpp, Email: cjumpp@wpi.edu
Dreya Martin, Email: dmartin2@wpi.edu
Michaela Mattson, Email: mjmattson@wpi.edu
Emma Shulenburg, Email: ehshulenburg@wpi.edu

Advisors: Funmi Ayobami, Email: funmia@wpi.edu
Zoe Reidinger, Email: azreidinger@wpi.edu

IRB Manager: Ruth McKeogh, Tel. (508)831- 6699, Email: irb@wpi.edu

Human Protection Administrator: Gabriel Johnson, Tel. 508-831-4989, Email: gjohnson@wpi.edu

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

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WPI IRB-1
3/1/2023 to 2/27/2024

☐ I give permission for researchers to publicize non-identifying images of myself in long and/or triple jump videos

☐ I would not like any images of myself from long and/or triple jump videos to be publicized

____________________________________ Date: ___________________

Study Participant Signature

____

Study Participant Name (Please Print)

____________________________________ Date: ___________________

Signature of Person who Explained this Study

____

Name of Person who Explained this Study (Please Print)

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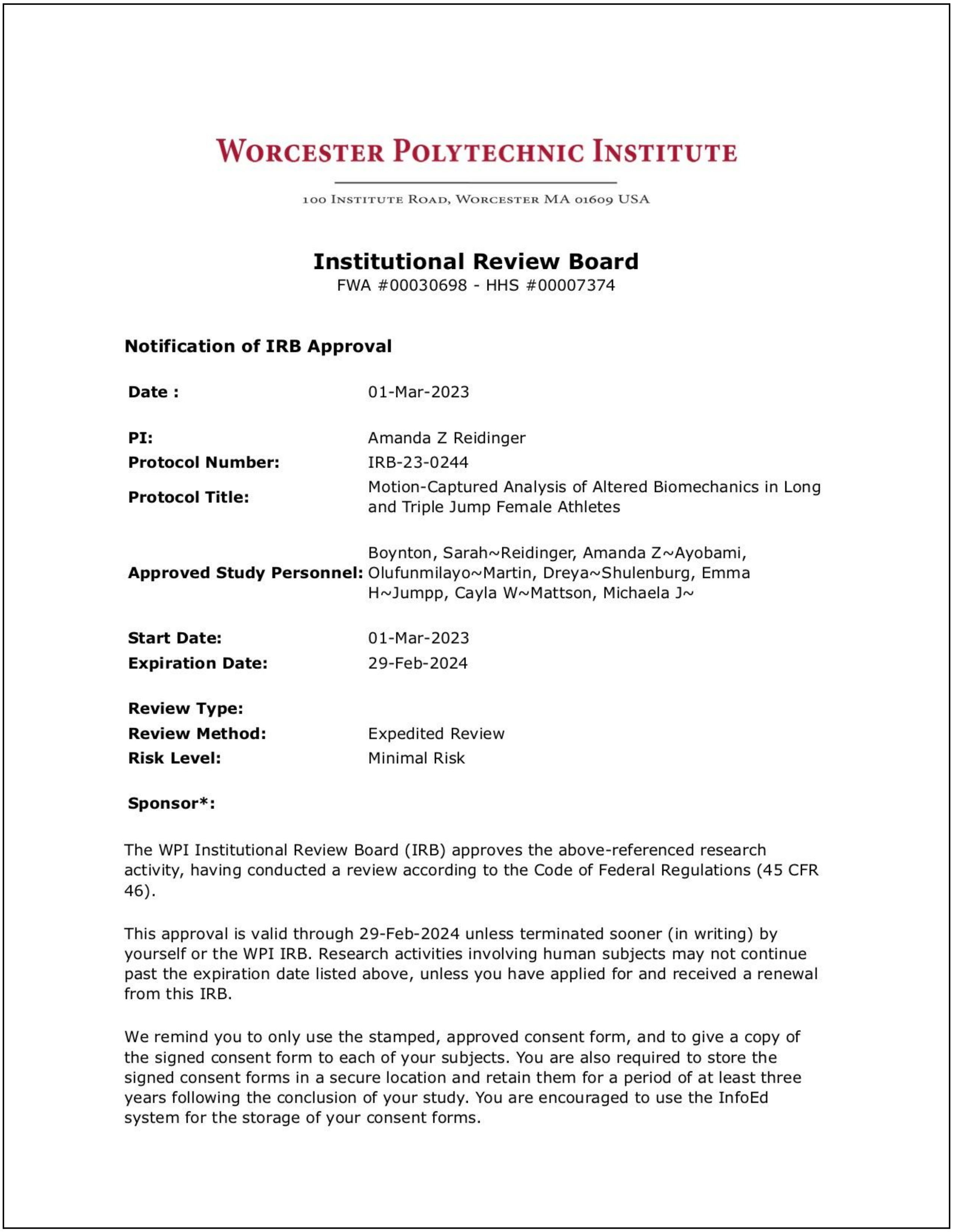
WPI IRB-1
3/1/2023 to 2/27/2024

Appendix B: IRB Approval



WORCESTER POLYTECHNIC INSTITUTE

100 INSTITUTE ROAD, WORCESTER MA 01609 USA

Institutional Review Board

FWA #00030698 - HHS #00007374

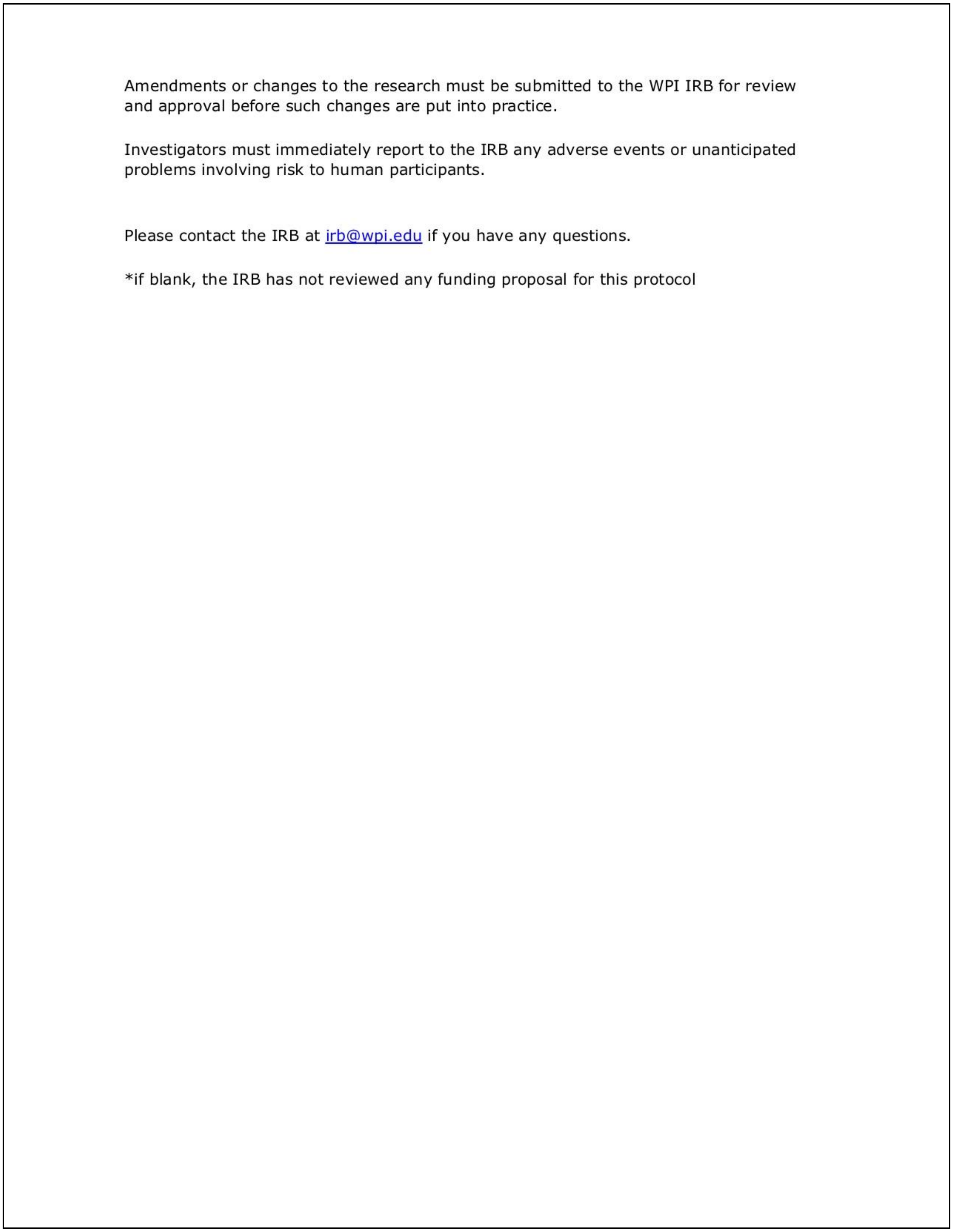
Notification of IRB Approval

Date :	01-Mar-2023
PI:	Amanda Z Reidinger
Protocol Number:	IRB-23-0244
Protocol Title:	Motion-Captured Analysis of Altered Biomechanics in Long and Triple Jump Female Athletes
Approved Study Personnel:	Boynton, Sarah~Reidinger, Amanda Z~Ayobami, Olufunmilayo~Martin, Dreya~Shulenburg, Emma H~Jumpp, Cayla W~Mattson, Michaela J~
Start Date:	01-Mar-2023
Expiration Date:	29-Feb-2024
Review Type:	
Review Method:	Expedited Review
Risk Level:	Minimal Risk
Sponsor*:	

The WPI Institutional Review Board (IRB) approves the above-referenced research activity, having conducted a review according to the Code of Federal Regulations (45 CFR 46).

This approval is valid through 29-Feb-2024 unless terminated sooner (in writing) by yourself or the WPI IRB. Research activities involving human subjects may not continue past the expiration date listed above, unless you have applied for and received a renewal from this IRB.

We remind you to only use the stamped, approved consent form, and to give a copy of the signed consent form to each of your subjects. You are also required to store the signed consent forms in a secure location and retain them for a period of at least three years following the conclusion of your study. You are encouraged to use the InfoEd system for the storage of your consent forms.



Amendments or changes to the research must be submitted to the WPI IRB for review and approval before such changes are put into practice.

Investigators must immediately report to the IRB any adverse events or unanticipated problems involving risk to human participants.

Please contact the IRB at irb@wpi.edu if you have any questions.

*if blank, the IRB has not reviewed any funding proposal for this protocol

Appendix C: User Guide

User Instructions for Detecting Altered Biomechanics During Track and Field Training

Last edited April 27, 2023

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Purpose:

The purpose of this document is to provide guidance for recording videos and utilizing the MATLAB code created as part of the 2022-2023 Major Qualifying Project labeled Detecting Altered Biomechanics Due to Athlete Fatigue in Track and Field Training.

Scope:

The scope of this procedure is for those who plan to record videos for analysis, as well as those analyzing athlete videos during practice. This includes, but is not limited to, Worcester Polytechnic Institute track and field athletes and coaches, specifically in the women's jump group.

Materials Required:

- Laptop with MATLAB software downloaded, along with an active MATLAB license, and a Video Labeler package downloaded
    - Note: The code included was developed using MATLAB version R2022b

- Indoor Track and Field:
    - Two phones with slow-motion recording capability
    - Two tripods (provided by MQP team)
- Outdoor Track and Field:
    - Three phones with slow-motion recording capability
    - Three tripods (provided by MQP team)
- MATLAB Jump Analysis Program (provided by MQP team)
- Leggings with biomechanical markers to be worn by the athlete being analyzed (provided by MQP team)

Setup Instructions:

To properly analyze biomechanics, the athlete must be wearing the leggings with biomechanical markers so the software can track the points. The video capture analysis is dependent on videos from the frontal view, as well as videos from the sagittal view. One phone is required for each view, and should have slow-motion capabilities. Each phone should be loaded into a tripod horizontally with the camera not covered by the clamp. The videos can be recorded manually or the remotes can be linked to the phones by bluetooth. One thing to note is the remotes sometimes disconnect if not used for too long, so manual recording may be preferred as a more reliable method. For the frontal view, the tripod should be set up behind the end of the sand pit and angled down to visualize the whole landing area. For the sagittal views, the tripods should be set up along the side of the landing area for each pit.

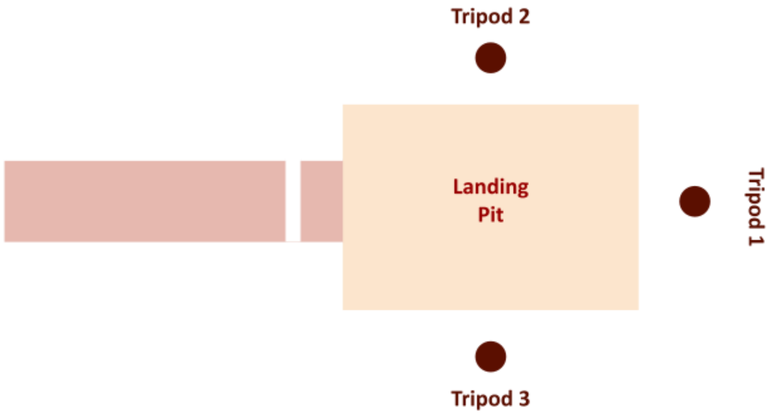


Figure 1. Tripod setup

When setting up the videos on the camera, slow-motion should be selected, as well as the highest frame rate (240 fps on an iPhone). To change the frame rate on an iPhone, press on the number in the top right corner. This should allow the user to switch between 120 fps and 240 fps. When recording, the videos should be started before the athlete starts their final jump into the pit and stopped after their landing is completed. Try to avoid making the videos longer than necessary, as this will increase video export time and delay data analysis. The videos do not have to be perfectly cropped, however, as they can be further cropped during video analysis.

Once recorded, videos should be exported and saved to a computer that contains the MATLAB Jump Analysis Program. The program is intended to be used during practice to indicate risk, so the videos would be exported after each jump to analyze injury risk. During the data collection period, videos were recorded all at once and then analyzed later to test data collection methods.

MATLAB Code Instructions:

1. Before opening the Jump Analysis Program, place the program and all videos to analyze in a single folder within the laptop. This will allow MATLAB to access the code and videos easily when performing analysis.
2. Open MATLAB software. Once loaded, select the “Browse for Folder” symbol in the upper left-hand corner of the screen and browse the file directory within the popup to find the folder that contains the MATLAB code and video files (Figure 2). Once the folder is selected it should be listed next to the box labeled “Folder:”. If the desired folder is listed, click “Select Folder” (Figure 3).

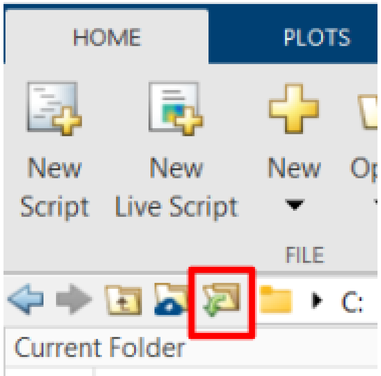


Figure 2. Browse for Folder symbol and location

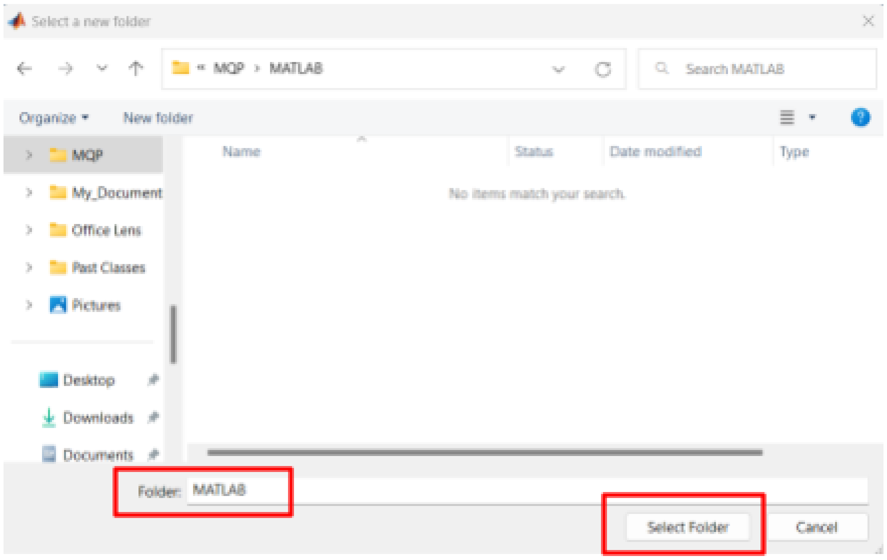
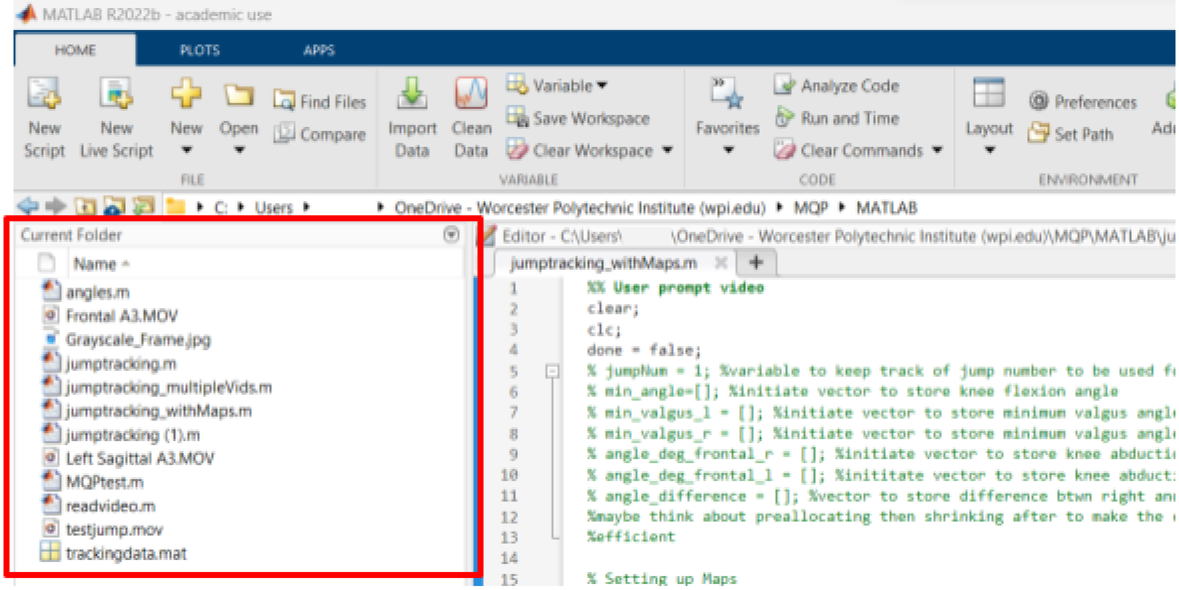


Figure 3. Folder selection panel

3. At this point, all content in the folder should be listed on the left side of the screen in the "Current Folder" panel (Figure 4). In this panel, double-click the Jump Analysis Program to open it in the editor in the center of the screen.



```
%% User prompt video
clear;
clc;
done = false;
% jumpNum = 1; %variable to keep track of jump number to be used f
% min_angle=[]; %initiate vector to store knee flexion angle
% min_valgus_l = []; %initiate vector to store minimum valgus angl
% min_valgus_r = []; %initiate vector to store minimum valgus angl
% angle_deg_frontal_r = []; %initiate vector to store knee abducti
% angle_deg_frontal_l = []; %inititate vector to store knee abduct
% angle_difference = []; %vector to store difference btwn right an
%maybe think about preallocating then shrinking after to make the
%efficient

% Setting up Maps
```

Figure 4. Current Folder panel location

4. Once open, clear all variables in the workspace on the right and any commands within the command window by entering "clear;clc;" into the command window at the bottom of the screen (Figure 5).

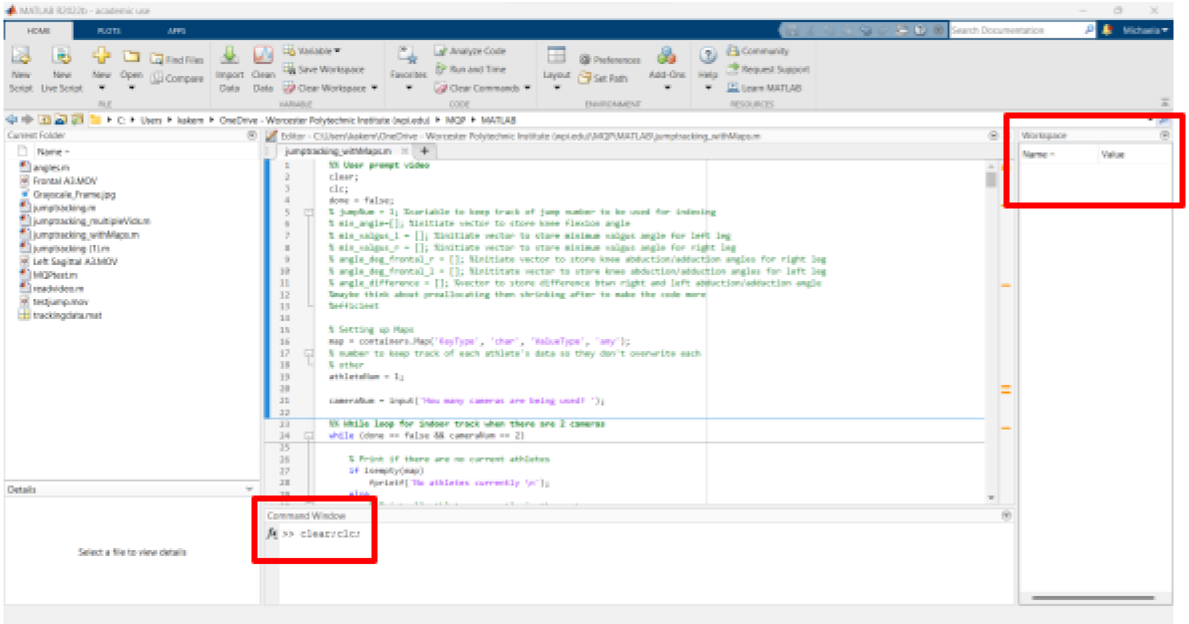


Figure 5. Clearing command window at bottom and workspace on right

5. Select the tab with the program name at the top of the editor window to open the editor tab along the top of the screen.

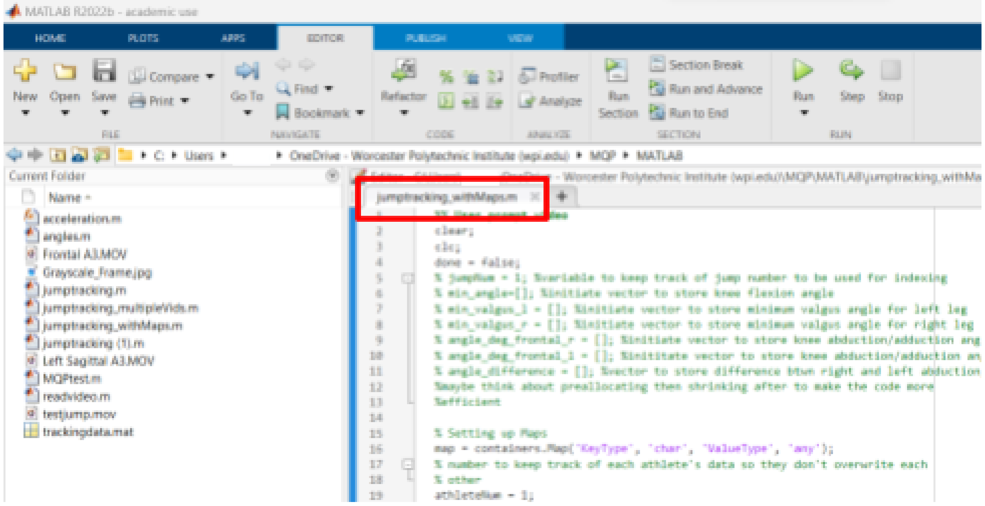


Figure 6. Tab to select to open editor

6. Next, select “Run” at the top of the screen (Figure 7).

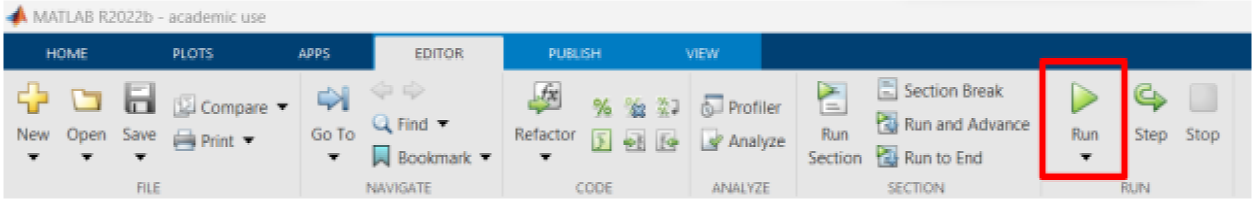
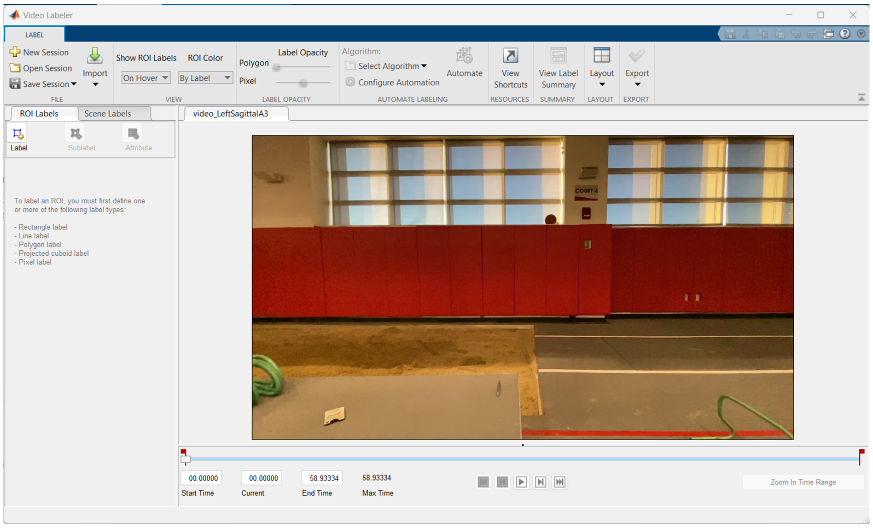


Figure 7. Run button location

7. At this point, in the command window at the bottom of the screen there will be a prompt reading “How many cameras are being used?” In the command window, type 2 or 3 depending on the number of tripods setup and then click enter on your keyboard. 2 is typically intended for indoor track use since there is no room to set up the camera for the right sagittal view, while 3 is preferred to get a more comprehensive calculation of biomechanics.
8. The current athletes being recorded in the system will appear in the command window. At the start, this will just list “No athletes currently.” Next, enter the name of the athlete whose videos are going to be analyzed. If the athlete is someone already in the system, ensure the name is written as it appears in the list of current athletes.
9. The command window should then prompt with “Add sagittal video file” for when there are 2 video files or “Add right sagittal video file” when there are 3 video files. Type out the name of the video file exactly as it appears in the folder. If you forget the name, it is easy to reference the files in the “Current Folder” tab on the left of the screen. Ensure you include the file extension i.e. “.mov” or “.MOV” for video files typically. Once the file name is typed correctly, click enter. For 2 video files, there will then be one more prompt to add the frontal video file, and for 3 video files there will be two more prompts to add the left sagittal video file, then the frontal video file. Fill out these prompts in the same way as the first video file prompt.
10. After completing all video name prompts, Video Labeler windows will open, one for each camera view (Figure 8).



To label an ROI, you must first define one
or more of the following label types:

- Rectangle label
- Line label
- Polygon label
- Projected cuboid label
- Pixel label

Start Time: 00.00000
Current: 00.00000
End Time: 58.93334
Max Time: 58.93334

Figure 8. Video Labeler Window

11. Along the bottom of the screen is a timeline showing the length of the video. Click and move the small white square (slider) located at the left of the timeline to scroll through the video. To select the start time of the video, move the slider to the point to start analysis. This should be the point at which the athlete's feet first make contact with the sand pit. This time will then be shown in the box labeled "Current." Copy this time and paste it into the box labeled "Start Time" to change the start time of analysis.

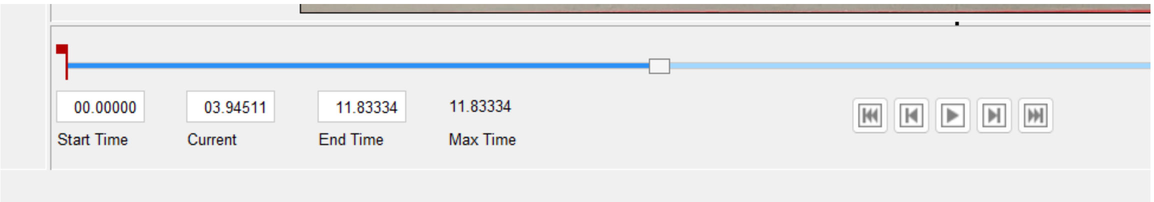

Start Time: 00.00000
Current: 03.94511
End Time: 11.83334
Max Time: 11.83334

Figure 9. Video timeline with Start Time, Current, and End Time

12. If the athlete lands in a sitting position in the sand, move the slider to the time when their butt makes contact with the sand and stops moving. Set this point as the end time by copying the time shown in the Current time box and pasting it into the End Time box. If the athlete does not land in a sitting position, the end time should be around when the athlete's hip reaches the lowest point.
13. Once satisfied with the start and end times, rewind to the first frame so the current time is the same as the start time. This can be done easily by pressing the First Frame button (Figure 10).

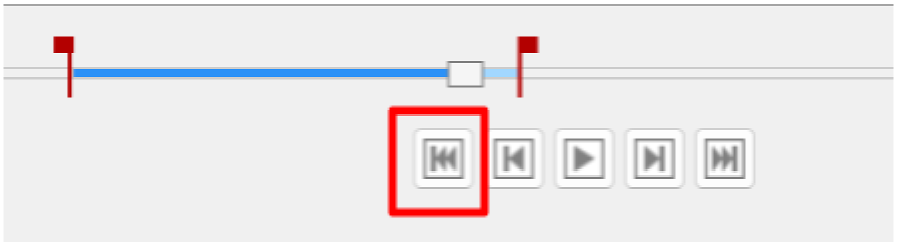
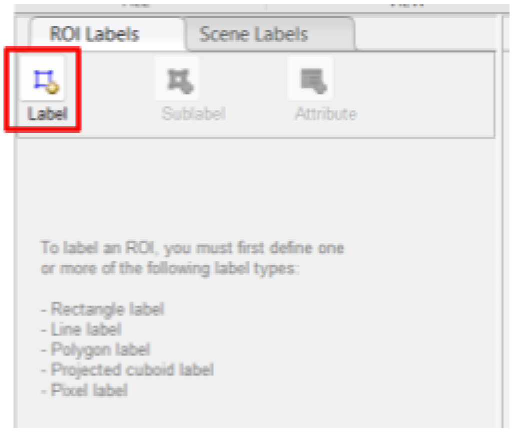


Figure 10. First Frame Button

14. Next, labels must be added to the joint markers as indicated on the leggings. For the sagittal videos, three markers will be tracked: hip, knee, and ankle. To add a label, press the label button located on the left side of the screen under the ROI Labels tab (Figure 11).

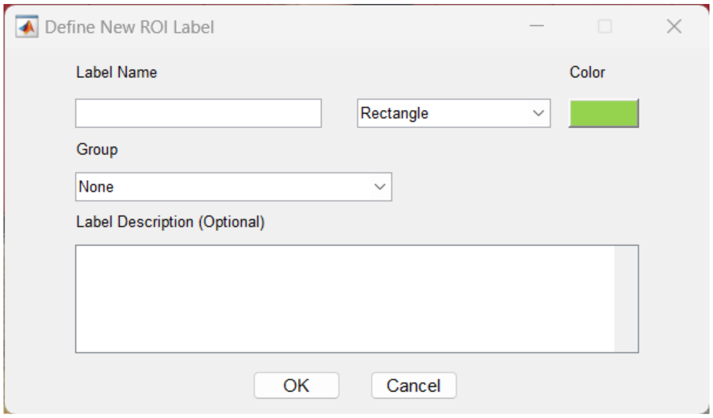


To label an ROI, you must first define one or more of the following label types:

- Rectangle label
- Line label
- Polygon label
- Projected cuboid label
- Pixel label

Figure 11. Button to add a label to joint markers

15. A tab to define the label will then open. The shape of the marker should be set to Rectangle and the names for the sagittal markers should be in all lowercase as follows: “hip”, “knee”, and “ankle” for each respective marker. For the frontal markers, the markers should be labeled as “hipr”, “hipl”, “kneer”, “kneel”, “ankler”, and “anklel”, for each respective left and right marker. The left side is labeled as the left portion of the video, and not necessarily the jumper’s left side. If the markers are labeled differently, the program will not work and there will be an error. Once the name is entered, press “OK.”



Define New ROI Label

Label Name

Rectangle

Color 🟩

Group

None

Label Description (Optional)

Figure 12. Define New ROI Label Window

16. Once "OK" has been selected, place your cursor over the video and click and drag to create a rectangle over each respective marker.

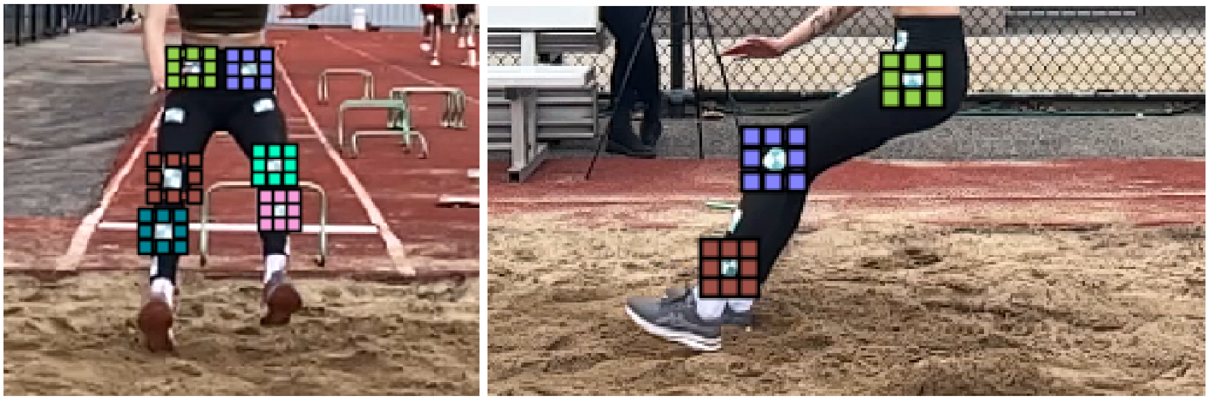


Figure 13 & 14. Frontal and Sagittal Videos with all ROI markers created

17. Once all markers have been created, hover your cursor over the video and select each label while holding Ctrl to highlight each marker in yellow.

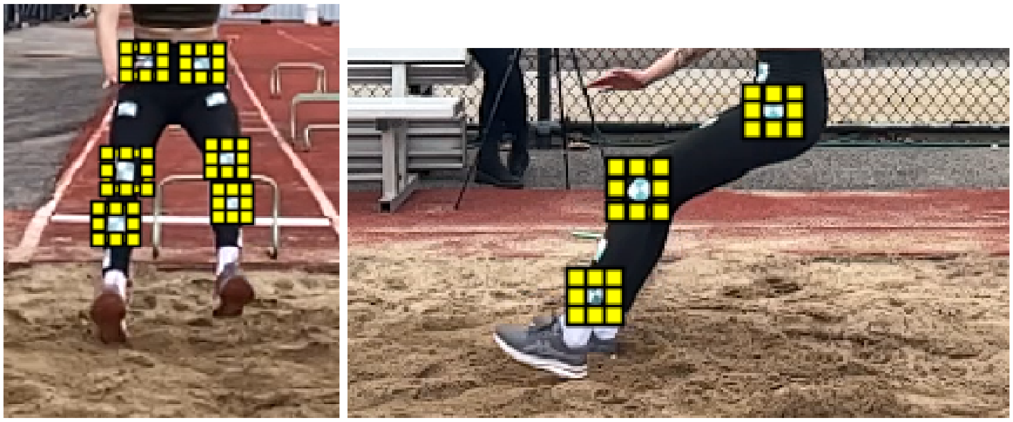


Figure 15 & 16. Frontal and Sagittal Videos with ROI markers highlighted

18. Next, navigate to the top of the window and click “Select Algorithm.” The algorithm we will be using is a point tracker to keep track of all markers so click “Point Tracker.”

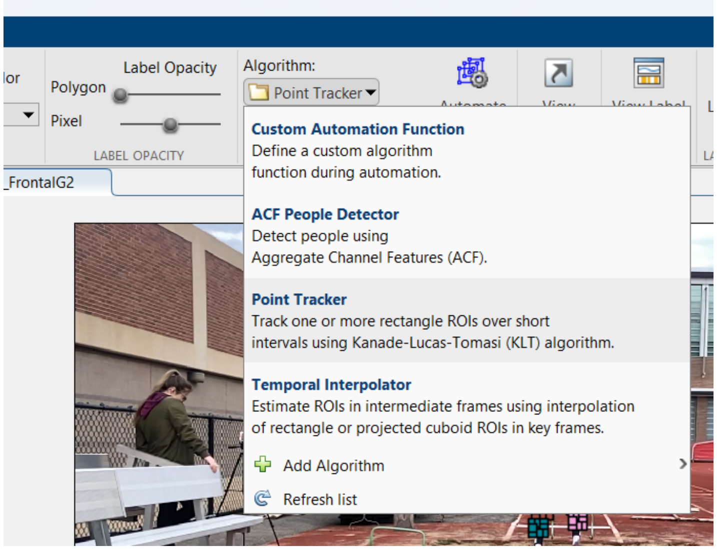


Figure 17. Algorithm selection dropdown

19. Once selected, look to the right of this drop-down and select “Automate.”

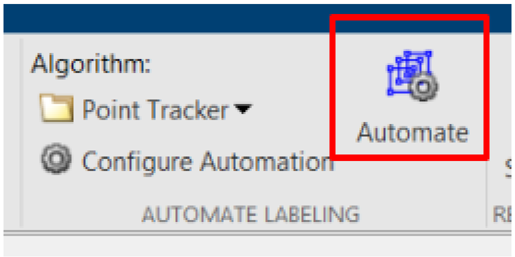


Figure 18. Automate button

20. A new window shown in Figure 19 should now appear. Click “Run” which should track the markers throughout the video. If there are issues with tracking, you may go back and change the positioning of the markers, choose to Rerun the automation, or change the positioning in each frame.

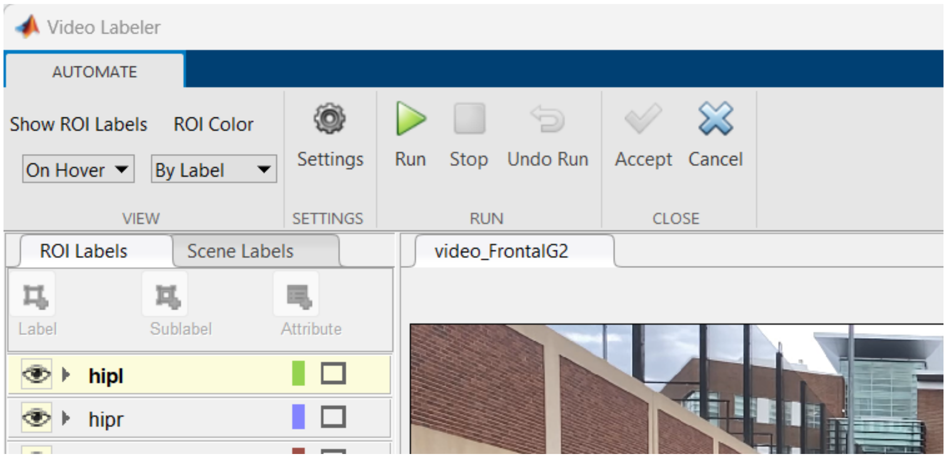


Figure 19. Automation window with "Run" button in the middle top

21. Once satisfied with the tracking of the markers, select "Accept," which should bring you back to the previous window.

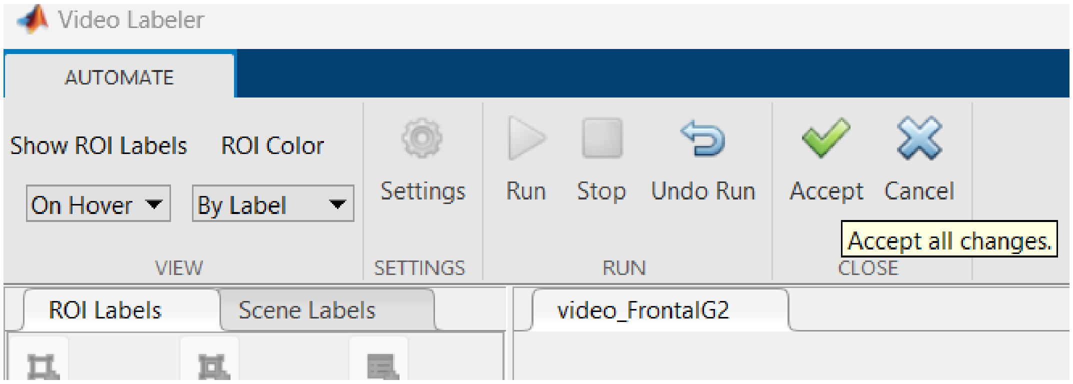


Figure 20. Automation window after running, with "Accept" button in top right

22. Then go to the export section and select "To Workspace." The auto-filled label is "gTruth." This variable name should be changed for each video as follows:

<u>For 2 cameras:</u>

- gTruthS for sagittal video
- gTruthF for frontal video

<u>For 3 cameras:</u>

- gTruthSR for right sagittal video
- gTruthSL for left sagittal video
- gTruthF for frontal video

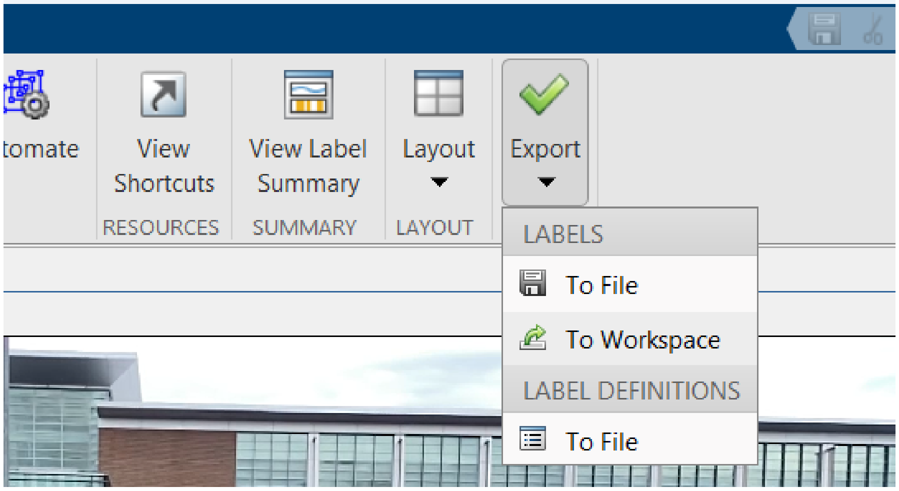
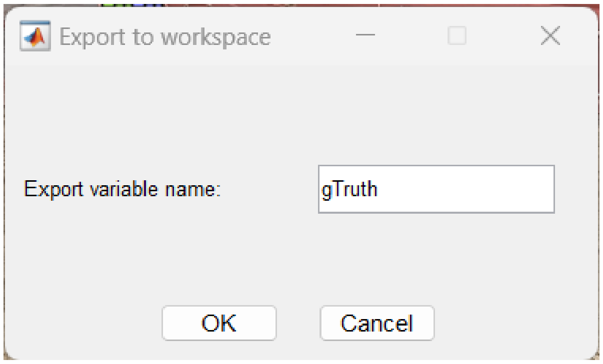


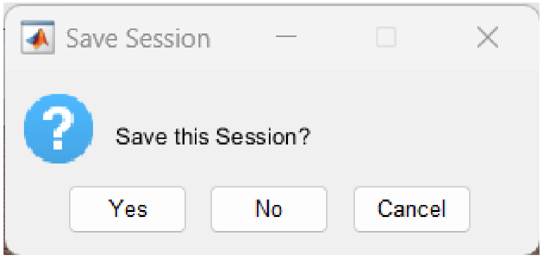
Figure 21. Export button with "To Workspace" selected



Export variable name: gTruth

Figure 22. Export variable naming window

23. Once the variables have been exported to the workspace for each camera view, the Video Labeler windows can be closed. You will have the option to save, and this is not necessary for the program to work, so click "No".



Save this Session?

Figure 23. Save session window

24. Once all gTruth variables have been exported to the workspace from each video, return to the main MATLAB screen and type "Y" into the command window to indicate you have completed labeling. At this point, the analysis will start and the Excel sheets with data will open. Additionally, if there is any valgus positioning, an increased hip vertical velocity, or an increased angular velocity, there will be a warning given in the command window.

25. The command window will then prompt you asking if you want to analyze more videos with the prompt “Add another video? (Y/N)”. If you type “N”, the code will stop running. If you type “Y”, the code will restart from the beginning to allow you to analyze more videos. If you choose to analyze more videos, close out the Excel sheets so the code can update them, because it cannot write to them while they are open on your computer.

Repeat steps 8-22 if analyzing more videos.

Appendix D: MATLAB Code

```
%% User prompt video
clear;
clc;
done = false;
% Setting up Maps
map = containers.Map('KeyType', 'char', 'ValueType', 'any');
% number to keep track of each athlete's data so they don't overwrite each
% other
athleteNum = 1;
cameraNum = input('How many cameras are being used? ');
%% While loop for indoor track when there are 2 cameras
while (done == false && cameraNum == 2)
   % Print if there are no current athletes
   if isempty(map)
       fprintf('No athletes currently \n');
   else
       % Print all athletes currently in the system
       % Meant to show names so ppl know how ppl are written in the system and
       % won't record people twice
       fprintf('Current athletes: \n');
       disp(map.keys);
   end
   % Prompt to see who's video they are trying to input
   name = input('Name of athlete in video: ', 's');
   % Check to see if this person already has a struct in the map
   if (isKey(map, name))
       % if the person already has data, should set the variables that are
       % being written to so they correspond to their data
       tempMap = map(name);
       jumpNum = tempMap.jumpNum + 1; %increase jumpNum
       jumpDataS = tempMap.jumpDataS; %accessing previous jumpData
       jumpDataF = tempMap.jumpDataF;

   else
       %if the person does not have data, need to create a new struct to store
       %their data
       % Creating struct to store info abt athlete in one place
       %jumpNum for athlete
       %jumpData to store data for all jumps
       athleteData(athleteNum) = struct('jumpNum',1, 'jumpDataS', struct([]),
'jumpDataF', struct([]));
       %still need to set variables to be written to later in the code
       jumpNum = 1;
       %putting athlete into map
       map(name) = athleteData(athleteNum);
       athleteNum = athleteNum + 1; %add 1 to athleteNum so data isn't
overwritten
   end
   file_sagittal = input('Add sagittal video file: ', 's');
   file_frontal = input('Add frontal video file: ', 's');
   videoLabeler(file_sagittal)
%https://www.mathworks.com/help/vision/ug/get-started-with-the-video-labeler.ht
ml
```

```
%https://www.mathworks.com/matlabcentral/answers/128697-using-image-processing-
tool-measure-the-angle
   % Identify hip, knee, and ankle tracker
   % Automate markers using point tracker
   % export data
   videoLabeler(file_frontal)
   % identify right and left hip, knee, and ankle markers
   % Exported Labels

   while 1
       complete = input('Done labeling? (Y/N)', 's');
           if(complete == 'Y')
               break;
           else
               continue;
           end
   end

   gTruthS %display label properties
   gTruthS.LabelDefinitions %display labels
   labelDataS = gTruthS.LabelData; %store label data
   head(labelDataS) %display label data
   %Creates struct with position data over time range
   %Label data is in format [x y width height]
   %y axis goes in reverse
   %For loop to only get data that has info
   started = false;
   for i = 1:height(labelDataS)
       %if there is no data
       if isempty(labelDataS(i,:).hip{1})
           %if this is the first instance of no data, set end time to then
           if started == true
               endTime = labelDataS(i,:).Time;
               break;
           else
               continue;
           end
       %if there is data
       else
           %if this is the first instance of data, set start time to then
           if started == false
               startTime = labelDataS(i,:).Time;
               started = true;
           else
               continue;
           end
       end
   end
   totalTime = datenum((startTime-endTime)*86400);
   gTruthIntervalS = labelDataS(timerange(startTime,endTime),:);
   % should prob change time range to full range of data
   head(gTruthIntervalS)
   %gTruthInterval(frame,:).label{1}(1=x,2=y)
   %gets y-value in the first frame
   %% While loop - sagittal analysis
   % Setting up struct to store jump data
```

```
   jumpDataS(jumpNum) = struct('time', [], 'hipx', [], 'hipy', [], 'kneex', [],
'kneey', [], ...
   'anklex', [], 'ankley' , [], 'hipdx', [], 'hipdy', [], ...
   'hipd', [], 'hipavgv', [],'hipavgv_vertical',[], 'flexion', [], 'angularv',
[]);
   %Setting up arrays to store values
   time = [];
   hipx = [];
   hipy = [];
   kneex = [];
   kneey = [];
   anklex = [];
   ankley = [];
   hipdx = [];
   hipdy = [];
   hipd = [];
   hipavgv = [];
   hipavgv_vertical = [];
   flexion = [];
   angularv = [];
   i=height(gTruthIntervalS);
   x=1;
   while x<=i
       hipx(x)= gTruthIntervalS(x,:).hip{1}(1);
       hipy(x)= gTruthIntervalS(x,:).hip{1}(2);
       kneex(x)= gTruthIntervalS(x,:).knee{1}(1);
       kneey(x)= gTruthIntervalS(x,:).knee{1}(2);
       anklex(x)= gTruthIntervalS(x,:).ankle{1}(1);
       ankley(x)= gTruthIntervalS(x,:).ankle{1}(2);
       P0 = [gTruthIntervalS(x,:).knee{1}(1), gTruthIntervalS(x,:).knee{1}(2)];
%defining each point
       P1 = [gTruthIntervalS(x,:).ankle{1}(1),
gTruthIntervalS(x,:).ankle{1}(2)];
       P2 = [gTruthIntervalS(x,:).hip{1}(1), gTruthIntervalS(x,:).hip{1}(2)];
       n1 = (P2 - P0) / norm(P2 - P0);  % Normalized vectors
       n2 = (P1 - P0) / norm(P1 - P0);
       angle = atan2(norm(det([n2; n1])), dot(n1, n2));
       flexion(x) = rad2deg(angle);
       time(x) = datenum((gTruthIntervalS(x,:).Time)*86400);
       if x>=4
           hipdx(x) = hipx(x) - hipx(x-3);
           hipdy(x) = hipy(x) - hipy(x-3);
           hipd(x) = sqrt(hipdx(x)^2 + hipdy(x)^2);
           hipavgv(x) = hipd(x) / 0.1;
           hipavgv_vertical(x) = hipdy(x)/0.1;
           angularv(x) = (flexion(x) - flexion(x-3))/0.1;
       else
           hipdx(x) = 0;
           hipdy(x) = 0;
           hipd(x) = 0;
           hipavgv(x) = 0;
           hipavgv_vertical(x) = 0;
           angularv(x) = 0;
       end
       timePassed = time(x) - datenum((startTime)*86400);
       if timePassed > totalTime/2
           if hipavgv_vertical(x)>157.48
```

```
            disp('High hip average vertical velocity detected \n')
        else
        end
        if angularv(x)<-8000
            disp('High average angular velocity detected \n')
        else
        end
    else
    end

    x = x+1;
end
jumpDataS(jumpNum).time=time';
jumpDataS(jumpNum).hipx=hipx';
jumpDataS(jumpNum).hipy=hipy';
jumpDataS(jumpNum).kneex=kneex';
jumpDataS(jumpNum).kneey=kneey';
jumpDataS(jumpNum).anklex=anklex';
jumpDataS(jumpNum).ankley=ankley';
jumpDataS(jumpNum).flexion=flexion';
jumpDataS(jumpNum).hipdx=hipdx';
jumpDataS(jumpNum).hipdy=hipdy';
jumpDataS(jumpNum).hipd=hipd';
jumpDataS(jumpNum).hipavgv=hipavgv';
jumpDataS(jumpNum).hipavgv_vertical = hipavgv_vertical';
jumpDataS(jumpNum).angularv=angularv';
figure
% For loop to graph all data on top of each other
for i = 1:jumpNum
    startTime = jumpDataS(i).time(1);
    plot(jumpDataS(i).time-startTime, jumpDataS(i).hipavgv, 'o')
    hold on
end
title("Hip Average Velocity: " + name + string(jumpNum))
xlabel('Time')
ylabel('Hip Velocity')
hold off
figure
% For loop to graph all data on top of each other
for i = 1:jumpNum
    startTime = jumpDataS(i).time(1);
    plot(jumpDataS(i).time-startTime, jumpDataS(i).hipavgv_vertical, 'o')
    hold on
end
title("Hip Average Vertical Velocity: " + name + string(jumpNum))
xlabel('Time')
ylabel('Hip Vertical Velocity')
hold off
figure
% For loop to graph all data on top of each other
for i = 1:jumpNum
    startTime = jumpDataS(i).time(1);
    plot(jumpDataS(i).time-startTime, jumpDataS(i).hipavgv, 'o')
    hold on
end
title("Knee Flexion Angle: " + name + string(jumpNum))
xlabel('Time')
```

```
   ylabel('Knee Flexion Angle')
   hold off
   figure
   % For loop to graph all data on top of each other
   for i = 1:jumpNum
       startTime = jumpDataS(i).time(1);
       plot(jumpDataS(i).time-startTime, jumpDataS(i).angularv, 'o')
       hold on
   end
   title("Knee Angular Velocity: " + name + string(jumpNum))
   xlabel('Time')
   ylabel('Knee Angular Velocity')
   hold off
   %Write sagittal data to spreadhseet
   sheetName = append(name, string(jumpNum));
   S=[jumpDataS(jumpNum)];
   writetable(struct2table(S),'Lsagittal.xlsx', 'Sheet', sheetName);
   winopen Lsagittal.xlsx
   %% Frontal Analysis
   gTruthF %display label properties
   gTruthF.LabelDefinitions %display labels
   labelDataF = gTruthF.LabelData; %store label data
   head(labelDataF) %display label data
   %For loop to only get data that has info
   started = false;
   for i = 1:height(labelDataF)
       %if there is no data
       if isempty(labelDataF(i,:).kneer{1})
           %if this is the first instance of no data, set end time to then
           if started == true
               endTime = labelDataF(i,:).Time;
               break;
           else
               continue;
           end
       %if there is data
       else
           %if this is the first instance of data, set start time to then
           if started == false
               startTime = labelDataF(i,:).Time;
               started = true;
           else
               continue;
           end
       end
   end
   gTruthIntervalF = labelDataF(timerange(startTime,endTime),:);
   % should prob change time range to full range of data
   head(gTruthIntervalF)
   % Setting up struct to store jump data
   jumpDataF(jumpNum) = struct('time', [], 'hipx_r', [], 'hipx_l', [],
'kneex_r', [], 'kneex_l', [], ...
   'anklex_r', [], 'anklex_l' , [], 'valgus', []);
   % Boolean to keep track of if there is valgus positioning in both legs
   isValgus = false;
   j = height(gTruthIntervalF); %value for indexing
   x=1;
```

```
% Boolean to keep track of if there are any more hip values or not
hipr_stopped = false;
hipl_stopped = false;
% Setting up arrays to store values
time = [];
hipx_r = [];
hipx_l = [];
valgus = [];
kneex_r = [];
kneex_l = [];
anklex_r = [];
anklex_l = [];
while x<=j

    %Checking to see if there is marker data for the hips since sometimes
    %the markers do not track the full landing since they're out of view
    if isempty(gTruthIntervalF(x,:).hipr{1})
        if hipr_stopped == false
            last_hipxr = hipx_r(x-1);
        else
        end
        hipx_r(x) = last_hipxr;
    else
        hipx_r(x)= gTruthIntervalF(x,:).hipr{1}(1);
    end
    % Checking left hip and setting value
    if isempty(gTruthIntervalF(x,:).hipl{1})
        if hipl_stopped == false
            last_hipxl = hipx_l(x-1);
        else
        end
        hipx_l(x) = last_hipxl;
    else
        hipx_l(x)= gTruthIntervalF(x,:).hipl{1}(1);
    end
    hipx_r(x)= gTruthIntervalF(x,:).hipr{1}(1);
    hipx_l(x)= gTruthIntervalF(x,:).hipl{1}(1);
    kneex_r(x)= gTruthIntervalF(x,:).kneer{1}(1);
    kneex_l(x)= gTruthIntervalF(x,:).kneel{1}(1);
    anklex_r(x)= gTruthIntervalF(x,:).ankler{1}(1);
    anklex_l(x)= gTruthIntervalF(x,:).anklel{1}(1);
    time(x) = datenum((gTruthIntervalF(x,:).Time)*86400);
    %Checking if there is valgus positioning on right
    if kneex_r(x)<hipx_r(x) && kneex_r(x)<anklex_r(x)
        valgus_r(x) = "Valgus";
    else
        valgus_r(x) = "No Valgus";
    end
    %Checking if there is valgus positioning on left
    if kneex_l(x)>hipx_l(x) && kneex_l(x)>anklex_l(x)
        valgus_l(x) = "Valgus";
    else
        valgus_l(x) = "No Valgus";
    end
    if strcmp(valgus_r(x),"Valgus") && strcmp(valgus_l, "Valgus")
        isValgus = true;
        valgus(x) = "Valgus";
```

```
        else
            valgus(x) = "";
        end
        x=x+1;
    end
    if isValgus == true
        fprintf('Valgus Positioning Detected \n')
    else
    end
    jumpDataF(jumpNum).time = time';
    jumpDataF(jumpNum).hipx_r = hipx_r';
    jumpDataF(jumpNum).hipx_l = hipx_l';
    jumpDataF(jumpNum).kneex_r = kneex_r';
    jumpDataF(jumpNum).kneex_l = kneex_l';
    jumpDataF(jumpNum).anklex_r = anklex_r';
    jumpDataF(jumpNum).anklex_l = anklex_l';
    jumpDataF(jumpNum).valgus = valgus';
    %Write frontal data to spreadsheet
    sheetName = append(name, string(jumpNum));
    S=[jumpDataF(jumpNum)];
    writetable(struct2table(S),'Frontal.xlsx', 'Sheet', sheetName);
    winopen Frontal.xlsx
    %% Updating and continuing
    % Need to update variables in map
    tempMap = map(name);
    tempMap.jumpDataS = jumpDataS;
    tempMap.jumpDataF = jumpDataF;
    map(name) = tempMap;

    while 1
    isDone = input('Add another video? (Y/N)', 's');
    if (isDone == 'Y')
        done = false;
        break
    elseif (isDone == 'N')
            done = true;
            break
    else
        fprintf('Invalid response. Please write Y or N \n');
        continue;
    end
    end
end

%% While loop for outdoor track when there are 3 cameras
while (done == false && cameraNum == 3)
    % Print if there are no current athletes
    if isempty(map)
        fprintf('No athletes currently \n');
    else
        % Print all athletes currently in the system
        % Meant to show names so ppl know how ppl are written in the system and
        % won't record people twice
        fprintf('Current athletes: \n');
        disp(map.keys);
    end
    % Prompt to see who's video they are trying to input
```

```
   name = input('Name of athlete in video: ', 's');
   % Check to see if this person already has a struct in the map
   if (isKey(map, name))
       % if the person already has data, should set the variables that are
       % being written to so they correspond to their data
       jumpNum = map(name).jumpNum + 1; %increase jumpNum
       jumpDataR = map(name).jumpDataR; %all right sagittal jump data
       jumpDataL = map(name).jumpDataL; %all left sagittal jump data
       jumpDataF = map(name).jumpDataF; %all frontal jump data
   else
       %if the person does not have data, need to create a new struct to store
       %their data
       % Creating struct to store info abt athlete in one place
       %jumpNum for athlete
       %need to think abt min angle and such and if they should be stored
       %separately which they prob should
       athleteData(athleteNum) = struct('jumpNum',1, 'jumpDataR', struct([]),
'jumpDataL', struct([]), 'jumpDataF', struct([]));
       %still need to set variables to be written to later in the code
       jumpNum = 1;
       %putting athlete into map
       map(name) = athleteData(athleteNum);
       athleteNum = athleteNum + 1; %add 1 to athleteNum so data isn't
overwritten
   end
   file_sagittal_r = input('Add right sagittal video file: ', 's');
   file_sagittal_l = input('Add left sagittal video file: ', 's');
   file_frontal = input('Add frontal video file: ', 's');
   videoLabeler(file_sagittal)
%https://www.mathworks.com/help/vision/ug/get-started-with-the-video-labeler.ht
ml

%https://www.mathworks.com/matlabcentral/answers/128697-using-image-processing-
tool-measure-the-angle
   % Identify hip, knee, and ankle tracker
   % Automate markers using point tracker
   % export data
   videoLabeler(file_frontal)
   % identify right and left hip, knee, and ankle markers
   % Exported Labels

   while 1
       complete = input('Done labeling? (Y/N)', 's');
           if(complete == 'Y')
               break;
           else
               continue;
           end
   end
%% Handling right sagittal video data

   gTruthSR %display label properties
   gTruthSR.LabelDefinitions %display labels
   labelDataSR = gTruthSR.LabelData; %store label data
   head(labelDataSR) %display label data
   %Creates struct with position data over time range
   %Label data is in format [x y width height]
```

```
   %y axis goes in reverse
   %For loop to only get data that has info
   started = false;
   for i = 1:height(labelDataSR)
       %if there is no data
       if isempty(labelDataSR(i,:).hip{1})
           %if this is the first instance of no data, set end time to then
           if started == true
               endTime = labelDataSR(i,:).Time;
               break;
           else
               continue;
           end
       %if there is data
       else
           %if this is the first instance of data, set start time to then
           if started == false
               startTime = labelDataSR(i,:).Time;
               started = true;
           else
               continue;
           end
       end
   end
   totalTime = datenum((startTime-endTime)*86400);
   gTruthIntervalSR = labelDataSR(timerange(startTime,endTime),:);
   % should prob change time range to full range of data
   head(gTruthIntervalSR)

   % Setting up struct to store jump data
   jumpDataR(jumpNum) = struct('time', [], 'hipx', [], 'hipy', [], 'kneex', [],
'kneey', [], ...
   'anklex', [], 'ankley' , [], 'hipdx', [], 'hipdy', [], ...
   'hipd', [], 'hipavgv', [],'hipavgv_vertical',[], 'flexion', [], 'angularv',
[]);
   % While loop
   i=height(gTruthIntervalSR);
   x=1;
   while x<=i
       hipx(x)= gTruthIntervalSR(x,:).hip{1}(1);
       hipy(x)= gTruthIntervalSR(x,:).hip{1}(2);
       kneex(x)= gTruthIntervalSR(x,:).knee{1}(1);
       kneey(x)= gTruthIntervalSR(x,:).knee{1}(2);
       anklex(x)= gTruthIntervalSR(x,:).ankle{1}(1);
       ankley(x)= gTruthIntervalSR(x,:).ankle{1}(2);
       P0 = [gTruthIntervalSR(x,:).knee{1}(1),
gTruthIntervalSR(x,:).knee{1}(2)]; %defining each point
       P1 = [gTruthIntervalSR(x,:).ankle{1}(1),
gTruthIntervalSR(x,:).ankle{1}(2)];
       P2 = [gTruthIntervalSR(x,:).hip{1}(1), gTruthIntervalSR(x,:).hip{1}(2)];
       n1 = (P2 - P0) / norm(P2 - P0);  % Normalized vectors
       n2 = (P1 - P0) / norm(P1 - P0);
       angle = atan2(norm(det([n2; n1])), dot(n1, n2));
       flexion(x) = rad2deg(angle);
       if x>=4
           hipdx(x) = hipx(x) - hipx(x-3);
           hipdy(x) = hipy(x) - hipy(x-3);
```

```
        hipd(x) = sqrt(hipdx(x)^2 + hipdy(x)^2);
        hipavgv(x) = hipd(x) / 0.1;
        hipavgv_vertical(x) = hipdy(x)/0.1;
        angularv(x) = (flexion(x) - flexion(x-3))/0.1;
    else
        hipdx(x) = 0;
        hipdy(x) = 0;
        hipd(x) = 0;
        hipavgv(x) = 0;
        hipavgv_vertical(x) = 0;
        angularv(x) = 0;
    end
    if time(x) > totalTime/2
        if hipavgv_vertical(x)>157.48
            disp('High hip average vertical velocity detected \n')
        else
        end
        if angularv(x)<-8000
            disp('High average angular velocity detected \n')
        else
        end
    else
    end
    x = x+1;
end
jumpDataR(jumpNum).hipx=hipx';
jumpDataR(jumpNum).hipy=hipy';
jumpDataR(jumpNum).kneex=kneex';
jumpDataR(jumpNum).kneey=kneey';
jumpDataR(jumpNum).anklex=anklex';
jumpDataR(jumpNum).ankley=ankley';
jumpDataR(jumpNum).flexion=flexion';
jumpDataR(jumpNum).hipdx=hipdx';
jumpDataR(jumpNum).hipdy=hipdy';
jumpDataR(jumpNum).hipd=hipd';
jumpDataR(jumpNum).hipavgv=hipavgv';
jumpDataR(jumpNum).hipavgv_vertical=hipavgv_vertical';
jumpDataR(jumpNum).angularv=angularv';

figure
% For loop to graph all data on top of each other
for i = 1:jumpNum-1
    startTime = jumpDataR(i).time(1);
    plot(jumpDataR(i).time-startTime, jumpDataR(i).hipavgv, 'o')
    hold on
end
title("Right Hip Average Velocity: " + name + string(jumpNum))
xlabel('Time')
ylabel('Hip Velocity')
hold off
figure
% For loop to graph all data on top of each other
for i = 1:jumpNum-1
    startTime = jumpDataR(i).time(1);
    plot(jumpDataR(i).time-startTime, jumpDataR(i).hipavgv_vertical, 'o')
    hold on
end
```

```
    title("Right Hip Average Vertical Velocity: " + name + string(jumpNum))
    xlabel('Time')
    ylabel('Hip Vertical Velocity')
    hold off
    figure
    % For loop to graph all data on top of each other
    for i = 1:jumpNum
        startTime = jumpDataR(i).time(1);
        plot(jumpDataR(i).time-startTime, jumpDataR(i).hipavgv, 'o')
        hold on
    end
    title("Right Knee Flexion Angle: " + name + string(jumpNum))
    xlabel('Time')
    ylabel('Knee Flexion Angle')
    hold off
    figure
    % For loop to graph all data on top of each other
    for i = 1:jumpNum
        startTime = jumpDataR(i).time(1);
        plot(jumpDataR(i).time-startTime, jumpDataR(i).angularv, 'o')
        hold on
    end
    title("Right Knee Angular Velocity: " + name + string(jumpNum))
    xlabel('Time')
    ylabel('Knee Angular Velocity')
    hold off
    %Wrtie sagittal data to spreadhseet
    sheetName = append(name, string(jumpNum));
    S=[jumpDataS(jumpNum, :)];
    writetable(struct2table(S),'Rsagittal.xlsx', 'Sheet', sheetName);
    winopen Rsagittal.xlsx
%% Handling left sagittal video data
    gTruthSL %display label properties
    gTruthSL.LabelDefinitions %display labels
    labelDataSL = gTruthSL.LabelData; %store label data
    head(labelDataSL) %display label data
    %Creates struct with position data over time range
    %Label data is in format [x y width height]
    %y axis goes in reverse
    %For loop to only get data that has info
    started = false;
    for i = 1:height(labelDataSL)
        %if there is no data
        if isempty(labelDataSL(i,:).hip{1})
            %if this is the first instance of no data, set end time to then
            if started == true
                endTime = labelDataSL(i,:).Time;
                break;
            else
                continue;
            end
        %if there is data
        else
            %if this is the first instance of data, set start time to then
            if started == false
                startTime = labelDataSL(i,:).Time;
                started = true;
```

```
            else
                continue;
            end
        end
    end
    totalTime = datenum((startTime-endTime)*86400);
    gTruthIntervalSL = labelDataSL(timerange(startTime,endTime),:);
    % should prob change time range to full range of data
    head(gTruthIntervalSL)
    %gTruthInterval(frame,:).label{1}(1=x,2=y)
    %gets y-value in the first frame
    % Setting up struct to store jump data
    jumpDataL(jumpNum) = struct('hipx', [], 'hipy', [], 'kneex', [], 'kneey',
[], ...
    'anklex', [], 'ankley' , [], 'hipdx', [], 'hipdy', [], ...
    'hipd', [], 'hipavgv', [], 'hipavgv_vertical', [], 'flexion', [],
'angularv', []);
    % While loop
    i=height(gTruthIntervalSL);
    x=1;
    while x<=i
        hipx(x)= gTruthIntervalSL(x,:).hip{1}(1);
        hipy(x)= gTruthIntervalSL(x,:).hip{1}(2);
        kneex(x)=gTruthIntervalSL(x,:).knee{1}(1);
        kneey(x)= gTruthIntervalSL(x,:).knee{1}(2);
        anklex(x)= gTruthIntervalSL(x,:).ankle{1}(1);
        ankley(x)= gTruthIntervalSL(x,:).ankle{1}(2);
        P0 = [gTruthIntervalSL(x,:).knee{1}(1),
gTruthIntervalSL(x,:).knee{1}(2)]; %defining each point
        P1 = [gTruthIntervalSL(x,:).ankle{1}(1),
gTruthIntervalSL(x,:).ankle{1}(2)];
        P2 = [gTruthIntervalSL(x,:).hip{1}(1), gTruthIntervalSL(x,:).hip{1}(2)];
        n1 = (P2 - P0) / norm(P2 - P0);  % Normalized vectors
        n2 = (P1 - P0) / norm(P1 - P0);
        angle = atan2(norm(det([n2; n1])), dot(n1, n2));
        flexion(x) = rad2deg(angle);
        if x>=4
            hipdx(x) = hipx(x) - hipx(x-3);
            hipdy(x) = hipy(x) - hipy(x-3);
            hipd(x) = sqrt(hipdx(x)^2 + hipdy(x)^2);
            hipavgv(x) = hipd(x) / 0.1;
            hipavgv_vertical(x) = hipavgv_vertical(x)/0.1;
            angularv(x) = (flexion(x) - flexion(x-3))/0.1;
        else
            hipdx(x) = 0;
            hipdy(x) = 0;
            hipd(x) = 0;
            hipavgv(x) = 0;
            hipavgv_vertical(x) = 0;
            angularv(x) = 0;
        end
        if time(x) > totalTime/2
            if hipavgv_vertical(x)>157.48
                disp('High hip average vertical velocity detected \n')
            else
            end
            if angularv(x)<-8000
```

```
            disp('High average angular velocity detected \n')
        else
        end
    else
    end
    x = x+1;
end
jumpDataL(jumpNum).hipx=hipx';
jumpDataL(jumpNum).hipy=hipy';
jumpDataL(jumpNum).kneex=kneex';
jumpDataL(jumpNum).kneey=kneey';
jumpDataL(jumpNum).anklex=anklex';
jumpDataL(jumpNum).ankley=ankley';
jumpDataL(jumpNum).flexion=flexion';
jumpDataL(jumpNum).hipdx=hipdx';
jumpDataL(jumpNum).hipdy=hipdy';
jumpDataL(jumpNum).hipd=hipd';
jumpDataL(jumpNum).hipavgv=hipavgv';
jumpDataL(jumpNum).hipavgv_vertical = hipavgv_vertical';
jumpDataL(jumpNum).angularv=angularv';
figure
% For loop to graph all data on top of each other
for i = 1:jumpNum
    startTime = jumpDataL(i).time(1);
    plot(jumpDataL(i).time - startTime, jumpDataL(i).hipavgv, 'o')
    hold on
end
title("Left Hip Average Velocity: " + name + string(jumpNum))
xlabel('Time')
ylabel('Hip Velocity')
hold off
figure
% For loop to graph all data on top of each other
for i = 1:jumpNum
    startTime = jumpDataL(i).time(1);
    plot(jumpDataL(i).time-startTime, jumpDataL(i).hipavgv_vertical, 'o')
    hold on
end
title("Left Hip Average Vertical Velocity: " + name + string(jumpNum))
xlabel('Time')
ylabel('Hip Vertical Velocity')
hold off
figure
% For loop to graph all data on top of each other
for i = 1:jumpNum
    startTime = jumpDataL(i).time(1);
    plot(jumpDataL(i).time-startTime, jumpDataL(i).hipavgv, 'o')
    hold on
end
title("Left Knee Flexion Angle: " + name + string(jumpNum))
xlabel('Time')
ylabel('Knee Flexion Angle')
hold off
figure
% For loop to graph all data on top of each other
for i = 1:jumpNum
    startTime = jumpDataL(i).time(1);
```

```
           plot(jumpData(L).time-startTime, jumpDataL(i).angularv, 'o')
           hold on
       end
       title("Left Knee Angular Velocity: " + name + string(jumpNum))
       xlabel('Time')
       ylabel('Knee Angular Velocity')
       hold off
       %Wrtie data to Excel sheet
       sheetName = append(name, string(jumpNum));
       S=[jumpDataS(jumpNum, :)];
       writetable(struct2table(S),'Lsagittal.xlsx', 'Sheet', sheetName);
       winopen Lsagittal.xlsx
       %% Frontal Analysis
       gTruthF %display label properties
       gTruthF.LabelDefinitions %display labels
       labelDataF = gTruthF.LabelData; %store label data
       head(labelDataF) %display label data
       %For loop to only get data that has info
       started = false;
       for i = 1:height(labelDataF)
           %if there is no data
           if isempty(labelDataF(i,:).kneer{1})
               %if this is the first instance of no data, set end time to then
               if started == true
                   endTime = labelDataF(i,:).Time;
                   break;
               else
                   continue;
               end
           %if there is data
           else
               %if this is the first instance of data, set start time to then
               if started == false
                   startTime = labelDataF(i,:).Time;
                   started = true;
               else
                   continue;
               end
           end
       end
       gTruthIntervalF = labelDataF(timerange(startTime,endTime),:);
       % should prob change time range to full range of data
       head(gTruthIntervalF)
       % Setting up struct to store jump data
       jumpDataF(jumpNum) = struct('time', [], 'hipx_r', [], 'hipx_l', [],
   'kneex_r', [], 'kneex_l', [], ...
       'anklex_r', [], 'anklex_l' , [], 'valgus', []);
       % Boolean to keep track of if there is valgus positioning in both legs
       isValgus = false;
       j = height(gTruthIntervalF); %value for indexing
       x=1;
       % Boolean to keep track of if there are any more hip values or not
       hipr_stopped = false;
       hipl_stopped = false;
       % Setting up arrays to store values
       hipx_r = [];
       hipx_l = [];
```

```
valgus = [];
while x<=j

    %Checking to see if there is marker data for the hips since
    %sometimes the markers do not track the full landing
    if isempty(gTruthIntervalF(x,:).hipr{1})
        if hipr_stopped == false
            last_hipxr = hipx_r(x-1);
        else
        end
        hipx_r(x) = last_hipxr;
    else
        hipx_r(x)= gTruthIntervalF(x,:).hipr{1}(1);
    end
    % Checking left hip and setting value
    if isempty(gTruthIntervalF(x,:).hipl{1})
        if hipl_stopped == false
            last_hipxl = hipx_l(x-1);
        else
        end
        hipx_l(x) = last_hipxl;
    else
        hipx_l(x)= gTruthIntervalF(x,:).hipl{1}(1);
    end
    hipx_r(x)= gTruthIntervalF(x,:).hipr{1}(1);
    hipx_l(x)= gTruthIntervalF(x,:).hipl{1}(1);
    kneex_r(x)= gTruthIntervalF(x,:).kneer{1}(1);
    kneex_l(x)= gTruthIntervalF(x,:).kneel{1}(1);
    anklex_r(x)= gTruthIntervalF(x,:).ankler{1}(1);
    anklex_l(x)= gTruthIntervalF(x,:).anklel{1}(1);
    time(x) = datenum((gTruthIntervalF(x,:).Time)*86400);
    %Checking if there is valgus positioning on right
    if kneex_r(x)<hipx_r(x) && kneex_r(x)<anklex_r(x)
        valgus_r(x) = "Valgus";
    else
        valgus_r(x) = "No Valgus";
    end
    %Checking if there is valgus positioning on left
    if kneex_l(x)>hipx_l(x) && kneex_l(x)>anklex_l(x)
        valgus_l(x) = "Valgus";
    else
        valgus_l(x) = "No Valgus";
    end
    if strcmp(valgus_r(x),"Valgus") && strcmp(valgus_l, "Valgus")
        isValgus = true;
        valgus(x) = "Valgus";
    else
        valgus(x) = "";
    end
    x=x+1;
end
if isValgus == true
    fprintf('Valgus Positioning Detected \n')
else
end
jumpDataF(jumpNum).time = time';
jumpDataF(jumpNum).hipx_r = hipx_r';
```

```
    jumpDataF(jumpNum).hipx_l = hipx_l';
    jumpDataF(jumpNum).kneex_r = kneex_r';
    jumpDataF(jumpNum).kneex_l = kneex_l';
    jumpDataF(jumpNum).anklex_r = anklex_r';
    jumpDataF(jumpNum).anklex_l = anklex_l';
    jumpDataF(jumpNum).valgus = valgus';
    %Write frontal data to spreadsheet
    sheetName = append(name, string(jumpNum));
    S=[jumpDataF(jumpNum, :)];
    writetable(struct2table(S),'Frontal.xlsx', 'Sheet', sheetName);
    winopen Frontal.xlsx
    %% Updating and continuing
    % Need to update variables in map
    tempMap = map(name);
    tempMap.jumpDataR = jumpDataR;
    tempMap.jumpDataL = jumpDataL;
    tempMap.jumpDataF = jumpDataF;
    map(name) = tempMap;

    while 1
    isDone = input('Add another video? (Y/N)', 's');
    if (isDone == 'Y')
        done = false;
        break
    elseif (isDone == 'N')
            done = true;
            break
    else
        fprintf('Invalid response. Please write Y or N \n');
        continue;
    end
    end
end
```