Metric to Characterize Baseball Pitcher Fatigue

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Abstract

High volumes of baseball pitches thrown by an athlete are associated with fatigue, which can decrease performance and increase injury risk. A system to identify certain biomechanical factors that have been linked with pitcher fatigue would be beneficial for the sport as a method of providing objective quantifications of a player's risk of becoming over-fatigued. The team used motion capture to evaluate collegiate and major league (Pittsburgh Pirates) level pitchers, and conducted data exploration and analysis of the results on the parallel datasets. This included factors such as mechanical variation, joint range of motion, rate of force development, performance metrics, kinetic chain, rest time, and joint forces/moments. From the team's data exploration, select candidate biomechanical factors were identified as the strongest indicators of fatigue, and were used to develop a fatigue metric. This metric included three biomechanical factors/outcomes, which characterized a pitch as "fatigued" upon failure of these factors/outcomes. The results presented a correlation between an increase in "fatigued" pitches as the number of pitches thrown increased.

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Authorship

This Major Qualifying Project represents an equal contribution of the four team members in the writing, editing and formatting of all the components in this report.

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1.0 Introduction

Baseball is a very popular sport with 5.7 million youth athletes in 2021, and 34,500 collegiate athletes in the same year [1], [2]. However, many pitchers of the sport get injured because they overwork their arm beyond what they can handle [3]. Many of these injuries stem from the player being fatigued, in fact, when adolescent pitchers regularly throw when fatigued, they can at up to 36 times greater risk of requiring surgery from their injury [4]. While there is evidence fatigue is a likely result of not taking sufficient precautions (such as stretching), or rest between rigorous competition, these are only preventative methods, and do not relate in-game performance to a pitcher's fatigue level and eventual injury risk [3]. This is in part due to the abstract concept of fatigue. Unlike characteristics commonly used to quantify baseball pitches such as speed and spin rate of the ball, fatigue is extremely player specific, primarily subjective, and has neve been successfully objectively quantified for in-game risk of over-fatigue, which is likely in part due to the lack of a standardized definition of the term in this field. If fatigue could be objectively quantified for pitchers, players of all ages would benefit both physically by keeping their bodies healthier for longer periods of time, and financially with the cost (both in time and money) of procedures to address the injuries that occur as a result of over-fatigue. A method to characterize a pitcher's fatigue levels based on their performance in the game would be useful to quantify their risk of over-fatigue, and potentially lead to a decrease in the occurrence of injuries due to the ability to remove a player from the game prior to when they reach dangerous levels of fatigue.

The team aims to develop a method to identify a baseball pitcher's fatigue level based on the biomechanics or outcomes of a pitcher's throw. The team collected two data sets that would be used in parallel to develop this method, or fatigue metric. The first data set was from a collaboration with the Pittsburgh Pirates Major League Baseball team. This included pitches thrown over multiple games of a pitcher's season at the major league level. This data set included ~15 locations on the body that were tracked during the pitch (estimated joint centers of the pitcher). The second data set was collected by the MQP team, on WPI collegiate level pitchers, collected in a motion capture lab. The team developed an IRB approved procedure, which included a custom marker set, an exercise protocol (to fatigue the pitcher), recruited participants, and conducted the data collection. This data set would provide objective characterization of whether or not a pitch thrown was when the player was fatigued, which is not information available with the data from the Pittsburgh Pirates. This dataset was tracking ~54 locations on the body, however, the number of pitches were not comparable to the pitches available with the Pittsburgh Pirates data set. This data was used to perform the necessary calculations on various biomechanical factors that could be linked to a pitcher's fatigue level.

Prior to data analysis with the WPI collegiate pitcher data, the team performed post-processing on two software platforms to translate floating markers in space into an anatomical skeleton model that could be used for more advanced data analyses. The team conducted data exploration on the data from the Pittsburgh Pirates while the WPI collegiate data was being post-processed for analysis. Some of the metrics that were evaluated for their connection to how fatigued a pitcher is include: mechanical variation of throwing arm, kinetic chain, joint range of motion, rate of force development, velocity and acceleration of segments, performance/outcomes (pitch speed), rest time, ball release height, joint angles and forces/moments at joints. Where applicable, these were explored between both data sets. Using what the team learned through this data exploration, the strongest factors that indicated fatigue were chosen for developing the finalized metric to characterize fatigue of the Pittsburgh Pirates pitcher. The chosen factors for this metric were mechanical variation of throwing arm, kinetic chain, and performance/outcomes (pitch speed).

The team defined that a pitch was considered "fatigued" when two of the three metrics failed for pitches 0-60, and just one of the three metrics failed for pitches 60+. These standards were put in place based on the assumption of fatigue accumulation over the course of the game, so fewer metrics need to be met to result in a "fatigued" pitch. 24.4% of the total pitches were fatigued, and 40% of these fatigued pitches occurred after 60 pitches were thrown. Through this data exploration and fatigue metric development, the team advanced towards understanding and implementing biomechanical analyses to characterize fatigue. The analyses showed that there was an effect of fatigue on the kinetic chain, in addition to mechanical variation, as the arm shifted closer to the body's center of mass as pitch number increased. The team recommends future work stemming from this project focus on collecting more data on pitchers, and dive deeper into the metrics the team began exploring to refine the final fatigue metric.

2.0 Literature Review

2.1 Pitch Biomechanics

Understanding of the throwing arm anatomy and physiology provides valuable information regarding limitations of the arm's motion and how athletes push this limit during the pitch. The sections below detail the pitching arm anatomy and pitch phases.

2.1.1 Pitching Arm Anatomy

The shoulder is a complex ball-and-socket joint that allows for the most range of motion in the body. The shoulder includes three bones, the clavicle (the collar bone), the scapula (the shoulder blade) and the humerus (upper arm). The shoulder can be characterized by three articulations, the major one is the glenohumeral joint, which is the primary "ball-and-socket" joint, and two minor articulations, including the sternoclavicular and acromioclavicular joints, which increase the range of motion the shoulder can perform [5]. These articulations, along with the skeletal anatomy of the shoulder are detailed in Figure 1.

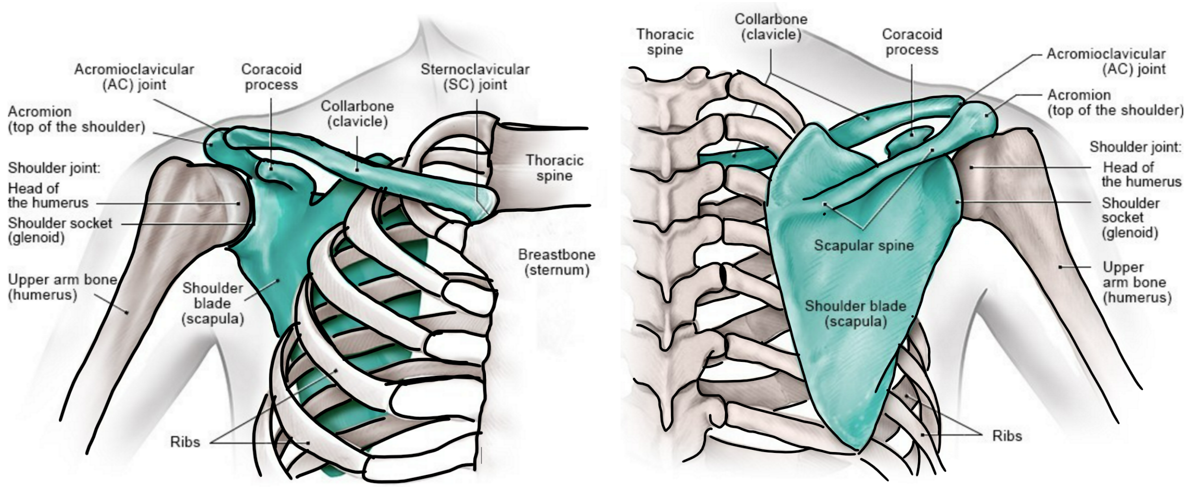

Figure 1: Skeletal Structure of the Shoulder. Anterior (front) view on left, posterior (back) view on right; Based off of original image: [6].

The glenohumeral joint is an articulation of the proximal head of the humerus and the lateral scapula, specifically the glenoid fossa (or cavity) of the scapula, and provides the primary range of motion for the shoulder complex [5]. The glenohumeral joint capsule surrounds the neck of the humerus and attaches to the rim of the glenoid fossa.

To reduce friction of the shoulder joint during dynamic movements, there is articular cartilage at the articulating surfaces of the bones, synovial membranes and fluid in the joint itself, and bursa (fluid-filled sac) at various locations to act as cushions for the joint [5]. These structures among others are pictured in Figure 2.

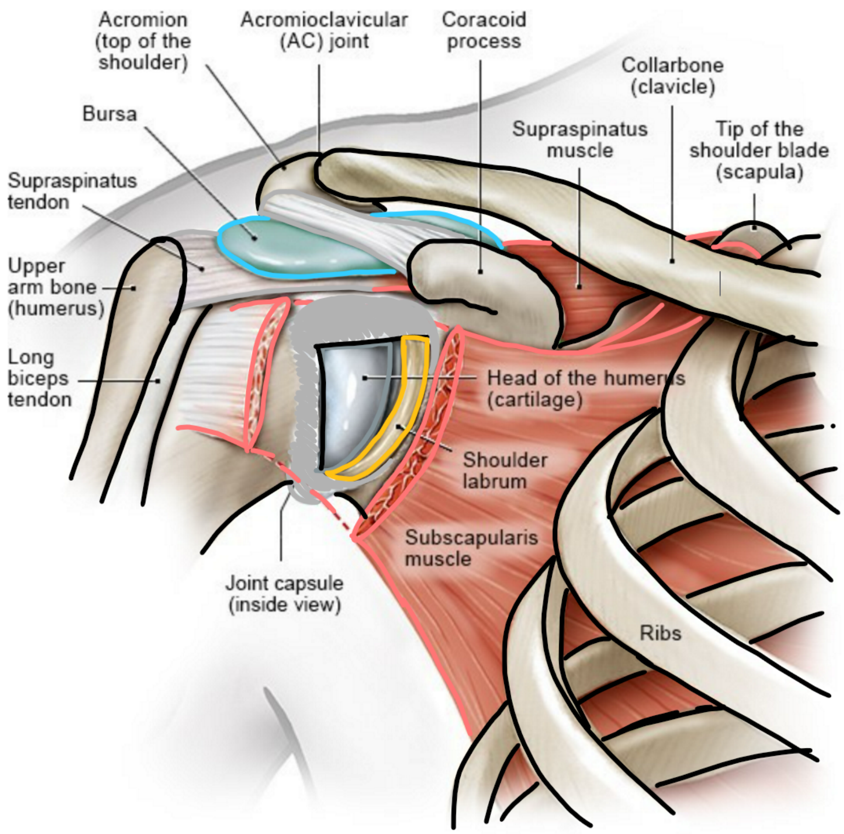

Figure 2: Overview of structures within and surrounding the glenohumeral joint; Based on the original image: [6].

Superior labrum, anterior to posterior tear, or SLAP tear, is when the superior portion of the labrum (fibrous tissue on the outer edge of the glenoid fossa, creating a deeper socket) is torn, this is a possible injury as a result of the repetitive throwing motion as seen in baseball pitchers, as it wears down the labrum over time [7]. This is illustrated in Figure 3.

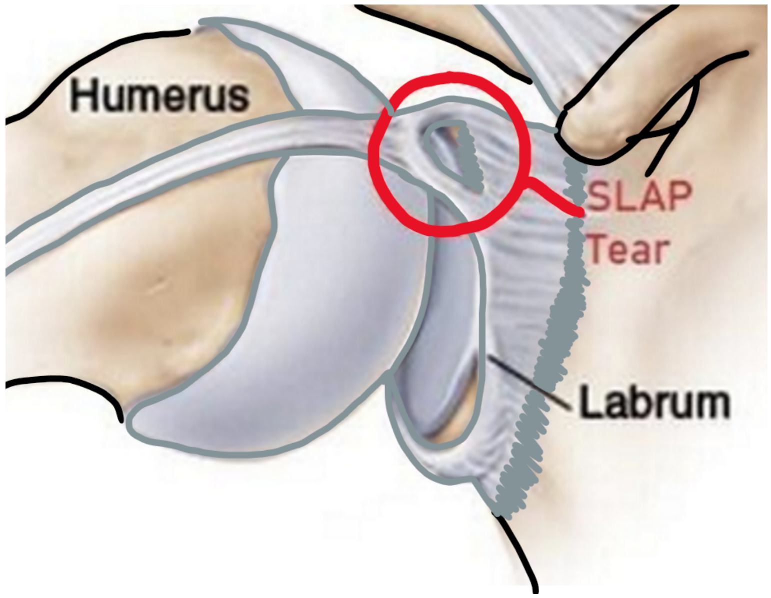

Figure 3: Diagram of SLAP tear at the shoulder; Based off original image: [7].

While the clavicle does aid in shoulder stability, the soft tissues of this complex are the primary stabilizers of this joint, due to the lack of joint stability from the immediate skeletal glenohumeral articulation itself. This allows for increased range of motion, at the cost of increased joint instability [5]. These soft tissues include ligaments such as the glenohumeral ligaments (superior, middle, and inferior, combined to form the joint capsule) are seen in Figure 2 and the muscles encapsulating the joint, specifically the rotator cuff muscles (supraspinatus, infraspinatus, teres minor and subscapularis) are seen in Figure 4.

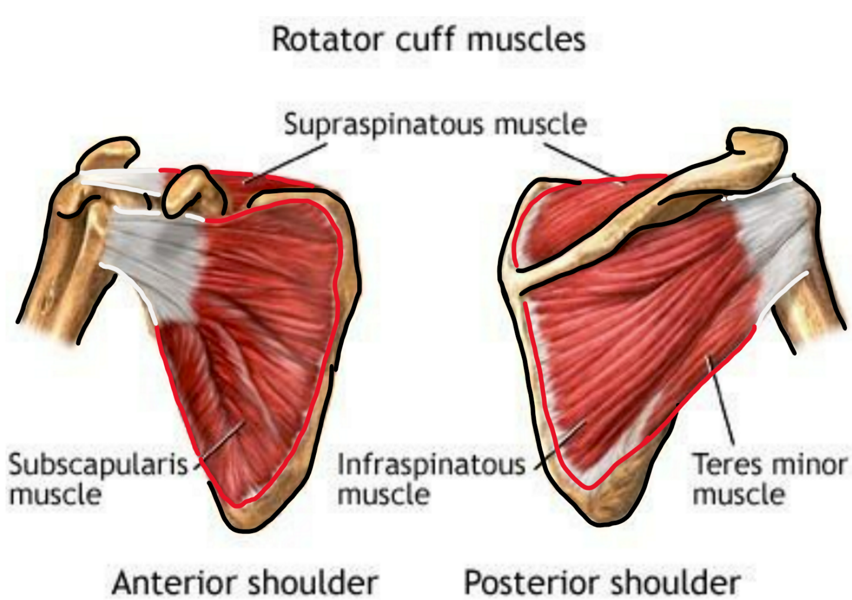

Figure 4: Rotator cuff muscles; Based off original image: [8].

The shoulder allows for three degrees of freedom (flexion/extension, internal/external rotation and adduction/abduction) with varying combinations to perform the pitching motion of interest for this project. The pectoralis major originates along parts of the clavicle, sternum and ribs, inserts at the crest of the greater tubercle of the humerus, and is responsible for arm adduction (bring arm closer to midline), and internal rotation (turn arm medially) [9]. The trapezius muscle is along the length of the back, originating medially and inserting laterally along the clavicle, scapula and spine, and is responsible for scapula stabilization and control (elevation/rotation) during throwing [10], [11]. The deltoid muscle originates along the clavicle, and the acromion and spine of the scapula, inserting at the humerus, and is responsible for flexion/extension, internal/external rotation and abduction of the arm [11], [12]. Each of these primary muscles along with minor muscles and additional ligament stabilization all contribute to the shoulder motion resulting in the powerful pitches performed by MLB baseball pitchers.

Another joint of interest in the context of baseball pitching is the elbow. The elbow is a complex synovial hinge joint that includes articulations between the proximal radius, proximal ulna and distal humerus, including the ulnohumeral, radiohumeral and proximal radioulnar joints [13]. Skeletal components that contribute to joint stability are the trochlea of the humerus and the ulnar olecranon (the articulation of the distal humerus sitting in the "scoop" of the ulna). The ulnar collateral ligament is the primary resistor to valgus (medial bending) instability that occurs during throwing motions [13], [14]. The UCL has a maximum load bearing capacity of 32Nm, and is estimated to provide 54% of the total valgus torque at the elbow during a baseball pitch [15]. The ulnar collateral ligament connects the ulna to the humerus and consists of three ligament bands, including the anterior bands (which provides the most stability to the joint), posterior bands and transverse bands [13], [14]. A diagram of this joint is seen in Figure 5.

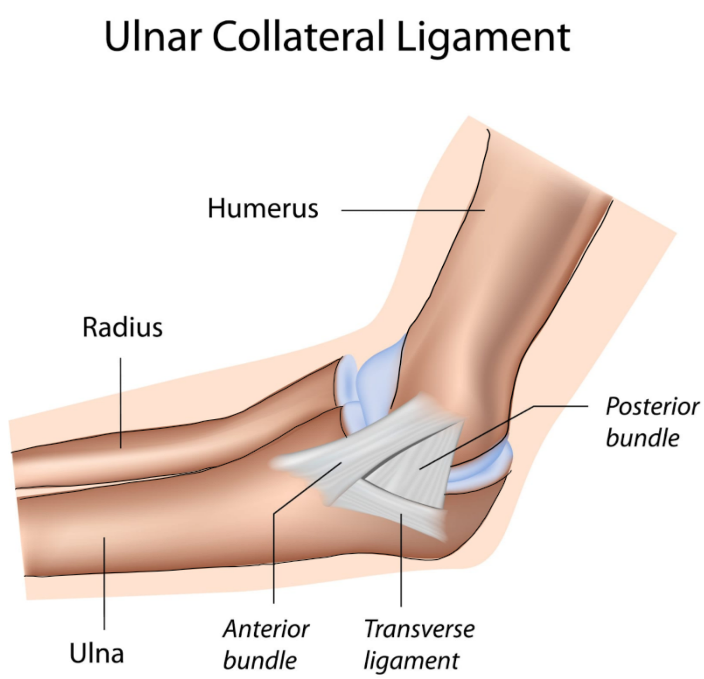

Figure 5: Ulnar collateral ligament Based off original image:[16].

Muscles that contribute to elbow motion include the biceps brachii, brachialis, brachioradialis and triceps brachii [13]. Biceps brachii is primarily used for flexion, with aid from the brachialis and brachioradialis. Triceps brachii are primarily used for elbow extension [13], [17].

2.1.2 Pitch Phases

The biomechanics of pitching a baseball can commonly be categorized into six phases including windup, early cocking (or stride), late cocking, arm acceleration, arm deceleration, and follow-through[18], shown in Figure 6.

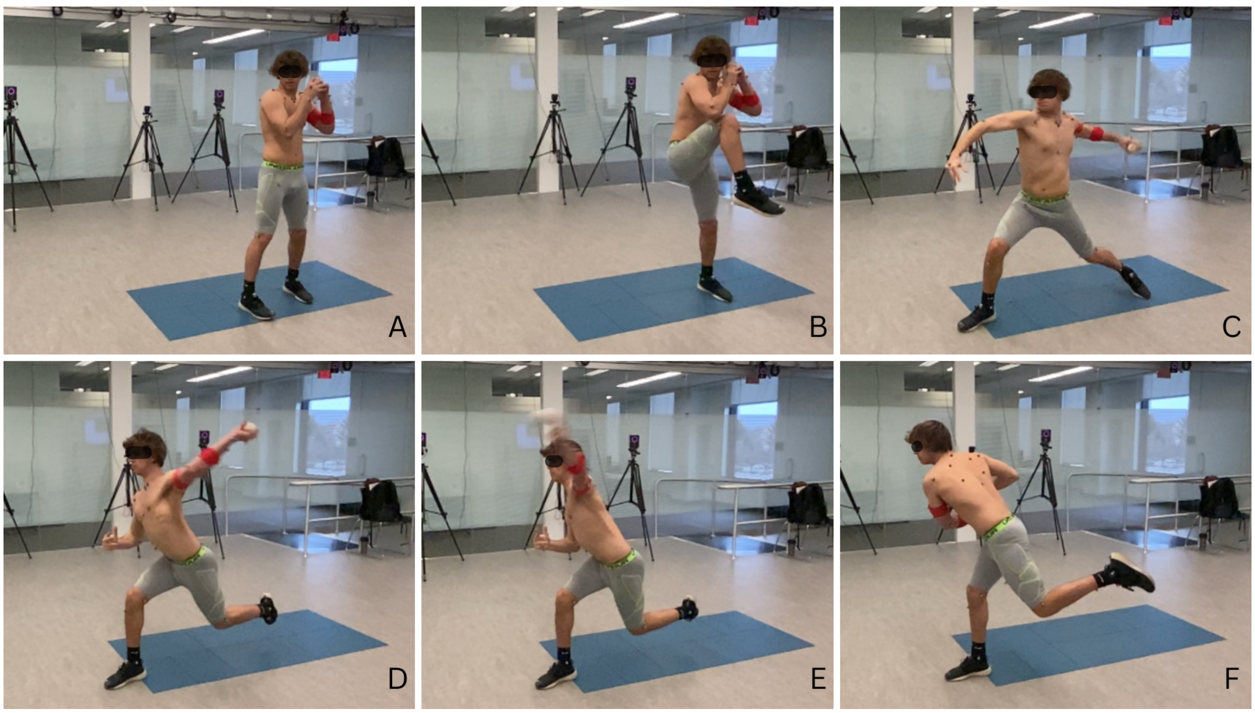

Figure 6. Six photographs corresponding with the phases of a baseball pitch.

Windup is characterized as the time from set (image [A] in Figure 6) to maximum knee height of the lead leg (image [B] in Figure 6) [18], [19]. The hands remain together (in the glove) during this phase.

Early cocking, or stride, is the portion of the pitch from maximum knee height to foot contact/strike (image [C] in Figure 6). During this phase, the pitcher will push off the ground with the non-leading leg, expose the ball by separating his hands from within the pitcher's glove, and plant his leading foot [18], [19].

Late cocking begins with foot strike and is considered to end at the point of maximum external rotation of the shoulder (image [D] in Figure 6) [18], [19]. This phase has the highest injury risk associated with it due to the intense external rotation angle and forces on the upper arm soft tissues, such as the ulnar collateral ligament in the elbow. This phase is approximately 50ms in length[20].

The acceleration phase happens from the maximum external rotation angle to ball release (image [E] in Figure 6). This phase is another critical portion of the pitch due to its high speeds and precise movements [18], [19]. This phase is also associated with trunk movement, which is associated with maintaining the upper arm angle at ball release[19].

Deceleration lasts approximately 35 ms after ball release (image [F] in Figure 6). During this phase, the shoulder produces a proximal force to resist shoulder distraction, and a posterior shear force to resist shoulder anterior subluxation, which ultimately causes the arm to decelerate [18], [19].

The final phase, follow through, is the remaining portion of the pitch. During this phase, the arm passes across the body, and allows forces to dissipate through larger muscles of the body, shifting the load from the stabilizing muscles of the shoulder[15].

The shoulder and elbow are under the greatest stress during the late cocking and acceleration phases. The forces and moments to develop the snap of the pitch and then dissipate them, place strain on the soft tissues of the arm. The transition from the late cocking to acceleration phase includes a sharp shift in the shoulder from maximum external rotation to internal rotation, and the elbow must resist the high valgus torque created by this motion [15]. This results in injuries taking place most frequently during the late cocking and acceleration phases. The deceleration phase also sees high loads on the posterior rotator cuff muscles, making this phase also a dangerous phase during the pitch [15].

2.3 Fatigue

2.3.1 Fatigue Definition

Fatigue is a complex phenomenon with no standardized definition across literature [21]–[28]. While some research focuses on fatigue as defined by physical or mechanical aspects of a player [21], [22], others focus on the influence of cognitive limitations [23], [24], and some focus on how a combination of the two result in an effect on performance [25]–[27]. While the primary focuses on the various definitions in literature differ, the premise of fatigue can be described as a physical symptom that poses a limitation to a player’s ability to perform at a level previously achievable (force generating capacity)[28]. Fatigue can also be quantified based on individual assessment. Assessment techniques such as the Borg Rating of Perceived Exertion level is one commonly used, and has a few modifications depending on its use [29].

2.3.2 Baseball Pitcher Fatigue

Apart from what constitutes a fatigued individual, there are several ways to categorize fatigue as a result of the exercise or activity type [26], [27], [30], [31]. This is a prominent concept within studies developed to understand the mechanisms that relate one’s fatigue level to performance. One characterization is the muscles activated during the exercise, such as the whole body fatigue versus localized fatigue [21]. Localized fatigue focuses on fatiguing specific muscles, whereas whole body fatiguing exercises is a more comprehensive fatiguing method [32]. Other ways exercises are characterized are by the exercise duration, frequency and type of muscle contraction [26]. For example, exercising at a constant (lower) intensity for a longer duration as opposed to exercising at a higher intensity for shorter durations, or intermittent versus continuous muscle contractions [26], [32].

Several biomechanical concepts have been linked to player fatigue in baseball and other sports at various levels. Kinetic chain is a concept focused on upper arm throwing and hitting sports, such as baseball, tennis and volleyball. Kinetic chain is the transfer of potential energy to kinetic energy at the end of the throw, through a specific sequence of muscles activated starting with the lower extremities and ending with the more distal extremities [33], [34]. Force generation follows the sequence of: feet, knee, pelvis, trunk, scapulothoracic articulation, shoulder, elbow and distal extremity or wrist [34]. Alteration of this sequence during a pitch has been associated with decreased performance (such as decreased ultimate velocity or force), or injury [15].

Throughout a pitch, the angles of the pitcher's arm at key points of the pitch such as at late cocking and ball release are critical components of the resulting pitch [35]. Studies have shown that maximum external rotation of the shoulder (end of late cocking phase) has been positively correlated with ball speed from pitch [15]. However, it has also been demonstrated that every increase of 8 degrees in angle, there was an increase in elbow varus torque by 1 Nm [15]. This increase in elbow varus torque to counter the valgus stresses on the elbow (which is highest in fastballs as opposed to curveballs or change-up pitches) has been linked to an increase in pitcher upper extremity injuries, an increase of 3 times as much as professional position players [36], [37]. The angle and height of the arm at ball release also might contribute to the outcome of the pitch [35], [36].

The concept of a player's range of motion focuses on analyzing the changes in the range of motion of joints of the pitcher such as the elbow, knee, and hips. These changes in the joint range of motion (JROM) may correlate with fatigue. A study completed on an elite soccer team found that the knee-joint range of motion declined 7% at both 24 and 48 hours post-match [38]. It is important to note that this study focused on pre- and post-match analysis, but there is an interest in the impact of JROM during a given game or over the course of a season in baseball as well, especially since this is a factor (shoulder joint range of motion) associated with elbow injury in youth players [4].

Similarly to other exercising activities, adequate rest is essential to allow for recovery. Rest allows muscles to recover and repair. If a player continues to play without sufficient rest, they can increase risk of injury from overuse [22], [39].

2.3.3 Impact of Fatigue on Athletes

Like many competitive sports, the intense physical demand on the athlete poses a risk of injury, especially for the throwing arm. Some injuries are a result of overfatigue and intense repetition, others are more likely a consequence of potential changes in pitching biomechanics when a player becomes fatigued or is sore [40]. For example, experienced pitchers begin extending their elbow just before the end of late cocking, which reduces the amount of torque on the shoulder. If this is delayed, it can increase risk of injury as the peak axial torque applied to the humerus could be greater than the typical torque strength of some soft tissues in the shoulder [15]. Another look at injuries is a result of mechanical fatigue from microstructural damage from cyclic or repetitive loading. As the microdamage propagates with overuse, the tensile strength of the tissue decreases, and will be more likely to fail under lower loading conditions [22].

Professional Level Athletes

Injured pitchers accounted for approximately 58.91% of all injured major league baseball players in 2022, and accounted for 58.10% of total cost spent on injured players [41]. A league's ability to assess injury risk based on fatigue levels of a player would help reduce injury recovery cost (with regards to recovery time and monetary value). Table 1 includes an assessment of injury costs per team of the six teams that spent the most money on player recovery (in player numbers, recovery time and monetary value) from the 2022 season.

Table 1: MLB injured pitchers by team with cost totals [41].

Cumulative Injured Pitcher List By Team			
Team	Players	Days	$ Spent on DL* Players
Boston Red Sox	16	1,416	$55,720,931
Washington Nationals	18	1,693	$49,783,272
New York Mets	17	1,140	$45,778,103
Los Angeles Dodgers	17	1,629	$37,242,380
New York Yankees	17	1,103	$29,951,824
Chicago Cubs	17	1,421	$23,403,803
Pitcher Total**	423	29,844	$475,753,678
All positions Total**	718	42,679	$818,985,803
Pitching percentage Total**	58.91%	69.93%	58.10%

**DL = Disabled List; **Total = All MLB Teams*

Ulnar collateral ligament injuries and corresponding surgery is one of the most prominent injuries for baseball pitchers, with around 25% of MLB pitchers having a history of the surgery [42]. Between 1974 and 2015, 400 UCL reconstruction surgeries had been performed, however, approximately ⅓ of those were performed between 2010 and 2015 alone [43]. This is a season ending injury 60% of the time at the professional level, a level of competition with the most medical and financial support to return the player to the game [44]. A study focusing on MLB pitchers who underwent UCL surgery between 2015 and 2019 had a 57.1% success rate of returning to the MLB. They returned 521 days (1.6 years) on average after surgery, and threw significantly fewer pitches and innings in their first season back [42].

Amateur and Intermediate Level Athletes

Baseball is one of the most prominent sports youth athletes participate in, second only to basketball. In 2021, 3.7 million kids ages 6-12 played baseball, and 2 million kids ages 13-17 played the sport[1](*Youth Sports Facts*, 2022). There are also approximately 34,500 collegiate baseball players in the country [2].

Although UCL reconstruction surgery is prominent in the major leagues of the sport, between 2003 and 2014, there was a 343% increase in the number of UCL reconstruction surgeries performed in New York [43]. The primary age group that received this surgery between 2007 and 2011 were athletes between the ages of 15 and 19 years old, accounting for 56.8% of all UCL procedures [43]. In comparison, athletes ages 20 to 24 accounted for 22.2% of the same procedure [43]. In the mid 90's, this procedure was only performed on 4 high-school athletes, which increased to the order of 30 by 2007 [43]. The high occurrence of UCL injury at young ages builds a need for further investigation of injury mechanisms, rest, and preventative measures [43].

Adolescent pitchers are at a 2 - 5 times greater risk of needing elbow or shoulder surgery or leaving the sport if they pitched greater than 80 pitches per game, 100 innings per year, greater than 8 months of the year or also played catcher [4]. However, athletes who regularly pitch through arm fatigue are at 36 times greater risk of requiring elbow or shoulder surgery, or leaving the sport [4]. Youth pitchers (ages 8-12) are at an increased risk of developing elbow pain. When this age group was assessed, 12 out of 25 athletes in the study displayed medial elbow abnormalities on their MRIs compared with pre-season MRIs, and the only associated factor that was seen was playing baseball for greater than 8 months per year [4]. Another study revealed that for highschool baseball pitchers, high baseball load (> 5.5 hours per day) increased the risk of injury by 2.6 times, with these injuries occurring 3.3 times earlier in their baseball careers [45].

Injuries of players at this young age have longer-lasting effects than those at the professional level. These athletes (hopefully) have a lifetime of participating in this sport ahead of them, and if this is not a possibility for them due to an injury, it creates a smaller sample size available for the professional leagues to find the best players.

2.3.4 Fatigue Mitigation and Assessment Techniques

Currently, there are numerous pieces of equipment and strategies to aid in managing fatigue levels of players, which in turn reduces injury risk.

Coaches and trainers at various levels of competition will assist and provide recommended warm-up practices to ensure the player is ready to perform at maximum capacity. As athletes reach more professional levels of competition, the training regime becomes more personalized, including trainers tailoring the athlete's offseason exercises to help strengthen the player in terms of increased pitch velocity and arm durability [3]. Trainers also use ice to reduce swelling of an area and heat is used to loosen the muscle fibers to increase the range of motion for the muscle [46]. A program implemented focusing on stretching and strengthening core muscle groups resulted in about a 50% reduction in medial elbow injuries during the year [4]. Amateur and intermediate players do not have the same level of support as professional players do, however, programs that focus on good stretching and strengthening practices can have a significant influence on injury prevention at this age.

Pitch count guidelines have been developed to decrease the occurrence of pitching injuries in the younger athletic population. Table 2 highlights these regulations grouped by the age of the athlete. For example, a 13-year-old pitcher should take four days rest if they pitch more than 66 pitches in a game.

Table 2: Rest days and pitch count recommendations for youth pitchers [47].

Rest Regulating (Pitchers 15-18 yrs)		Rest Regulating (Pitchers <14 yrs)		Maximum Pitches	
Pitches Per Game	**Recommended Number of Rest Days**	**Pitches Per Game**	**Recommended Number of Rest Days**	**Age**	**Pitches Per Day**
75+	4	66+	4	7 - 8	50
61 - 75	3	51 - 65	3	9 - 10	75
46 - 60	2	36 - 50	2	11- 12	85
31 - 45	1	21 - 35	1	13 - 16	95
1 - 30	0	1 - 20	0	17 - 18	105

Load management at the professional levels can include pitch count limitations, but also incorporate player schedules, traveling logistics and biometric data to assess their condition to pitch, both mentally and physically [48].

Other devices used to mitigate fatigue include weighted balls, or Plyos, and resistance bands for warm-ups. Warm-up techniques with these devices can help stretch muscles that are not normally stretched with traditional techniques. The weighted balls can help prepare the arm to perform at maximum effort, while increasing stamina and arm strength [49]. Figure 7 is an example of a weighted ball compared to a standard baseball. Resistance bands help stretch and strengthen smaller muscles of the rotator cuff to help decrease injury risk, shown in Figure 8.

Figure 7: Display of a red weighted Plyo ball (left) and a normal baseball (right) [49].

Figure 8: Display of commonly used resistance bands[50].

Another device used in more advanced levels of baseball, but is less common than weighted balls and resistance bands is the ShoulderSphere. This device is the only rotator cuff exercise device that strengthens all four rotator cuff muscles simultaneously in a rotational manner [51]. This device has a ball rotating inside a globe in a circular motion, resulting in all muscles moving in a synchronized and balanced fashion [51]. This device also has a built-in verification aspect that the user can use to make sure they are doing the exercise correctly. If the ball is bouncing around the globe, then there is an imbalance motion with the rotator cuff [51]. A wrist strap in place helps prevent the person from using other muscles to rotate the ball, and ensures that the area of focus is the rotator cuff. This device shown in Figure 9 can help these pitchers achieve rotator cuff and multidirectional strength required during a pitch.

Figure 9: Display of the ShoulderSphere, which strengthens muscles in the rotator cuff [51].

2.3.5 Throwing Arm Sport Specific Device

The Motus Arm Sleeve is a wearable product that aids with performance and claims to help in injury prevention [52]. This sleeve, shown in Figure 10, is currently on the market today, and provides a numerical value of the stress placed on the arm when throwing, the speed at which the arm is moving, the angle the arm creates, as well as the rotation of the shoulder, along with a few others [52]. The motus arm sleeve also provides values of the arm stress, which is peak elbow torque, the angle the forearm makes relative to the ground, angular velocity, as well the number of throws [52]. It mainly is used to understand and quantify certain metrics related to stress. These values are critical to understand and know for a pitcher, as this provides information on arm stress, which can help assess performance [52].

Figure 10: Display of the Motus arm sleeve is a device that aids in biomechanical analysis [53].

The main metric in use would be to understand the arm stress. It can be concluded that it can be more dangerous to obtain a higher stress throw compared to a lower stress one [52]. A higher stress can imply that there is more torque being placed on the ulnar collateral ligament. If there is more stress placed on the ligament, it can lead to overuse and further fatigue [52].

A limitation that might occur may be the limited tolerance and the error range. This would lead to determining what stress is placed on specific parts of the arm. However, the device would react to the different throwing patterns and provide solid metrics of the values wanted by the user [53].

2.4 Systems for Collecting Biomechanical Data

Since fatigue is a complex concept, detecting and quantifying an athlete's level of fatigue can be challenging. This challenge leads studies to use various methods to collect data on measures that might provide information related to athlete performance, fatigue and injury risk. These data collection methods may include collected information (accelerometers and gyroscopes), surface electromyographic signals (sEMG signals), inertial measurement units (IMUs), power output measures, marker motion capture, markerless motion capture, and global positioning system (GPS) signaling [26], [54], [55]. Some of the systems that can be used to collect biomechanical data including accelerometers, motion capture technology and force plates, are described in detail in this section.

2.4.1 Accelerometers, Electromyography, Inertial Measurement Unit

An accelerometer is a sensor that measures the acceleration forces acting on an object [56]. When accelerometers are part of a worn sensor system, they are typically positioned at the hip, wrist or thigh during data collection [57](Arvidsson, D., et al, 2019). These sensors collect raw data along three axes, resulting in the magnitude and direction of the acceleration along each axis with respect to the unit of earth's gravity (unit g). A typical sampling rate frequency for sensors used in athletic research settings is between 30 and 100 Hz [57]. According to the Nyquist theorem, a device's sampling rate in data collection should be at least twice the frequency of the highest frequency component of the signal [58].

Using these accelerometers for data collection is very advantageous in that it makes direct conclusions about forces and torques, it is a compact system that is easy to assemble and operate, and it is a wireless technology, which provides the user with the freedom to place the sensor anywhere on the participant [59].

Electromyography (EMG) is another data collection method that records muscle responses via electrodes directly on or into a muscle, by surface or needle electrodes respectively. An oscilloscope is used to display any electrical activity that is recorded by the electrodes. The electrical activity data of the muscles is represented as waves which will vary given the contraction state of the muscle. For example, a muscle at rest, meaning there is no contraction occurring, should not produce an electrical signal, which would produce no electrical signal on the oscilloscope [60]. Some common EMG companies used in industry and research are Delsys, Noraxon, BTS Bioengineering and BIOPAC [61]. EMG applications are widespread including performing risk assessments by monitoring fatigue in workers, development of industrial equipment, movement predictions and neuromusculoskeletal disease analysis [62].

Despite the vast applications of this technology, there are several drawbacks when using it for data collection. One major limitation is the electrode signal being lost from moving throughout a procedure. The needle electrodes may help combat this drawback, but they tend to be less comfortable for users. Another primary issue with EMG technology is the amount of noise produced with a signal, which if it is too high, makes the data very difficult to interpret [62].

As previously mentioned, Delsys is a well-known EMG company. More specifically, it is a leading company that designs and manufactures high performing electromyography (EMG) instruments [63]. Delsys has a wireless EMG biofeedback system referred to as the Trigno System. The system includes compact, wireless Trigno Avanti sensors, which directly transmit a signal to a base station within the system. The system is built to collect movement data, force signals, contact pressures, timing and information regarding triggering. More specifically, these sensors collect both EMG and inertial measurement unit (IMU) data.

IMU is a device which collects several types of motion data. They have the ability to collect angular rates, as well as acceleration data, therefore encompassing the functions of gyroscopes and accelerometers respectively [63]. The IMUs have nine degrees of freedom (DOF) to collect acceleration, rotation and earth magnetic field data. The data can be used to understand the movement of a participant via the time stamps in conjunction with the EMG data [64]. Additionally, the Delsys technology has the capability to link the sensors to a software called EMGworks, allowing the acquisition of data to occur instantly on a computer.

Figure 11 is an image of the Trigno Avanti sensors and a placement in which they may be used for data collection. The sensors are attached to a participant with tape that allows for electrode to skin contact for EMG data collection. The sensors should be applied with the arrow graphic pointing upwards, as shown in Figure 11, for the purposes of orientation to the system and consistency across all sensors collecting data.

Figure 11: Typical Delsys accelerometer placement on the forearm and bicep of a participant.

2.4.2 Force Plates

Force plates are a tool used to measure the ground forces throughout a specific motion, and ultimately provide additional biomechanical data surrounding the kinematics and dynamics of motion [65]. A typical force plate is a metal plate with sensors incorporated to measure the amount of force on the plate via electrical output. The main function of force plates in a biomechanical setting is to measure the ground reaction forces and moments during a specific motion or a static pose [65]–[67]. Other applications of force plate data can be applied to gait analysis, balance studies, and research that analyzes changes in the rate of force development of an individual[68].

Force plates function to output forces by relying on load cells [66], which essentially are transducers that read the force upon the plate and output the result into a digital form that can be understood by the user [69]. Furthermore, when a force occurs on a force plate, the sensors within the plate read the force by undergoing distortion and output a voltage change that corresponds to the given force. The directions and magnitudes of forces can also be determined by orienting the sensors in various positions. A typical force plate can also produce data relating to center of pressure, center of force and the axial moments [66].

The use of force plates can open the door to significant amounts of data by using various motion equations. Other data that can be calculated from force plates is the center of mass velocity, impulse, and jump height using energy equations [66].

AMTI is a leading company that produces technologies related to multi-axis force measurements and testing, which are commonly applied in sports research settings to measure forces and motions. The company offers a variety of force plates including their Optima Biomechanics Measurement Series (BMS) force plates which output data with high accuracy and frequency and can be used for a multitude of applications. The most common uses of these force plates are for gait and balance studies, as well as sports research. Additionally, this technology allows for the combination of several AMTI plates in a set up for more dynamic movement studies or more widespread motion that covers more area [70].

The OPT400600 force plate is a specific AMTI force plate as part of the Optima series. This force plate has dimensions of 400 x 600 mm and has a natural frequency sampling rate range of 370 to 400 Hz. The average accuracy of the center of pressure measurements are within 0.2 mm of the true value. The accuracy of the force measurements generally is within +/- 0.1% of the applied load, making this plate very accurate in collecting force data [71].

In order for the force plate data to be properly read and recorded, an amplifier must be used. AMTI manufactures an OPTIMA-SC amplifier which must be used in conjunction with the Optima force plate systems [70]. Once properly installed and calibrated, the amplifier will turn the force plates on, have the ability to zero them, and amplify the signal to produce accurate measurements.

2.4.3 Motion Capture

Motion capture, also referred to as mocap, is a widely used technological process that records participant movement. There are numerous applications for using motion capture, including robotics, sports therapy, gait analysis and the general biomechanics of various motions [72]. There are many types of motion capture technology, some of the most common methods being optical-passive and video, or markerless motion capture. The two methods are described in detail in the following sections.

Optical-Passive (Marker) Motion Capture

Marker motion capture is a motion capture technique that is widely used in biomechanics, and is considered the more traditional or “mainstream” motion capture method [73]. This technology has the ability to capture and follow the movement of a marker on a participant, as well as record this motion data [73]. This method is also commonly referred to as the passive optical method. The attached retroreflective markers create three-dimensional coordinates, which estimate the position of each part of a participant’s body [73]. Every spot where a marker is placed on a participant will act as a point to be calculated. The cameras figure out where the markers are from the calibration methods stated later on. For example, three markers on the hip, knee and ankle allow for the calculation of joint rotations and angles [74].

Marker motion capture requires inverse kinematic calculations to produce results other than the output Cartesian coordinates. These calculations factor in the geometry of the joints and their coordinates, as well as the movement of positions, velocity and angular acceleration [74]. According to Vicon, a motion capture software system manufacturer, passive optical motion capture tends to have the highest accuracy for data collection [72].

Despite this method being commonly used, there are several limitations that may impact the accuracy or amount of data being collected. The process of attaching the markers can be tedious and complex with various complicated body markings, readjustment of the many cameras and post-processing of the data [73]. Additionally, this type of motion capture may be more difficult and less reliable in areas with strenuous activity such as sporting games [75], as the markers can fall off and therefore make data collection more challenging.

The optical passive motion capture method requires the application of a predetermined markerset to each participant with retroreflective markers, as well as calibration of the system to ensure proper orientation and ensure the highest quality data [72].

As previously mentioned, Vicon is a motion capture company that provides a multitude of technologies that can be applied to better understanding and analyzing the study of motion. Vicon Nexus 2.14 is a specific software of motion capture technology from Vicon that is designed to be used for applications such as animal science, gait analysis and rehabilitation, neuroscience and motor control, and sports performance and biomechanics [72]. This software allows for seamless data collection and precise marker readings from the cameras.

Alternative Motion Capture Systems

In the industry today, there are several competing softwares other than Nexus Vicon that have their own advantages and disadvantages. Some of the competitors include GPS systems, Motion Analysis Corporation, Codamotion, and many others. Although the team chose to use the Vicon motion capture software mainly due to its accessibility, the competitors provide a similar output. These examples are different full body motion capture software companies.

Codamotion revolves around motion capture innovation, focusing mostly on clinical research and movement analysis. The service uses the gait analysis laboratory system, which contains at the minimum two CX1 sensor units which allow for a proper unit measurement in 3D [76]. Similar to the Vicon system, there is the use of AMTI force plates, with the addition of Kistler force plates. Furthermore, the software used is called Odin which provides real time monitoring of inputted data, as well as in depth analysis of the "spatio-temporal data" [76].

The Motion Analysis Corporation provides, at a baseline, twelve cameras and six markers. For cameras, there are two ranges, the BaSix camera range and the Kestrel camera range. However, these cameras are designed mostly to track rigid bodies which is not ideal in tracking human movement. This system mostly aligns well with drones and robotic technologies.

GPS use for motion capture and marker motion capture have been used to quantify athlete biomechanics, however, limitations such as hidden markers or indoor events can make these measures difficult to implement for in-game analysis [26], [77].

Markerless Motion Capture

Markerless motion capture is a technique that is used in the human sciences, and includes using the 3D aspect to look into certain motor performances [75]. This type of motion capture mainly is an adaptation and an advancement to the optical passive technique previously described. This technique requires no markers being put on the participant, and solely relies on the software being used to track and collect data on the movement occurring [72]. The data being collected can consist of understanding kinetic chain, the location of the pitcher, joint angles, and further in depth biomechanical data. The most important aspect of markerless motion capture is the technical equipment and the code that will collect the data and movements. The accuracy of motion capture techniques are crucial for properly understanding the movements being recorded, however, there tends to be more error with markerless motion capture than there is with marker-based motion capture [72].

Currently, there are certain laboratory conditions that need to be considered before using the technique [78]. The area has to be large enough for the movement and there has to be sensors that are targeted at certain body parts. The advancement of markerless motion capture has allowed for medial axis transformation and certain propagations such as shape encodement [78]. The 3D portion of representation can lead to estimations of the kinematics using multiple cameras around the participant. There is a large limitation of the accuracy in the cameras. However, there are some advancements regarding motion capture, such as Theia3D and Hawk-Eye. Both softwares deal with tracking specific biomechanical properties.

Hawk-Eye is a software used by several MLB teams to collect data from practices and games at the stadium in which the software is incorporated. Hawk-Eye uses a series of cameras which cover a majority of the movements and has a high resolution per second. It is important that the capture speed is relatively high in order to track and catch quick or subtle movements [79]. It can be broken down to extremely small margins and locate them. Hawk-Eye has a 2.2mm margin of error. Additionally, the Hawk-Eye system collects data at up to 340 frames per second. Figure 12 shows an example of the Hawk-Eye system being used to collect data on a baseball pitcher [79].

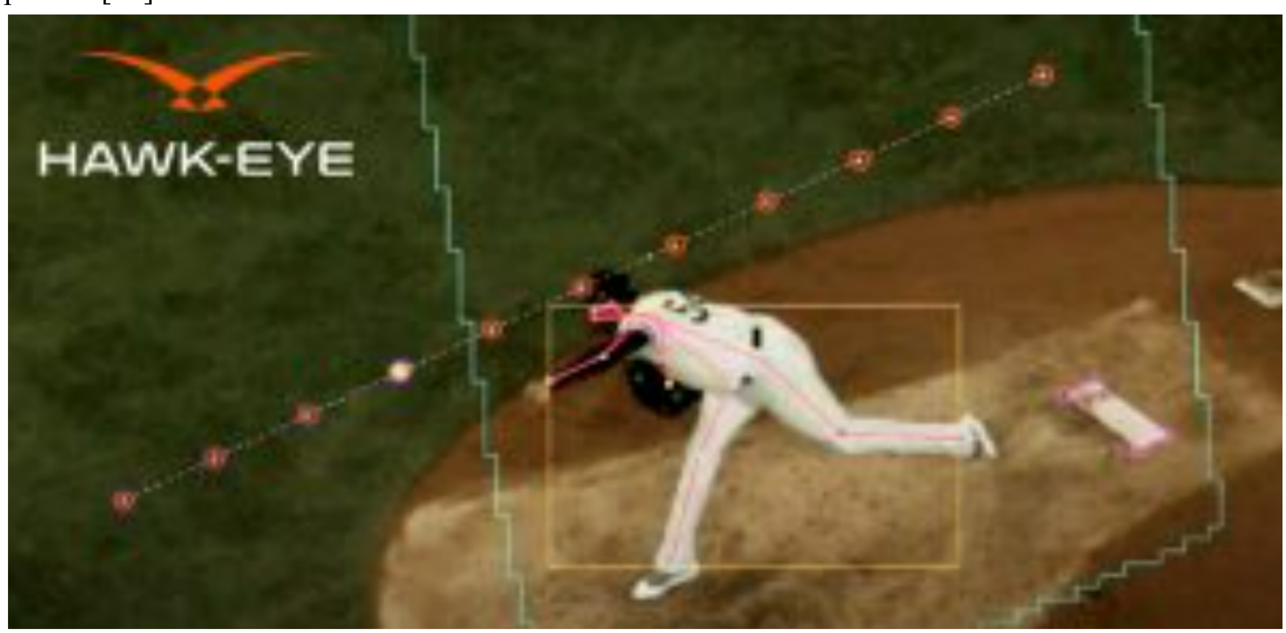

Figure 12: Breakdown of Hawkeye Motion Capture working by calculating estimated joint centers of the pitcher (Sony, 2020).

Visual 3D Post-Processing system

Visual3D Professional is a research software used to analyze and model three-dimensional motion capture data. In simple terms, the main functions of Visual 3D are modeling, analysis, and reporting. More specifically, the software allows for the input of motion capture data into a biomechanical skeletal model, analysis of numerous data types, and the reporting of this data through graphs and exportable data files. The data is calculated directly by the software through kinematic and inverse dynamic calculations [80]. The software performs calculations by using the mass and height of the participant, as well as segment dimensions. Some of the data which can be calculated are joint angles, moments, the center of pressure, energies, and rotations [81]. This data is a necessary aspect to understanding the biomechanics of how segments interact at a joint during the motion of a pitch, and trends of this data in a non-fatigued versus fatigued-state. For example, the software can determine elbow forces and moments by calculating the interacting between the upper and lower arm segments. The advantages of using this system are that it allows for custom marker sets, and it is intuitive and user-friendly throughout the entire process from model generation to data exporting [81]. A drawback of the system is that the models created can only be applied to motion files with that exact marker set. If one marker is different, the analysis will not be possible or accurate [81]0].

Visual3D uses C3D files directly from a given motion capture source, like Vicon Nexus, where the user can upload the anatomical motion capture pose and begin assembling the skeletal model within Visual3D. The models within this software are six DOF link models, which means each segment of the body will have six degrees of freedom. Additionally, each segment is assumed to be a rigid body, meaning it has a fixed mass and dimensions, which are inputted by the user, and it cannot be deformed under a force [80].

Visual 3D involves the generation of a skeletal model which motion files can be run on. The model is generated via landmarks, which ultimately make the segment. The process of creating this model is explained in full in the later sections. Figure 13 shows the Visual 3D interface with an example of a skeletal model in an anatomical pose. From this point in the Visual 3D process, the user could add a motion file onto the static file and see the skeleton perform the motion that was recorded in the motion capture system. Once the motion files have been run over the static skeletal model, significant amounts of data can be extracted to better understand what is occurring in the movements.

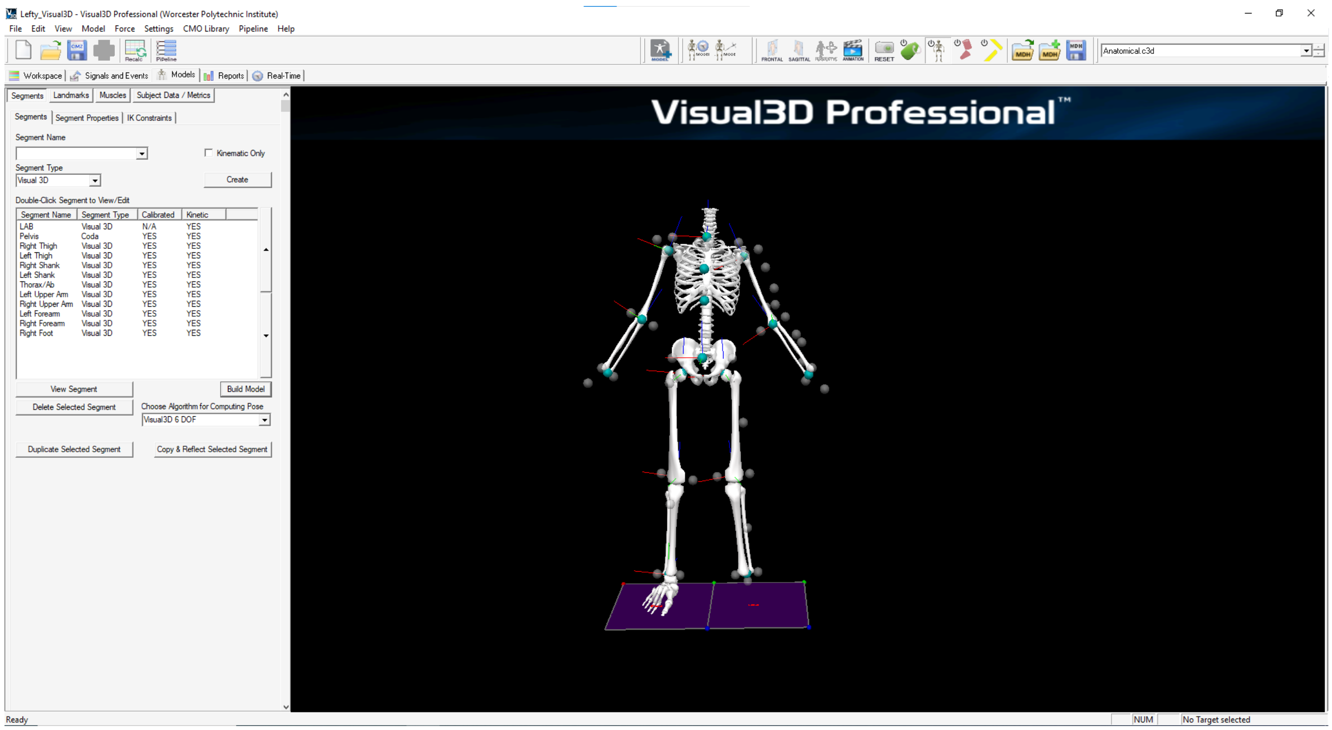

Figure 13: Visual 3D interface.

2.5 Summary

Baseball is a high-intensity sport, especially for the pitcher. Numerous muscle groups work together to achieve high-powered pitching action at various levels of competition (from youth to professional leagues). The focus of this paper is on the shoulder and elbow, as those are typically the joints at the highest risk during a pitch. Specifically, the transition from the late cocking phase of a pitch, where the elbow is at its maximum external rotation, and generating the greatest moment, to ball release (end of acceleration phase) is when the pitcher is at the greatest risk of injury.

For this project, the team focused on physical fatigue, defined as a physical symptom that poses a limitation to a player's ability to perform at a level previously achievable. Fatigue has been assessed in numerous ways, with varying focuses depending on application and research interest area. Several candidate factors of fatigue have been assessed in literature, including: joint range of motion, rate of force development, kinetic chain, rest time, performance metrics, velocity/acceleration of segments, mechanical variation in throwing arm, ball release height, and joint angles. Fatigue has an impact on pitchers of all levels, financially, physically, and mentally. With the increasing number of injuries occurring in young players (ages 15-19 accounting for 56.8% of all ulnar collateral ligament reconstruction procedures between 2007 and 2011), there is a need to assess the mechanisms of fatigue and eventual injury risk. If identifying these factors of fatigue can help prevent a player from playing while fatigued, (which increases an athlete's risk of elbow or shoulder injury 36-times) then there could be more players entering the professional leagues injury-free, ready for competition.

Efforts have been put forth to mediate these fatigue levels, including specialized training techniques and equipment, and load management and pitch count limitations on players. However, most of these have elements of subjective measurement/assessment, and not all levels of baseball competition have the means to this type of quality care.

There are numerous systems in place to evaluate an individual's biomechanics, some of which have been used to characterize players' motion in baseball and other sports. Accelerometers are small devices that collect data of the magnitude and direction of the acceleration along various axes evaluated. This can provide information regarding the general movement and direction of movement of a segment. Force plates can be used to measure the ground reaction forces and moments during a specific motion or static pose. These can be accompanied with various equations to understand concepts about the participant such as center of mass, impulse or rate of force development. Motion capture is currently a gold standard for assessing an individual's motion. Optical-passive (marker) motion capture uses several cameras around an area to triangulate on reflective markers placed upon the participant to create 3-D coordinates that correspond to the underlying skeleton of the participant. Markerless motion capture performs the same analysis, however, through the use of estimated joint center locations. Post processing of both softwares in some form are necessary to perform biomechanics calculations/analyses (such as using Vicon software).

Visual 3D Professional is a common system used to assess kinematics. Visual 3D generates an anatomical (skeletal) model of the participant based on the locations of the markers placed upon the participant during data collection. This model is then used to perform the desired biomechanics calculations to assess the participant's movement.

3.0 Project Strategy

This section focuses on the team's approach to developing the scope and desired outcome of the project. This includes the initial client statement, design objectives, requirements and specifications, the revised client statement, and course of action to accomplish the tasks within the time constraints.

3.1 Initial Client Statement

The goal of this study is to design and validate a metric to characterize baseball pitcher fatigue levels.

By using the provided motion capture data from an MLB (Major League Baseball) team and self-acquired team data, identify increased fatigue using a sensor system and then validate those findings with the MLB motion capture data.

1. *The system will be able to detect variation among pitch qualities through a device & motion capture analysis system.*
2. *The system will validate the idea that pitch variation increases as the pitcher pitches more pitches.*
3. *The system will identify abnormal trends that may lead to increased injury risk or trends that reach a higher level of fatigue faster.*

3.2 Design Requirements

From the initial client statement, the team ran through several iterations of the project focus, altering the client statement when appropriate. The initial client statement was centered around using motion capture data to identify and prevent injuries in baseball pitchers. After careful consideration, literature review and input from advisors and collaborators, the team decided to focus primarily on fatigue detection in pitchers, rather than injury. The main reason for this was that injury data are difficult to collect for ethical reasons and that pre-existing injury motion capture data are fairly minimal in numbers. The team felt the topic of fatigue needed more research and it was the most feasible option for a data collection study with human participants. Additionally, the team's fatigue study can potentially be correlated to injury prevention in future studies. From these considerations, the team began to establish the overall goal of the project, which was to create a system to process and validate biomechanical data from baseball pitchers and implement a metric to evaluate player fatigue. To accomplish this task, the team explored a variety of methods, outlined by the design requirements of the project.

3.2.1 Project Scope

With the goal of evaluating biomechanics of pitchers, the team investigated the various ways this could be realistically achieved given the project time constraints. The team determined that the developed fatigue metric solution could be strengthened with the implementation of a validation component. While the metrics evaluated were derived from literature, having two data sets that could corroborate literature findings and direct areas for further data exploration would increase the validity of the resulting assessments of pitchers.

The team wanted to collect categorical fatigue data, essentially be able to objectively characterize a pitch as fatigued based on whether it was before or after intense exercise. The team also wanted a very detailed marker set, especially of the upper arm during a pitch. To accomplish this, the team pursued collecting marker-based motion capture data on collegiate level pitchers from WPI, which included a large marker set and a fatigue protocol to college data on datum pitches and fatigued pitches. This included the development of a procedure to fatigue a pitcher, a marker set to best evaluate the player's movement, and submit for IRB approval and participant consent. The primary advantages to this data collection method is the categorical data of if a player is fatigued or not fatigued during pitching, in addition to precise measures of the player's movement with the custom marker set. The primary drawback of this method is the fact that this data collection would be in a lab as opposed to on the field, meaning the conditions are less realistic to what an actual baseball game would be like. This includes the pitcher throwing into a net, on flat ground instead of a mound.

The team wanted to have a large dataset to evaluate a pitcher's changes over the course of a full game, or over the season, on the field (as opposed to in a lab setting). To accomplish this, the team initiated a collaboration with a Major League Baseball team, which had access to a large dataset of markerless motion capture data on a professional player during their games. Hawk-Eye is a markerless motion capture system that has been implemented in a variety of major league stadiums, in which MLB teams recently began collecting data within the last couple years. The project team connected with the Pittsburgh Pirates MLB team as collaborators for the data analysis portion of the project. Markerless motion capture data of the pitchers provided by the Pittsburgh Pirates MLB team allowed the team to evaluate in-game data of an elite level pitcher. The drawback of this is the control of the data, such as the post-processing procedure, and the complexity of the marker set which includes the markers located primarily only at joint center locations on the body.

The project aims to develop a fatigue metric from both methods in parallel, as each method assists in the data exploration and metric implementation of the other.

3.2.2 Objectives

The goal of this study is to design and validate a metric to characterize baseball pitcher fatigue levels. The team developed a series of objectives to achieve this goal, and they are as follows:

1. Establish candidate metrics to categorize baseball pitcher fatigue from literature.
2. Develop procedure for motion capture data collection of WPI collegiate players using motion capture, accelerometer and force plate data.

3. Explore candidate metrics from the Pittsburgh Pirates markerless motion capture data from professional pitchers.
4. Process and analyze the data using focusing on the established concepts derived from the data exploration of the candidate metrics.
5. Finalize and validate the final fatigue metric with both data sets.
6. Create a report to display the findings to Pittsburgh Pirates' R&D staff, coaches, players, and biomechanical researchers in the field of study.

3.2.3 Constraints

There are a variety of constraints that help define the direction and scope of the project.

Time: The team had one academic year to complete the project. All the objectives and the report should be completed prior to May of 2023. This put limitations on the amount of data that could be collected, processed and analyzed by the team.

Budget: The team is allotted $250 per member towards funding for the project. The Pittsburgh Pirates were also able to reimburse the team up to $1000 for project related expenses.

Type of Participants: Due to time constraints with participant recruiting, and the anticipated time allotted for post-processing and analysis of collected data, the team was limited to data on collegiate and professional level baseball pitchers.

Quantity of Participants: For the WPI pitchers, as a safety precaution, the team only recruited WPI pitchers who were active. Since data collection occurred during the off-season (determined by the timeline available), this limited the sample size available for recruitment. For the MLB pitchers, the team was limited by the quantity of data available to process, and the amount shared by the Pittsburgh Pirates.

Pitching Scenarios: For the WPI pitchers, the team collected data in a motion capture lab. Due to the team's desire to collect force plate data in addition to the motion capture information, the pitcher was not throwing on a mound. The pitcher was also throwing into a net that was sitting approximately 15 feet away from the pitcher. The mental component of pitching in a game cannot be represented in the motion capture lab. For the Pittsburgh Pirates, the motion capture data was collected during a professional game.

Technical Complications: For the WPI pitchers, a limitation during data collection was the motion capture equipment. Specifically, if the cameras were disconnecting during data collection, they need to be rebooted prior to collecting more data. Also, if the retroreflective markers on the pitchers fell off, they needed to be replaced prior to the next pitch of data collection. For the MLB data, this information (with regards to the collection of the markerless motion capture data) and the post-processing procedure was not disclosed.

3.2.4 Functions and Specifications

The primary function for this project is to create a metric that can inform a party about whether a pitcher is fatigued or becoming fatigued. The metric will supply coaches, players, and stakeholders with a detailed breakdown of the pitcher's fatigue levels throughout a singular game or season. Biomechanical and dynamic data from Hawk-eye's markerless motion capture system will be used to calculate the metric. Some key functions the final metric should focus on include: dataset consistency, quantitative aspect, pitcher variety accommodation, and report summary.

Dataset Consistency: This function focuses on the implementation of the metric using data that is acquired from motion capture systems currently in use, such as the Hawk-eye systems at MLB stadiums. Since it is not practical for teams to place markers on their players during a game, this would allow in-depth analysis of a pitcher's biomechanics in-game.

Quantitative aspect: The metric needs to have a quantifiable output that can measure different levels of fatigue and be easily assessed. Fatigue is extremely abstract and is different for everyone, so having a quantitative aspect helps eliminate this issue.

Pitcher Variety Accommodation: This function for the development of the final metric focuses on the applicability of the metric to a variety of pitchers. Ideally, the metric would be incorporated for all pitchers, not just for starting pitchers for example.

Report Summary: The goal of this function is to ensure that all coaches, trainers, and other professionals who are not trained in the biomechanics field, are still able to use the metric and understand the results.

Table 3 summarizes the team's approach to the decision process with regards to prioritizing the above functions in the development of the final metric. This chart compares every potential function in the metric with the other and is "ranked" against it. All of the metric functions are listed on the top and the side of the chart and two different functions are compared against each other at a time. A "1" was used if the row function was more important, and a "0" if the row function was less important. For example, in comparing data consistency (row) with quantitative aspect (column), the team determined that data consistency was more important, so it scored a "1". This assessment ranked the focus for the metric development in the following order:

1. Dataset Consistency
2. Pitcher Variety Accommodation
3. Quantitative Aspect
4. Report Summary

Table 3: Pairwise comparison chart.

Pairwise Comparison Chart	Dataset Consistency	Quantitative Aspect	Pitcher Variety Accommodation	Report Summary	**Result**
Dataset Consistency		1	1	1	3
Quantitative Aspect	0		0	1	1
Pitcher Variety Accommodation	0	1		1	2
Report Summary	0	0	0		0

3.3 Standards for Design Requirements

The current definition for a medical device developed by the International Medical Device Regulators Forum (IMDRF) is: "a medical device is a product, such as an instrument, machine, implant, software or in vitro reagent that is intended for use in the diagnostic, prevention, and treatment of diseases or other medical conditions". The resultant of this project is a fatigue characterization metric (designed in software) that has potential implementations of injury association and prevention. There are currently two classifications regarding medical device software, including: Software *in* a Medical Device (SiMD), or embedded software, and Software *as* a Medical Device (SaMD), or a standalone software. The two international organizations with standards focusing on SaMD development are International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC).

ISO:

1. ISO 13485: Medical devices - Quality management system standard
2. ISO 14971: Medical devices - Application of risk management ot medical device

IEC

1. IEC 62304: Medical device software - Software life cycle processes
2. IEC 62366: Medical devices - Part 1: Application of usability engineering to medical devices
3. IEC 81001-5-1: Health software and health IT systems safety, effectiveness and security - Activities in the product life cycle

3.4 Revised Client Statement

Define and validate a fatigue metric for baseball pitchers by using kinematic and dynamic calculations from a worn sensor system and motion capture data.

1) The defined fatigue metric will be able to detect variation among biomechanical metrics through a device and/or motion capture data.
2) The different data sets available will validate the defined fatigue metric.
3) Analysis will produce a reliable metric that can be applied and understood by players and coaches in the future.

3.5 Project Approach

To accomplish the objectives set out for this project, the team approached the project from two separate angles: data exploration from Pittsburgh Pirates MLB team markerless motion capture, and data collection and analysis of WPI collegiate players.

3.5.1 Term Breakdown

A - Term

The primary focus during this term was project definition. This included identifying project topic and scope through extensive background research and consulting with external collaborators. The initial project interest was evaluating baseball pitcher injuries, however, over the course of the term, the project became more defined as a fatigue metric that could lead to injury risk assessments.

The team was able to develop collaborations with both Dr. David Magit, who is an orthopedic sports medicine surgeon who works with baseball pitchers, and the Pittsburgh Pirates Major League Baseball team, who have markerless motion capture data collected in-game. With the support and expertise of both parties, and the project advisor, the team developed a method to incorporate two different types of motion capture data to attempt to characterize pitcher fatigue. This included developing a procedure and conducting a fatiguing data collection trial with collegiate participants, and performing data analysis on the markerless motion capture data of the MLB player data. During this term, methods and plans for what analysis to conduct on both data sets and how to approach data collection were developed.

B - Term

WPI Collegiate Pitchers

The goals for this term included finalizing the data collection procedure, finalizing the IRB proposal, completing all motion capture training, completing most of the data collection, begin post processing in VICON software, and report upon the progress of the term.

The team was able to collect data on four participants prior to the conclusion of the term, and made plans to complete the data collection process in the beginning weeks of the following term. The team developed a custom marker set, and completed training and testing prior to working with participants. The team also developed a standard operating procedure (SOP) for the data collection, including elements both for the software and the physical procedure.

MLB Pittsburgh Pirates

The goals for this term included data exploration with the data provided by the Pittsburgh Pirates motion capture system. This process began with normalizing the data based on pitcher position, and doing some data cleaning (eliminating games and pitches deemed not viable for analysis). The following topics were analyzed:

- Rate of force development
- Joint range of motion
- Ball release height
- Mechanical variation in throwing arm
- Velocity and acceleration of segments
- Performance metrics
- Analyzing mechanical changes of the throwing arm in the x, y, z
- Analyzing marker data by bucketing pitches
- Analyzing marker data by breaking up the pitcher's motion into stages
- Created code to find velocity and acceleration of segments
- Analyzing performance metrics for the pitcher throughout the game (pitch velocity)
- Mass correlation of all categories

C - Term

WPI Collegiate Pitchers

The goals for this term included completing data collection with WPI collegiate participants, continue training on Vicon and Visual 3D software systems, post-processing data in both softwares, and begin exploration of accelerometer and force plate data. All of these were completed, and were able to provide data to conduct analysis previously done on the MLB data, on the WPI collegiate athletes.

MLB Pittsburgh Pirates

Goals for this term included more efficient normalization methods, evaluation of data based on pitch phase, rest time, joint angles (in local coordinate system), kinetic chain and fatigue metric development (narrowing down criteria). All of these were tackled, in addition to more efficient data cleaning methods, the beginnings of machine learning models to predict fatigue, and the beginnings of analysis on WPI collegiate athletes.

D - Term

Goals for this term included establishing details regarding the finalized fatigue metric developed from data exploration of both WPI collegiate pitchers and MLB pitchers. This included completing the post-processing of the WPI pitchers of interest, concluding data exploration, and conducting final analyses across both pitcher levels (collegiate and professional). In addition to this, the final abstract, report, and presentation were prepared.

4.0 Design Process

This section focuses on the direction of the project as developed from the project approach in the prior section. This includes the value proposition, the development of the metric (ie. concepts explored), and the process for data collection and post-processing process for the WPI pitchers data.

4.1 Value Proposition

4.1.1 Need

The accumulation of fatigue in baseball pitchers is a common occurrence across a season or a career as a result of overuse and lack of rest [28]. Several studies have identified that the accumulation of fatigue can be linked to kinematics, performance, tissue stress and potentially injury [28]. In order to better understand the relationship between fatigue and these outcomes, a fatigue metric must be designed as a system to identify fatigue level and the potential risk this poses for the pitcher.

In the Major Leagues, nearly 820 million dollars are spent on pitchers on the injured list [41]. If fewer pitchers were injured, this money could be used to better the fan experience and keep athletes on the field and playing. However, fatigue and injuries also greatly affect youth players. The rate at which youth players are getting Tommy John surgery, a surgery done to rebuild the UCL in a pitcher's throwing arm, is increasing drastically and, as of 2011, more than half of Tommy John surgeries were done on kids ages 15 to 19 [82]. Many doctors have stated that overthrowing and pitching year round is the main reason for this influx in youth injuries. Current pitching standards are not adequate and do not bring fatigue into the equation. These standards only give coaches and pitchers specific pitch counts, and do not give any information on what happens when a pitcher is fatigued. This causes coaches to have pitcher's throw an unsafe amount of pitches. In order to prevent wasted funds and youth injuries, fatigue itself must be better understood as well as what level of variation classifies a pitcher as fatigued in the sport of baseball. Pitchers and coaches are currently left in the dark when it comes to fatigue, but by designing a fatigue metric based on a pitcher's biomechanics can ultimately reduce injuries, save players, and lessen expenses each season.

4.1.2 Approach

To design a metric that accurately and effectively quantifies fatigue, the team collected and analyzed multiple sets of data that stemmed from professional and collegiate pitchers. The Pirates' data has allowed the team to analyze in-game data and hundreds of pitches from a singular professional pitcher. This data has provided the team with a large enough dataset to analyze long-term trends from this specific pitcher. The collegiate data set offers the team a controlled setting where the team can manipulate the players into being fatigued. The extreme differences from the pre and post-fatigue cycle data have allowed the team to validate the initial trends discovered in the Pirates data. This approach has allowed the team to get the best of both worlds: a large amount of in-game data and data from a controlled setting that includes categorical fatigue data. The two data sets have allowed the team to define specific fatigue metrics that correlate strongly between both datasets.

4.1.3 Benefit

As addressed previously, the primary benefits of a fatigue evaluation metric is the ability to identify when a player is at an increased risk of injury. With the focus of an athlete's physical health and condition, being able to identify increased risk of injury and remove them from play prior to an injury occurring would spare a massive amount of pitchers from career altering injuries, from the youth leagues all the way to the professionals. At the major leagues, injured pitchers account for over half the total injuries in the league, and equate to a proportional amount of economic strain. At this level, being able to identify when a player is at an increased risk of injury as a result of over-fatigue could aid in injury prevention. In the youth divisions, pitchers ages 15-19 years old accounted for 56.8% of all UCL reconstruction surgeries performed between 2007 and 2011. If there was a way to identify when these players are at an increased risk (aside from their pitch count), this could help prevent these injuries, as the players could be pulled from the game prior to an injury happening as result of fatigue. At the youth levels, the players hopefully have a longer future in the sport. The ability to prevent these injuries from happening at a young age can increase the athlete's chances to reach the professional level, benefiting the athlete physically, and economically.

4.1.4 Competition

In terms of competition for biomechanical pitcher data, analysis that includes control and an in-game dataset is relatively very new and may have never been done before. The Pirates have stated that Major League Baseball is the only organization in the world with access to this amount of pitcher data. Therefore, it is very unlikely that outside organizations or non-affiliated MLB groups have this amount of data. However, other MLB teams do have access to this data. Currently, nearly every major league club has someone on staff that explores biomechanical data. However, the amount of staff and bandwidth of these clubs vary drastically from club to club. These MLB team's R&D staff may be working on something similar, but MLB teams do not disclose this to other teams or the public at all.

On the other hand, there are other methods that can be used to manage or limit the adverse effects of fatigue. Currently, many professional sports teams are practicing load management. Load management is designed to give players calculated rest days to ensure that they are performing at the highest level for other games. This is practiced in Major League baseball through the five-man starting rotation. Also, some teams rely more on the strength and conditioning staff to depict fatigue in players. For instance, some teams use ten-yard burst time or jump height to visualize how fatigue affects a player throughout the season.

In addition, many teams measure fatigue based on the number of pitches they throw during a game. For instance, many high schools and little leagues translate the number of pitches a player throws to the number of days of rest they need after that. For instance, a pitcher that throws 20-40 pitches will need one day off from pitching again. However, there are many drawbacks to this type of fatigue regulation. For instance, some coaches will have a pitcher throw one less pitch than the current pitch bucket allows. Thus, they will have a pitcher throw 39 pitches so they only have one day off rather than 40 which would cause 2 days of rest. This manipulation does not take into account the number of pitches the pitcher throws weekly or yearly. The team believes that our strategy will take into account how the body is reacting to the number of pitches, not just an arbitrary standard. All in all, the competition in this field is very scarce as fatigue is such an abstract and complex topic and, in order to get an accurate measurement, a large amount of data must be collected and analyzed.

4.2 WPI Data Collection Process

A primary goal for the team included validation of the candidate metrics to develop the final fatigue metric between two data sets: MLB motion capture data and WPI collegiate pitcher data. In addition to overall validation, the two datasets were analyzed in parallel, driving the development and implementation of the final fatigue metric.

The purpose of data collection is to collect biomechanical data on pitchers that are known to be unfatigued and fatigued. The following data was collected:

- Markered motion capture data with Vicon/Nexus 2.14 system
- Force plate data (AMTI OPT400600)
- Accelerometer data (Delsys Trigno EMG System and Avanti Sensors)
- Fatigue Rating (Borg Rating of Perceived Exertion)
- Heart Rate

Participants:

- < 30 pitches pre fatiguing exercise and < 30 pitches post fatiguing exercise on 6 pitchers
- Both left handed pitchers and right handed pitchers
- All participated in a fatiguing exercise cycle developed by the team
- All gave written informed consent
- All were monetarily compensated for their participation

Procedure:

All team members completed CITI human participant research training, as well as developed and submitted a research proposal to the IRB (IRB-23-0202).

Prior to data collection the motion capture systems were set up and the participant stretched as they normally would when throwing a 70 pitch bullpen (typical practice pitching area). Once the pitcher was warmed up, the team placed the retroreflective markers on the pitcher, and the accelerometers, corresponding to the custom marker set developed for this study. This marker set was modified from a Helen Hays gait marker set and included fifty-five markers and two accelerometers, with increased definition on the player's pitching arm [83]. This included cluster markers placed throughout the arm for post-processing orientation, and an accelerometer on both the forearm and upper arm of the pitcher's throwing arm. The team then collected categorical data on the participant's fatigue level, which included a Borg rating and heart rate [29]. The team used a Borg scale of perceived exertion which ranged from 1 to 10, with 1 representing "not fatigued", and 10 representing the highest level of fatigue. The force plates were set such that it would collect the force exerted during the pitch by the pitcher's stance leg.

The first stage of the data collection procedure included the pitcher throwing fastballs into a net on the opposing wall of the motion capture lab. The goal of this stage was to collect baseline, or non-fatigued data. Throughout the data collection, the team made note of any markers or accelerometers that fell off during the pitch, and replaced the marker back onto the pitcher prior to their next pitch. More specifically, the team noted if the marker that fell off was an essential (bony landmark marker) or a non-essential (cluster marker) marker. This was important for post-processing the data, as the loss of an essential marker could result in a loss of data for that pitch. At the conclusion of this stage, the pitcher's heart rate and borg rating were recorded.

The next stage had the participant perform a set of exercises selected to fatigue the body and throwing arm of the pitcher. The participant performed three sets of a HIIT workout, including exercises such as burpees, squats, resistance band pull stretches, pushups, with resting intervals in between. The participant would do each exercise for 30 seconds, and take 15 second breaks in between. The team incorporated each exercise into the fatiguing protocol to target specific areas of the body. The burpees were aimed to fatigue the participant's whole body, the squats were included to fatigue the core and below, the resistance bands would fatigue the rotator cuff and shoulder muscles, and push-ups would also contribute to general muscle fatigue. Table 4 is a breakdown of this workout. At the conclusion of this exercise cycle, the team recorded the participant's heart rate and borg rating, and any markers that fell off during exercise were put back on the participant.

Table 4: HIIT workout structure for the fatigue cycle.

Time (minutes:seconds)	Exercise
0:00-0:30	Burpees
0:30-0:45	*Rest*
0:45-1:15	Squats
1:15-1:30	*Rest*
1:30-2:00	Resistance Bands Pull Aparts
2:00-2:15	*Rest*
2:15-2:45	Pushups
2:45-3:00	*Rest*

Following the exercise cycle, the participant performed the same pitching procedure as the first stage. The goal of this stage was to collect fatigue data, or pitching data from when the participant was considered "fatigued." Similar to other stages of the protocol, the team collected the heart rate and borg rating of the participant after pitching.

4.3 Concept Generation & Introducing Leading Concept

4.3.1 Concept Ideation

Following research conducted by the team and reported in the literature review, brainstorming sessions with the team and advisors/collaborators, the team developed a few key candidate metrics to begin the data exploration process with the datasets available. The final 5 concepts include: Mechanical positional changes, Joint range of motion & flexibility, Effect on pitching performance/outcomes, Kinetic chain sequencing, Rate of force development. For each of these concepts, the focus is to evaluate a specific change in these. Due to the fact the dataset provided by the Pittsburgh Pirates does not include information regarding the pitcher's fatigue state, the team's motion capture data collection procedure with the WPI pitchers provides a dataset with explicit information regarding the pitcher's level of fatigue. The combination of evaluating these concepts with both data sets provides the categorical fatigue information to validate the finalized metric.

Concept 1- Mechanical Positional Changes

This concept is focused on the idea that as a person pitches more times over a short period, they will increasingly become more fatigued from this repetition. Motion capture systems can detect the changes in a pitcher's mechanics correlated with a pitcher's level of fatigue (discussed in the literature review section). The team aims to use the datasets available to detect these changes in a pitcher's mechanics over the course of the game. This metric would be a pitcher-to-pitcher case, with similarities across similar pitchers (for example, pitchers who have similar arm slots). The two parallel data sets can be used to validate the prevalence of this candidate metric with relation to fatigue assessment.

Pittsburgh Pirates: Season long data available for one professional pitcher allows for a large dataset that can be used to identify clear trends in the data. With the data (position of a certain 'marker' of interest) able to be plotted with respect to pitch count or a specific time code, the team can evaluate any changes as the game/season goes on. The strength of the potential relationships could be assessed based on their correlation with pitch count or time code, and can be further characterized based on different groupings, or bucketing of pitches (such as the first 20 pitches vs the last 20 pitches thrown).

WPI Pitchers: This data set provides categorical data regarding whether a pitcher is fatigued vs not fatigued, providing discrete context to the analyzed data. If changes in a pitcher's mechanics are seen between the fatigued and non-fatigued pitches of the WPI players and the Pittsburgh Pirates pitchers, it is a strong candidate metric to be used in the final metric. However, the dataset size is smaller than that available for the Pittsburgh Pirates, and may not be able to detect these changes as easily.

Concept 2- Joint Range of Motion & Flexibility

Joint range of motion (JROM) focuses on evaluating how the changes in joint angles, with corresponding flexibility and joint range of motion outcomes, correlate with fatigue. Motion capture systems can be used to calculate these, to varying levels of complexity based on the markerset used. As this is similar to changes in pitch mechanics, this would be a metric developed on a pitcher-to-pitcher case. The two data sets with the team can be used to validate the prevalence of this candidate metric.

Pittsburgh Pirates: Full games and season long data for a professional pitcher allows for large data sets to evaluate trends and the strength of this metric for assessing pitchers at an elite level. However, the markerset is limited to joint centers, and does not allot for analysis of rotational aspects of the throwing arm during a pitch.

WPI Pitchers: This data set provides information regarding whether a certain pitch is a "fatigued" pitch or a "non-fatigued" pitch. This data set is also more complex, and can provide information regarding segment rotation.

Concept 3- Effect on Pitching Performance/Outcomes

Through conversations with collaborators and literature, another fatigue concept discussed was how a pitcher's ball velocity, spin rate and accuracy alter as the pitcher becomes more fatigued. This concept is looking at the 'outcomes' of the pitch based on the mechanics of the pitch, such as the metrics of a pitch at release, in flight and where it ends. With a current constraint on focusing primarily on fastballs, the team can design a way to analyze fluctuations of the pitcher's throw. For example, evaluating a decrease in pitch speed, or an increase in pitches thrown outside the strike zone (also known as a ball). These metrics may show a distinguishable pattern and potential correlation with the increase in a pitcher's fatigue level. Although straightforward, the margin of change at a professional pitcher level may not fluctuate as much as predicted by this team, as professional pitchers are highly trained to conserve energy and maintain velocity and pitching metrics. However, this concept could be beneficial to incorporate as a validation metric in conjunction with other concepts to evaluate the reliability of the final metric. It also could have more practical applications at more amateur levels of competition, due to the simplistic nature of this concept.

Concept 4- Kinetic Chain Sequencing

Kinetic chain is the specific sequencing of a pitcher's pitching motion. The ideal kinetic chain sequence as reported in literature for fastballs (focusing on the upper arm) is when the shoulder reaches maximum velocity, then the elbow, and then the wrist [19]. This allows for effective flow of energy from the shoulder to the wrist once originated from the lower body. The team's hypothesis stems from hypotheses made in prior concepts, where fatigue has an effect on the pitcher's consistency to reliably meet all the ideal marks during a pitch. For example, if a pitcher's joint angle alters when fatigued, this could create a change in the amount of movement required to achieve the same desired outcome (a fast and accurate pitch), shifting the overall mechanics of the pitch, resulting in a less efficient flow of energy in the throwing arm. This concept was hypothesized to accompany other concepts, to evaluate how changes in the pitching mechanics become less efficient as the pitcher becomes fatigued. For example, at the beginning of the game, the pitcher may have a kinetic chain of successes of around 70%, but towards the game, the rate decreases to around 50%. For professional pitchers, the expectation is that their decrease over the course of the game would not be as significant as for pitchers who are not as trained. If this concept proves to correlate with fatigue, this could be another more simple metric used to evaluate a player's fatigue level.

Pittsburgh Pirates: Provided with the joint center locations of the shoulder, elbow and wrist for the throwing arm, this is a very simple analysis to evaluate their pitch efficiency, and prompt for a more in-depth analysis as to what else is being affected by the pitcher in this state (such as a change in throwing arm position).

WPI Pitchers: Similar to other metrics, the knowledge of if a pitch is explicitly a fatigued vs non-fatigued pitch would be valuable to validate this concept with the professional levels. This could also lead to an increased understanding of the mechanics of a non-professional pitcher, and possible applications for more amateur level competitors.

Concept 5- Rate of Force Development

This concept relates to rate of force development, which is defined as the ability to move an object or system mass rapidly. This is a key indicator of explosive strength [84]. Based on the physical demands and longevity of a season, it can be concluded that the rate of force development of professional athletes may be affected if a certain amount of fatigue is accumulated during a pitcher's start [84]. Research has shown that an increased amount of volume load and work over an extended period of time can decrease rate of force development [84]. In order to monitor this, motion capture data would be used to find the acceleration of the limbs of the body and force plates would be used to find the forces during a pitcher's motion. These forces and power values may change from a pitcher's first start of the season versus their last. Therefore, analyzing rate of force development is a potential metric for fatigue.

This method has been supported and successful in the NBA, but not yet with baseball players [84]. This method tends to work better for vertical jumps, so it may not function as efficiently in an in-game scenario for data collection. However, the additional MLB data will assist in comparing trends identified in the beginning of the season with those at the end of the season. If there is a drastic change in rate of force development, then this concept can be monitored closely by MLB teams and may help identify when a player is in a state of fatigue.

4.3.2 Pugh Analysis of the 5 Concepts

The following table displays a pugh analysis for the above five concepts the team generated. This table aids in the understanding of how the initial concepts compare against the team's established functional specifications, or evaluation criteria. The analysis also shows how the team's concepts compare to the "gold standard." For this study, the team identified the gold standard as professional training staff. This staff would include multiple professional athletic trainers that understand the basics behind categorical fatigue treatment. However, they are not able to quantify fatigue on any level as they are more focused on what the players are saying. Also, they only know what occurs in their training room and don't know how other teams are treating players with similar categorical fatigue levels. Ultimately, the gold standard doesn't have a way of standardizing or quantifying fatigue on a player to player basis. Table 5 represents the pugh analysis for the concepts.

Table 5: Pugh analysis of the five concepts.

Pugh Analysis	Weight	Gold Standard	Concept 1 (Variation)	Concept 2 (JROM)	Concept 3 (Performance Metrics)	Concept 4 (Kinetic Chain)	Concept 5 (Rate of Force Development)
Dataset Consistency	4	0	1	1	1	1	1
Quantitative Aspect	2	0	1	1	1	1	1
Pitcher Variety Accommodation	3	0	1	1	-1	1	0.5
Report Summary	1	0	-1	-1	-1	-1	-1
Total		**0**	**13**	**9**	**1**	**13**	**10**

Based on the Pugh analysis, using variation as a fatigue metric may be the most practical and efficient metric. Concept 1 (variation) revolves around the team collecting multiple data sources and seeing if variation in a pitcher's motion will increase as they become more fatigued and throw more pitches. An equally equivalent assessment is kinetic chain, with force development, joint range of motion, and performance metric following in order of decreasing importance. The team prioritized the data analysis in this order of importance, and included more data exploration topics as more was discovered.

4.3.3 Concept Map Summarization

The team compiled their ideas from the brainstorming sessions to better visualize the project concept and the aspects which contribute to the goal. Figure 14 represents the map the team created with the overall function branching into subfunctions and the necessary steps needed to take to fulfill the functions.

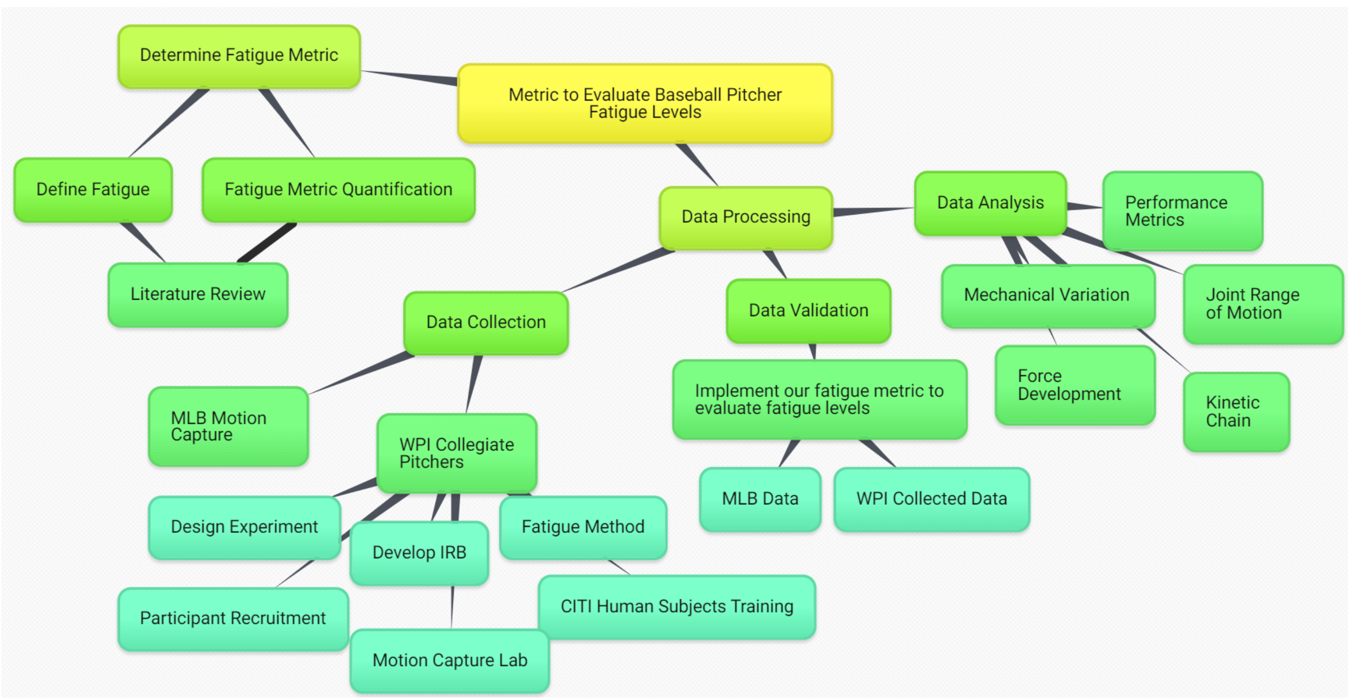

Figure 14: Concept map showing the breakdown of concepts to fulfill the project goal.

4.4 Means & Testing

This section is designed to explain the means to complete the different functions as well as explaining the testing that will be done prior to data collection. The team will have an IRB submitted and approved that will detail the team's plans for data collection. However, prior to collection the motion capture systems, accelerometer sensors, and force plates will be tested to ensure that they are up to the teams standards. These tests will verify their portrayed characteristics.

4.4.1 Function Mean Analysis

The team developed a function-means analysis table to assess different approaches to fulfill each functional specification aimed at achieving the final project goal. As stated previously, the functional specifications of the project relate to having a consistent datasets to evaluate the metric, having a quantitative aspect, accommodating all pitchers that use the system, and generating a report summary which makes the information intuitive for all users. The means are the aspects involved with each of the functional specifications. For example, some methods the team used to evaluate the quantitative aspect of the finalized fatigue metric include raw calculations, matlab / python calculations, and visual3D and Vicon/Nexus generation analyses.

Function: Dataset Consistency

Means: Markerless Motion Capture Data (MLB position coordinate data collected in-game); Marker Motion Capture Data (WPI Collegiate baseball pitchers collected in motion capture lab); Accelerometers; Force Plates

Function: Quantitative Aspect

Means: Numerical calculations; Matlab; Python; Visual3D; Vicon/Nexus

Function: Pitcher Variety Accommodation

Means: Bucket pitchers; Pitch count; Weight; Height; Position; Age

Function: Report Summary

Means: Quantitative information understood by coaches; players; trainers; general managers; owners

4.5 Motion Capture Data Collection

The section below describes a breakdown of the process for the collegiate data collection. It includes the motivation behind the marker set used, the various iterations of the marker set, the motion capture testing process, post-processing the data, as well as the challenges with post-processing, and model-building and data extraction from Visual3D.

4.5.1 Marker Set

A marker set was created in order to properly extract the necessary data as well as develop a skeletal model in the Visual3D software. The team decided on the placement of 55 markers using the Helen Hays marker set as a baseline (Visual 3D Wiki Documentation). Figure 15 shows the marker placement used on the collegiate pitchers.

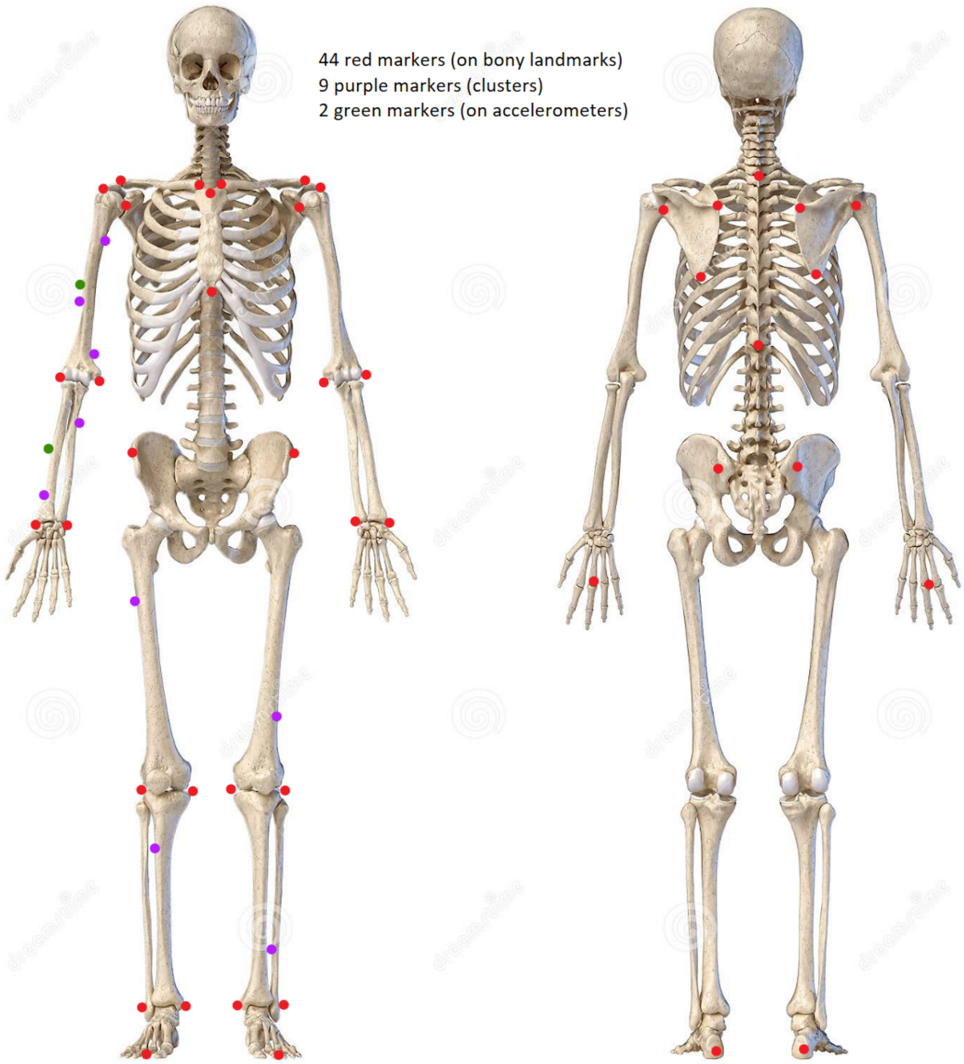

Figure 15: Final marker set.

The marker set consisted of a total of 55 retroreflective markers placed on the participant. 44 of these markers were placed on bony landmarks, nine were designated cluster markers, and one marker was placed on top of each of the two accelerometer sensors. The placement of the fifty-five markers were derived from previously made markersets that evaluated upper arm biomechanics of wheelchair propulsion, and gait [83]. The team wanted emphasis on the throwing arm, specifically the shoulder. However, it was crucial that there would be enough markers to extract enough biomechanical data to understand full body fatigue. The accelerometers were placed on the throwing arm; one on the forearm and one on the upper arm. These are marked by green dots shown on the skeleton in Figure 15. The team concluded it would be important to be able to track where the accelerometers were located and labeled on the Vicon software.

As for the bony landmarks, there were a few extremely crucial points that needed to be hit. For example, it was critical for the shoulder to be well labeled in order to accurately extract the joint centers and maximum external rotations. Figure 16 shows where the cluster markers were placed on the participants. These markers on the throwing arm would be mirrored for the left handed pitchers.

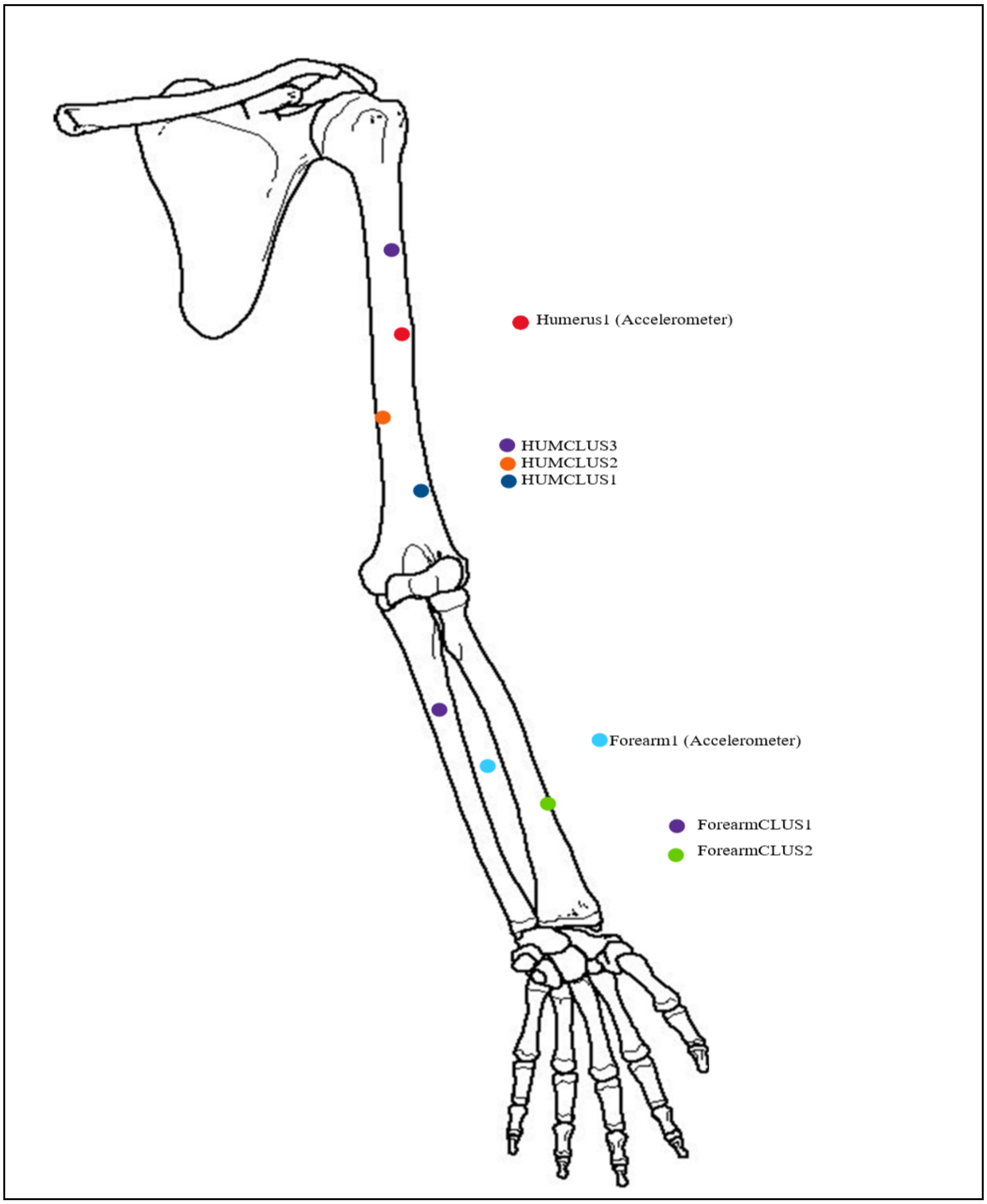

Figure 16: Cluster marker placements.

It was important that the group's marker set took into account the whole-body to fully understand the subject's fatigue. Without certain markers, it is difficult to properly create the skeleton in Visual3D. Without certain shoulder markers, it would be extremely difficult for the team to find the joint center. Also the marker placements help define the segments which separate specific areas that are isolated in Visual3D.

4.5.2 Changes to the Marker Set

The team went through a few iterations of the marker set, making some changes as the preliminary testing went on (prior to data collection). The general goal was to understand full body fatigue, with a concentration on the upper body. The original marker set excluded several essential points on the legs. Figure 17 shows the first marker set version.

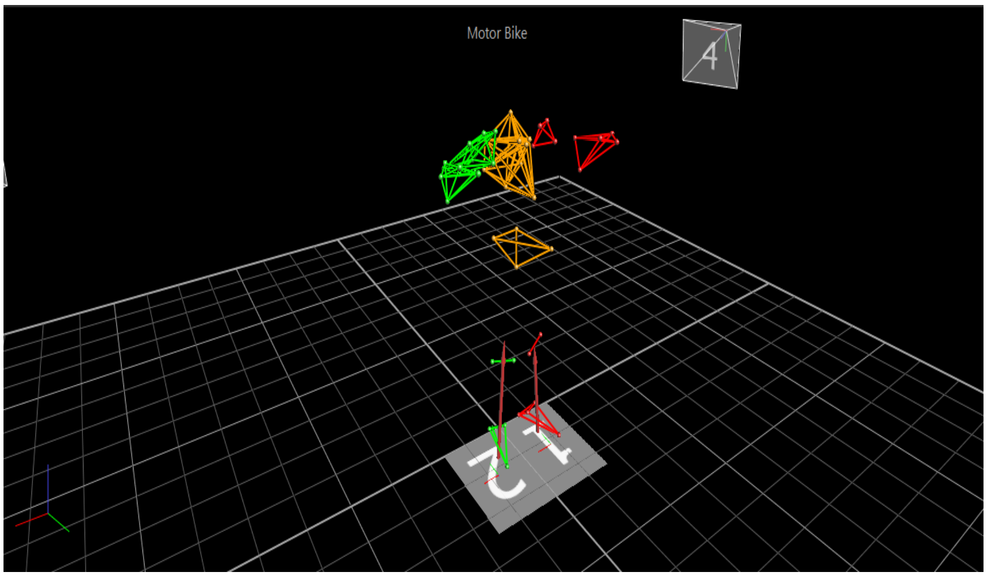

Figure 17: Original marker set.

As shown in Figure 17, there were minimal markers placed on the lower extremities of the pitchers. So, the team decided on adding two staggering femur cluster markers, where the right leg femur marker would be placed a bit higher compared to the left leg marker. There was also the addition of the two tibia markers. Similar to the femur markers, they were placed in a staggering manner, where the right leg's marker was placed a bit higher compared to the left leg.

Another major change was the amount of markers placed on the accelerometers. Originally, the team had three small markers on each of the accelerometers. However, once the post-processing steps came around, it was found to cause a problem with marker label swapping in the Vicon Nexus software. This means that the marker labels would switch around frame by frame, and then once fixed, would swap back to the incorrect one. Thus, the team decided to place one large marker on each accelerometer instead.

The last change to the marker set was shifting to using smaller markers on the clavicles. Similar to the accelerometer issue, with the use of bigger markers on the clavicle, it caused marker labeling to be extremely difficult, switching back and forth per frame.

4.5.3 Motion Capture Process

This project involved six WPI baseball pitchers to complete a procedure previously outlined to track their fatigue levels throughout pitching. Prior to data collection, the player completed their typical warmup routine, as they would prepare for a practice or a game. Simultaneously, the team prepared the lab space with the necessary materials for data collection. The team arrived at the lab twenty minutes prior to the scheduled session in order to turn on the cameras and system. This ensured that the cameras would be warmed up and the team was able to ensure everything was working properly for an efficient data collection process.

After the player was warmed up, the team placed reflective markers on the participant with double sided tape and each marker location would be marked with a pen. This allowed the team to quickly place the fallen markers back onto its respective location, if needed, throughout data collection.

Once the markers were placed following the team's marker set, the force plates were zeroed and they were oriented to the correct coordinates on the Vicon software. Afterwards, the participant left from in-view of the cameras while all reflective objects in the room were masked. This ensured that the cameras would only pick up the markers and nothing else that may have reflective qualities as well. The next step was to calibrate the cameras using the calibration wand, where one of the team members walked while waving it around. This ensured that the software could detect that each camera was working and thus would collect the motion to provide high quality data values. The origin of the force plates were also set using the calibration wand, ensuring the global coordinate system was properly established.

Additionally, the EMG analysis software was set up each time in order to collect the accelerometer data simultaneously to the cameras running. Each accelerometer was associated with a number and each number was designated the location, such as the "upper arm" or the "forearm".

Once the team completed all the preparation work, the participant first completed three static poses. The team had the participant pose in an anatomical, chair pose and motorbike pose. These static poses were crucial to the analysis steps in Visual3D later on. Figure 18 shows the static calibration poses for the motor bike and chair pose. After the static calibration trials, the participant would begin the protocol. As stated earlier, there would be a series of pitches, following a ten minute HIIT workout, and it concluded with another series of pitches. The procedure had the collegiate pitchers pitch fifteen fast balls, then go through burpees, mountain climbers, resistance bands, and pushups with fifteen second rest time in between each exercise. Afterwards, there would be an additional set of fifteen fastball pitches. By pitch eight in each pre and post fatigue cycle, the team removed the glove from the participant and the glove marker was placed on the middle knuckle. Following the whole trial, the data was exported and placed onto a flash drive for the next data collection steps.

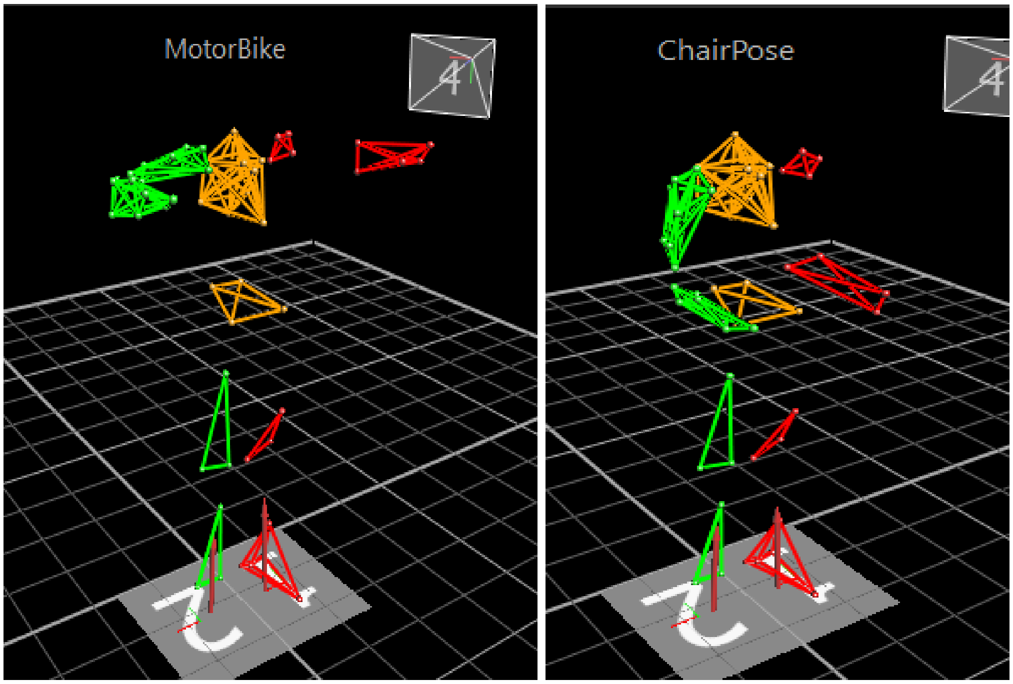

Figure 18: Motor bike (L) and chair pose (R) Vicon static calibration.

4.5.4 Vicon Post-Processing

The Vicon Nexus software version 2.14 was used in order to complete the following steps of data analysis. In general, the team followed the order of post-processing (labeling markers), gap filling, and filtering before sending the pitches over to the Visual3D software. The Vicon software is a tool that was used to prepare the marker motion capture pitches. Prior to processing the pitches, the team made the marker set in the software, naming each marker, and grouping them into segments. The team created ten different segments, separating generally by location, including the thorax, both left and right shoulders which included the humorous clusters, the left and right forearms, the pelvis, and finally, the femur and fibula area (which includes the feet). Figure 19 shows the anatomical position after post processing, separating the markers into their respective segments.

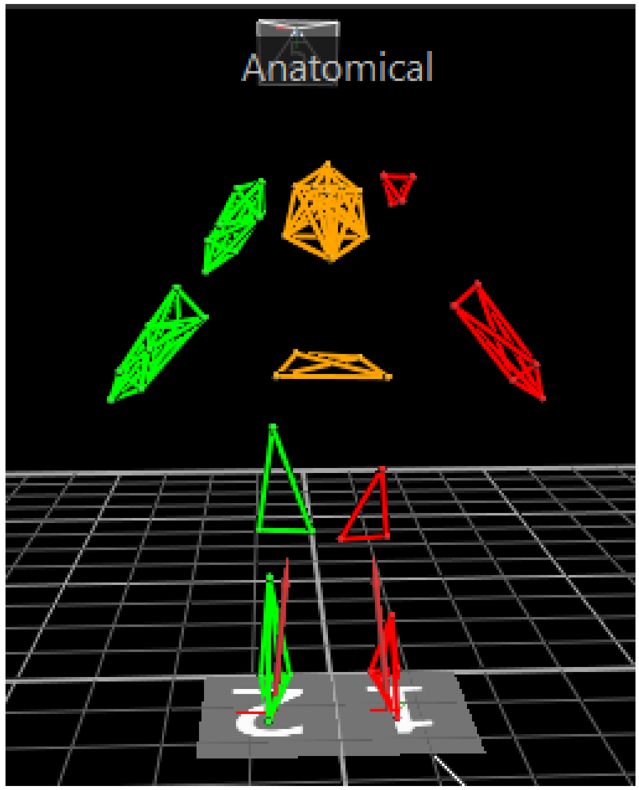

Figure 19: Anatomical position pose Vicon static calibration.

The markers would be tediously labeled by each frame, making sure that there were no unlabeled markers. The labels would be from the marker set designed prior. The next steps afterwards would be to gap fill. Gap filling ensures that when the marker is not visible, it can be tracked by other further visible markers nearby, preferably those in the same segments or in the rigid body. The Vicon software was able to detect how many gaps there were in the quality section, allowing the team to map the marker to the nearest ones, giving the software a trajectory to follow. Once the gap number reached zero, the pitch was ready to be filtered.

The process of filtering required a pipeline operation which provided a smooth trajectory for the markers to follow, and was an essential step prior to starting the Visual3D software process. The pitch was filtered with a 20 Hz cut-off frequency and was a low pass filter. Once a pitch was filtered in Vicon, it could not be filtered again, so the team created backups of every pitch to ensure data was not lost if a mistake was made.

4.5.5 Vicon Post-Processing Difficulties

There were many issues the team faced while post-processing the motion capture data. The first main step was to manually go in and label each marker at least once. The software would follow certain trajectories and continue with auto labeling; however, it would leave a majority of the markers unlabeled. The team had to label every marker on a frame by frame basis in order to ensure that each marker is labeled in every frame of the pitch. Many of them included the markers blinking out every other frame, the labels would continuously switch to the one nearest to it. This is important as if the shoulder markers for example had remained unlabeled, the Visual3D software would omit and not provide those data values for those specific frames. However, it is important to note that many markers flew off during the data collection process and with those, the moment it leaves the general location of where the marker was supposed to be, the team decided to keep them unlabeled.

4.5.6 Visual 3D Post-Processing

As previously mentioned in Chapter 2, Visual 3D is a software that outputs extensive biomechanical data and analysis from motion files via a motion capture system. More specifically, it performs inverse kinematic and dynamic calculations based on the anatomical skeletal model that the user creates. Before the team implemented their motion capture data into the software, they had to build a skeletal model based on the markers in one of the static poses from Vicon. The team selected one of the three static poses from the motion capture trial in Vicon, made sure all the markers were visible in one frame, and trimmed the capture to be one frame in length. From there, the team followed the same procedure for filtering of the static pose in the Vicon software. After filtering, the team imported the static trial pose into the Visual 3D software. Figure 20 shows the template of the markers on Visual 3D prior to building the skeleton.

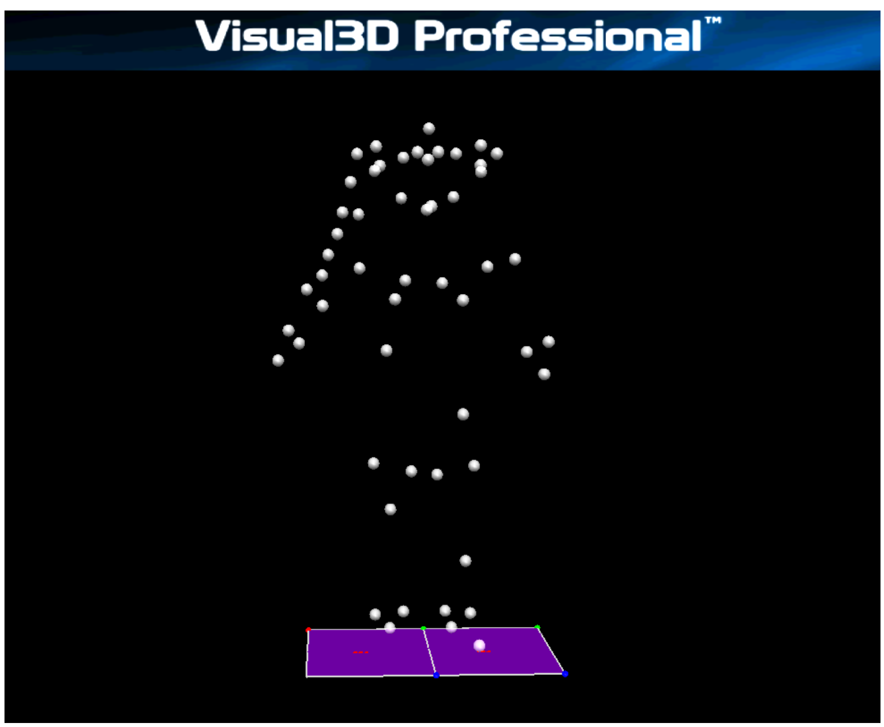

Figure 20: Imported markerset into Visual 3D.

The Visual 3D software auto populates the marker names previously set in Vicon and does not require relabeling. The team followed a Plug-In Gait lower limb and full body tutorial via C-Motion on Wikipedia. The software requires certain inputs for the skeleton such as height (m), weight (kg), segment radius values (m), and marker radius values (m). For this project, the team achieved the participant's height from their public athletic roster and inputted the value in meters. For the weight of the participant, the team used the z-direction force plate data in Vicon. Using the downward force in Newtons when the pitcher is in set position, the team could convert this value to kilograms by dividing by 9.81 N/kg, or the acceleration due to gravity.

$$\frac{764\ N}{9.81\ N/kg} = 77.88\ kg$$

The segment radius values were needed for the shoulders, elbows, and wrists. The elbow and wrists radius values were calculated by finding half the distance from the medial and lateral markers at each of those joints. Appendix L shows the formulas inputted to achieve the radius values using specific joint centers. The shoulder radius value was determined from a literature review which stated the average humeral head diameters for many participants. According to the source, the average male humeral head diameter was approximately 49.0 mm [85]. Therefore, the team inputted 0.0245 m, or 24.5 mm for the humeral head radius. Lastly, the team inputted the marker radius values for the retroreflective motion capture markers they used during data collection. Since the team used a combination of large and small markers, the radius values were 7.0 mm and 4.75 mm respectively.

Once the metrics for the participant were recorded in the system, the process of constructing the skeletal model was started. Visual 3D functions by creating landmarks and then creating segments based on these landmarks. An example of a segment is "Right Upper Arm," and this could be constructed using joint center landmarks at both the shoulder and the elbow. Landmarks are essential to create a target to be used for orientation within a segment coordinate system [80]. In this project, the majority of the landmarks are joint centers, aside from the landmarks contained on the thorax segment.

The first segment assembled was the pelvis segment, which was created using the CODA pelvis model. This is one of the models that can be used to create a pelvis in Visual 3D and it is used by Charnwood Dynamics, which is a company that focuses on the analysis of clinical movement [80]. The CODA model uses the anatomical locations of the Anterior Superior Iliac Spine and the Posterior Superior Iliac Spine. These marker placements can be difficult to find on participants, however they are known for being reference points that can define the segment coordinate system for regression equations related to hip joint centers [80]. The creation of the pelvis segment requires no landmarks, as it creates the segment solely based on the four hip markers placed on the participant.

Once the pelvis segment was created, the hip joint centers were established using the Bell and Brand regression equations. When using the CODA pelvis in Visual 3D, the Bell and Brand regression equations are used to automatically create the hip joint centers. The Bell and Brand regression equations were determined through in vivo medical imaging of pelvis samples [86]. The hip joint center formulas are the same for the right and left hip, aside from the left hip having a negative in the medial-lateral (ML), or transverse axis. The Bell and Brand regression equations are shown below for the ML, AP (anterior-posterior) and axial axes [80], for the right hip joint center (RHJC) and the left hip joint center (LHJC). The variable ASIS defined in the equations below represents the anterior superior iliac spine locations.

RHJC: ML=0.36*ASIS_Distance, AP= -0.19*ASIS_Distance, Axial= -0.3*ASIS_Distance

LHJC: ML=-0.36*ASIS_Distance, AP= -0.19*ASIS_Distance, Axial= -0.3*ASIS_Distance

The remainder of the segments were created using landmarks at the joint centers, which were determined to be the middle point in between two markers on a given joint. For example, the left forearm segments used the elbow joint center and wrist joint center, which were defined as LEJC (left elbow joint Center) and LWJC (left wrist joint center) respectively.

The team created two skeletal models in Visual 3D, one for the right-handed pitchers and another for the left-handed pitchers. It required two separate models since the right-handed marker set prioritizes the right arm with significantly more markers, and the same for the left-handed marker set. Figure 21 shows both skeletal models, and the dominant arm clearly shows significantly more markers.

An aspect to note regarding the models is the absence of the head, hands and a foot segment. The head and one of the feet were not included due to the lack of markers in these areas. This does not impact the data as the team did not need any data surrounding the head or foot segments. The right foot was not included on the right pitcher and the left foot was not included on the left pitcher. The team originally had included this marker, but due to pitchers dragging their toe leading up to the pitch, the marker would not stay on the subject.

Once the skeletal model was complete, motion files, or pitches, could be applied to the static pose model. This essentially means pitches could be imported onto the model for analysis. Visual 3D has the ability to export significant amounts of data for further analysis. Some of the data options include joint acceleration, joint angle, joint rotation, target path, segment velocity and joint velocity. The team exported the target path, which essentially exports the path on which a chosen joint center moved throughout the pitch, as well as joint angle, joint forces, joint moments, and segment velocity for their motion capture data.

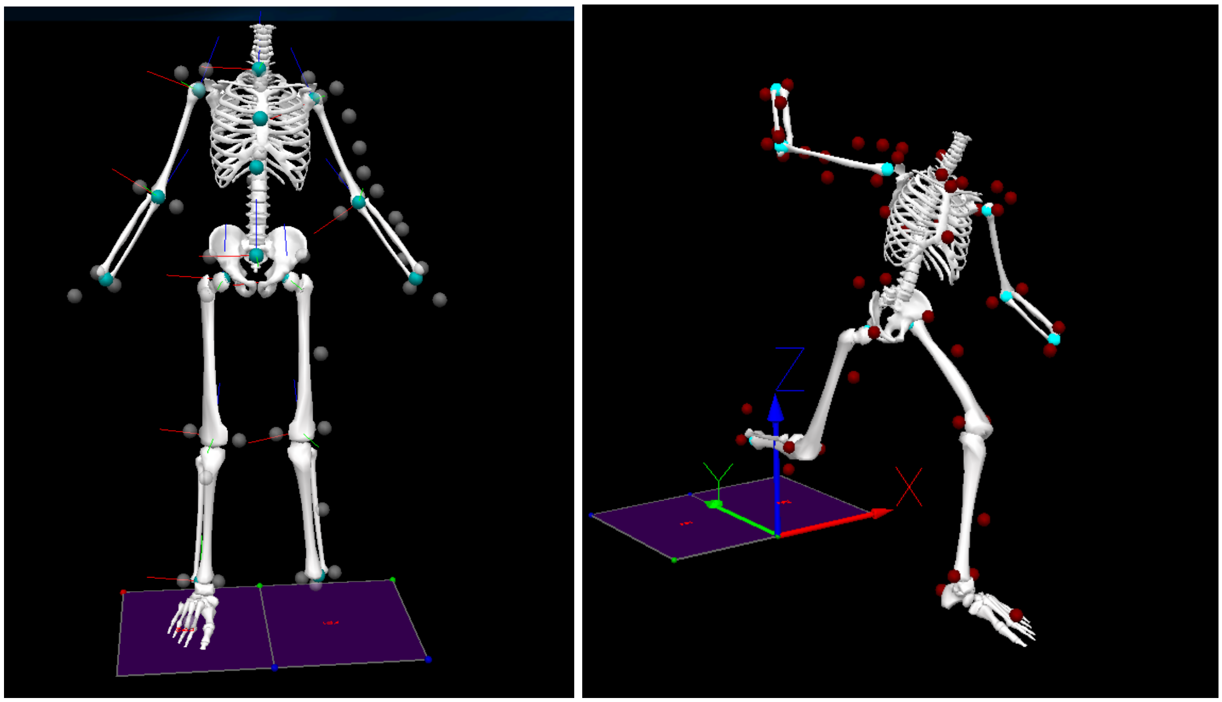

Figure 21: Images of the left-handed (left) and right-handed (right) Visual 3D skeletal models.

4.6 Datasets Analyzed

The team successfully conducted analyses on contrasting datasets, both the MLB Pittsburgh Pirates dataset, and the WPI collegiate pitchers dataset.

Following data cleaning of the Pittsburgh Pirates dataset, the team was able to evaluate 500+ pitches for one pitcher over eight games. This dataset has 15 estimated joint center locations. The joint centers of interest included shoulders, elbows, wrists, hips, knees, and ankles. This data set also provides some basic information on pitch outcomes, such as pitch speed. The strength of this dataset lies in the quantity of pitches available for analysis. This dataset is also collected under in-game settings, as opposed to in a laboratory. The drawback of this analysis is the simplicity of the markerset, which poses a limitation on the types of analyses available for calculations. It also does not have categorical information regarding the fatigue levels of the pitchers, and the post-processing methods of the data were not disclosed.

Following the data collection process for the WPI collegiate pitchers, the team has data on six different pitchers (four right handed pitchers, two left handed pitchers). All pitchers participated in the pre-fatigue data collection, five pitchers completed the post-fatigue pitching component of the data collection. Depending on technical difficulties, each pitcher threw on average 15 pre-fatigue pitches and 15 post-fatigue pitches. Approximately 72% of pitches recorded were considered good or great (meaning no essential markers, or markers on bony landmarks, fell off during the pitch). The strength of this dataset lies in the categorical data collected, providing the ability to categorize a pitch thrown as fatigued vs non-fatigued. It also is a much more detailed markerset, especially with regards to the throwing arm, and the team conducted all the post-processing of the data. The drawback of this analysis is the number of pitches available, and the fact that this was collected pitching in a motion capture lab, into a net. Time constraints resulting in the full analysis were completed for two pitchers.

5.0 Design Verification

In order to ensure that the fatigue metric and motion capture data resulted as expected, the data was verified through a series of tests. This section explains how the data for the fatigue metric was calculated and how the data was verified to ensure its accuracy. The data was analyzed in Python and the motion capture data was verified in a series of different ways.

5.1 Fatigue Metric Development

5.1.1 Data Processing

Data Normalization

The in-game markerless motion capture data from the Pittsburgh Pirates on their MLB players is labeled and filtered when given to the team. The filtering process was not disclosed, but all of the joint location (markerless marker location) data was referenced as coordinates in a global coordinate system. Figure 22 is the global coordinate system used by the motion capture system, with the y-axis along home plate and second base, the x-axis towards the first base, and the z-axis along the vertical axis.

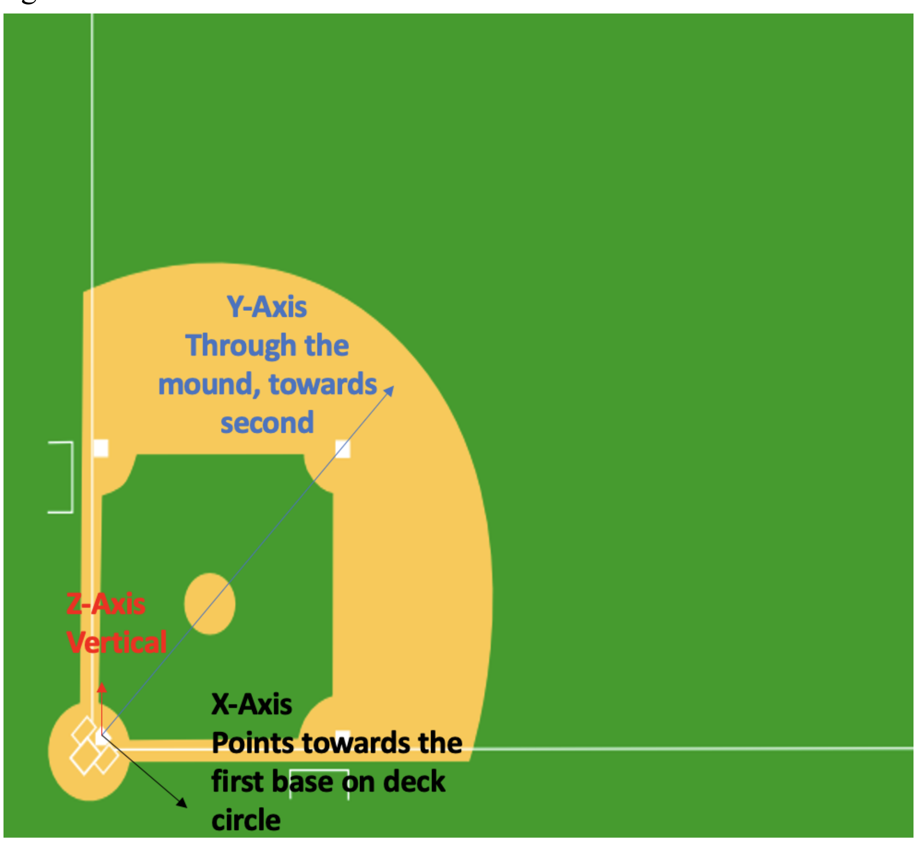

Figure 22: Hawkeye markerless motion capture coordinate system.

Since the team's data analysis focuses on the raw coordinates of the athlete's joint centers, using the global coordinate system would impair the calculations as the pitcher's position on the mound would be influencing the results. To overcome this, the entire data set was normalized, based on the starting location of the pitcher. Each joint center coordinate marker was evaluated relative to the pitcher's right ankle at the start of data collection for each pitch (prior to windup). This normalized data set was used for all later calculations. See appendix A for the code.

Data Cleaning

Working with real biological data, there is a tendency for noise and data of ranging qualities. For the purposes of the team's analysis each game was evaluated and determined viable or not viable for analysis. This included assessments such as missing a large number of frames per pitch, an unreasonable number of pitches thrown in a game, or unreasonable movement (such as five feet of shoulder movement during a pitch). After the data cleaning process, the team had eight variable games, six games with all pitches viable, and two games which included some not viable pitches. This resulted in 573 pitches to analyze, however, only fastballs were used, resulting in 218 pitches available for analysis. This created smaller data sets to work with once the analyses were bucketing based on pitch number. For example, 85 fastballs were available for analysis in the category of less than the first 20 pitches thrown in a game, however, when looking at the number of fastballs thrown during the last portion of the game (pitch number 80+), data are available for just 14 pitches. The team takes into consideration this gap, but understands that it is the result of working with this type of data. See Appendix B for the code.

Pitch Phase Breakdown

To provide more detailed information regarding a pitcher's performance, the team broke down each pitch into five phases of the pitch (windup, early cocking, late cocking, acceleration and deceleration). Follow through was deemed not as important (very few injuries occur in this phase).

This phase breakdown method underwent several iterations to increase the accuracy for catering the pitch phase breakdown to each individual pitch thrown. The first iteration of the pitch phase method was based solely on time frames provided in literature. For example, it was estimated that the late cocking period lasted about 50ms in length [20]. So each pitch was broken up into phases based on this generalized estimation.

The next iteration of the pitch phase breakdown included location time points of maximum knee height and foot contact of the lead leg. These points were able to define both the windup and early cocking periods. For this iteration, late cocking was still the generalized estimation of 50ms. Maximum knee height of the lead leg was determined by finding the maximum coordinate along the z axis, and indexing the frame of that point for the other marker locations. To find the frame at which foot contact occurred, the right ankle marker was used for the assessment. First, the locations where the ankle "stabilizes" was determined by finding the indices of where the difference between a point and its preceding point were minimal (less than 0.009 ft of change). Then, the largest gap in index values would correspond to the frame at which the least distance change occurs, and therefore is when the foot contacts the ground. The first point at which this occurs is the exact frame where the foot is stabilized, and is on the ground.

The final iteration included calculating the maximum external rotation angle of the shoulder to determine the end of late cocking and the start of the acceleration phase. To evaluate this, a local coordinate system for the upper arm was established, such that the forearm movement would be captured. The local coordinate system was referenced from the elbow (0,0,0), and an established shoulder location that would be along a parallel axis to the elbow (0,1,0), and the wrist location varying depending on the coordinate value of that frame/pitch, as shown in Figure 24. The angle was evaluated in the following way:

$$arccos(\frac{(shoulder\_elbow\_x * wrist\_elbow\_x) + (shoulder\_elbow\_y * wrist\_elbow\_y) + (shoulder\_elbow\_z * wrist\_elbow\_z)}{\sqrt{((shoulder\_elbow\_x\ shoulder\_elbow\_y + shoulder\_elbow\_z) * (wrist\_elbow\_x + wrist\_elbow\_y + wrist\_elbow\_z)}})$$

or

$$arccos(\frac{dot\_product}{magnitude})$$

The frame at which this angle occurred was the end of late cocking, and start of acceleration. Acceleration end time was at ball release, and deceleration was maintained at 35 ms after ball release in accordance with literature [20].

5.1.2 Fatigue Metrics

Mechanical Positional Changes - Concept 1

The team defined mechanical variation in a few specific ways. The team looked into average segment location, standard deviation of a segment, variance of the pitcher's arm, and correlation of segment movement to pitch count to define mechanical variation during a defined time frame. The team used a standard process to get the kinematic movement of the pitcher for every pitch into a singular data point.

In order to get a singular point of data for each specific pitch the team found the average marker coordinate location between two specific time points. The first time point that was selected was an additional 20 frames previously to the point that late cocking occurred in that specific motion. The second time point that was selected was pitch release or when time is equal to 0.

Late cocking was determined by calculating the maximum angle of the arm after the previous phase in the pitcher's motion. The previous phase before late cocking is early cocking. Early cocking occurs when the pitcher's leading foot hits the ground of the mound. In order to optimize run time, the average time plus two standard deviations of foot contact time for all the fastballs the pitcher threw was calculated. This value was found to be -0.094 seconds. Thus, the angle of the throwing arm was calculated from -0.094 to 0, or pitch release.

The angle of the throwing arm was calculated in a specific way to give the team a better chance of finding the ideal late cocking angle for that specific pitch. In order to do this, the team shifted the global coordinate system to the location of the elbow. Therefore, the right elbow was now (0, 0, 0). The team then shifted the location of the right wrist to align with this new coordinate system. Now for the third point, the team created a reference point that was determined to be (0, 1, 0). Now that the team had three points, the angle was calculated from these points. From previous research stated above and insight from the project advisors, the team expected a late cocking angle to range from 100 to 160 degrees. The team found the late cocking angle for this specific pitcher to average 131.13 degrees with a standard deviation of 4.53 degrees. The diagram in Figure 23 displays this change from the global coordinate system to the elbow.

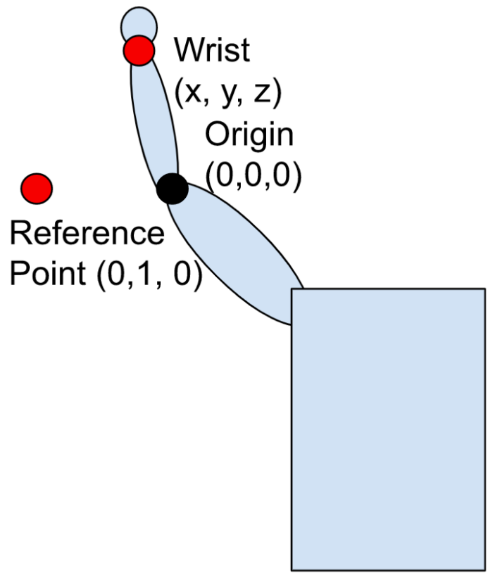

Figure 23: Display of elbow coordinate system (frontal view).

Once the pitch time location of late cocking was determined, the time frame was pushed back 20 frames or 0.067 seconds. This was done to get the full motion of a pitcher's arm and to capture early cocking in the pitcher's motion as well. Thus, the total time frame was considered to be late cocking angle time + 0.067 seconds to pitch release. Based on this time frame, the average location of the throwing arm's wrist, elbow, and shoulder was determined. The team conducted this complete analysis in python from a Google Colab notebook. The code that ran was able to successfully conduct these calculations and the code did what it was intended to do. The code successfully calculated the late cocking time, late cocking angle, average segment location, the standard deviation of the segment location, and variance of the segment location. This was done for the shoulder, elbow, and wrist in the X, Y, and Z planes. Therefore, each segment had 9 total columns of data that could be analyzed.

In order to verify that the code was doing what it was intended to do, the team spot checked the data with the following table. This table displays five frames of data for the shoulder, elbow, and wrist for the Pirates' pitcher. These five frames of data were spot checked by the team and excel.

Table 6: Table of sample data of the Pirates' pitcher.

Frame	Shoulder (ft)			Elbow (ft)			Wrist (ft)		
	X	Y	Z	X	Y	Z	X	Y	Z
1	-0.341	-3.084	3.218	0.031	-2.252	3.162	0.124	-2.471	3.840
2	-0.365	-3.136	3.220	-0.060	-2.273	3.179	0.101	-2.523	3.838
3	-0.393	-3.189	3.224	-0.161	-2.299	3.202	0.075	-2.576	3.834
4	-0.422	-3.244	3.230	-0.267	-2.334	3.233	0.046	-2.628	3.828
5	-0.451	-3.302	3.238	-0.378	-2.379	3.271	0.014	-2.679	3.819

From table 6, the team had the created code, team members, and excel conduct the following calculations: average segment location, standard deviation of the segment location, and the arm angle. Based on this table, the code was able to conduct the correct calculations. Any slight errors can be attributed to rounding differences in the team's methods and python. The following table summarizes the results of the three data sources.

Table 7: Summary of verification for mechanical positional changes.

Calculation	Team's Calculations	Excel	Created Code
Average Shoulder Location X (ft)	-0.394	-0.394	-0.394
STD of Shoulder Location X (ft)	0.045	0.044	0.044
RArm Angle Frame 1 (degrees)	122.76	122.75	122.75
RArm Angle Frame 2 (degrees)	123.30	123.31	123.31
RArm Angle Frame 3 (degrees)	123.89	123.89	123.89
RArm Angle Frame 4 (degrees)	124.46	124.47	124.47
RArm Angle Frame 5 (degrees)	125.04	125.04	125.04
Note: The RArm angle is the angle created by the shoulder, elbow, and wrist			

During the creation of the code, the team picked on a few things that helped the analysis. At first, the team was running throughout the whole index of rows, which totaled over 50,000 rows. The code took around 5-7 minutes to run. In order to optimize this the team embedded an if statement in the for loop to pass the row index if that unique pitch identifier was already analyzed. This decreased the code runtime to about 15 seconds. In addition, the original final CSV did not pull the late cocking angle or time that the max angle occurred. The team included this in version 2 to understand if any outliers occurred. See appendix C for the code.

Joint Range of Motion - Concept 2

This section of the metric revolves around the angles that the pitcher created with his arm throughout his motion. This was considered the joint range of motion for the shoulder, which the diagram in Figure 24 represents. The angle was calculated by finding the vectors between the shoulder and elbow as well the vector between the wrist and elbow. The magnitudes of these vectors were then plugged into the following equation to find the angle that the vectors create.

$$cos(\theta) = \frac{A \cdot B}{|A||B|}$$

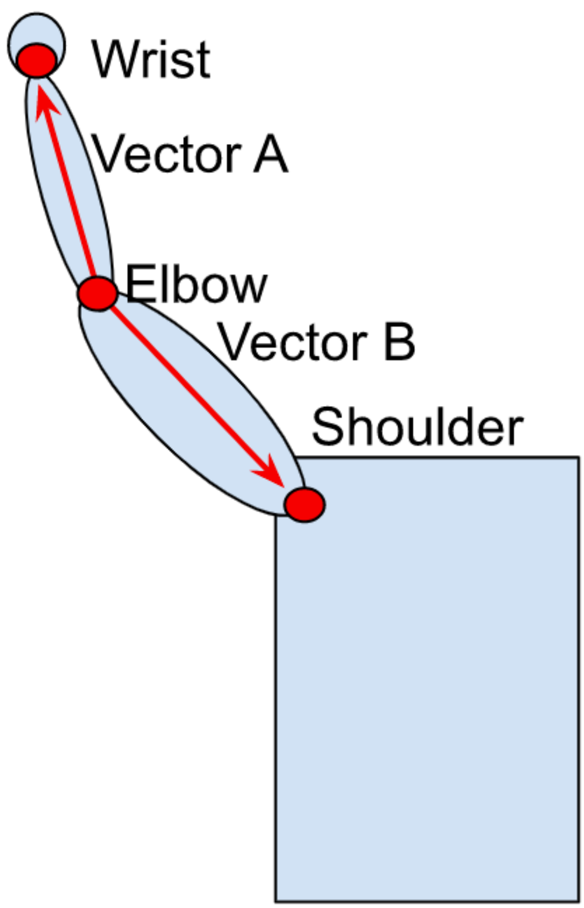

Figure 24: Joint range of motion vector calculation.

In terms of python coding, the dot product between the two vectors was calculated individually, then the magnitude of each vector, and then a final calculation was done to find the angle. The produced value needed to be adjusted to degrees from radians, but the final value was the angle produced by the three joint centers throughout the motion of the pitch. The code was verified by grabbing joint center coordinate values and calculating the angle by hand. Each check produced the same value that the python code calculated. Therefore, the code was successfully doing what it was supposed to do by finding the joint angle between the shoulder, elbow, and wrist of the pitcher's throwing arm. The following tables describe the results of these hand calculations. See Appendix D for the code.

Table 8: Table of data for joint angle verification.

Frame	Shoulder (ft)			Elbow (ft)			Wrist (ft)		
	X	Y	Z	X	Y	Z	X	Y	Z
1	-0.341	-3.084	3.218	0.031	-2.252	3.162	0.124	-2.471	3.840
2	-0.365	-3.136	3.220	-0.060	-2.273	3.179	0.101	-2.523	3.838

Table 9: Display of results for joint angle verification.

Calculation	Team's Calculations	Excel	Created Code
RArm Angle Frame 1 (degrees)	122.76	122.75	122.75
RArm Angle Frame 2 (degrees)	123.30	123.31	123.31
Note: The RArm angle is the angle created by the shoulder, elbow, and wrist			

Performance Metric - Concept 3

For the fatigue metric, the sole performance metric that the team received from the Pirates was pitch velocity. The units for pitch velocity were miles per hour and were captured by Statcast. The performance metric was verified by the Pirate's internal system and team. In addition, the Pirates verified that the average pitch velocities for all the pitches that this pitcher threw were in the range of data that was sent to the project team.

The team conducted a spot check as well on the data. The team went through the data to find specific pitch types like a 4-seam fastball, change-up, sliders, and curveball. The team found that pitch velocities made sense for that specific pitch as all the fastballs were thrown harder than the offspeed pitches, like change-up, curveballs, and sliders. The following table describes the average velocity for each of the pitcher's pitches. This table clearly displays that fastballs were thrown the hardest.

Table 10: Table of pitch velocity analysis.

Pitch Type	4-Seam fastball	Change Up	Slider	Curveball
Average Pitch Velocity (mph)	95.58	89.61	83.80	78.43
Standard Deviation of Pitch Velocity (mph)	1.17	1.20	1.67	1.38
Count	599	31	448	148

Kinetic Chain - Concept 4

The kinetic chain can be a very complex type of analysis. The team decided to simplify the process by simplifying the kinetic chain. The team determined the kinetic chain as the successful flow of energy from the shoulder to the wrist. The data provided by the Pirates limits the team's potential to dive deep into the pitcher's metrics. Because the Hawkeye data are just the estimated joint center and there are only a few useful markers, calculating the shoulder or hip rotation is nearly impossible and the analysis must be watered down. Therefore, the successful flow of energy was defined as the flow of maximum velocity in the shoulder, elbow, and wrist. Ideally, the pitcher's maximum velocity in the shoulder would be reached before the elbow and wrist and the maximum velocity in the elbow would occur before the wrist velocity. If this flow of maximum velocity occurred in sequential order, then that pitch would be considered a successful kinematic sequence.

In order to calculate this chain and analyze the results, the time value of each maximum velocity must be found in the data. The first thing the team did was calculate velocity from the estimated joint centers for the shoulder, elbow, and wrist of the pitcher's throwing arm. This was done by finding the difference between the row above the current row and dividing that by the frame rate, which is 1/300 seconds. This would give the project team the velocity for all of these joint centers. This was done through python. Figure 25 displays the velocity versus time graph for the throwing arm segments. In this case the shoulder reached maximum velocity at -0.05 seconds, elbow at -0.04 seconds, and wrist at -0.01 seconds.

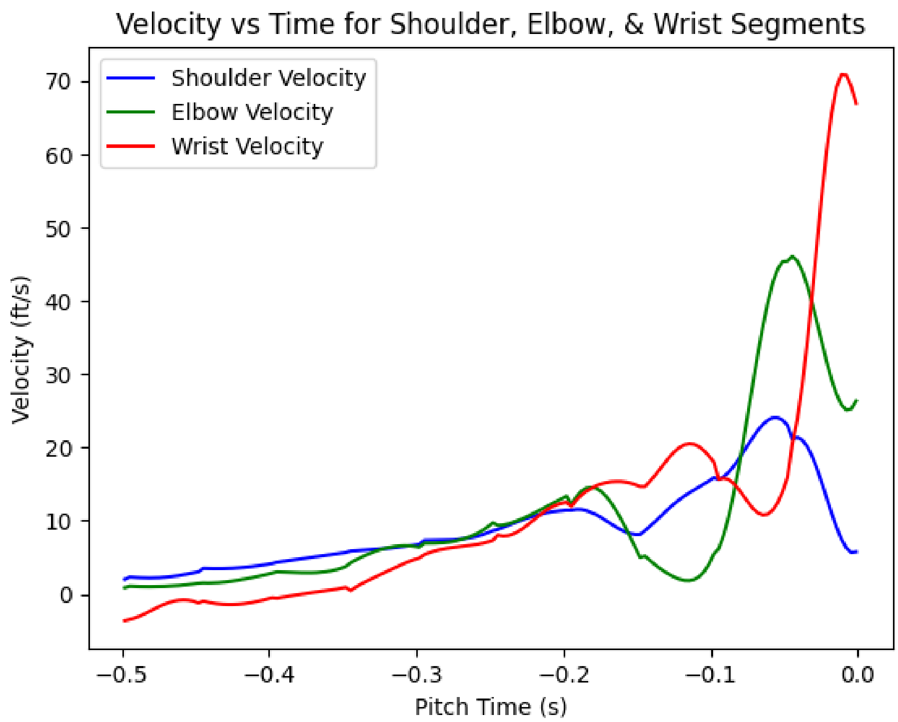

Figure 25: Display of velocity vs. time for the throwing arm of Pirates' pitcher.

Now that the velocities are calculated python can be used to analyze the data and create case scenarios. A series of for loops and if statements were used to break the data into sections and find if the pitch had the correct flow of kinetic energy. The for loop was used to loop through the index of all the pitches and determine when the maximum velocity and the maximum velocity of the shoulder, elbow, and wrist were for that pitch. Then the if statements were used as logical statements to see how exactly the flow of energy occurred and if the pitch was a success or a failure.

In addition, to the determination of the kinematic sequencing, the time at which the maximum velocity occurred and the value of the maximum velocity was for that joint center. Also, the differences in each time value for each joint center were calculated.

After writing the code to do this, the code was analyzed to see if it actually accomplished what the original definition of the kinetic chain was defined as. Based on the outputs of the code, the code does successfully find the velocities of the segments and has the correct logic statements to determine if the kinetic chain was done successfully. This was confirmed when the team did random spot checks throughout the data. All spot-checks came back as clean and all made sense. Therefore, the kinetic chain code was verified, and successfully does the calculations for the kinetic chain concept. The following table displays the process to find segment velocity.

Table 11: Table of segment velocity verification.

Frame	Shoulder X (ft)	Distance Differential (ft)	Team Segment Velocity (ft/s)	Code Segment Velocity (ft/s)
1	-0.341	—	—	—
2	-0.365	-0.024	-7.20	-7.19
3	-0.393	-0.028	-8.40	-8.40

The following table displays sample verification for two pitches thrown by the Pirates' pitcher to verify the code had the correct kinetic chain logic. After doing random spot checks, the code was confirmed to do everything that it was intended to do. See Appendix E for the code.

Table 12:Display of kinetic chain logic verification.

Pitch Number, Game Number	Max Shoulder Time (s)	Max Elbow Time (s)	Max Wrist Time (s)	Team Spot Kinetic Check	Code Kinetic Check
1, 1	-0.055	-0.046	-0.011	Success	Success
1, 13	-0.041	-0.048	-0.010	Fail	Fail
Note: when time is equal to 0, the pitcher releases the baseball					

Rate of Force Development on the Shoulder Joint Center - Concept 5

In order to find the force that the shoulder produces throughout the pitch, a few things need to be calculated beforehand. First, the velocity of the shoulder must be calculated. Next, the acceleration of the shoulder must be calculated from the velocity of the shoulder. Lastly, the force must be calculated from the acceleration data and the estimated mass of the joint segment. It is important to note that the marker data was converted from feet to meters to work better with the calculations. The equation that was used to calculate the force produced from the shoulder is:

$$Force = Mass * Acceleration$$

The velocity was found by finding the distance created from two separate locations for the shoulder joint center marker data and dividing that value by the time it took to cover the distance. The difference between sequential markers was used to determine the distance traveled by the shoulder in that specific plane. This value was then divided by the framerate that Hawkeye records at. The framerate is 300 frames per second, or a frame is recorded every 0.003 seconds. In order to verify the code, the first two rows of data were used to calculate the velocity that the shoulder has in the X direction. The calculations were done by multiple group members on paper and the code produced the correct velocity values.

Because linear acceleration is calculated in a very similar way to velocity, the code was modified to find the difference in velocity from sequential rows of data. Once again, the difference in velocity was divided by the framerate of the Hawkeye system. This calculated value was the acceleration of the segment during that specific change in frames. The acceleration data was verified in the same way as the velocity data. The results of the verification confirmed that the code produced the correct acceleration values. It is important to note that some accelerations were extremely high and unrealistic because the data were divided by 1/300 twice. This causes the error to explode exponentially at some points.

Table 13: Table of velocity verification.

Frame	Shoulder X (ft)	Distance Differential (ft)	Team Segment Velocity (ft/s)	Code Segment Velocity (ft/s)
1	-0.341	—	—	—
2	-0.365	-0.024	-7.20	-7.19
3	-0.393	-0.028	-8.40	-8.40
4	-0.422	-0.029	-8.70	-8.69

Table 14: Table of acceleration verification.

Frame	Shoulder X Velocity (ft/s)	Velocity Differential (ft/s)	Team Segment Acceleration (ft/s^2)	Code Segment Acceleration (ft/s^2)
1	—	—	—	—
2	-7.20	—	—	—
3	-8.40	-1.20	360.00	359.97
4	-8.70	-0.30	90.00	90.29

The last part of this metric is to calculate the force from the produced acceleration values. In order to do this the estimated mass of the shoulder must be found. The Pirates stated that this player weighed 203 pounds or 92.08 kg. Based on the anthropometric table, the estimated mass of the glenohumeral joint is 2.8% of the total body mass. The team defined the glenohumeral joint as the shoulder [87]. Therefore, the estimated mass of the shoulder is 2.58 kilograms. The estimated mass of the shoulder was then multiplied by the linear acceleration values produced earlier. The product of this multiplication produced the estimated force that the shoulder produced during the pitcher's motion. The data was then verified by the team by conducting calculations by hand to determine if the code produced the same results. Once again, the code produced the desired values and the procedure was completely verified. The following table describes projected force values for frames 3 and 4. See appendix F for the code.

Table 15: Display of force verification.

Frame	Team Segment Acceleration (ft/s^2)	Code Segment Acceleration (ft/s^2)	Team Force Value	Code Force Value
3	360.00	359.97	928.80	928.72
4	90.00	90.29	232.20	232.95

Rest Time Analysis

The team wanted to explore how the rest time between pitches and innings affected the pitcher's performance. In order to do this, the team asked the Pirates to supply the team with time stamps of each pitch. The Pirates supplied the project team with the time of the pitch in the format "Hours: Minutes: Seconds PM/AM". Therefore, in order to break this data into a usable number that is easy to manipulate in python, the team had to create a new column of data to break down the time code into total seconds, or a singular integer.

In order to do this, the team created code to find the first ":", second ":", and the third ":". Once this was done, the numbers before those values were converted into a variable. These variables were then multiplied by 3600 for the hours, 60 for the minutes, and kept the same for the seconds. These numbers were then added together to total seconds for that time frame. This value for total seconds was then run through a for loop to find the smallest number of seconds for the first pitch of the game and this value was used to subtract all of the additional time values. Therefore, the new time code for pitch 1 was "0 seconds" and pitch 2 was most likely in the range of 15 to 30 seconds.

In order to verify that the code subtracted all the values in a proper way, the data was exported to excel and analyzed. Random rows of data were selected and the team manually calculated the seconds values based on the given Pirates game time number. In all cases, the coded value always equaled the manually calculated value. Therefore, the code successfully created a linear display of time that is different from pitch count. The following table displays verification calculation for the team and the produced code. See appendix G for the code.

Table 16: Table of rest time verification.

Pitch Number	Pitch Time Code	Team Seconds (s)	Code Seconds (s)	Team Rest Time (s)	Code Rest Time (s)
1	6:37:33 PM	23853	23853	0	0
2	6:37:50 PM	23870	23870	17	17
3	6:38:34 PM	23914	23914	61	61
4	6:38:54 PM	23934	23934	81	81

5.2 WPI Motion Capture Verification

This section describes the marker motion capture verification methods used for the collegiate pitcher data portion of the project. The verification ensured that the equipment was working properly and tested prior to data collection. This allowed for a proper baseline to grasp and know that the data collected is accurate.

5.2.1 Marked Motion Capture Data

The team's marker motion capture setup was determined and tested prior to collecting participant data for this study. The team conducted a series of training sessions with the WPI PracticePoint (WPI's research and development testing facility, including the motion capture lab) staff. This staff allowed the team to understand the verification that needed to be done prior to running the system to record a pitch. The calibration wand was used for the cameras and to orient the system to where the origin is. The calibration step allowed for the team to see which cameras were off and not properly working prior to data collection. Before testing began, the origin was verified by placing the wand at the center of the force plates and the team was able to see the location of the coordinates on the Vicon programming system. This verified that the global coordinate system is correct and that the Vicon system is reading the coordinates properly. The team could verify that setting the origin and calibrating the cameras was accurate by referencing the set up view on the Vicon software. If the force plates or cameras are not in the same orientation as they are in the laboratory, the system was not calibrated properly. Figure 26 shows the Vicon software with some of the camera orientations (shown by the boxed numbers in the background) that can be compared to the actual motion capture lab.

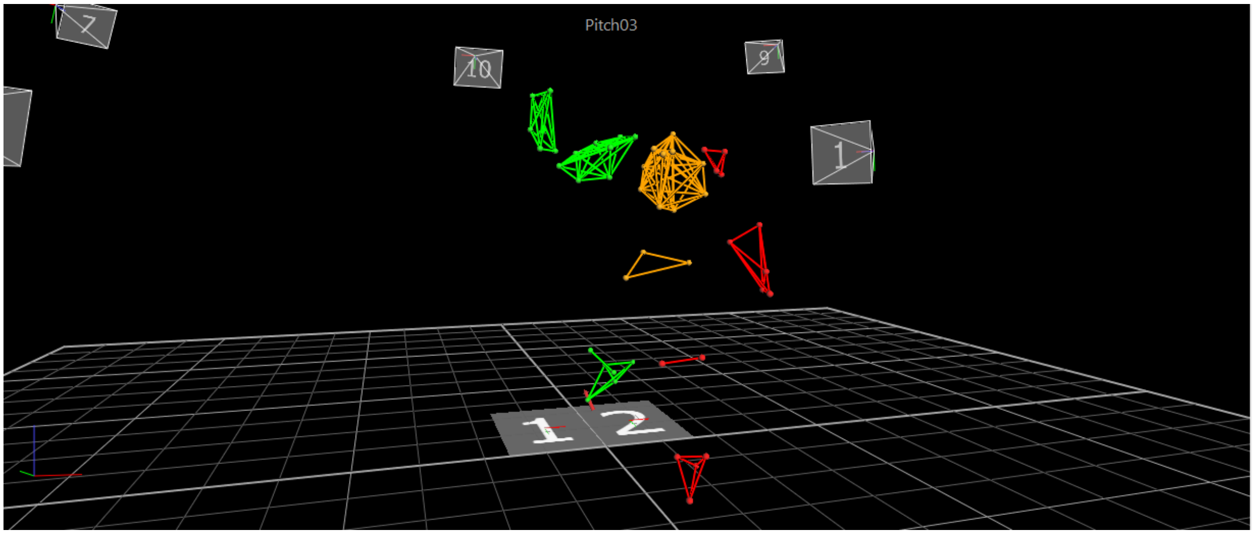

Figure 26: Image of Vicon interface representing camera setup within the software.

Since the data collected at WPI's on-campus facility resulted in raw coordinate files of the markers, post-processing was needed prior to using another software for investigating biomechanics. The team used the Vicon software to process the data, which included labeling markers, fixing missed markers by going through frame by frame to ensure the markers shown were always labeled, gap filling to provide a clean trajectory for the missing markers to follow, and filtering. Once these steps were completed, the team used Visual3D to establish the orientation of the segments, label each coordinate and pull out the joint centers, as well as extract the external maximum rotation angles.

In addition, the frequency of the cameras in the motion capture lab, which was 300 hertz, was verified when the data was analyzed. The team ensured that the cameras were in fact collecting the data at 300 hertz. During the data collection phase, the team monitored the Vicon system to ensure that all cameras were working properly and were calibrated correctly. The system warns users as soon as a camera is moved or a camera is off. When the camera was bumped, nothing would be done as data was still being collected. However, when the camera shuts off entirely, the team would reboot the camera. If the camera was still not functioning after this, the team would take about five minutes to recalibrate the cameras. This was key information the team marked down throughout data collection, including when and which cameras turned off. If the cameras continued to shut down and not function properly, the team would rearrange some of the cameras to maximize the capture of the pitcher. Then the recalibration process was repeated. This helped ensure that the coordinate system was properly working and at the minimum, the crucial cameras, which were the ones directly facing the pitcher's throwing arm, were capturing data.

5.2.2 Markerless Motion Capture Data (MLB provided)

The team developed a connection and sponsorship with the Pittsburgh Pirates Major League Baseball team, which has access to Hawk-eye markerless motion capture data collected on the pitchers during MLB games. The Hawk-eye data that was sent to the MLB team was previously verified by the Hawk-eye's internal system. The Pirates did not receive any data if the system was corrupted and did not collect the data correctly. However, the team is working on a way to additionally verify that the data to ensure it can be used for analysis. The team verified that the data are collected at the expected frequency of 300 hertz. They verified this by looking at the data and ensuring that the sample rate matches a frequency of 300 hertz. Additionally, the team ensured that there were no gaps or missing data points, as this would cause a disruption in the analysis. Any biomechanical data that was shown as null or was not there in the data entries within a pitch was not analyzed; however, the team acknowledged that there was some sort of issue. This would be noted and was used as a future recommendation to fix and to catch in order to work towards this from happening again. Aside from these verification methods, this data was verified from the internal Hawk-eye system.

5.2.3 Accelerometer Sensor

The team also tested the accelerometer on the EMG to ensure that it was working properly. The sensor must be able to record linear and angular accelerations. In order to properly collect this data on the upper body, the accelerometers had designated locations on each participant's arm. There were two accelerometers, one placed on the upper and lower parts of the throwing arm. This verification was done through the EMG works analysis software. A test trial was performed by beginning a trial in EMG works and the accelerometers were each moved individually to ensure they were both collecting acceleration data, and corresponding to the correct part of the arm. This also verified that the software was properly displaying data the accelerometer data collection by showing the corresponding data as it was coming in. The team made sure that the accelerometer displayed the linear and angular acceleration of the arm in the x, y, and z plane on the results file. These testing methods ensured that the sensor was working properly and could be used during the analysis.

5.2.4 Force Plate Data Collection Verification

During the data collection process, the team utilized the force plates by having the pitcher begin each pitch standing on them. It was necessary that the functionality of the force plates was verified prior to data collection. The force plate was never physically moved, however, it needed to be oriented correctly on the Vicon software using the correct orientation coordinates. The motion capture standard operating procedure (SOP) in Appendix J discusses how the force plates were properly setup prior to data collection, including the orientation coordinates used. The participant stood on the force plates and the Vicon software would output a line showing the upward force equivalent to their weight, similar to a force vector. On the software, there would be a red line, indicating the force on the plate. Then the player could walk around and the orientation of the force plate was verified. The line should be pointed vertically at the location it is at, whether it was in the corner, center, or one or both of the force plates. If the Vicon system correctly displayed the proper force plate with the corresponding foot, the team concluded that the force plates were orientated properly, and therefore verified. Figure 27 shows an image of the two force vectors, one on each force plate, generated by the Vicon software upon force placement on the plates.

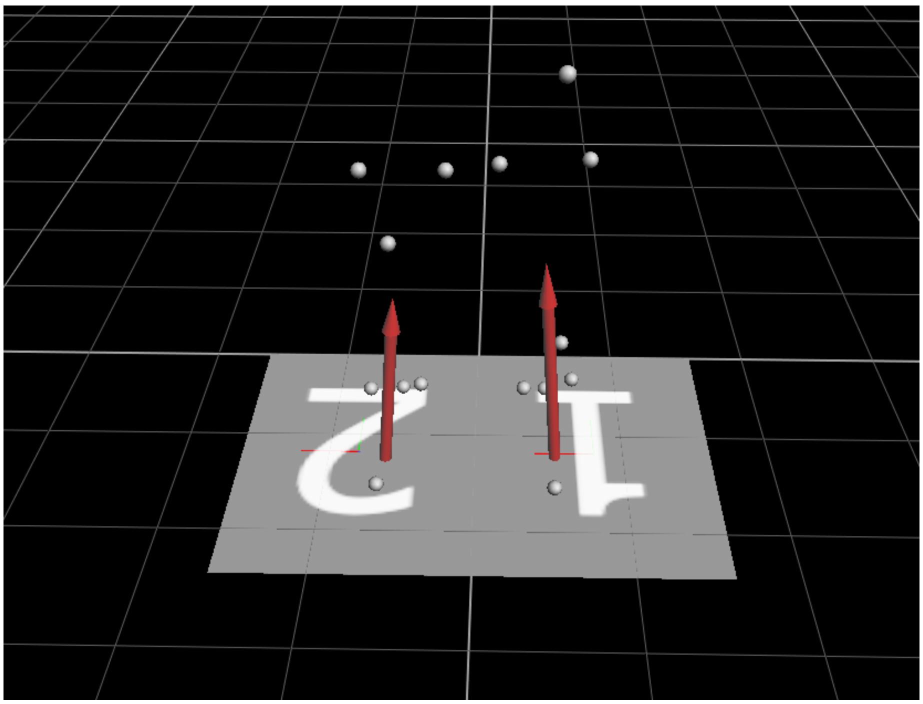

Figure 27: Image of the Vicon force vectors when a participant stands on both force plates.

5.2.5 Force Plate Data Verification

After data collection, the team verified the force plate data by ensuring they were reasonable values for ground forces. The team was able to look at the force plate data in the x, y, and z directions within Vicon. Since the z-axis is the downward direction in Vicon, the team looked at the values it was outputting to ensure it showed reasonable force values for a human. Similarly for determining the weight of the subject for the Visual 3D skeletal model, the team converted the z-direction force in Newtons into kilograms as a verification test. As previously stated in Chapter 4, one participant had a 764 Newton force in the z-direction, which converts to 77.88 kilograms. Converting that number further to the imperial system, that value represents a mass of 171.7 pounds, which appears to be a reasonable value. Although this was the process the team used, it may have been better to put a weight on the force plate so a more accurate data collection could have been used.

This is a simple verification method that ensures the data are a reasonable value. Verifying that the ground force was sitting in an acceptable range was crucial before using that data for any further analysis.

5.2.6 Frame Rate Verification

The team collected motion capture data at 300 Hz. In order to ensure the Vicon software accurately collected the data, the team verified that the final output of data in Visual 3D reflected the proper frequency rate. To verify the frame rate, the team looked at a pitch in Visual 3D, where it showed the total frames and total time in seconds for a given pitch. Using the frequency formula of frames per second the team was able to verify that the data was reflecting the proper frame rate. An example of this verification is shown below.

$$Frame\ rate = \frac{958\ frames}{3.19\ seconds} = 300.3\ Hz$$

5.2.7 Maximum External Rotation Verification

The team performed a verification test on the maximum external rotation data which was obtained from the Visual3D software. The software outputs a data sheet which includes the frame number, and x, y and z coordinate values which correspond to flexion and extension, abduction and adduction, and axial rotation respectively. The maximum external rotation value was obtained by determining the lowest number from the abduction and adduction column. Once this value was obtained, it was subtracted from 180 degrees to get the maximum angle. The team verified this value by determining which frame this maximum value occurred at, and going to the same frame on the Visual3D pitch simulation with the skeleton model. If the model appeared to be oriented in what appears to be the maximum angle throughout the pitch, the data was properly calculated and therefore verified. For example, in one of the pitches, the abduction and adduction number was 28.557 at frame 581. As a result, this makes the maximum external rotation value 151.443 degrees. The team verified this was correct by going onto the Visual3D model with the same pitch, finding frame 581 of the pitch and ensuring the model appeared to be at its maximum external rotation of the pitch. Figure 28 shows the image of the verified pitch, previously described, at its maximum external rotation in correspondence with the frame number.

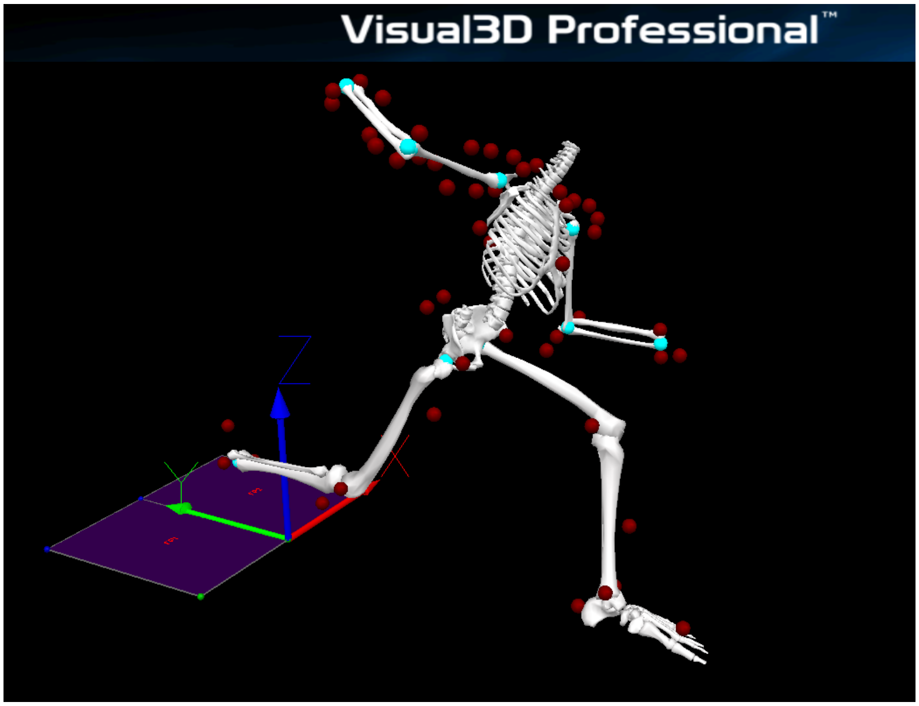

Figure 28: Maximum external rotation angle in Visual 3D.

5.2.8 Fatigue Exercise Cycle Verification

Throughout the duration of the motion capture data collection, the participants were asked to rate their level of perceived exertion based on a modified Borg scale (scores ranging from 1-10), and their heart rate was collected, prior to and immediately following each pitching session. Figures 29 and 30 summarize the results from these assessments for all participants. The change in both the levels of perceived exertion and heart rate were statistically significant (visualized by the error bars on the figures).

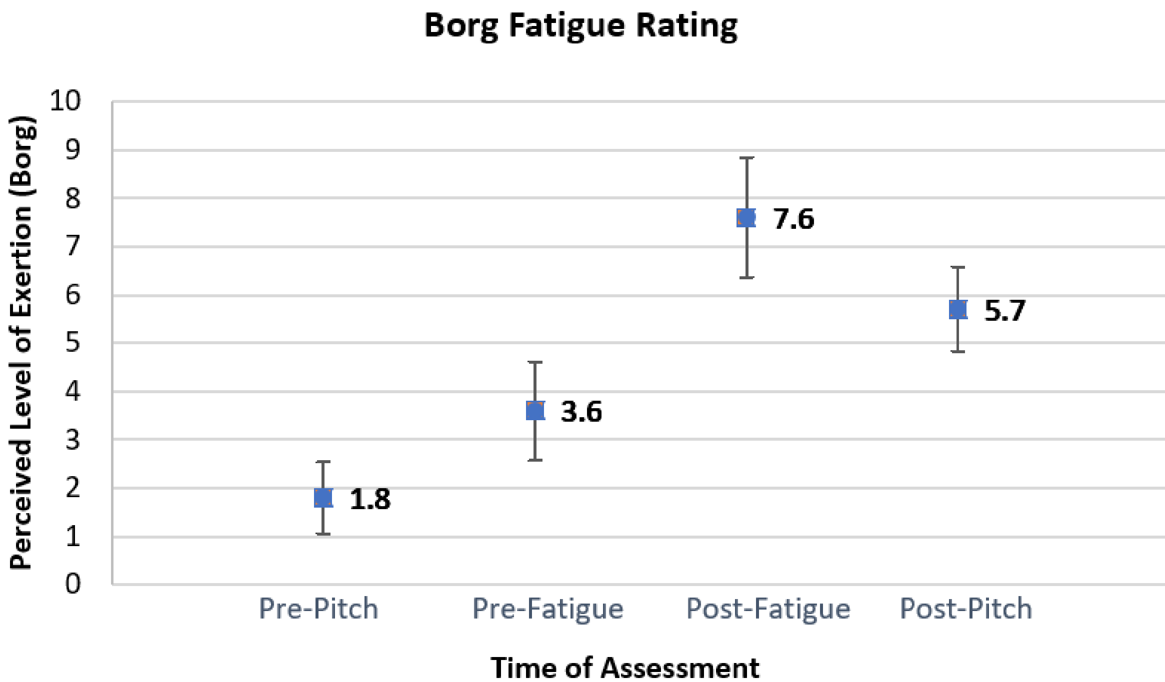

Figure 29: Borg scale for rating a person's perceived exertion level (1-10), prior to and immediately following the two pitching sessions for all pitchers that participated in the team's motion capture data collection.

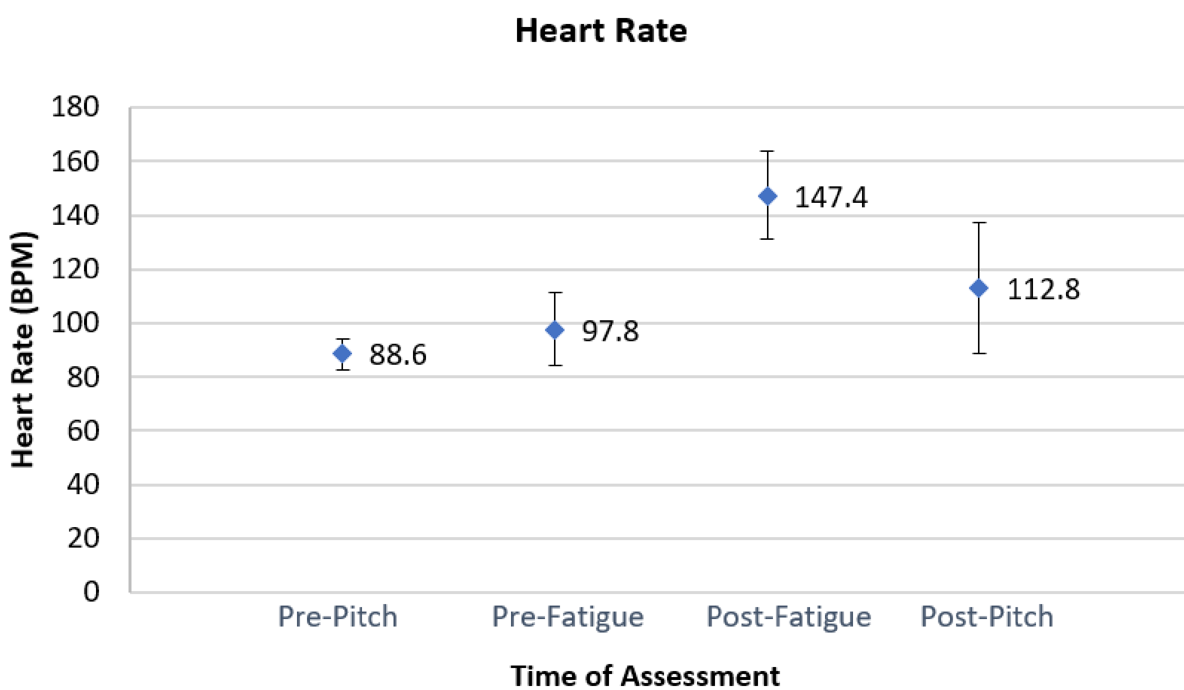

Figure 30: Heart rate in beats per minute, prior to and immediately following the two pitching sessions for all pitchers that participated in the team's motion capture data collection.

6.0 Final Design & Validation

6.1 Fatigue Metric

In order to validate the following potential metrics, the team analyzed the data in two ways. The first way revolves around the assumption that as the game goes on, the pitcher becomes more fatigued. Therefore, pitches late in the game are considered “fatigued.” The second method is backed by categorical data from the WPI pitchers since the Pirates did not have any categorical data on their pitcher’s pitches. The “post-fatigued” portion of data collection was used to validate and back the metrics.

6.1.1 Mechanical Positional Changes

In order to validate that mechanical positional changes was a strong potential metric for fatigue, the team used the Pittsburgh Pirates data to find the correlation between the verified calculated values and the pitch number. The team is assuming that pitches thrown later in the game are considered to be fatiguing because the pitcher is working hard throughout the game to perform well for his team. From this analysis, the team determined that the X plane, which is the plane that is from the dugout to dugout or the horizontal plane, segments have a very high correlation with pitch count. Table 17 describes these results.

Table 17: Correlation values for mechanical positional changes & pitch number.

Metric	Correlation Value with Pitch Number (-1 to 1)
RShoulder X Avg Location	0.307
RElbowX Avg Location	0.277
RWrist X Avg Location	0.292

Based on this table, it is clear that as the game goes on the pitcher’s X coordinate location is changing. Specifically, the pitcher is moving their arm closer to their center of mass. Based on this, it is safe to assume that the pitcher’s arm is not extending out as far toward the away dugout as he usually does as the game goes on. Thus, the pitcher is “flying open”. This term is utilized by pitching coaches to describe the action which occurs when the throwing arm opens with the stride leg and front hip. Usually, pitcher’s want to stay closed and the throwing arm should open later in the pitcher’s motion. This relationship is displayed in Figures 31, 32 and 33. It is important to note that game one, most likely occurred toward the very beginning of the season. Therefore, this may explain why some pitches seem to be jumping around and producing odd results compared to other games because the pitcher is still ramping up to midseason form.

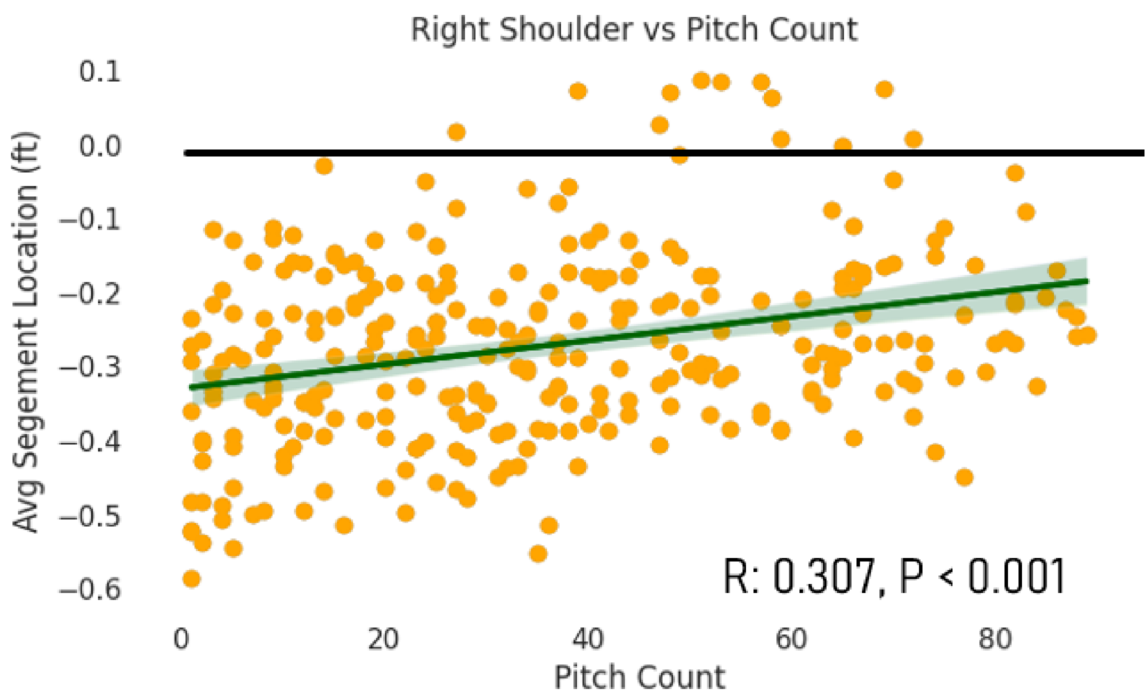

Figure 31: Display of relationship between average arm segment location (ft) of the right throwing arm shoulder and pitch count.

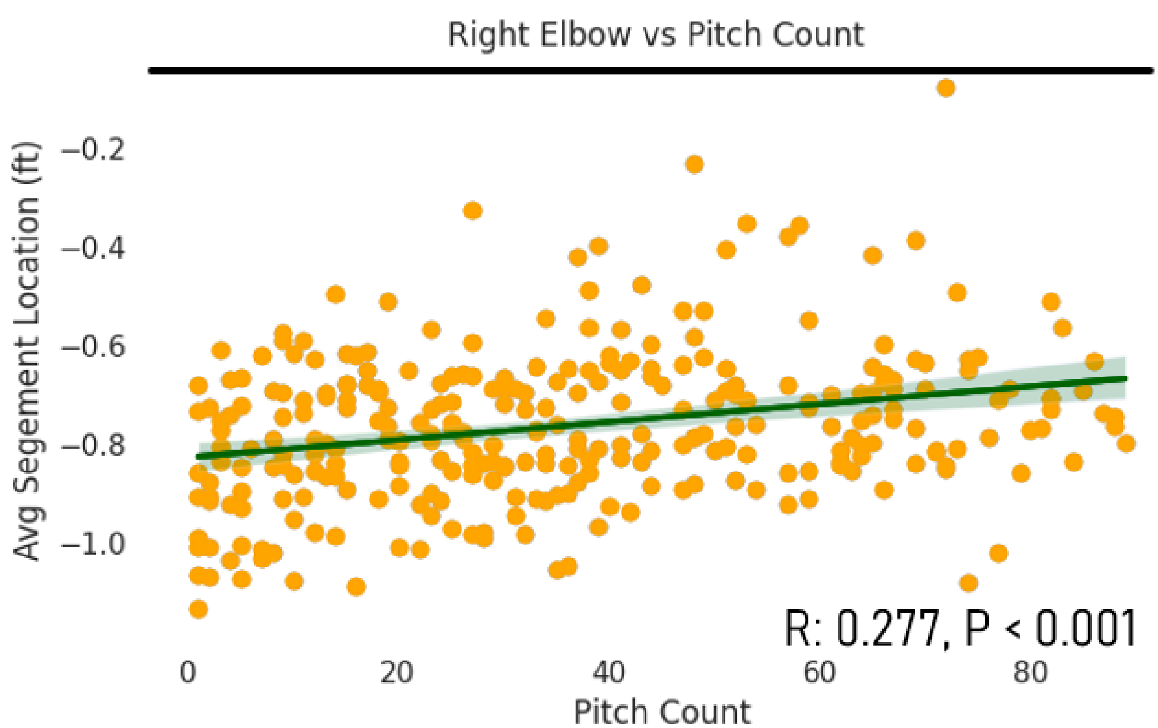

Figure 32: Display of relationship between average arm segment location (ft) of the right throwing arm elbow and pitch count.

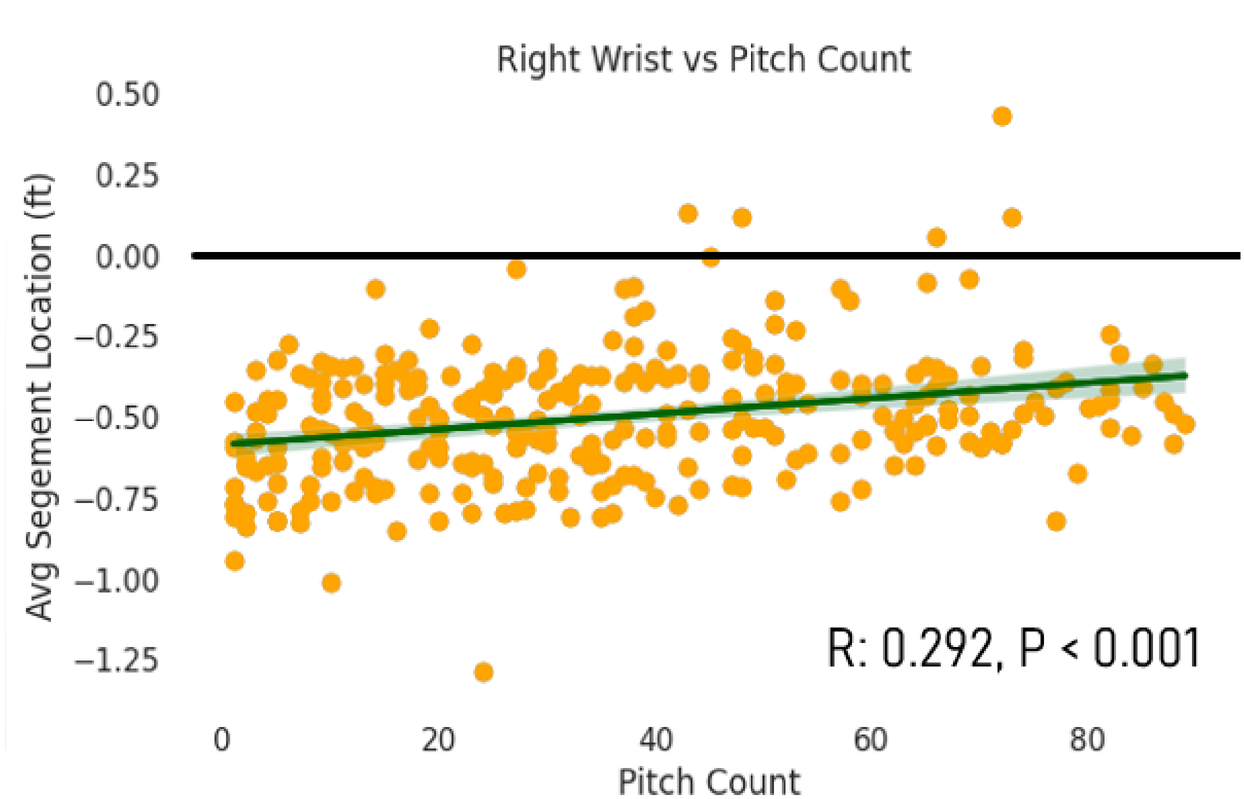

Figure 33: Display of relationships between average arm segment location (ft) of the right throwing arm wrist and pitch count.

In addition to just simply correlation, the team also broke down the data into specific pitch buckets. The pitch buckets were defined as 0-20, 20-40, 40-60, 60-80, and 80+.

Table 18: Correlation values for mechanical positional change values and pitch number based on pitch bucket.

Pitch Bucket	ShoulderX & Pitch Count Correl	ElbowX & Pitch Count Correl	WristX & Pitch Count Correl
0-20	0.392	0.380	0.362
20-40	0.057	0.113	0.185
40-60	0.075	0.034	-0.038
60-80	-0.094	-0.158	-0.085
80+	-0.249	-0.347	-0.376
Total	*0.307*	*0.277*	*0.292*

From the above table, there is a clear plateau effect in the data. Basically, as the pitcher begins the game, pitches 0-20, his throwing arm is generally moving closer to his center of mass and where his arm originally started in the set position. This is the beginning of the plateau as it increases. Then between pitches 20-60 the pitcher's correlation is consistent. This means that his arm is generally on the same plane throughout all the pitches. This is the flat part of the plateau. Next, between pitches 60-80, the pitcher is beginning to move his throwing arm further from his center of mass and his original starting position. However, this is very slow, but there is a slight correlation in the negative direction. Lastly, of the pitches that are 80+, there is a drastic change in the correlation. In this area, the pitcher's throwing arm is much further from his body as he throws. This is the decline of the plateau.

In addition to analyzing the correlation of the data with fatigue, the physical coordinate data were analyzed. The analysis revolves around the average coordinate location of the joint centers during a specific time frame discussed in the verification section. In this data the average of all the points taken and that value plus one standard deviation of data was taken. This created a range that included around 68.2% of the data. Simply, code was run that found if the average segment location for that specific pitch fell within the range of the average +/- one standard deviation. If the pitch fell within the boundaries then it was considered a successful pitch. The following table summarizes these results.

Table 19: Breakdown of pitch buckets and segment movement success rate.

Pitch Bucket	ShoulderX % Inside Range	ElbowX % Inside Range	WristX % Inside Range
0-20 (86)	53.5%	57.0%	64.0%
20-40 (80)	58.8%	66.3%	63.8%
40-60 (54)	66.7%	72.2%	62.7%
60-80 (47)	66.0%	83%	78.7%
80+ (13)	84.6%	84.6%	84.6%
Total (290)	61.0%	68.6%	67.6%

The above table produces surprising results. Initially, the team hypothesized that the pitches in the 60+ range would be a lower percentage and fall into the range less. However, most of these pitches did in fact fall in the range. This informs the team that the physical marker location should not be used in mechanical variation, but the correlation should be used. In addition, the table suggests that the pitcher is in the correct range of data consistently when he is throwing toward the end of the game.

The WPI pitcher’s were able to back up these results. The team found that both pitcher’s shoulders produced strong correlations and parallels with the Pirates pitcher’s shoulder. Similarly, these pitcher’s were “flying open” throughout their session. The average segment location was correlated with pitch count as well. It is important to note that the pitches thrown later in the game are considered more fatigued because this is post fatigue cycle. The following table displays the results.

Table 20: Breakdown of WPI pitcher’s segment correlation relationships.

WPI Pitcher ID	RShoulderX Correlation	RElbowX Correlation	RWristX Correlation
A	0.265	-0.049	-0.126
B	0.404	0.349	0.087

6.1.2 Joint Range of Motion (JROM)

The team initially hypothesized that the pitcher’s flexibility or joint range of motion would change throughout the game and specifically when they are fatigued. This is the angle at the elbow created by the vectors of the forearm and upper arm segments as shown in Figure 24. However, as the team analyzed the data they quickly realized that there was little to no correlation. Generally, this makes sense as the mechanical variation only changes slightly in specific planes, which would only slightly affect the angle created by the arm.

In order to validate this metric, the team looked into the arm angle during specific phases of the pitcher’s motion. The phases that were analyzed were early cocking, late cocking, and arm deceleration. The following graphs display the relationship of joint range of motion during the specific phases of game 6. All games were used to validate this metric, but, for the case of simplification, the following graphs just show game 6.

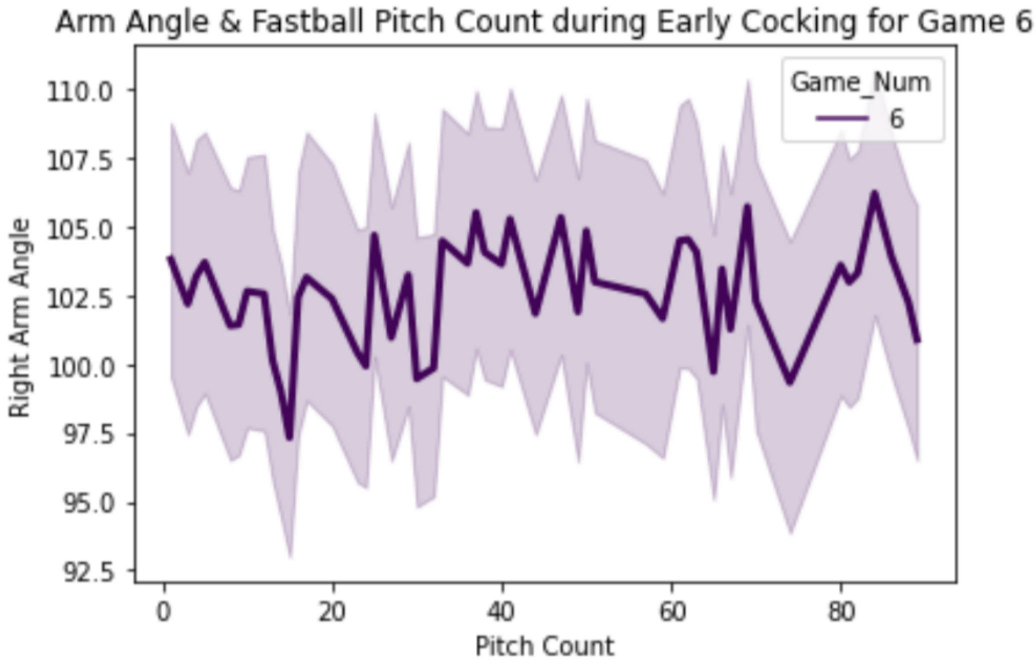

Figure 34: Throwing Arm elbow angle during early cocking versus pitch count of Pirates' pitcher in one game (Dark line is the average arm angle, shaded region is 1 standard deviation from the average).

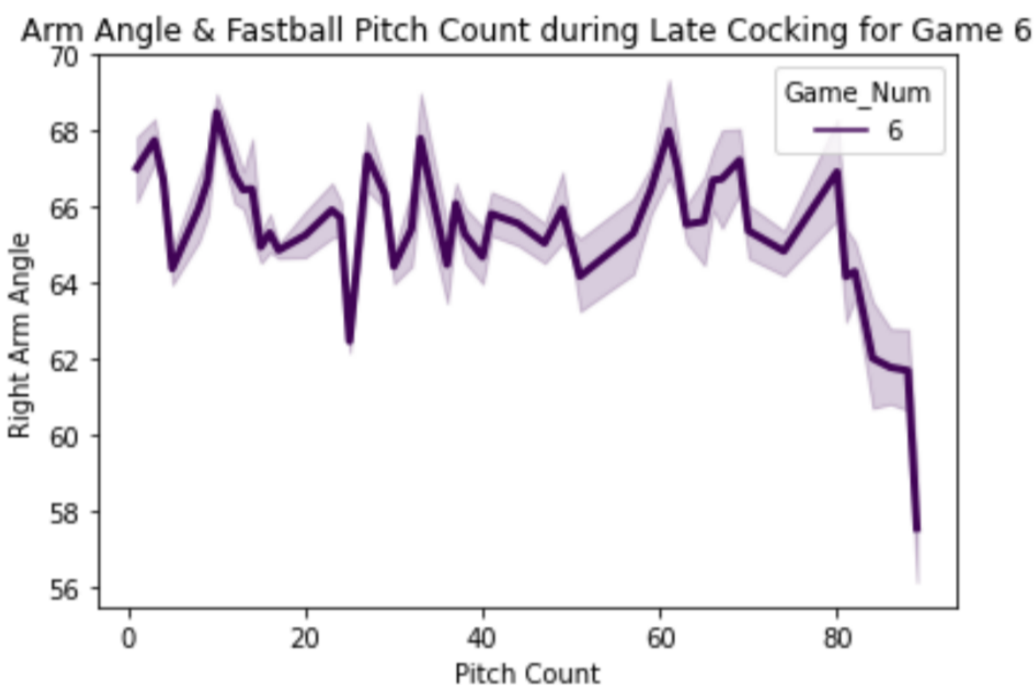

Figure 35: Throwing Arm elbow angle during late cocking versus pitch count of Pirates' pitcher in one game (Dark line is the average arm angle, shaded region is 1 standard deviation from the average).

In general, there are no clear trends in the data. This was also consistent when all the games were analyzed in a larger analysis. The team found that the majority of the correlation hung right around 0. This means that there is no correlation between the angle of the right arm and the pitch count of the pitcher. The data did produce some peaks and dips in games, but there is no clear pattern, and seems to be almost random. These random dips and peaks could be a product of Hawkeye's data messing up or missing frames.

However, when the team attempted to validate the metric, the team discovered no clear consistency or pattern. Therefore, the team shifted gears from arm angle and focused on other potential metrics.

6.1.3 Performance Metric

During initial talks with the Pirates, the team found that they measure the fatigue level of a pitcher by their drop in velocity throughout the game. In order to validate this the team found the correlation of pitches in specific buckets. From this, the team created graphs and tables to validate the metric. The following table breaks down the findings from this analysis.

Table 21: Breakdown of pitch buckets and pitch velocity.

Pitch Bucket	Correlation of Pitch Velocity to Pitch Number
0-20	0.122
20-40	-0.031
40-60	-0.091
60-80	-0.203
80+	0.114
All	-0.316

In the above table, there are some findings that can be noticed in this data. Like mechanical positional changes, the data shows a similar plateau effect. In the beginning, the pitcher is gaining velocity and then, as he settles in from pitch 20 to 40, he remains at a constant velocity. However, on pitches 60-80 there is a steep drop-off in velocity with a correlation value of -0.203. This shows that there is a strong correlation between pitch count and decreasing pitch velocity. Interestingly, for fastballs that are thrown in the 80+ range, the pitcher actually gains velocity. This may be the case on paper, but only 13 fastballs were used for the 80+ range. In addition to the small sample size, the pitcher is most likely operating at a very high level with adrenaline running through the body which may cause an increase in velocity. Also, the pitcher is most likely going to get pulled from the game because of the number of pitches he threw, so he is exerting all of his energy to throw the hardest fastball he can. Figure 36 displays this relationship.

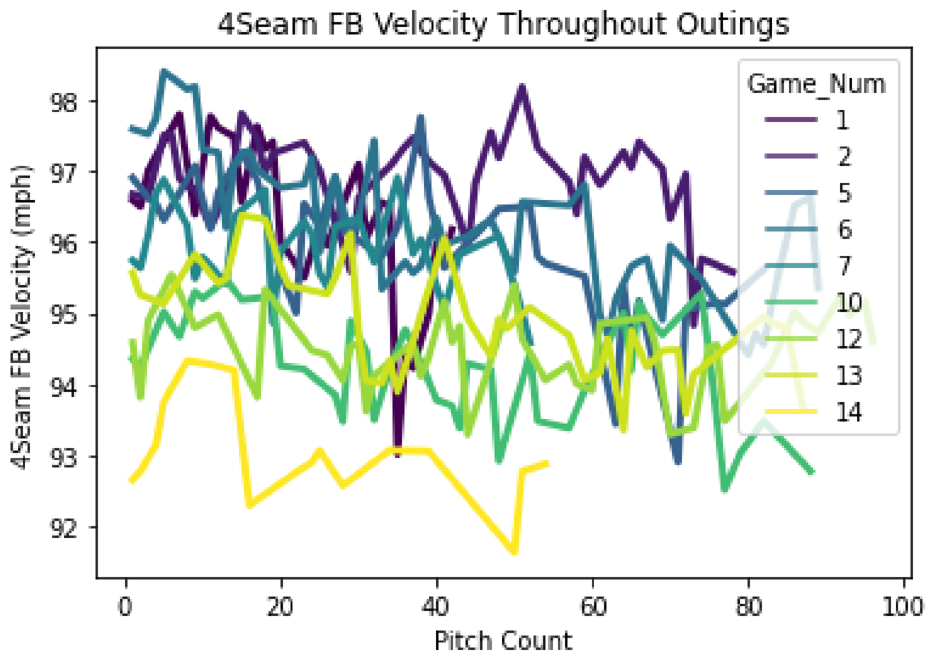

Figure 36: Relationship of fastball velocity and pitch count.

Based on the graph and table above, there is clearly a relationship that correlates fatigue and pitch velocity. The pitcher's fastball velocity is generally decreasing as the game goes on because the correlation value for all pitches, -0.316, is relatively high with a negative relationship. All in all, the performance metric that revolves around velocity is validated and can be used to analyze fatigue.

6.1.4 Kinetic Chain

The kinetic chain was defined as a successful flow of energy from the shoulder, then elbow, and then finally the wrist. The flow of energy was defined as the point where the maximum velocity occurred in the pitcher's motion. In order to validate this metric, the team took a similar approach to the analysis by breaking down the pitches into specific buckets. The results mirror the results of mechanical variation and the performance metric. Figure 37 summarizes the results of the kinetic chain analysis for fastballs thrown by the Pirates pitcher.

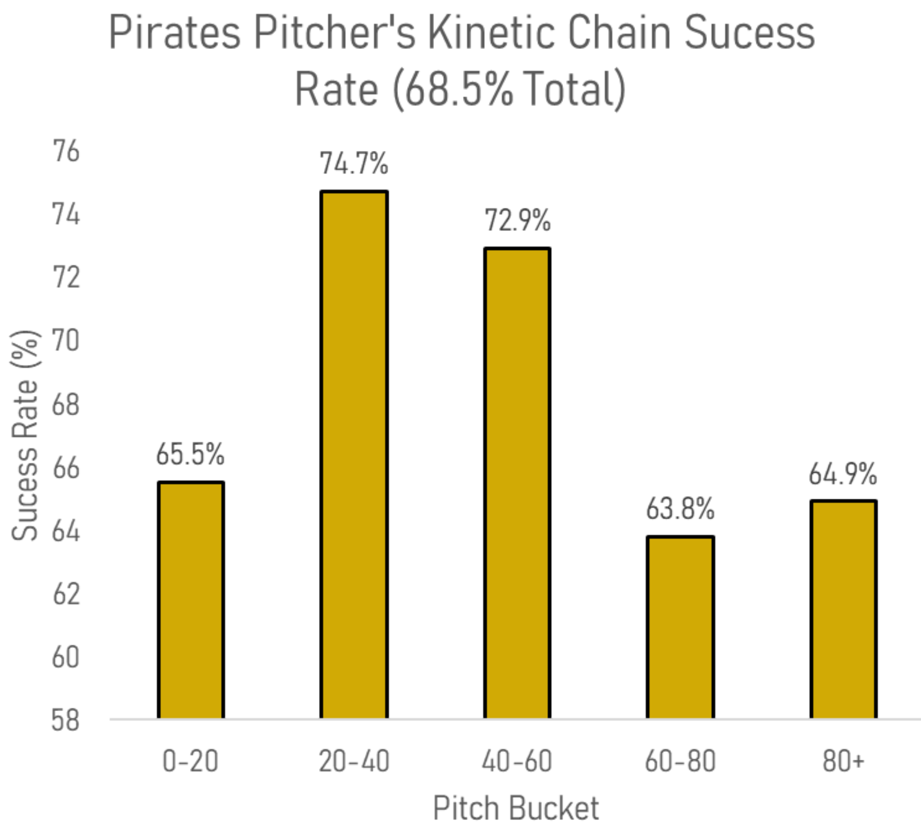

Figure 37:Breakdown of pitch buckets and kinetic chain success rate.

The above table displays a similar flow of data as the performance and mechanical variation metric. The data suggests that the player is warming up when he is under 20 pitches before he reaches his plateau. The flat part of his plateau occurs from pitches 20-60. In this range, the pitcher is consistently having a strong kinetic chain flow, with a success rate above 70%. After 60 pitches, the pitcher returns to a low sixties success rate. All in all, the success rate of the pitcher's kinetic chain shows that there is a clear flow of fatigue throughout his outings. Thus, the kinetic chain is a successful metric that can be used to validate fatigue.

In terms of validating this metric in the WPI pitchers, the team found the pitchers didn't complete the kinetic chain correctly, but they were affected by fatigue in another way. Of the 33 pitches, only two pitches resulted in the correct kinematic sequencing of max shoulder velocity followed by max elbow velocity and then max wrist velocity. This is most likely due to the fact that these are amateur pitchers throwing and the players were in an abnormal lab setting.

However, the two pitchers did experience fatigue. Both pitchers had an increased average time between their elbow and shoulder reaching maximum velocity. Figures 38 and 39 display this relationship. The black dots are pitches prior to the fatiguing exercises and the red dots are pitches after the fatiguing exercises.

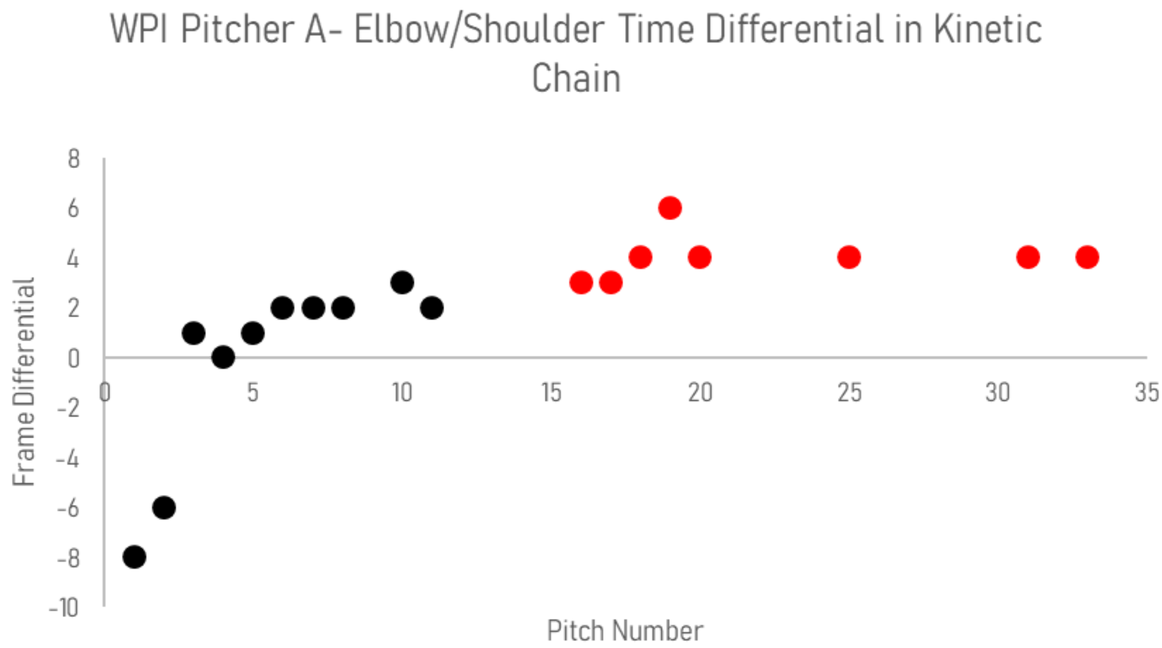

Figure 38: Display of differences in the elbow and shoulder from pre and post fatigue cycle for WPI Pitcher A.

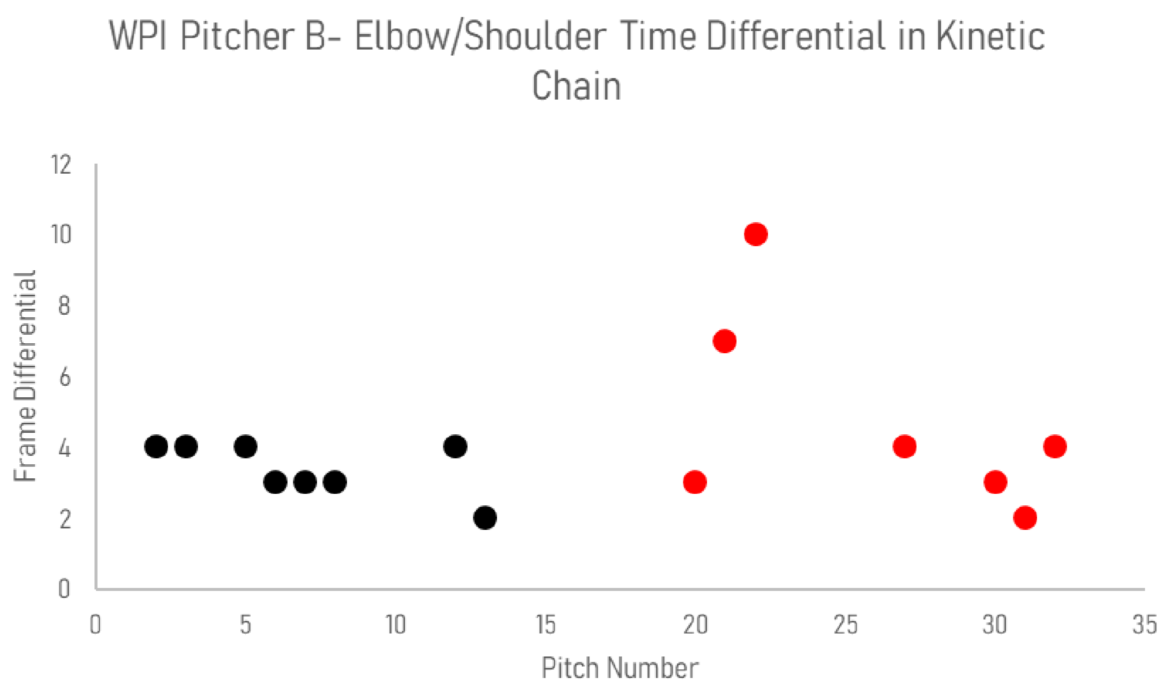

Figure 39: Display of differences in the elbow and shoulder from pre and post fatigue cycle for WPI Pitcher B.

Pitcher A's relationship was statistically significant with a p value of 0.006. However, Pitcher B's relationship was not statistically significant (p value of 0.3115), but the time difference was 1.2 frames/0.004 seconds higher on average from pre and post. Therefore, the WPI pitchers, mainly pitcher A, shoulders were lagging behind their elbows when they became more fatigued.

Based on the analysis conducted on the Pirates and WPI pitchers, it is clear that the kinematic sequencing of a pitcher changes when they become fatigued. For the Pirates' pitcher, he failed the kinematic sequencing at a higher rate towards the later part of the games while the WPI pitcher's shoulders lagged behind their elbows. Therefore, kinematic sequencing may be a valid way to analyze and pick up on fatigue.

6.1.5 Rate of Force Development on the Shoulder Joint Center

The team hypothesized that there would be a change of force, specifically a decrease in the force, produced by the shoulder as the game goes on. However, when analyzing the data, the team determined that there is no correlation between shoulder force development and fatigue. This is mainly caused because the data are too noisy and Hawkeye's data may be incorrect. This could have been potentially fixed if the data was filtered, but the Pirates stated that the data are already filtered by the Hawkeye system. The Pirates did not disclose how Hawkeye exactly filters the data, which prevented the chances of our team from effectively filtering the data. The team is assuming that the filter is still able to capture key events at 300 hertz. The following table breaks down the shoulder force development throughout the game.

Table 22: Breakdown of pitch buckets and shoulder force development.

Pitch Bucket Category	Avg Value (N)	Median (N)	Standard Deviation	Correlation of Force vs Pitch Number
0-20	148.6	143.8	23.31	-0.14
20-40	152.3	147.8	23.00	0.06
40-60	148.8	141.0	24.7	0.02
60-80	153.8	144.3	28.6	-0.08
80+	150.5	145.5	19.3	-0.21
ALL	150.4	145.0	24.0	0.04

Based on the above table, there is no clear correlation or pattern with the data. In addition, the fact that the average is much higher than the median shows that the skewed to the right with outliers. In addition, all of the correlations hovered very close to 0, which means that there is no relationship between the force values and the pitch buckets. In addition, the data was very noisy. This can be seen by the high standard deviation. This is also supported by Figure 40.

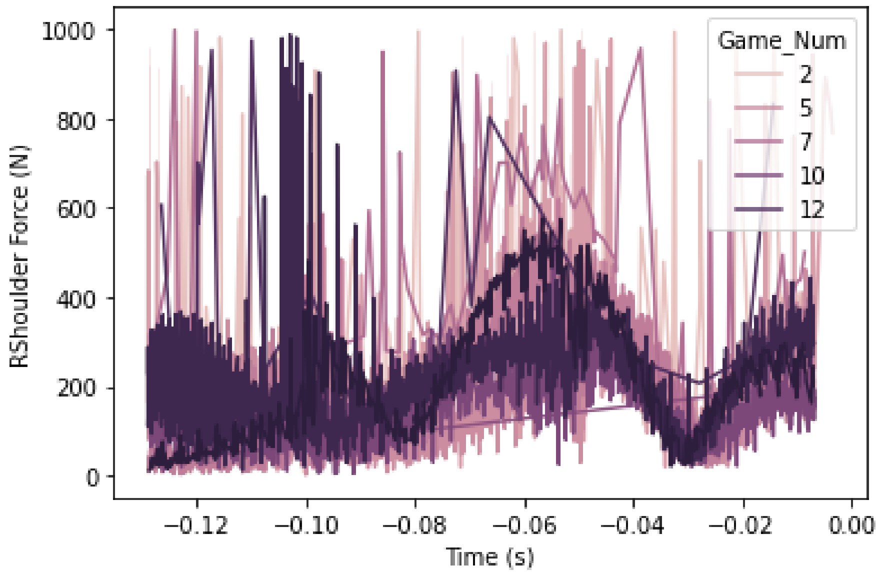

Figure 40: Shoulder force vs time throughout late cocking to release phase.

All in all, the validation of the shoulder force development proved that there was no clear correlation between force development and pitch number. This is mainly caused by the error that needs to occur in order to calculate the metric. If the Pirates disclosed how Hawkeye filters their data, the team could have explored this metric more by filtering the data and making the movement smoother. However, filtering something that is already filtered will cause problems that the team was not equipped to solve because the original filtering methods are unknown.

6.1.6 Joint Angles/Forces/Moments at Late Cocking

The joint angle at the end of late cocking, defined as the maximum external rotation angle of the throwing shoulder, was accessed for each pitcher. Out of the two WPI pitchers evaluated (pitcher A), one showed a statistically significant decrease in maximum external rotational angle ($p < 0.001$). The Pittsburgh Pirates pitcher did not seem to exhibit this shift in maximum external angle. The maximum external rotations of the WPI pitchers A and B are shown in Figures 41 and 42 respectively.

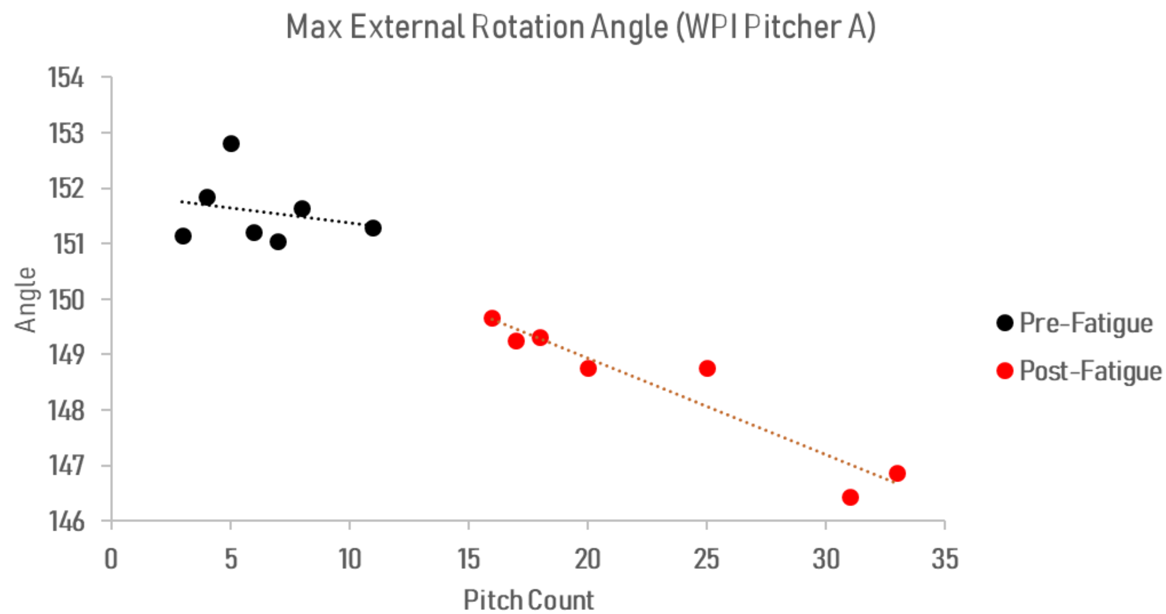

Figure 41: Maximum external rotation angle (degrees) vs pitch count for WPI pitcher A analyzed pre and post-fatigue cycle.

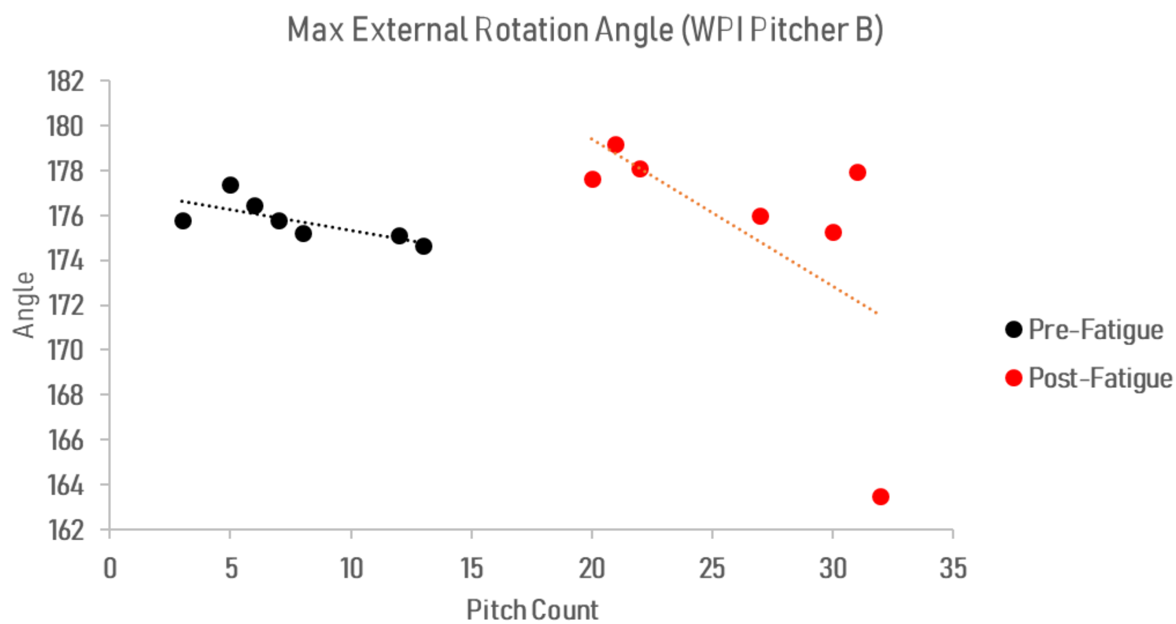

Figure 42: Maximum external rotation angle (degrees) vs pitch count for WPI pitcher B analyzed pre and post-fatigue cycle.

Due to the small sample size, the conclusions were non-conclusive, and the decision was made to not include this concept in the final metric at this time. This does however provide information on the potential for future analyses of more pitchers to determine if this is a trend seen in fatigued pitchers.

For the WPI pitchers, the Visual3D program was used to calculate forces and moments of the shoulder and elbow at points of interest. While the values for Pitcher B did not prove to be statistically significant, the changes between pre and post fatigue cycle for Pitcher A were statistically significant ($p < .005$) or close to it ($p \sim .08$). The data on Pitcher B showed more variance, likely resulting in the poor statistical significance. The results for both pitchers showed an increase in the averages for maximum elbow moment, maximum shoulder moment, elbow forces experienced at the instant of maximum external rotation angle, and shoulder forces exhibited at the instant of maximum shoulder moment. While the sample size is too small to make conclusive statements, the consistent increase in forces and moments on the pitcher's elbow and shoulder as they become fatigued which can relate to increased strain on these joints, and potential injury. Table 23 summarizes key analyses run on this concept, with standard deviations in parentheses. Less pitches were evaluated for Pitcher B in comparison to Pitcher A for this analysis due to the quality of the resulting data.

Table 23: Breakdown of force and moment analysis on WPI pitchers (parenthesis values are standard deviations).

Force / Moment Analysis	Pitcher A		Pitcher B	
Fatigue State	Pre-Fatigue	Post-Fatigue	Pre-Fatigue	Post-Fatigue
Maximum Elbow Moment (Nm)	9.22 (1.2)	10.62 (1.0)	11.43 (3.1)	12.33 (4.4)
	p = 0.089		p = 0.736	
Maximum Shoulder Moment (Nm)	61.17 (1.7)	68.88 (2.4)	77.01 (16.4)	123.0 (95.9)
	p < 0.001		p = 0.282	
Elbow forces at Max External Rotation (N)	106.54 (9.1)	121.62 (18.6)	54.56 (25.1)	55.86 (32.8)
	p = 0.088		p = 0.590	
Shoulder forces at Max Shoulder Moment (N)	286.13 (8.4)	304.21 (6.5)	453.58 (26.3)	452.0 (19.3)
	p = 0.005		p = 0.889	

6.1.7 Final Metric

The team developed a potential metric to predict fatigue in a pitcher's motion. The criteria for a fatigue pitch took data from the three successful potential metrics. These metrics are mechanical variation, performance, and kinetic chain metrics.

The criteria for a fatigued pitch are listed below. The metric took into account all three different metrics to produce a singular binary response. For mechanical variation, if any of the following criteria fails, then the pitch is considered fatigued. The criteria for mechanical variation is below…

- Right Shoulder X is outside 1 STD of the mean
- Right Elbow X is outside 1 STD of the mean
- Right Wrist X is outside 1 STD of the mean

The performance metric of this analysis revolves around the pitch velocity of the pitcher. The goal of this metric is to pick up on pitches that drop below the 1 standard deviations below the mean. The criteria for the kinetic chain metric was simplified as well. Any pitch that had an error in the flow of energy was considered a fatigued pitch. The combination of these three different metrics produced a fatigue rate of 40.4% of the data. In addition, the fatigue data points are spread throughout the outing and aren't just backloaded. The reason why the criteria to be a failed pitcher changed after 60 pitches (from two failed metrics to one) is because the Pirates' pitcher consistently showed a plateau effect with his data. For the kinetic chain and mechanical variation data, the pitcher was consistent, but the further analysis showed that these metrics dropped after 60 pitches. Thus, the team believed that this relationship should be reflected in the criteria.

Table 24: Breakdown of fatigued pitches defined by metric

Pitch Bucket	Criteria to be a Failed Pitch	% of Fatigue Pitches
0-20 (n = 65)	2 Failed Metrics	15.5%
20-40 (n = 63)	2 Failed Metrics	22.2%
40-60 (n = 38)	2 Failed Metrics	21.0%
60-80 (n = 38)	1 Failed Metric	36.8%
80+ (n = 14)	1 Failed Metric	49.9%

7.0 Discussion

7.1 Methodology Summary

The team started the project by conducting initial research to develop a stronger understanding of the current problem, and provide possible directions for a solution. This research provided background information on the anatomy of the pitching arm, the mechanics of a baseball pitch, and the concept and impact of fatigue. Additionally, the background information included the assessment and mitigation of fatigue in baseball for amateur and professional athletes, and the variety of measurement methods for biomechanical analyses. This research allowed the team to understand the significance of and how fatigue in baseball impacts a pitchers performance, as well as develop a list of biomechanical factors that might suggest a pitcher is fatigued.

Following the team's research, the team evaluated different data collection methods that would best meet the goals of the team, taking into consideration the constraints. This first includes identifying these goals and constraints from literature review, and communications with external sources, and use these to drive areas for potential paths for the project. With these guidelines for datasets, the team developed collaborations with the Pittsburgh Pirates Major League Baseball team, and the WPI Baseball Team. With the large sample size of in-game data available with the Pittsburgh Pirates and the detailed markerset with a fatigue (vs non-fatigued) pitch characterization from the data collection on the WPI collegiate level players, the team was able to focus on the strengths of each set to build the metric.

The team performed data exploration with the Pittsburgh Pirates data and the data collection and post processing of the WPI collegiate level players in parallel. Working on these two datasets in parallel as we did, the team was able to adjust the data analysis based on what was learned from each dataset to help drive metric development and increase the strength of the metric.

The team developed a procedure and with approval from the WPI IRB and informed consent from all participants, collected marker-based motion capture data on six WPI pitchers, using a custom marker set and fatiguing protocol. The post processing of the pitchers was performed on the best pitches of two players (the least amount of essential markers flew off during the pitch). Post processing of the marker set was performed in Vicon, and an anatomical model for calculations was built in the Visual 3D software.

With the information from both datasets, the team developed a fatigue metric (in Python) to identify a "fatigued" pitch of a Pittsburgh Pirates player based on the success of three metrics, including kinetic chain, mechanical positional change and performance (pitch velocity).

7.2 Summary of Data Collection and Analysis

The primary results of this project include WPI pitcher data collection, post processing of data for both Pittsburgh Pirates and WPI pitcher data, data exploration, and final fatigue metric definition and results.

7.2.1 WPI Pitcher Data Collection Results

The aim of collecting information on WPI pitchers was to bridge some of the gaps seen with the Pittsburgh Pirates data, such as the detail of the dataset, as well as categorical information of whether a pitcher is fatigued. The team developed and implemented a custom marker set which included an increased number of markers (and accelerometers) on the pitcher's throwing arm, shown in Figure 43.

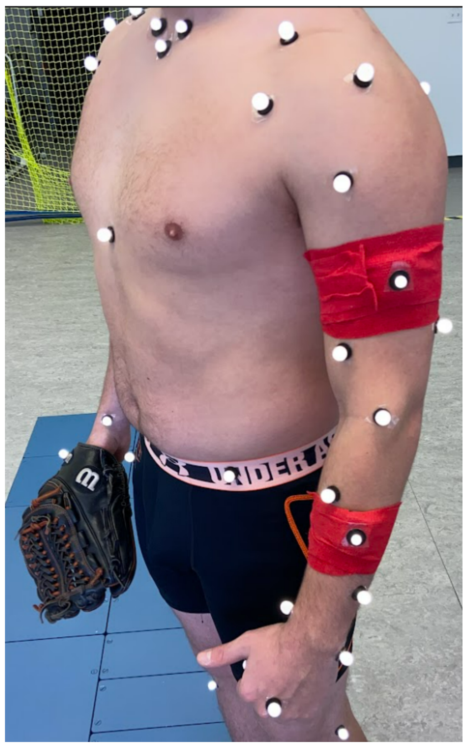

Figure 43: Example of markerset placement on WPI pitcher with increased number of markers on pitching arm.

The team performed motion capture data collection on six participants. Five participants performed both pitching session 1(pre-fatigue) and pitching session 2(post-fatigue), and one participant performed only pitching session 1. Approximately 72% of the pitches recorded were either classified as good or great, based on the markers that fell off during a pitch. Figure 44 is an example of how the team recorded information on the markers that fell off during a pitch, and the classification of the pitch. The team was successful in implementing a detailed markerset successfully, as the majority of the pitches retained essential markers.

Pitching Session 2								
Borg Rating	8							
Heart Rate	156							

Pitch Number	Assessment	Cluster Markers Lost	Essential Markers Lost	Accelerometers Lost	Markers Lost	Data Collection Notes	Key	
1	Great						Great	All units & markers stay
2	Great						Good	Non-essential markers came off
3	Great						Okay	< 2 Essential markers fell off
4	Great						Poor	>= 2 Essential markers fell off
5	Okay		1		[Lateral Throwing Elbow]		Bad	5+ Essential markers fell off
6	Good	1			[Middle Bicep Cluster]			
7	Great							
8	Okay		1		[Proximal Geno Throwing]			
9	Okay		1		[Lateral Throwing Elbow]			
10	Great							
11	Poor	1	2		[Medial Bicep Cluster] [Ra	No Glove		
12	Poor	1	2		[Knuckle] [Radial Wrist] [M	No Glove		
13	Great					No Glove		
14	Great					No Glove		
15	Good	1			[Medial Bicep Cluster]	No Glove		
16	Great					No Glove		
17	Great					No Glove		
18	Great					No Glove		

Figure 44: Pitch classification for WPI collegiate level pitcher motion capture data collection.

The fatiguing protocol (HIIT workout) developed by the team was also deemed successful, as both heart rate and Borg fatigue rating (perceived exertion level) were statistically significant prior to and immediately following the fatigue cycle. The summary of all WPI pitcher's Borg fatigue ratings are shown in Figure 45. The team was successful in implementing a fatiguing protocol that designated all the pitches in pitching session 1 as non-fatigued, and all the pitches in pitching session 2 as fatigued pitches.

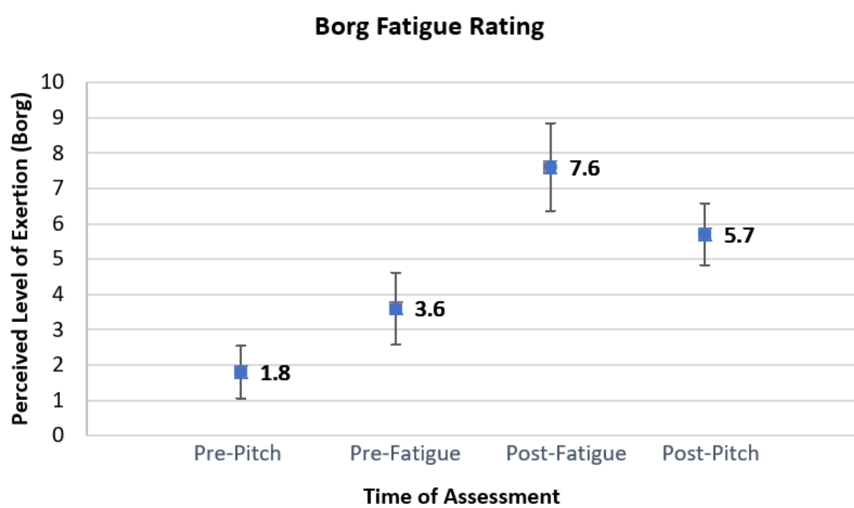

Figure 45: Borg scale for rating a person's perceived exertion level (1-10), prior to and immediately following the two pitching sessions for all pitchers that participated in the team's motion capture data collection.

7.2.2 Post Processing Results

The goal for post processing of the Pittsburgh Pirates data was to ensure the analysis performed would be on complete datasets, and the analysis would not be influenced by the player's position on the mound. Since the data from the Pittsburgh Pirates had already been filtered (by a non-disclosed process) and labeled with the appropriate markers, the team's data cleaning focused on the data collection frequency. With the knowledge that the data was collected at 300Hz for three seconds, valid pitches had data for 900 frames of a pitch. Therefore, pitches missing a large number of frames were excluded from analyses, as there was not sufficient detail in the data set to perform some of the calculations required for the analysis. The dataset was also condensed to include only fastballs, and other games such as ones that had an unreasonable number of pitches thrown in a game, or unreasonable movement (such as 5 feet of shoulder movement during a pitch) were eliminated. The data was also normalized based on the pitcher's starting location on the mound (right ankle location prior to windup). The team was successful in producing a dataset of greater than 200 pitches to analyze, of data considered "valid" as defined above.

The goal of post processing of the WPI collegiate level pitchers was to go from a "marker cloud" to an anatomical skeleton that could be used to perform calculations to parallel those of the Pittsburgh Pirates, in addition to others that the Pittsburgh Pirates data set is detailed enough to evaluate. Figure 46 highlights the process the team implemented to go from the "marker cloud", or just the raw marker set in space, to a labeled set in the Vicon software, to an anatomical skeleton in the Visual3D software. This process included challenges of markers blinking out, or becoming unlabeled in certain frames, as well as troubleshooting in the implementation of the skeletal model based on the marker set to get the skeleton to reference the correct markers. The post processing of the WPI collegiate pitchers was successful, as the team was able to develop skeletal models for pre and post fatigue cycle pitches on two WPI pitchers.

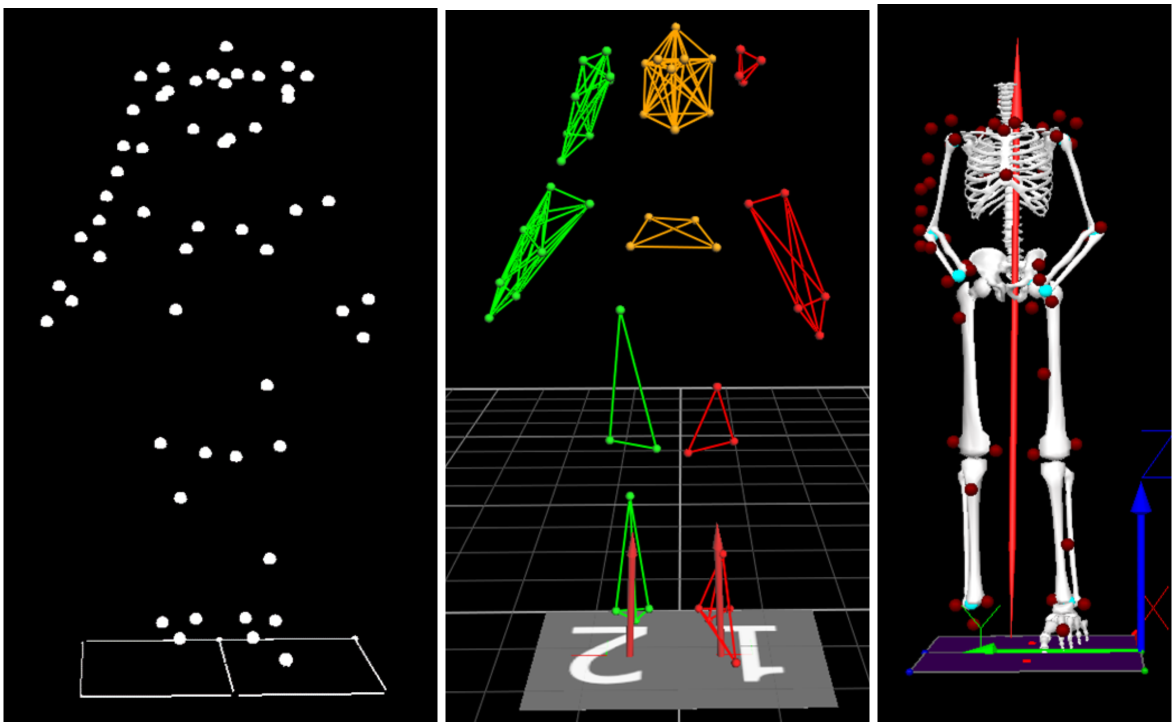

Figure 46: WPI Collegiate pitcher post processing process from "marker cloud" to anatomical skeleton.

7.2.3 Data Exploration Results

The goal for the data exploration was to determine the candidate biomechanical/ performance factors that have the strongest correlation with fatigue, or an increased pitch count. Table 25 summarizes the factors that were explored and the corresponding dataset they were analyzed with.

Table 25: List of candidate factors analyzed and corresponding dataset for the analysis.

Candidate Factors	Pittsburgh Pirates	WPI Pitchers
Mechanical Positional Change	X	X
Joint Range of Motion	X	X
Kinetic Chain	X	X
Velocity & Acceleration of Segments	X	X
Performance (Pitch Velocity)	X	
Joint Forces and Moments		X
Rate of Force Development	X	
Ball Release Height	X	
Rest Time	X	

Factors explored such as rest time during a game, ball release height, joint range of motion and rate of force development showed minimal if any correlation with increased pitch count or fatigue. Joint forces and moments of the WPI pitcher showed some correlation, however, due to the limited data, and the detail of the dataset for the Pittsburgh Pirates, this candidate factor was not used in the final fatigue metric. Mechanical positional change and kinetic chain resulted in the highest correlation with fatigue and increased pitch count. The data exploration was successful as the team was able to determine factors that seem to show correlation with fatigue and increased pitch count, and were implemented into the final fatigue metric to characterize fatigue.

7.2.4 Fatigue Metric Results

The goal of the fatigue metric was to characterize a pitcher based on their level of fatigue, as either fatigued or not fatigued. The metric was defined based on the success of metrics including mechanical positional change, kinetic chain, and performance (pitch velocity). The incorporation of pitch velocity was suggested by collaborators, and showed correlation with pitch count of the Pittsburgh Pirates. A failed kinetic chain is when the pitcher does not have the desired sequencing of maximum velocities in the arm. A failed mechanical positional change is when a joint of the arm is greater than 1 standard deviation away from their typical arm path. A failed performance metric is when a throw is 1 standard deviation slower than their typical pitch velocity. For a pitcher throwing less than 60 pitches in the game, a pitch was considered "fatigued" when two or more metrics failed, and for greater than 60 pitches, a pitch was considered "fatigued" when one or more metrics failed.

Table 24 summarizes the outcome of the metric when applied to the Pittsburgh Pirates pitcher. This showed that there was an increase in the number of pitches considered "fatigued" as the pitch count increased. The fatigue metric was successful in determining whether a pitch was considered "fatigued" as defined by the team's characterization of a fatigued pitch, there was a steady increase in fatigued pitches following a plateau between 20-60 pitches thrown.

7.3 Impacts of Final Design

7.3.1 Economics

There are several financial components that would result from the implementation of this metric. With future iterations of this metric and determining exact specifications of fatigue factors that directly relate to injury risk, this metric has the potential to decrease the occurrences of pitching injuries that require surgery. With this decrease in injury, is a decrease in the financial burden on those responsible for the cost of performing surgeries on the injured athletes. Whether this is the families of amateur athletes, or the organizations that hire professional players, the decrease in costs spent on surgeries has a positive impact on these stakeholders. Pitchers who are injured, especially at a younger age, and must carry the effects of this injury throughout the rest of their life, this not only impacts the sports they can participate in, but this could also have an impact on other occupational activities (beyond a professional pitcher) that is now compromised. Being able to track and mitigate these injuries would be advantageous for any player in the sport, or with future implementation, possibly any sport. This metric could also shift the focus of professional training staff, as if they know what exactly results in increased injury risk during their performance, their efforts can be more catered and effective, and can put their focus into those areas. Since this metric does need to go through future iterations and more extensive data analysis, this might require the cost of the motion capture systems used to collect this analysis. However, once an established metric is in place, this upfront cost will be countered with the decrease of over-fatigued players and injuries. If this metric were to prevent just 5% of pitcher injuries in the MLB, then the metric would save $23,787,733.90 and about 21 pitchers every year [41]. This number would drastically increase once it is tailored for the 5.7 million youth players that play baseball every year [1].

7.3.2 Environmental Impact

At this point, the proposed fatigue metric does not pose any significant environmental impacts. The potential environmental impacts that could arise from the advancement of this metric are the manufacturing of the motion capture camera system and the implementation into baseball stadiums. If this system were to become widespread across most baseball teams, the materials used to manufacture a large quantity of motion capture camera systems could produce negative environmental impacts through increased waste if they go unused. Additionally, any modifications to a baseball stadium during implementation could result in wasted resources.

7.3.3 Societal Influence

The goal of this project is to detect fatigue in baseball pitchers during a practice or game. As a result, the fatigue detection will alert coaches when they should pull a pitcher out, as their fatigue levels are too high. This would provide more quantitative data rather than the current method of using qualitative data to describe fatigue. By developing a system to monitor and detect fatigue in baseball pitchers, coaches can prevent their pitchers from throwing while in a fatigued state. As a result, the risk of injury in pitchers will significantly be diminished. With additional data in the future, the team believes that this metric can be further developed to encompass all age categories in baseball, thus broadening the societal influence. As the positive trends in preventing injury of this product are recognized, the sales will increase, especially amongst professional leagues where injury has a major economical impact.

7.3.4 Political Ramifications

With future iterations and implementations of this fatigue metric, this could not only revolutionize characterizing fatigue in a popular sport here in the United States, but a similar process of metric development could be used and implemented to characterize fatigue in sports popular around the world such as soccer. All the effects mentioned throughout this report on baseball could be applicable to other sports and occupations as well.

7.3.5 Ethical Concerns

Overall, the gradual rise of participants playing baseball, can lead to a high volume of injuries. Specifically, pitchers account for a majority of those injuries, which can include damaging the ulnar collateral ligament for example. This injury is just one example of the many injuries that can arise, thus further emphasizing the concern of pitchers pitching while fatigued. The metric developed is targeted towards pitchers and to help coaches understand when to allow for rest time to prevent injuries. With this, there are several ethical concerns that should be addressed and noted when discussing the proposed fatigue metric. If this metric were to become widely used, it should not be the only form of identification for fatigue. Fatigue may look different for every pitcher, so fully relying on the metric to determine if they should continue playing may not be the best or safest option depending on the scenario. For example, currently, the metric does not factor in previous injury history, so fatigue in a player that was recently injured may show different results than in a player who has never shown a history of injury. Additionally, there may be a situation where the player appears to not be fatigued and the metric supports that, but the player still sustains an injury anyways. It is important to note that the cause of injury can be due to many factors other than fatigue. Therefore, teams should not fully rely on this system to prevent injury and the team cannot be held liable for injuries that may occur while the metric is in place.

If teams choose to use this metric for data collection and monitoring of their pitchers, the athlete should have the option to opt out of using it if they desire. Additionally, the coaching staff should have the option of whether or not they incorporate this metric. For the athletes and coaches that choose to use the metric, there should be no privacy concerns. More specifically, the information collected with this metric will not be published anywhere without the consent of the coaches and athletes, and additionally, the system will use unique identifiers for each user, as opposed to using their names. Another reason for the metric not being available would be due to the cost. The system can be costly and is necessary to pull the unique identifiers for each user.

7.3.6 Health and Safety Issues

As previously stated throughout this paper, pitching injuries are extremely prevalent in baseball, as more than half of injured players in the MLB are pitchers and adolescents can have their chances of needing surgery more than doubled when pitch count guidelines are not followed. This fatigue metric could assist in the health and safety of baseball pitchers by identifying high levels of fatigue and advising the player to stop pitching at this point. This will prevent overuse, or pitching while fatigued, which is commonly linked to injuries, such as ulnar collateral ligament and ulnar collateral ligament tears. It should be noted that this metric should not be the only resource used to prevent injuries, as there are other methods currently used to mitigate the effects of fatigue, and these should be continued to be practiced. In conjunction with these methods, this metric could significantly diminish the number of pitching injuries.

7.3.7 Manufacturability

This product is easily reproduced as it requires the use of motion capture systems that are already in place in many stadiums. However, it can be easily reproduced in these specific major leagues, minor leagues, and some collegiate fields. Thus, it would not be able to be used in a little league or a high school game.

Currently, this product uses technologies that are currently on the market and collects biomechanical data to inform players and coaches. If this metric solution became widespread, motion capture companies could increase the manufacturing of their systems. With regards to implementing this beyond data collection and post-processing, the metric itself is primarily derived from code-based analyses. With a standardized procedure on what types of analyses to conduct, and how to perform these analyses with a specified dataset, the metric can easily be reproduced and adjusted to cater to the increased detail of the dataset for example, as the technology becomes more advanced and intricate.

7.3.8 Sustainability

The implementation of this product (the fatigue metric) would have minimal effect on sustainability. While the implementation of the metric does not have a great impact, the sustainability of the data collection process, such as the motion capture cameras at various stadiums could likely be improved upon by being rechargeable, or powered by a renewable energy source. For implementation at an outdoor stadium, solar energy could be a possible renewable energy source for the cameras used at the stadium.

7.4 Limitations

This project implemented assumptions and generalization, producing additional limitations and areas for improvement in the future.

An assumption made by the team was the direct relationship with the pitcher's perceived exertion level as an objective level of their true fatigue level. The scale used for this is a standardized scale, and this was corroborated with heart rate data. However, this was an assumption made by the team that the subjective personal assessment is directly related to their objective fatigue level, which is stronger than the conventional subjective assessments currently in use.

Due to the limitation of using strictly fastballs in the team's analysis, this not only decreases the sample size available (such as with the Pittsburgh Pirates), but it also makes an assumption about the metric that fatigue is primarily assessed with the number of fastballs thrown. Due to the time and person-power available for this project, the scope contained the team to focus on fastballs, but in reality, other types of pitches have an impact on the pitcher's fatigue level. Future work should assess this area, and address the impact of varying pitch types on fatigue and injury risk.

For calculations such as force and moment of the arm, the team did not factor in the mass of the baseball during the pitch. This would have an impact on the results, and should be addressed in future work, as the ball's mass changes the weight distribution on the arm during a pitch.

Overall limitations with this project are due to time constraints and the amount of data. With the time frame available, the team was restricted to the number and type (active pitchers) of pitchers available to be recruited from the WPI baseball team. The team was also restricted to the amount of post-processing that was able to be conducted, due to the length of time it takes to post-process motion capture collected data. The team also was restricted on the number of pitchers available at the professional level, a threshold set based on the data available by the Pittsburgh Pirates, but also with the amount of data that was not able to be analyzed after the data cleaning process. Future teams should collect more data and perform more post-processing of the data this team collected, such that the WPI dataset is stronger, and more in-depth analyses can be performed on the detailed dataset. The WPI dataset also includes force plate and accelerometer information that this team was unable to perform sufficient analysis of due to time constraints, which is another area available for future work.

8.0 Conclusions and Recommendations

8.1 Conclusions

Baseball is played by over 5 million youth athletes, over 34,000 collegiate athletes, and hundreds of professional athletes every single year. In the Major Leagues, pitcher injuries account for 58.9% of all MLB injuries. However, professional athletes aren't the only players getting hurt. The incidence of UCL injuries is five times greater in ages between 15 and 19, and accounts for the most UCL reconstruction surgeries than any other age group. Many of these injuries can sideline a player for months and, sometimes, derail their baseball career to an abrupt stop. Additionally, these injuries are usually a direct result of player fatigue. The current approach to mitigating and preventing fatigue involves players managing load, following pitch count guidelines, strengthening shoulder muscles through various exercises, and following proper post-throwing rehabilitation techniques. All of these approaches are limited by quantifiable data and in-game data. The technology to collect in-game biomechanical data has only recently reached the highest level of baseball, Major League Baseball, a few years ago. With the help of the Pittsburgh Pirates, the WPI team is one of the few non-MLB research groups to have access to this data to analyze biomechanical fatigue. With this data, the team's goal for this project is to define and validate a fatigue metric for baseball pitchers by using kinematic and dynamic calculations from a worn sensor system and motion capture data from WPI collegiate pitchers and Pirate's professional pitchers.

By combining the Pirates' data with motion capture data from WPI collegiate pitchers, the two data sources validated multiple fatigue metrics. These initial metrics were explored and defined from the Pirates' data and then validated with the markered data. From this approach, the team found reliable findings regarding mechanical variation in a pitcher's motion as well as changes in the pitcher's kinematic sequencing. The validated metrics suggest that the fatigue is identifiable, but physical values will be personalized for each pitcher. However, more data and more pitchers need to be analyzed to refine the metric.

The developed metric successfully fulfilled most of the project goals defined in this report. The defined goals were for the metric to detect biomechanical variation, for validation through multiple data sets, and for the metric to be reliable. First off, the defined metrics were able to detect variation among biomechanical metrics through motion capture data. The two metrics that produced the most interesting results were mechanical variation and the kinematic sequencing of the pitcher. Secondly, the WPI and Pirates' datasets were able to validate the fatigue metrics by finding similar results in the defined fatigue metric. By successfully validating the metrics against multiple data sources, the team believes that the metrics will be reliable. However, in order for the metric to be considered very reliable, more data needs to be analyzed. Through further development and analysis, this type of strategy could be used to prevent millions of injuries throughout various fields and applications.

8.2 Future Recommendations

The analysis and breakdown of the fatigue metric were successful in meeting the requirements outlined in the client statement. However, the metric could be improved in certain areas. The tea recommends the following improvements for future development:

- **More Data Analysis on WPI Collegiate Pitchers:** Due to time constraints and data collection, the team was only able to analyze two WPI collegiate pitchers. The team prioritized specific pitchers based on efficient post-processing potential and performance in the motion capture lab. However, the team collected over 50 other pitches in WPI's motion capture lab. The team recommends that future teams analyze these extra data points and collect more data on collegiate pitchers.
- **More Data Analysis on Professional Pitchers:** Major League Baseball is most likely the organization in the world that has access to this amount of biomechanical pitching data. The team recommends exploring more than just one pitcher. By analyzing more pitchers, trends will become more clear and analysis can be done on how fatigue affects different types of pitchers.
- **Streamline the Successful Metrics into a Sensor System:** After analyzing the data, the team found that mechanical variation and the kinematic sequencing of a pitcher could be key indicators of fatigue. The team recommends creating an arm sleeve or sensor system to pick up on these indicators. The sensor system would need to collect segment velocities and relative segment positioning.
- **Use the Metric and Findings to Redefine Youth Baseball Standards:** Current youth baseball guidelines are restricted to just pitch counts and days rest. This fatigue metric has the potential to optimize these guidelines and inform coaches about key visual indicators of fatigue. By redefining these guidelines, thousands of young baseball players will not be sidelined due to fatigue-related injuries.
- **Match the Potential WPI & Pirates Metrics:** The methods to collect data between the WPI collegiate pitchers and the Pirates' pitchers were different. Because of this, the team could only perform certain types of calculations on specific data sets. Therefore, if the team had more time, the team matched the metrics together so each dataset had the same metrics.

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Appendices

Appendix A: Data Normalization Code

```
df_file = df_sort
# print(df_file)
# print(list(df_file[0:0]))
joint_list_x = ['LAnkleX', 'LEarX', 'LElbowX', 'LEyeX', 'LHipX', 'LKneeX',
'LShoulderX', 'LWristX', 'NeckX', 'NoseX',
                 'RAnkleX', 'REarX', 'RElbowX','REyeX', 'RHipX', 'RKneeX',
'RShoulderX', 'RWristX']
joint_list_y = ['LAnkleY', 'LEarY', 'LElbowY', 'LEyeY', 'LHipY', 'LKneeY',
'LShoulderY', 'LWristY', 'NeckY', 'NoseY',
                 'RAnkleY', 'REarY', 'RElbowY','REyeY', 'RHipY', 'RKneeY',
'RShoulderY', 'RWristY']
joint_list_z = ['LAnkleZ', 'LEarZ', 'LElbowZ', 'LEyeZ', 'LHipZ', 'LKneeZ',
'LShoulderZ', 'LWristZ', 'NeckZ', 'NoseZ',
                 'RAnkleZ', 'REarZ', 'RElbowZ','REyeZ', 'RHipZ', 'RKneeZ',
'RShoulderZ', 'RWristZ']
g = 1
for g in range(1, 15):
   df_game = df_file[df_file['Game_Num'] == g]
   p = 1
    pitch_max = df_game["PitchNum"].max() + 1  # look at how many pitches
are thrown in game n
   if g == 3 or g == 8 or g == 11:
       continue
   while p < pitch_max:
       df_pitch = df_game[df_game['PitchNum'] == p]
       min_time = df_pitch['Pitch_Time'].min() + .2
       df_norm_vals = df_pitch[df_pitch['Pitch_Time'] < min_time]
       norm_val_x = df_norm_vals['RAnkleX'].mean()
       norm_val_y = df_norm_vals['RAnkleY'].mean()
       norm_val_z = df_norm_vals['RAnkleZ'].mean()
         for i in range(len(joint_list_x)):  # for all the joints in the
joints list
             joint_x = joint_list_x[i]  # locate the joint you want to look
into for this loop iteration
           new_val_x = df_pitch[joint_x] - norm_val_x
           # print(new_val_x)
```

```
            # print(norm_val_x)
            # print(df_pitch[joint_x])
              df_file.loc[(df_file['PitchNum'] == p) & (df_file['Game_Num']
== g), joint_x + '_N'] = new_val_x
        for i in range(len(joint_list_y)):  # for all the joints in the
joints list
             joint_y = joint_list_y[i]  # locate the joint you want to look
into for this loop iteration
            new_val_y = df_pitch[joint_y] - norm_val_y
              df_file.loc[(df_file['PitchNum'] == p) & (df_file['Game_Num']
== g), joint_y + '_N'] = new_val_y
        for i in range(len(joint_list_z)):  # for all the joints in the
joints list
             joint_z = joint_list_z[i]  # locate the joint you want to look
into for this loop iteration
            new_val_z = df_pitch[joint_z] - norm_val_z
              df_file.loc[(df_file['PitchNum'] == p) & (df_file['Game_Num']
== g), joint_z + '_N'] = new_val_z
       p = p + 1


   df_file = pd.DataFrame(df_file)
#2-5 min runtine
```

Appendix B: Data Cleaning Code

```
df_file = df_file[df_file['PitchType'] == 'FF']
df_RArm_Vari = df_file[["Uuid", "Pitch_Time", "time_sec_N", "Game_Num",
"PitchNum", "RWristX_N", "RWristY_N", "RWristZ_N", "RElbowX_N",
"RElbowY_N", "RElbowZ_N", "RShoulderX_N", "RShoulderY_N", "RShoulderZ_N"]]
```

```
df_RArm_Vari_filt = df_RArm_Vari

df_Mech_AVG1 = df_RArm_Vari_filt[df_RArm_Vari_filt['Game_Num'] != 4]
df_Mech_AVG2 = df_Mech_AVG1[df_Mech_AVG1['Game_Num'] != 12]
df_RArm_Vari_filt = df_Mech_AVG2[df_Mech_AVG2['Game_Num'] != 9]

df_RArm_Vari_filt1 = df_RArm_Vari_filt[df_RArm_Vari_filt['Pitch_Time'] >
-0.1]
```

```
df_RArm_Vari_filt  =  df_RArm_Vari_filt1[df_RArm_Vari_filt1['Pitch_Time']  <
0]
```

Appendix C: Mechanical Positional Changes - Concept 1 Code

```
df_RArm_Vari_filt['Mag']                                                          =
((df_RArm_Vari_filt['RWristX_N']**2)+(df_RArm_Vari_filt['RWristY_N']**2)+
(df_RArm_Vari_filt['RWristZ_N']**2))**0.5
df_RArm_Vari_filt['LateCockingAngle']                                             =
np.degrees(np.arccos(df_RArm_Vari_filt['RWristY_N']/df_RArm_Vari_filt['Mag
']))
```

```
ColB = df_RArm_Vari_filt.columns.get_loc("Game_Num")
ColC = df_RArm_Vari_filt.columns.get_loc("PitchNum")

ColA = df_RArm_Vari_filt.columns.get_loc("Uuid")

df_Variation_Summary = []
pitch_last = 0

df_RArm_ALL_AVG   =   df_RArm_Vari_filt[df_RArm_Vari_filt['Pitch_Time']   >
-0.094]
df_RARM_RSHOULDERX_MEAN = df_RArm_ALL_AVG['RShoulderX_N'].mean()
df_RARM_RSHOULDERY_MEAN = df_RArm_ALL_AVG['RShoulderY_N'].mean()
df_RARM_RSHOULDERZ_MEAN = df_RArm_ALL_AVG['RShoulderZ_N'].mean()

df_RARM_RELBOWX_MEAN = df_RArm_ALL_AVG['RElbowX_N'].mean()
df_RARM_RELBOWY_MEAN = df_RArm_ALL_AVG['RElbowY_N'].mean()
df_RARM_RELBOWZ_MEAN = df_RArm_ALL_AVG['RElbowZ_N'].mean()

df_RARM_RWRISTX_MEAN = df_RArm_ALL_AVG['RWristX_N'].mean()
df_RARM_RWRISTY_MEAN = df_RArm_ALL_AVG['RWristY_N'].mean()
df_RARM_RWRISTZ_MEAN = df_RArm_ALL_AVG['RWristZ_N'].mean()

for index in range(len(df_RArm_Vari_filt)):
 pitch_curr = df_RArm_Vari_filt.iloc[index, ColA]
 game_num = df_RArm_Vari_filt.iloc[index, ColB]
 pitch_num = df_RArm_Vari_filt.iloc[index, ColC]
 if pitch_curr == pitch_last:
```

```
    pass
  else:
    pitch_last = pitch_curr
      df_current_pitch  =  df_RArm_Vari_filt[(df_RArm_Vari_filt["Uuid"]  ==
pitch_curr)]
                                          LateCockingTime_UN               =
df_current_pitch.loc[df_current_pitch['LateCockingAngle'].idxmin()]['Pitch
_Time']
                                        LateCockingTime_Angle              =
df_current_pitch.loc[df_current_pitch['LateCockingAngle'].idxmax()]['LateC
ockingAngle']
    LateCockingTime_OF = LateCockingTime_UN - 0.066667
    df_current_pitch_TIME = df_current_pitch[df_current_pitch['Pitch_Time']
> LateCockingTime_OF]
#############################
    RShoulderX_STD = df_current_pitch_TIME['RShoulderX_N'].std()
    RShoulderX_Pitch_AVG = df_current_pitch_TIME['RShoulderX_N'].mean()
    RShoulderX_Variance = RShoulderX_Pitch_AVG - df_RARM_RSHOULDERX_MEAN

    RShoulderY_STD = df_current_pitch_TIME['RShoulderY_N'].std()
    RShoulderY_Pitch_AVG = df_current_pitch_TIME['RShoulderY_N'].mean()
    RShoulderY_Variance = RShoulderY_Pitch_AVG - df_RARM_RSHOULDERY_MEAN

    RShoulderZ_STD = df_current_pitch_TIME['RShoulderZ_N'].std()
    RShoulderZ_Pitch_AVG = df_current_pitch_TIME['RShoulderZ_N'].mean()
    RShoulderZ_Variance = RShoulderZ_Pitch_AVG - df_RARM_RSHOULDERZ_MEAN
##############################
    RElbowX_STD = df_current_pitch_TIME['RElbowX_N'].std()
    RElbowX_Pitch_AVG = df_current_pitch_TIME['RElbowX_N'].mean()
    RElbowX_Variance = RElbowX_Pitch_AVG - df_RARM_RELBOWX_MEAN

    RElbowY_STD = df_current_pitch_TIME['RElbowY_N'].std()
    RElbowY_Pitch_AVG = df_current_pitch_TIME['RElbowY_N'].mean()
    RElbowY_Variance = RElbowY_Pitch_AVG - df_RARM_RELBOWY_MEAN

    RElbowZ_STD = df_current_pitch_TIME['RElbowZ_N'].std()
    RElbowZ_Pitch_AVG = df_current_pitch_TIME['RElbowZ_N'].mean()
    RElbowZ_Variance = RElbowZ_Pitch_AVG - df_RARM_RELBOWZ_MEAN
```

```
################################
   RWristX_STD = df_current_pitch_TIME['RWristX_N'].std()
   RWristX_Pitch_AVG = df_current_pitch_TIME['RWristX_N'].mean()
   RWristX_Variance = RWristX_Pitch_AVG - df_RARM_RWRISTX_MEAN

   RWristY_STD = df_current_pitch_TIME['RWristY_N'].std()
   RWristY_Pitch_AVG = df_current_pitch_TIME['RWristY_N'].mean()
   RWristY_Variance = RWristY_Pitch_AVG - df_RARM_RWRISTY_MEAN

   RWristZ_STD = df_current_pitch_TIME['RWristZ_N'].std()
   RWristZ_Pitch_AVG = df_current_pitch_TIME['RWristZ_N'].mean()
   RWristZ_Variance = RElbowZ_Pitch_AVG - df_RARM_RWRISTZ_MEAN

    df_Variation_Summary.append ({
       'Uuid': pitch_curr,
       'Game_Num': game_num,
       'PitchNum': pitch_num,
       'LateCockingTime': LateCockingTime_UN,
       'LateCocking_Angle': LateCockingTime_Angle,
       'RShoulderX_STD': RShoulderX_STD,
       'RShoulderX_AVG': RShoulderX_Pitch_AVG,
       'RShoulderX_Vari': RShoulderX_Variance,
       'RShoulderY_STD': RShoulderY_STD,
       'RShoulderY_AVG': RShoulderY_Pitch_AVG,
       'RShoulderY_Vari': RShoulderY_Variance,
       'RShoulderZ_STD': RShoulderZ_STD,
       'RShoulderZ_AVG': RShoulderZ_Pitch_AVG,
       'RShoulderZ_Vari': RShoulderZ_Variance,

       'RElbowX_STD': RElbowX_STD,
       'RElbowX_AVG': RElbowX_Pitch_AVG,
       'RElbowX_Vari': RElbowX_Variance,
       'RElbowY_STD': RElbowY_STD,
       'RElbowY_AVG': RElbowY_Pitch_AVG,
       'RElbowY_Vari': RElbowY_Variance,
       'RElbowZ_STD': RElbowZ_STD,
       'RElbowZ_AVG': RElbowZ_Pitch_AVG,
       'RElbowZ_Vari': RElbowZ_Variance,

       'RWristX_STD': RWristX_STD,
```

```
        'RWristX_AVG': RWristX_Pitch_AVG,
        'RWristX_Vari': RWristX_Variance,
        'RWristY_STD': RWristY_STD,
        'RWristY_AVG': RWristY_Pitch_AVG,
        'RWristY_Vari': RWristY_Variance,
        'RWristZ_STD': RWristZ_STD,
        'RWristZ_AVG': RWristZ_Pitch_AVG,
        'RWristZ_Vari': RWristZ_Variance,
        })
```

```
df_Variation_Summary = pd.DataFrame(df_Variation_Summary) #Making it a
dataframe
df_Variation_Summary = df_Variation_Summary.drop_duplicates(keep='first')
#Dropping duplicates
df_Variation_Summary_Final = df_Variation_Summary.reset_index()

df_Variation_Summary_Final
```

Appendix D: Joint Range of Motion - Concept 2 Code

```
df_filt['RArm_angle'] =
np.degrees(np.arccos(((((df_filt['RShoulderX']-df_filt['RElbowX'])*(df_fil
t['RWristX']-df_filt['RElbowX']))
+((df_filt['RShoulderY']-df_filt['RElbowY'])*(df_filt['RWristY']-df_filt['
RElbowY']))
+((df_filt['RShoulderZ']-df_filt['RElbowZ'])*(df_filt['RWristZ']-df_filt['
RElbowZ'])))))/((sq_rt(((df_filt['RShoulderX']-df_filt['RElbowX'])**2)+((df
_filt['RShoulderY']-df_filt['RElbowY'])**2)+((df_filt['RShoulderZ']-df_fil
t['RElbowZ'])**2)))*(sq_rt(((df_filt['RWristX']-df_filt['RElbowX'])**2)+((
df_filt['RWristY']-df_filt['RElbowY'])**2)+((df_filt['RWristZ']-df_filt['R
ElbowZ'])**2))
))))

df_filt['LArm_angle'] =
np.degrees(np.arccos(((((df_filt['LShoulderX']-df_filt['LElbowX'])*(df_fil
t['LWristX']-df_filt['LElbowX']))
+((df_filt['LShoulderY']-df_filt['LElbowY'])*(df_filt['LWristY']-df_filt['
LElbowY']))
```

```
+((df_filt['LShoulderZ']-df_filt['LElbowZ'])*(df_filt['LWristZ']-df_filt['
LElbowZ']))))/((sq_rt(((df_filt['LShoulderX']-df_filt['LElbowX'])**2)+((df
_filt['LShoulderY']-df_filt['LElbowY'])**2)+((df_filt['LShoulderZ']-df_fil
t['LElbowZ'])**2)))*(sq_rt(((df_filt['LWristX']-df_filt['LElbowX'])**2)+((
df_filt['LWristY']-df_filt['LElbowY'])**2)+((df_filt['LWristZ']-df_filt['L
ElbowZ'])**2))
))))
```

Appendix E: Kinetic Chain - Concept 4 Code

```
df_RArm_Vari_filt = df_RArm_Vari

df_Mech_AVG1 = df_RArm_Vari_filt[df_RArm_Vari_filt['Game_Num'] != 4]
df_Mech_AVG2 = df_Mech_AVG1[df_Mech_AVG1['Game_Num'] != 12]
df_RArm_Vari_filt = df_Mech_AVG2[df_Mech_AVG2['Game_Num'] != 9]

df_RArm_Vari_filt1  =  df_RArm_Vari_filt[df_RArm_Vari_filt['Pitch_Time']  >
-2]
df_RArm_Vari_filt  =  df_RArm_Vari_filt1[df_RArm_Vari_filt1['Pitch_Time']  <
0.25]

df_Kinematic_Seq = df_RArm_Vari_filt
framerate = 1/300

######################################                                VELO
###########################################################
df_Kinematic_Seq['RWrist_X_Velo']                                          =
(df_Kinematic_Seq['RWristX_N'].diff()/framerate)
df_Kinematic_Seq['RWrist_Y_Velo']                                          =
(df_Kinematic_Seq['RWristY_N'].diff()/framerate)
df_Kinematic_Seq['RWrist_Z_Velo']                                          =
(df_Kinematic_Seq['RWristZ_N'].diff()/framerate)

df_Kinematic_Seq['RElbow_X_Velo']                                          =
(df_Kinematic_Seq['RElbowX_N'].diff()/framerate)
df_Kinematic_Seq['RElbow_Y_Velo']                                          =
(df_Kinematic_Seq['RElbowY_N'].diff()/framerate)
df_Kinematic_Seq['RElbow_Z_Velo']                                          =
(df_Kinematic_Seq['RElbowZ_N'].diff()/framerate)
```

```
df_Kinematic_Seq['RShoulder_X_Velo'] =
(df_Kinematic_Seq['RShoulderX_N'].diff()/framerate)
df_Kinematic_Seq['RShoulder_Y_Velo'] =
(df_Kinematic_Seq['RShoulderY_N'].diff()/framerate)
df_Kinematic_Seq['RShoulder_Z_Velo'] =
(df_Kinematic_Seq['RShoulderZ_N'].diff()/framerate)

###################################### ACCEL
############################################################
df_Kinematic_Seq['RWrist_X_Accel'] =
(df_Kinematic_Seq['RWrist_X_Velo'].diff()/framerate)
df_Kinematic_Seq['RWrist_Y_Accel'] =
(df_Kinematic_Seq['RWrist_Y_Velo'].diff()/framerate)
df_Kinematic_Seq['RWrist_Z_Accel'] =
(df_Kinematic_Seq['RWrist_Z_Velo'].diff()/framerate)

df_Kinematic_Seq['RElbow_X_Accel'] =
(df_Kinematic_Seq['RElbow_X_Velo'].diff()/framerate)
df_Kinematic_Seq['RElbow_Y_Accel'] =
(df_Kinematic_Seq['RElbow_Y_Velo'].diff()/framerate)
df_Kinematic_Seq['RElbow_Z_Accel'] =
(df_Kinematic_Seq['RElbow_Z_Velo'].diff()/framerate)

df_Kinematic_Seq['RShoulder_X_Accel'] =
(df_Kinematic_Seq['RShoulder_X_Velo'].diff()/framerate)
df_Kinematic_Seq['RShoulder_Y_Accel'] =
(df_Kinematic_Seq['RShoulder_Y_Velo'].diff()/framerate)
df_Kinematic_Seq['RShoulder_Z_Accel'] =
(df_Kinematic_Seq['RShoulder_Z_Velo'].diff()/framerate)

df_Kinematic_Seq['Rarm_Angle'] =
np.degrees(np.arccos(((df_Kinematic_Seq['RShoulderX_N']-df_Kinematic_Seq['
RElbowX_N'])*(df_Kinematic_Seq['RWristX_N']-df_Kinematic_Seq['RElbowX_N'])
+(df_Kinematic_Seq['RShoulderY_N']-df_Kinematic_Seq['RElbowY_N'])*(df_Kine
matic_Seq['RWristY_N']-df_Kinematic_Seq['RElbowY_N'])+(df_Kinematic_Seq['R
ShoulderZ_N']-df_Kinematic_Seq['RElbowZ_N'])*(df_Kinematic_Seq['RWristZ_N'
]-df_Kinematic_Seq['RElbowZ_N'])) /
(((df_Kinematic_Seq['RShoulderX_N']-df_Kinematic_Seq['RElbowX_N'])**2)+((d
f_Kinematic_Seq['RShoulderY_N']-df_Kinematic_Seq['RElbowY_N'])**2)+((df_Ki
```

```
nematic_Seq['RShoulderZ_N']-df_Kinematic_Seq['RElbowZ_N'])**2)*(((df_Kinem
atic_Seq['RWristX_N']-df_Kinematic_Seq['RElbowX_N'])**2)+((df_Kinematic_Se
q['RWristY_N']-df_Kinematic_Seq['RElbowY_N'])**2)+((df_Kinematic_Seq['RWri
stZ_N']-df_Kinematic_Seq['RElbowZ_N'])**2)))))
df_Kinematic_Seq['Rarm_Angle_Velo']                                       =
(df_Kinematic_Seq['Rarm_Angle'].diff()/framerate)
df_Kinematic_Seq['Rarm_Angle_Accel']                                      =
(df_Kinematic_Seq['Rarm_Angle_Velo'].diff()/framerate)



#df_RArm_Vari_filt=df_RArm_Vari_filt.dropna()
#df_RArm_Vari_filt.isna().sum()
#df_RArm_Vari_filt

df_RArm_Vari_filt1   =   df_Kinematic_Seq[df_Kinematic_Seq['Pitch_Time']   >
-1.95]
df_Kinematic_Seq_Filt                                                     =
df_RArm_Vari_filt1[df_RArm_Vari_filt1['Pitch_Time'] < 0]

df_Kinematic_Seq0                                                         =
df_Kinematic_Seq_Filt[df_Kinematic_Seq_Filt['Game_Num'] != 12]
df_Kinematic_Seq2 = df_Kinematic_Seq0[df_Kinematic_Seq0['Game_Num'] != 2]
df_Kinematic_Seq_Filt = df_Kinematic_Seq2[df_Kinematic_Seq2['Game_Num'] !=
7]

df_Kinematic_Seq_Filt
```

```
ColB = df_Kinematic_Seq_Filt.columns.get_loc("Game_Num")
ColC = df_Kinematic_Seq_Filt.columns.get_loc("PitchNum")

ColA = df_Kinematic_Seq_Filt.columns.get_loc("Uuid")

df_Kinematic_Max = []
game_last = 0

for index in range(len(df_Kinematic_Seq_Filt)):
 game_curr = df_Kinematic_Seq_Filt.iloc[index, ColA]

 if game_curr == game_last:
```

```
    pass
  else:
    game_last = game_curr
    game_num = df_Kinematic_Seq_Filt.iloc[index, ColB]
    ptich_num = df_Kinematic_Seq_Filt.iloc[index, ColC]

    df_current_pitch = df_Kinematic_Seq_Filt[(df_Kinematic_Seq_Filt["Uuid"]
== game_curr)]
                                              Max_Wrist_Velo              =
df_current_pitch.loc[df_current_pitch['RWrist_Y_Velo'].idxmin()]['Pitch_Ti
me']
                                            Max_Wrist_Velo_Ft             =
df_current_pitch.loc[df_current_pitch['RWrist_Y_Velo'].idxmin()]['RWrist_Y
_Velo']

                                              Max_Elbow_Velo              =
df_current_pitch.loc[df_current_pitch['RElbow_Y_Velo'].idxmin()]['Pitch_Ti
me']
                                            Max_Elbow_Velo_Ft             =
df_current_pitch.loc[df_current_pitch['RElbow_Y_Velo'].idxmin()]['RElbow_Y
_Velo']

                                            Max_Shoulder_Velo             =
df_current_pitch.loc[df_current_pitch['RShoulder_Y_Velo'].idxmin()]['Pitch
_Time']
                                         Max_Shoulder_Velo_Ft             =
df_current_pitch.loc[df_current_pitch['RShoulder_Y_Velo'].idxmin()]['RShou
lder_Y_Velo']
    df_Kinematic_Max.append ({
        'Uuid': game_curr,
        'Game_Num': game_num,
        'PitchNum': ptich_num,
        'Max_WristY_Velo_Time': Max_Wrist_Velo,
        'Max_WristY_Velo_Value':Max_Wrist_Velo_Ft,
        'Max_ElbowY_Velo_Time': Max_Elbow_Velo,
        'Max_ElbowY_Velo_Value': Max_Elbow_Velo_Ft,
        'Max_ShoulderY_Velo_Time': Max_Shoulder_Velo,
        'Max_ShoulderY_Velo_Value': Max_Shoulder_Velo_Ft,
        })
```

```
df_Kinematic_Max = pd.DataFrame(df_Kinematic_Max) #Making it a dataframe
df_Kinematic_Max      =      df_Kinematic_Max.drop_duplicates(keep='first')
#Dropping duplicates
df_Kinematic_Max_Final = df_Kinematic_Max.reset_index()

df_Kinematic_Max_Final0                                                    =
df_Kinematic_Max_Final[df_Kinematic_Max_Final['Game_Num'] != 12]
df_Kinematic_Max_Final2                                                    =
df_Kinematic_Max_Final0[df_Kinematic_Max_Final0['Game_Num'] != 2]
df_Kinematic_Max_Final                                                     =
df_Kinematic_Max_Final2[df_Kinematic_Max_Final2['Game_Num'] != 7]

df_Kinematic_Max_Final
```

```
df_Kinematic_Max_Final['Wrist_Elbow_Time_Diff']                            =
df_Kinematic_Max_Final['Max_ElbowY_Velo_Time']-df_Kinematic_Max_Final['Max
_WristY_Velo_Time']
df_Kinematic_Max_Final['Elbow_Shoulder_Time_Diff']                         =
df_Kinematic_Max_Final['Max_ShoulderY_Velo_Time']-df_Kinematic_Max_Final['
Max_ElbowY_Velo_Time']

ColA  =  df_Kinematic_Max_Final.columns.get_loc("Max_ShoulderY_Velo_Time")
#Locating column
ColB   =   df_Kinematic_Max_Final.columns.get_loc("Max_ElbowY_Velo_Time")
#Locating column
ColC   =   df_Kinematic_Max_Final.columns.get_loc("Max_WristY_Velo_Time")
#Locating column
Shoulder_AVG = df_Kinematic_Max_Final['Max_ShoulderY_Velo_Time'].mean()
Shoulder_STD = df_Kinematic_Max_Final['Max_ShoulderY_Velo_Time'].std()

Shoulder_Min = Shoulder_AVG - Shoulder_STD

for pitch in range(len(df_Kinematic_Max_Final)): #Running through all rows
in dataframe
 Max_Shoulder  = df_Kinematic_Max_Final.iloc[pitch, ColA] #Getting column
value for each pitch
  Max_Elbow  =  df_Kinematic_Max_Final.iloc[pitch,  ColB]  #Getting  column
value for each pitch
  Max_Wrist  =  df_Kinematic_Max_Final.iloc[pitch,  ColC]  #Getting  column
value for each pitch
```

```
  if    Max_Shoulder  >  Shoulder_Min  and  Max_Shoulder  <  Max_Elbow  and
Max_Elbow < Max_Wrist: #Seeing if pitch sequence was a success
   df_Kinematic_Max_Final.loc[pitch, ['Kinetic_Chain']] = [1] #1 if true
 else:
        df_Kinematic_Max_Final.loc[pitch,  ['Kinetic_Chain']]  =  [0]  #0  if
false
```

Appendix F: Rate of Force Development on the Shoulder - Concept 5 Code

```
######################################                              VELO
###########################################################

df_Kinematic_Seq['RShoulder_X_Velo']                                   =
(df_Kinematic_Seq['RShoulderX_N'].diff()/framerate)
df_Kinematic_Seq['RShoulder_Y_Velo']                                   =
(df_Kinematic_Seq['RShoulderY_N'].diff()/framerate)
df_Kinematic_Seq['RShoulder_Z_Velo']                                   =
(df_Kinematic_Seq['RShoulderZ_N'].diff()/framerate)

######################################                             ACCEL
###########################################################
df_Kinematic_Seq['RShoulder_X_Accel']                                  =
(df_Kinematic_Seq['RShoulder_X_Velo'].diff()/framerate)
df_Kinematic_Seq['RShoulder_Y_Accel']                                  =
(df_Kinematic_Seq['RShoulder_Y_Velo'].diff()/framerate)
df_Kinematic_Seq['RShoulder_Z_Accel']                                  =
(df_Kinematic_Seq['RShoulder_Z_Velo'].diff()/framerate)

df_Kinematic_Seq['RShoulder_X_Force']                                  =
df_Kinematic_Seq['RShoulder_X_Accel']*2.58
df_Kinematic_Seq['RShoulder_Y_Force']                                  =
df_Kinematic_Seq['RShoulder_Y_Accel']*2.58
df_Kinematic_Seq['RShoulder_Z_Force']                                  =
df_Kinematic_Seq['RShoulder_Z_Accel']*2.58
```

Appendix G: Rest Time Analysis Code

```
# Get gametime_into seconds

def time_frame(t):
 h = 0 #set hours
 m = 0 #set minutes
 s = 0 #set seconds

 h = int(t[0:t.index(':')]) # the hours in this string are before the
first :
 t = t[t.index(':') + 1 : len(t)] # this removes the string up to and
including the first :

 m = int(t[0:t.index(':')]) # the minutes is from the start of the NEW
string to the :
 t = t[t.index(':') + 1 : len(t)] # removes minutes from the string

 s = int(t[0:t.index(' ')]) # the seconds is up to the " " before the PM
in the file
 # print(h,m,s) #proof

 sec = (h * 3600) + (m * 60) + s # convert the time frame into seconds
 # print(sec) #proof
 return sec #give me the number

vals = df_meta["Game_Time"]
df_meta['time_sec'] = ""
for i in range (0, len(vals)):
 new_time = time_frame(vals[i])
 df_meta.at[i, 'time_sec'] = new_time
from datetime import datetime

df_meta_TEST = df_meta
ColA = df_meta_TEST.columns.get_loc("Game_Num")
ColB = df_meta_TEST.columns.get_loc("PitchNum")
ColC = df_meta_TEST.columns.get_loc("time_sec")

df_Meta_Simp= []
```

```python
for index in range(len(df_meta_TEST)):
 game_curr = df_meta_TEST.iloc[index, ColA]
 pitch_curr = df_meta_TEST.iloc[index, ColB]
 time_curr = df_meta_TEST.iloc[index, ColC]


 df_current_game = df_meta_TEST[(df_meta_TEST["Game_Num"] == game_curr)]

 Game_Start = df_current_game['time_sec'].min()
 norm_time = time_curr-Game_Start

 df_Meta_Simp.append ({
     'Game_Num': game_curr,
     'PitchNum': pitch_curr,
     'time_sec_N': norm_time,
      })
 df_Meta_Simp = pd.DataFrame(df_Meta_Simp) #Making it a dataframe
df_Meta_Simp    =    df_Meta_Simp.drop_duplicates(keep='first')    #Dropping
duplicates


df_meta = pd.merge(df_meta, df_Meta_Simp, on=['Game_Num', 'PitchNum'])
```

Appendix H: IRB Approval Letter

WORCESTER POLYTECHNIC INSTITUTE

100 INSTITUTE ROAD, WORCESTER MA 01609 USA

Institutional Review Board
FWA #00030698 - HHS #00007374

Notification of IRB Approval

Date :	08-Nov-2022
PI:	Karen Troy
Protocol Number:	IRB-23-0202
Protocol Title:	Defining and Validating a Fatigue Metric for Baseball Pitchers using Biomechanics
Approved Study Personnel:	Troy, Karen~Kokernak, Charlotte M~Ngan, Amy H~Johns, Kyle T~Murray, Crystal J~
Start Date:	08-Nov-2022
Expiration Date:	07-Nov-2023
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 07-Nov-2023 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 I: Informed Consent Agreement Agreement for Participation in a Research Study- As Approved by the Worcester Polytechnic Institutional Review Board

Informed Consent Agreement for Participation in a Research Study: Defining and Evaluating Fatigue Metric in Baseball Pitchers

Investigator: Kyle Johns, Charlotte Kokernak, Crystal Murray, Amy Ngan

Contact Information:
Worcester Polytechnic Institute
100 Institute Dr.
Worcester, MA 01609
Email: gr.troyMQP23@wpi.edu
Sponsor: Karen Troy Ph.D

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 have a fully informed decision regarding your participation.

Purpose of the study:

The goal of this study is to understand how baseball pitchers get fatigued when pitching. To measure how tired a pitcher is, the team will look at the throwing mechanics of a pitcher, and this will be captured using a motion capture system. Every year thousands of baseball players get hurt due to being overworked and fatigued, so this study is designed to evaluate early warning signs of fatigue through the means of motion capture, force plate, and accelerometer sensor data. The defined metric will be able to detect variation among biomechanical metrics such as mechanical variation, flexibility, and power production.

Procedures to be followed:

Preparation:

We will ask you to wear close-fitting clothing so it will more accurately measure the body's motion. We will place reflective markers on your skin using a light adhesive. We will also place small sensors that measure the arm's movement on the surface of your skin using a light adhesive. In addition, the team will supply the user with an apple watch, unless the participant already has one, to collect heart rate and overall workout metrics. Placing the reflective markers and sensors on your skin usually takes 30 to 45 minutes.

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WPI IRB-1
11/8/2022 to 11/7/2023

Testing:

We will ask you to complete a pitching and exercise activity that is broken down into 3 different phases. During phase 0, we will ask you to stretch similarly to their pre-game stretch procedure. We will ask you for a self-assessment of your current level of fatigue, and relevant injury history. During phase 1, we will ask you to throw a series of pitches (no greater than 40) indoors into a net. You will then be asked for a self-assessment of your fatigue level following this initial pitching series. Next is the fatigue cycle, where you will perform a variety of dynamic cardio and general strength exercises for a period of time (no more than 15 minutes), broken up by periods of rest. You will then be asked for a self-assessment of your fatigue level following this exercising session. During phase 2 you will be asked to throw a series of pitches (no greater than 40) indoors into a net. You will then be asked for a self-assessment of your fatigue level following this secondary pitching series.

Photographs:

Please initial the box below if you are willing to give us permission to take photographs or video during the biomechanics testing. Any photographs or video that are presented publicly or shared in any way will have your face blurred out and will be presented for scientific purposes only.

________ I give permission to have my photograph or video taken during this research. I understand that I can revoke this permission at any time by contacting the research team.

Risks to study participants:

The participant, who is a collegiate varsity baseball player, will be throwing a baseball and will experience fatigue. Participants may experience soreness after throwing and will be put through a high intensity interval training regiment to fatigue them during the data collection session. The throwing section and fatigue cycle may cause soreness to the participants muscles.

Benefits to research participants and others:

This study revolves around analyzing fatigue, which is very much tailored toward the individual. By participating in this study, our team will be able to help inform the participant of their early warning signs of fatigue such as mechanical variation or smaller joint range of motions. This participant then would be able to take this information and use it to improve their fatigue level or be able to identify the period where fatigue increases accurately.

Alternative procedures or treatments available to potential research participants:

There are no alternative procedures or treatments available to potential research participants.

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WPI IRB-1
11/8/2022 to 11/7/2023

Record keeping and confidentiality:
For this study, we will assign you a unique identifier, which will be used to link all of your data. Your name will never be shared outside of the study team. Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsors and, under certain circumstances, the Worcester Polytechnic 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:
In the event of injury during your participation in this data collection, you may seek medical treatment through your regular care provider. No compensation will be provided. You do not give up any of your legal rights by signing this statement.

Cost/Payment:
Participants will be compensated with $15 in the form of either cash or a visa gift card for participating in the data collection part of the study.

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

Name	Cell Phone Number	Email
Kyle Johns	732-599-4277	ktjohns@wpi.edu
Charlotte Kokernak	518-878-6567	cmkokernak@wpi.edu
Crystal Murray	401-280-5098	cjmurray@wpi.edu
Amy Ngan	781-502-5990	ahngan@wpi.edu
Ruth McKeogh	508-831-6699	irb@wpi.edu
Gabriel Johnson	508-831-4989	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.

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WPI IRB-1
11/8/2022 to 11/7/2023

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.

Study Participant Signature ____________________________

Date: ____________________

Study Participant Name (Please print) _____________________________________

Date: ____________________

Signature of Person who explained this study____________________________

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WPI IRB-1
11/8/2022 to 11/7/2023

Appendix J: WPI Collegiate Pitcher Data Collection Procedure

PracticePoint Data Collection Procedure

Created/Modified: Crystal Murray/Charlotte Kokernak/Amy Ngan: 04/17/23
2022-2023 MQP: Metric to Characterize Baseball Pitcher Fatigue

The following is the procedure used with the modifications developed as the procedure was used. The IRB associated with this procedure/study is: IRB-23-0202.

Marker Set

Final Marker Set

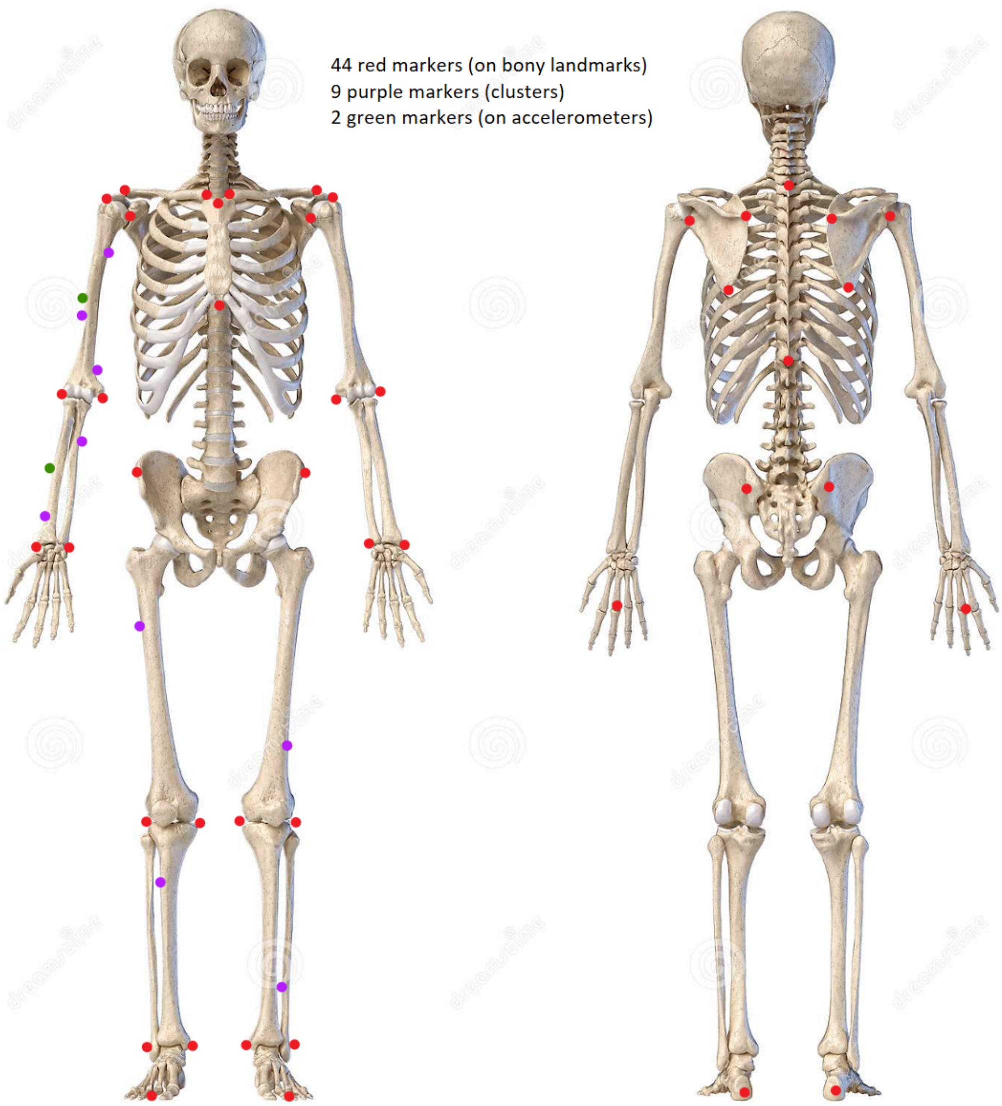


Figure 1. Final Marker Set for a right handed pitcher (with the exception of the toe on the leg of the throwing arm side)

Total of 54 markers

Upper Body

- **Throwing Arm**
    - **Medial Humeral Epicondyle (Medial Elbow)**
    - **Lateral Humeral Epicondyle (Lateral Elbow)**
    - **Ulnar Styloid (Pinky side of wrist)**
    - **Radial Styloid (Thumb side of wrist)**
    - **2nd Metacarpal (Knuckle)**
    - **Bicep Accelerometer**
    - **Forearm Accelerometer**
    - **Humeral Cluster 1 (Proximal)**
    - **Humeral Cluster 2 (Middle)**
    - **Humeral Cluster 3 (Distal)**
    - **Forearm Cluster 1 (Proximal)**
    - **Forearm Cluster 2 (Distal)**
- **Non-Throwing Arm**
    - **Medial Humeral Epicondyle (Medial Elbow)**
    - **Lateral Humeral Epicondyle (Lateral Elbow)**
    - **Ulnar Styloid (Pinky side of wrist)**
    - **Radial Styloid (Thumb side of wrist)**
    - **2nd Metacarpal (Knuckle/Glove)**
- **Shoulder (Throwing Arm)**
    - **Anterior Proximal Humerus (Anterior Gleno socket)**
    - **Posterior Proximal Humerus (Posterior Gleno socket)**
    - **Acromion (End of shoulder)**
    - **Acromioclavicular Joint (Distal Clavicular Joint)**
- **Shoulder (Non-Throwing Arm)**
    - **Anterior Proximal Humerus (Anterior Gleno socket)**
    - **Posterior Proximal Humerus (Posterior Gleno socket)**
    - **Acromion (End of shoulder)**
    - **Acromioclavicular Joint (Distal Clavicular Joint)**
- **Trunk (Anterior)**
    - **Sternoclavicular Joint (Throwing Arm Side)**
    - **Sternoclavicular Joint (Non-Throwing Arm Side)**
    - **Sternum/Suprasternal notch (Between the 2 SC Joints)**
    - **Xiphoid Process (Bottom of Sternum)**
- **Trunk (Posterior)**
    - **Trigonum Spinae Scapulae (Top bump of shoulder blade)**

    - Inferior Angle of Scapula (Bottom tip of shoulder blade)
    - C7 (Bottom of Neck - line of spine)
    - T8 (Bottom of rib cage - line of spine)
- Hips
    - Anterior Superior Iliac Spine (Throwing Arm Side)
    - Anterior Superior Iliac Spine (Non-Throwing Arm Side)
    - Posterior Superior Iliac Spine (Throwing Arm Side)
    - Posterior Superior Iliac Spine (Non-Throwing Arm Side)
- Lower Limb (Throwing Side)
    - Medial Femoral Condyle (Medial Knee)
    - Lateral Femoral Condyle (Lateral Knee)
    - Medial Malleolus (Medial Ankle)
    - Lateral Malleolus (Lateral Ankle)
    - Heel
    - Thigh Cluster (Distal)
    - Shank Cluster (Distal)
- Lower Limb (Non-Throwing Side)
    - Medial Femoral Condyle (Medial Knee)
    - Lateral Femoral Condyle (Lateral Knee)
    - Medial Malleolus (Medial Ankle)
    - Lateral Malleolus (Lateral Ankle)
    - Heel
    - Toe
    - Thigh Cluster (Proximal)
    - Shank Cluster (Proximal)

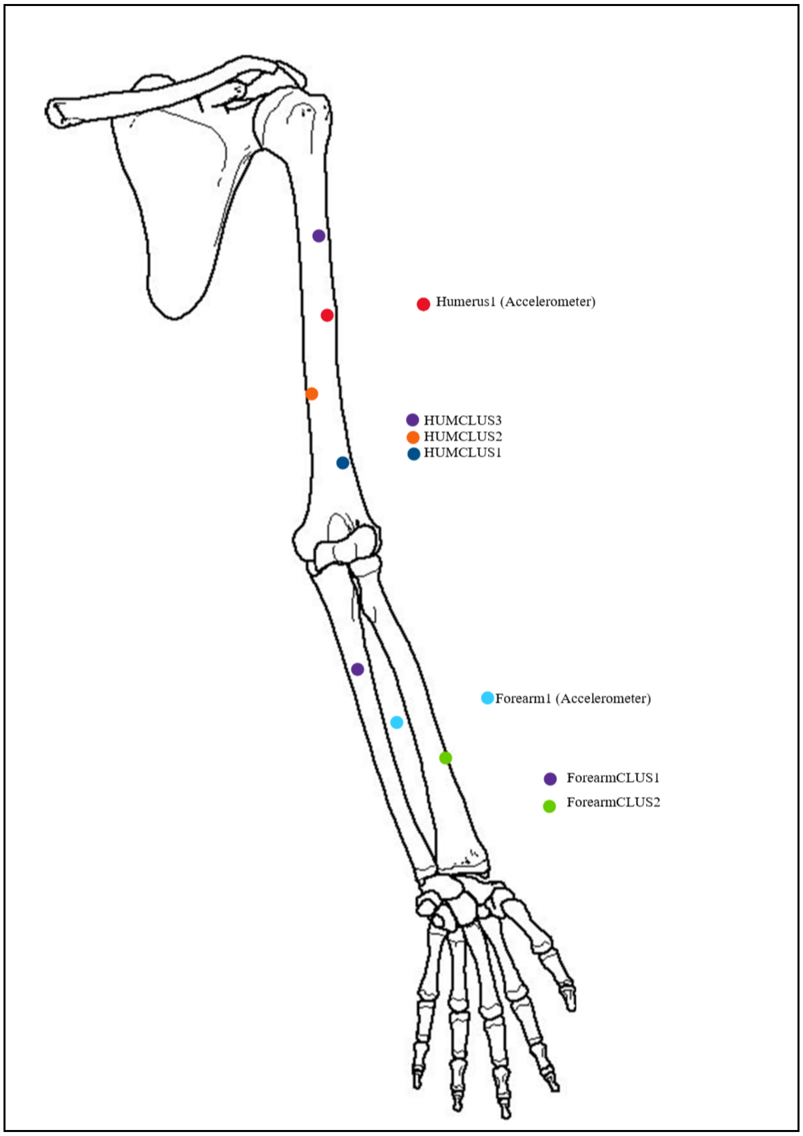


Figure 2. Diagram of the team's cluster and accelerometer marker labeling conventions in Vicon/Nexus

HUMCLUS1,2,3 is scattered on the arm
Humerus1,2,3 is the EMG sensor

ForearmCLUS1 is random marker
Forearm1,2,3 is on EMG

Notes on marker set:

- C7 and T8 markers are not always on that exact vertebrae, but they are in line with the spine. Difficulty finding these on some participants, it was deemed not critical if these markers were placed on C6 vs C7 for example for our analysis

- Custer positions will vary as well, but there are always proximal/distal ones as described in the marker set. Again, not deemed critical on exact placement for these, especially since there is no bony landmark for them
- Markers on the feet were placed on the participants shoes (aka, heel was placed on the outside of the sole of the shoe) - see marker set appendix for examples
- Toe marker on throwing side of participant was removed due to the consistency of pitchers dragging this toe, the marker always fell off
- All markers were placed by mqp team members with the exception of the ones on the hips, where participants were described what to feel to find these landmarks, and the mqp team placed the marker based on the identified location.
- The anterior/posterior geno sockets were placed based on feeling where the socket on the pitcher is. This marker is likely subject to some error due to muscle mass in some pitcher's shoulders, making this location more difficult to find.
- Markers such as the knuckle, wrist and arm clusters were some that consistently fell off during trials.
- For lefties, everything was consistent, except the left and right arm accelerometers and clusters were flipped to focus on the pitcher's throwing arm
- Clavicle and shoulder markers are easiest to find when the person putting them on follows the collarbone from the medial point to the lateral point of the bone
- Scapula markers easiest to find when they move their shoulders around a bit
- https://www.c-motion.com/v3dwiki/index.php/Marker_Set_Guidelines#Upper_Arm_and_Lower_Arm_Segment

Prior to Data Collection

Materials

- Materials from us
  - KT tape (place on wrist and gleno-markers)
  - Athletic tape (for all markers)
  - Resistance bands (if participant does not have their own)
  - Towel (if participant does not have their own)
  - Markers
  - Marker double sided tape (should be provided by PracticePoint)
  - IRB consent document
  - Financial compensation
- Materials from participant
  - Athletic clothing
  - Water

Procedure

PracticePoint Setup

- Move net into place
- Check all cameras are pointed in the direction of the force plates, and will capture area slightly in front of the force plates (where the pitcher will be at the conclusion of the pitch)

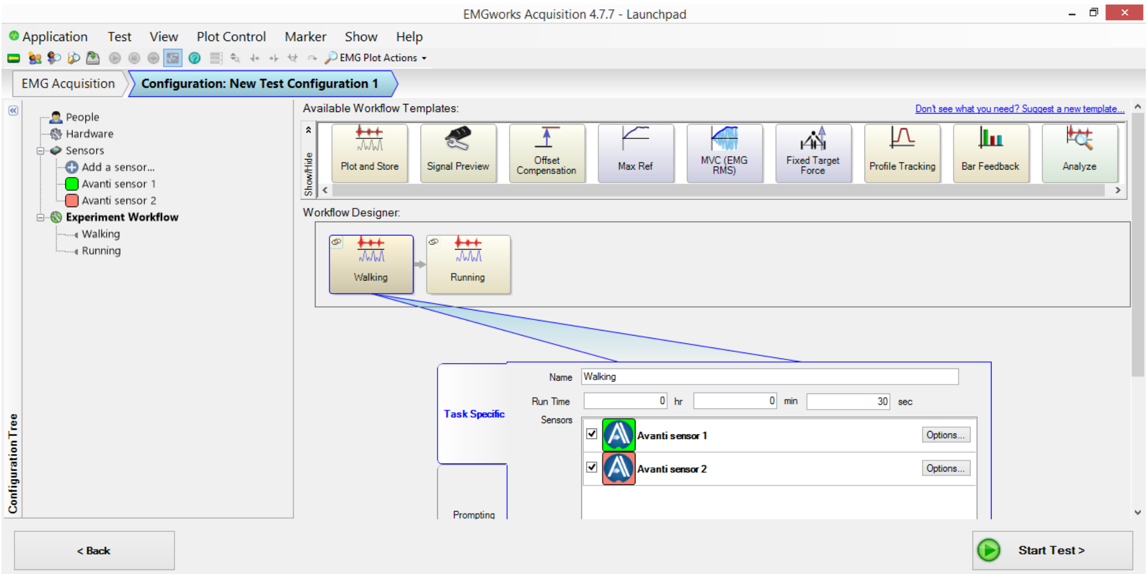
Opening Vicon

- Turn on cameras about 20 mins before calibration
- Plug in the system into the vicon main compartment (it will light up and turn blue when it is ready)
- Open Vicon Nexus 2.8.1 on computer
  - Locate Pitching MQP 2023 folder
  - Find subject or create new
  - Create a folder within subject folder titled the date (i.e "11_16")
- Grayscale mode "ALL" - shows everything (change from 3D perspective to camera view on left dropdown menu)

Participant Arrival

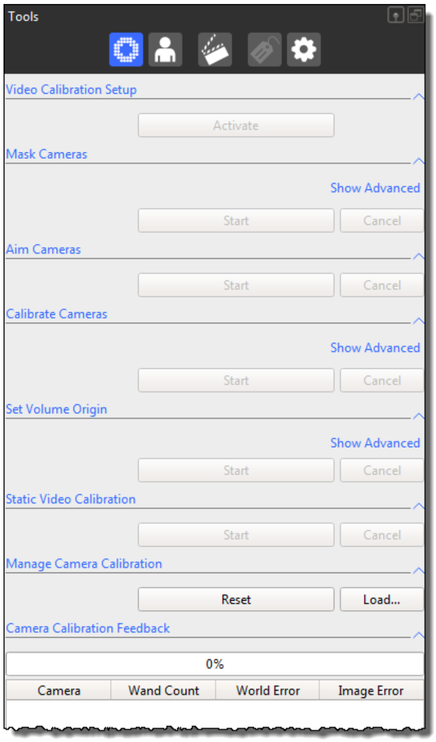
- Sign IRB informed consent document
- Participant will perform their warm-up exercises / pitches / stretches prior to entering motion capture room
- While participant is warming up, Vicon/Nexus system is being warmed up
  - Linking Vicon system to EMG Acquisition
  - Connect accelerometers
  - Begin placing tape on markers

EMG Setup



- Also open EMG works application
  - Navigate to “Pitching MQP 2023” folder
    - This PC → OC (C:) → Users → Public → Public Documents → Vicon Data → Pitching MQP2023
  - Find subject folder or create new
  - Create a folder within subject folder titled the date (i.e “11_16”)
- Click “run test,” get to main testing dashboard
- Click arrow button, this will bring up a dashboard to connect EMGs to
  - Take an EMG out of case and hold it over magnet “lock” sticker
  - Repeat for desired amount of sensors
    - They are already programmed to be assigned up the bicep and then the forearm
- Click “Plot and Store”
  - Ensure the settings show EMG and Mag uncheck for each sensor and the time is set to 4 minutes
- Click “start test”
  - Click to save it to team folder
- Click “Run Task”
  - Click “start” when ready to collect data
  - Recommended: run a test run and move both accelerometers to ensure they are working properly

<u>Camera Calibration</u>



- Follow steps top to bottom on dashboard shown to the right, beginning with masking the cameras
- Mask cameras (takes about 10 seconds)
  - Ignores other unwanted objects in room that may be picked up by cameras
  - Make sure the subject is not in the room w/ markers on
    - Can be in the back room, behind the wall
  - Make sure the markers aren't seen on table, should be hidden
  - Glasses can be picked up on this, it is recommended they are not in sight either
- Aim Cameras
    - Place wand on force plates
    - Click aim cameras
- Calibrate cameras
  - Have a team member get the calibration wand turn it on so the red lights are visible
  - Hit “start” on Vicon dashboard
  - Begin the wand wave process by doing figure-8, looping motions, while walking around the room (staying within circle of cameras)
    - Don't do repetitive motions
    - Don’t stay in one place
    - Don’t get too close to cameras (5-6ft away)
    - If you wave the wand lower may be able to capture more cameras together at the same time
    - Little circles (pies) on the camera’s tell you how complete each camera is

            - Camera 5 is covered by the net- team member might need to wave wand higher so it can see over the night
        - When complete, the system will say “Wand wave complete”
        - Before doing anything else, wait for the calibration to complete in the system- it is done when the system reads “Calibration Complete”
- Calibrate Origin
    - Make sure it is set to Camera view - 3D perspective
    - Place calibration wand on the floor in the force plates, little plates dip into the location of the force plates, use the screws to get it level with the little bubble inside
    - Under “Set Volume Origin,” click “start
    - Then click “set origin”
- Plug wand back in on the wall
- Establish force plate coordinates (dimensions in blue book)
    - On Vicon interface click Force Plate 1 and “show advanced”
    - Position (x,y,z) and rotation (x,y,z)
        - FP1 (-200, 300, 0) and rotation (0,0,180)
        - FP2 (200, 300, 0) and rotation (0,0,180)
        - Check they are setup properly by having someone stand on force plate- make sure where they step matches on Vicon force plates
- Ensure the sampling rate is set correctly
    - Click on Vicon cameras and “show advanced”
    - Make sampling rate 300 Hz
    - Further down, the settings may have a warning sign, and you may need to adjust the “requested sampling rate” to 300 Hz here too

<u>Marker Placement</u>

- Use pen or marker to label all markers prior to putting on the markers (that way when they fall off they can be placed on the site of the mark)
- Double side tape all markers
    - Easy to place all markers on a strip of tape (staggering them) and then cut each marker away individually
- All markers are 14mm, with the exception of the sternoclavicular joint on both sides, and the sternum/suprasternal notch, and the two accelerometers, which are the 10mm
- Do not use reflective tape
- Marker set used is modified from Helen Hayes / Glen Flasig / Karen Troy marker sets - detailed in the marker set section of this doc
-

<u>Participant Questions</u>

- Is participant a lefty or righty?

- Before first pitching session, after first pitching session, after fatigue cycle, and after second pitching session Fatigue level and heart rate collected
    - Rate your level of perceived exertion on a scale of 0-10. 0 being none, 10 being maximum level of exertion. How fatigued the person feels
        - Borg CR10 Scale

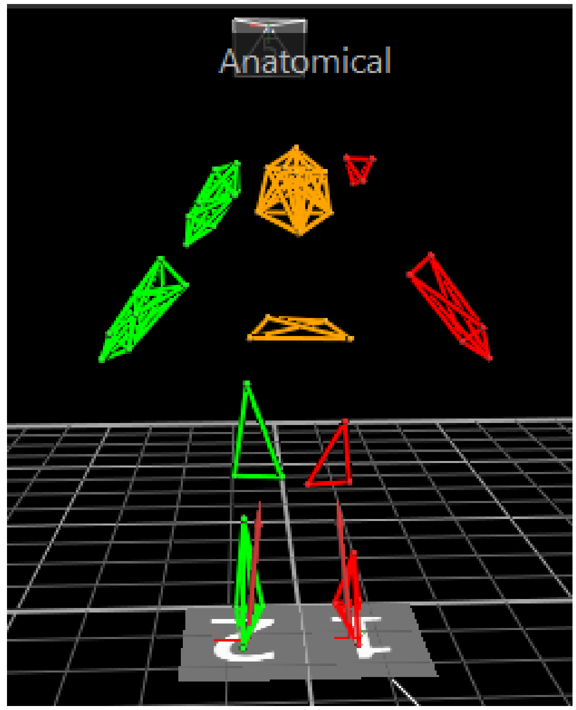
Scoring	Level of Exertion
0	No Exertion
0.5	Very very Slight
1	Very Slight
2	Slight
3	Moderate
4	Somewhat Severe
5	Severe
6	
7	Very Severe
8	
9	Very very Severe
10	Maximal

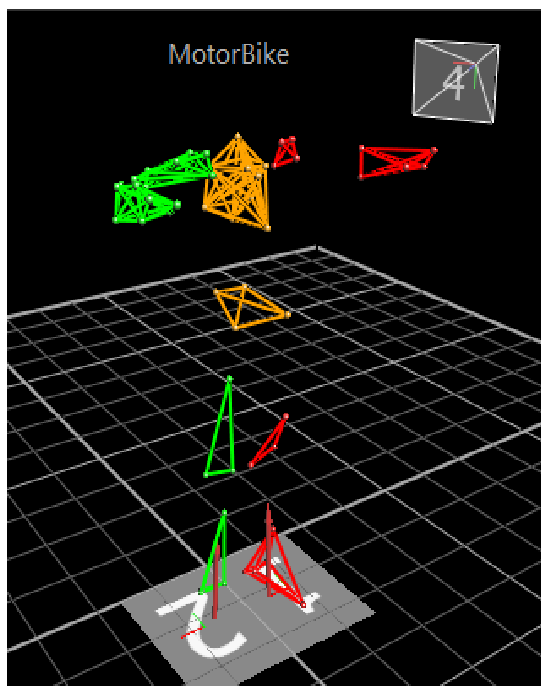
    - Heart rate - calculate using neck pulse (count beats for 15 seconds and multiply by 4 to get bpm)

Data Collection

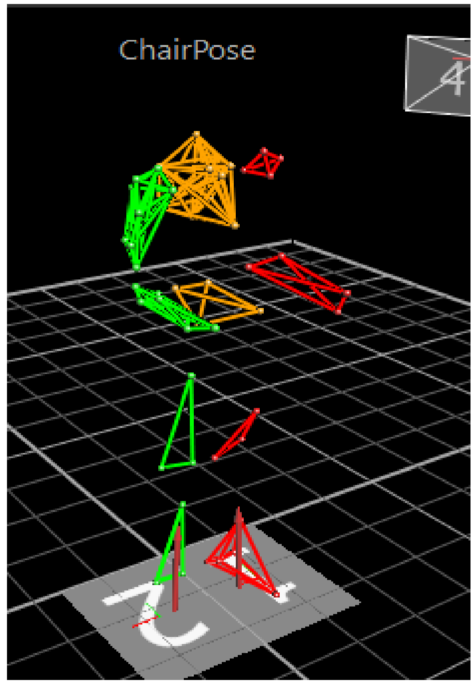
<u>Data Collection Procedure</u>

- Once participant is warmed up, has all markers on, and calibration is complete:
    - 3 static calibration poses
        - Anatomical
            - Participant faces the computers, in standing in anatomical position (palms facing forward, arms down and slightly away from body, and legs slightly spread

- 

■ Motor Bike
  - Participant faces the computers, lower legs in same position as anatomical, elbows abducted 90 degrees, forearms 90 degrees from upper arms, and palms facing down
  - 

■ Chair pose
  - Same as motor bike, except now with arms adducted, palms facing down

- 

- Pitching session 1 (pre-fatigue)
    - Throw 15 fastballs into the net
    - Any markers that fall off, replace them and make note of what marker fell off on what pitch number (to help determine the quality of each pitch for post processing)
    - Make sure they start on the force plate that we are collecting data on
    - Make sure to collect full pitch - wait for them to pitch after the system says “capture started” and end it after follow through of the pitch
    - If a camera is bumped, keep going (it is still collecting with the yellow ! icon)
    - If a camera goes offline - reboot it (it is not collecting with the red ! icon)
    - First 7 pitches, pitch with glove, remove glove for remaining pitches
    - Try to make the downtime between pitches as minimal as possible
    - Collect participant questions at the end of this session
- Fatigue cycle
    - Remove markers that might get in the way (toe marker / knuckle) during the exercise cycle.
    - Perform the following exercises - have someone time and make sure they are doing the exercises, and to let them know what exercise/rest to do
    - 3 sets of this to equate to approx 9 minutes of this exercise

Time (minutes:seconds)	Exercise
0:00-0:30	Burpees

0:30-0:45	*Rest*
0:45-1:15	Squats
1:15-1:30	*Rest*
1:30-2:00	Resistance Bands Pull Aparts
2:00-2:15	*Rest*
2:15-2:45	Pushups
2:45-3:00	*Rest*

    - During this time, if cameras were finicky, reboot or recalibrate the system to ensure quality data for the second pitching session
        - Dealing with the quality of the data at this stage is critical in saving time in the post processing part
    - Replace markers when done (re-draw markings if necessary)
    - Collect participant questions at the end of this session
- Pitching session 2 (post-fatigue)
    - Same procedure as pitching session 1
    - Collect participant questions at the end of this session
- Clean-up
    - Save data
    - Put markers, accelerometers & net back
    - Unplug Vicon and turn off force plates

<u>Begin Data Collection</u>

- When calibration is completed, bring the subject back into the room
- Click "Go Live"
- Have the subject stand on the force plates to perform a trigger test
    - This ensures all the markers are visible and that the EMG and Vicon systems are linked to start simultaneously
- Name the trial (i.e. Trigger Test)
- Then uncheck the button that says data collection stops after 1 second.
- Uncheck run pipeline after capture
- Click "Arm" and the lock button to the lock the system
    - Now the system is ready and waiting for something to trigger it to start
    - **Be sure to arm and lock before each trial run
    - Click start / stop on remote trigger
- On the EMG software, click "start"

    - This should automatically link with the Vicon software, and you will know it did when the software says "Capture Started"
- After the first run, navigate to the folder within file explorer and ensure the EMG data are uploading in real time
    - This PC → OC (C:) → Users → Public → Public Documents → Vicon Data → Pitching MQP2023 → Subject Folder
- After the trigger test is complete, perform the 3 static calibration tests with the subject
    - Anatomical
    - Motor Bike
    - Chair Pose
- Then the team is ready to collect pitching trials
    - Begin by naming the first trial "Pitching01"
        - The system will automatically make it increase numerically each trial

<u>Saving Trials</u>

- When data collection is complete, click "Go Offline" on Vicon
- Open a Vicon trial and click "reconstruct"
    - Or you can export and reconstruct all the files at once by checking the boxes for those options and clicking the "play" button
- The EMG data are automatically uploaded to the folder in file explorer
- Once the Vicon data are exported to the subject's folder, take the entire folder for that day (i.e. KJ→ 11_16) and put it on a flashdrive/network drive

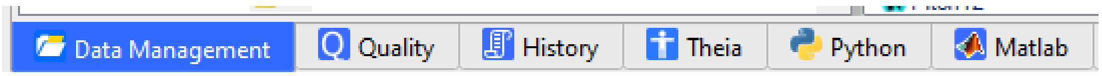
Appendix K: Vicon Nexus (v. 2.14) Standard Operating Procedure

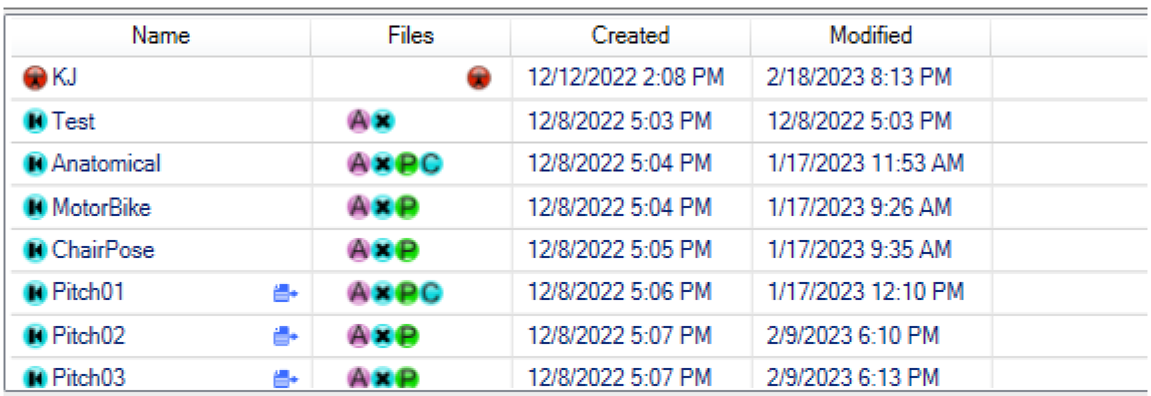
<u>Vicon Nexus (v.2.14) Standard Operating Procedure</u>

This standard operating procedure (SOP) will provide the necessary steps for proper post processing techniques in Vicon Nexus (v. 2.14). This includes marker naming, marker labeling, gap filling, and filtering. These are the crucial preparation work prior to advancing on to data extraction and exportation in softwares such as Visual3D.

Marker Naming in Vicon Nexus

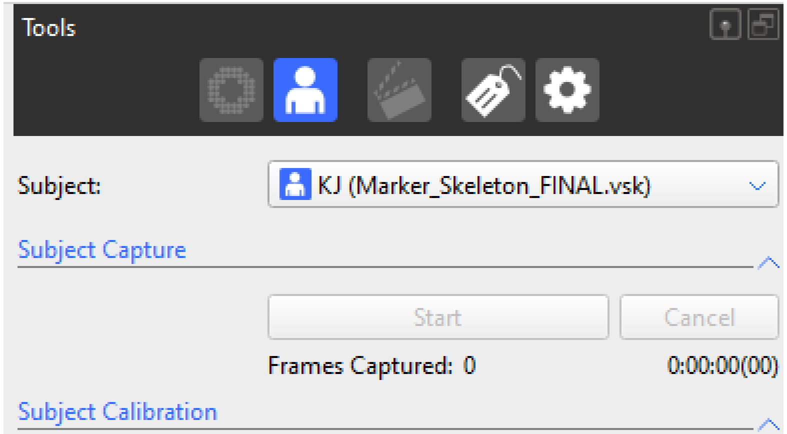
Prior to any marker labeling, the user must start with first organizing which markers go into which segment as well as any proper marker naming. The steps are as follows:

1. Open the Data Management tab at the bottom. This should be the default tab to open when Vicon Nexus is run.
   a. 

2. Navigate the folder where the trials are contained. When the folder is clicked, it should show the trial names, files, when it was created, and when it was modified. An example is shown below.
   a. 

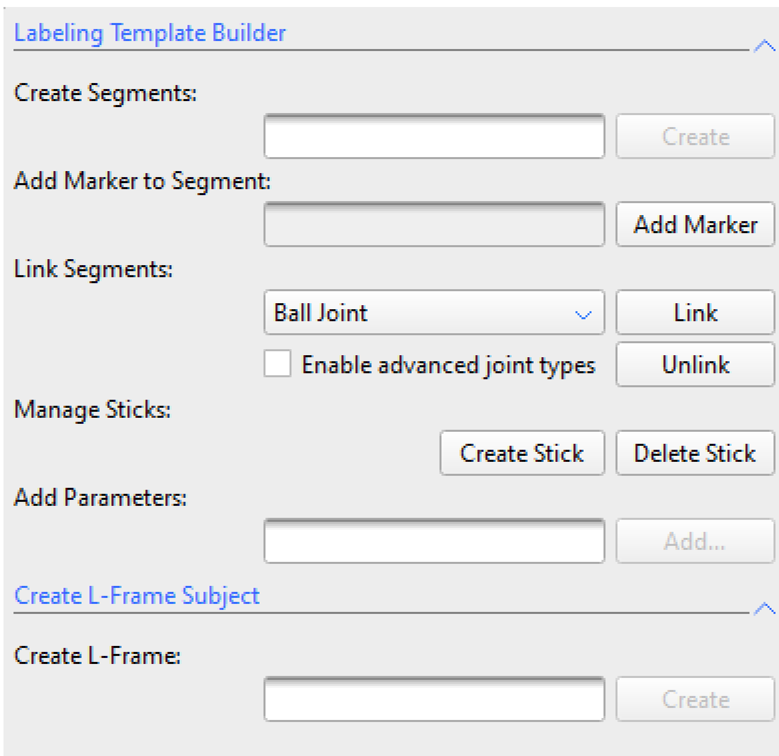
Name	Files	Created	Modified
KJ		12/12/2022 2:08 PM	2/18/2023 8:13 PM
Test		12/8/2022 5:03 PM	12/8/2022 5:03 PM
Anatomical		12/8/2022 5:04 PM	1/17/2023 11:53 AM
MotorBike		12/8/2022 5:04 PM	1/17/2023 9:26 AM
ChairPose		12/8/2022 5:05 PM	1/17/2023 9:35 AM
Pitch01		12/8/2022 5:06 PM	1/17/2023 12:10 PM
Pitch02		12/8/2022 5:07 PM	2/9/2023 6:10 PM
Pitch03		12/8/2022 5:07 PM	2/9/2023 6:13 PM

   b. The KJ is the "marker template"
3. The user should click on one of the static poses, typically the anatomical pose to start the marker naming process. Once this is done, hit the subject preparation under "tools" to start (typically on the top right). It is the person button highlighted in blue.



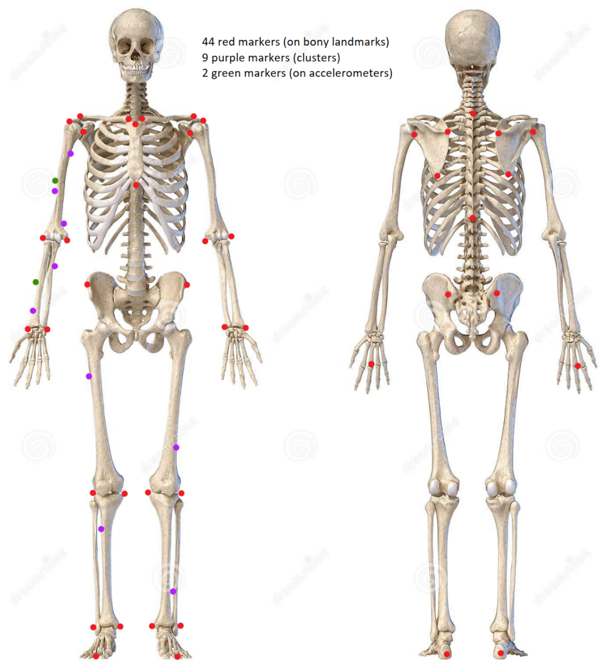
a.

4. It is important to have a sense of which markers would go into which segment. Typically, the rigid body markers, such as the torso and the pelvis, would be their own segment. The bottom image will produce a labeling template builder, where the user can create segments, name them, and add markers to the segments.



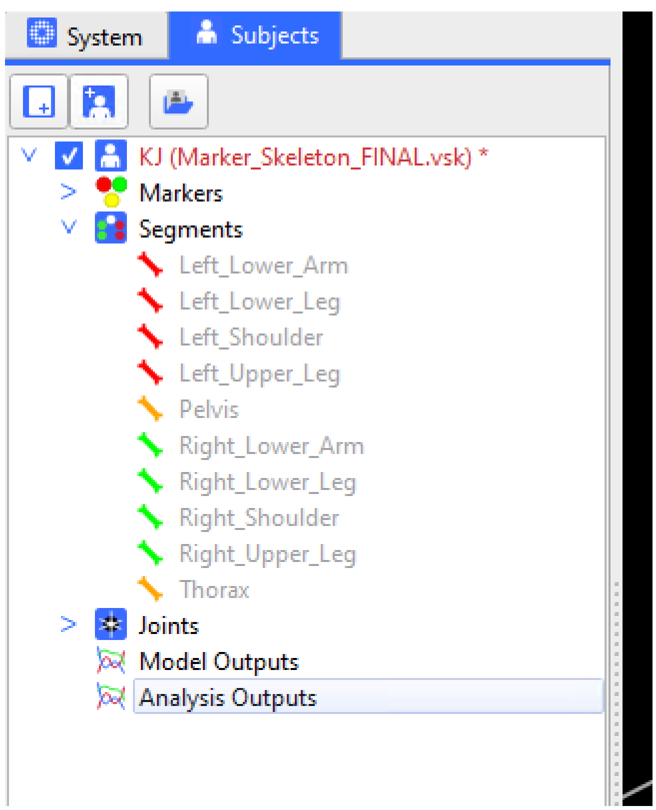
a.

5. Below is the marker set that the 2022-2023 - Troy - Baseball team used.

a. 

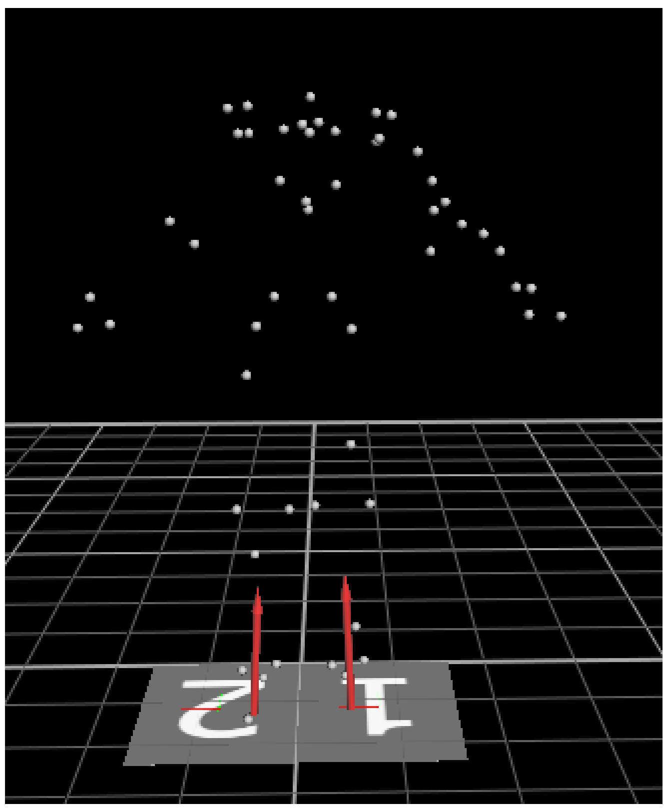
b. Please navigate to this link https://www.c-motion.com/v3dwiki/index.php/Marker_Set_Guidelines to view the naming conventions used for each marker

c. The segment names are shown below

i. 

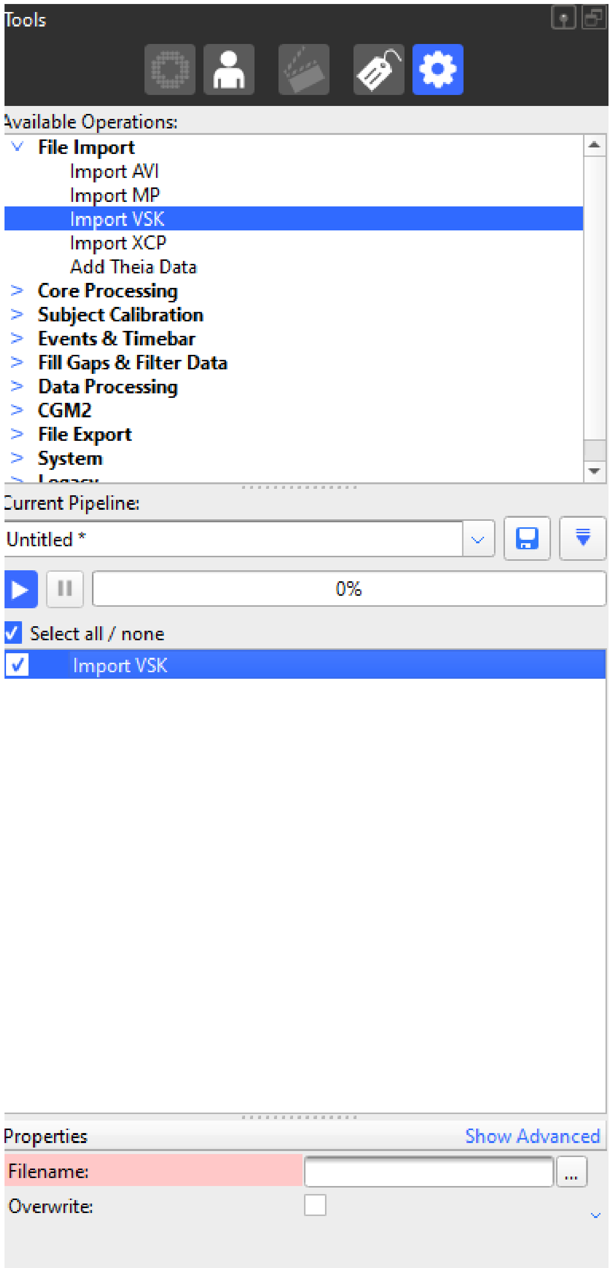
Marker Labeling in Vicon Nexus

After the finalization of the skeleton marker set, typically in a .vsk format, the next steps would be to label the markers. When the trial is clicked on, the user is presented with a cloud of grey markers. This indicates that the markers are "unlabeled"

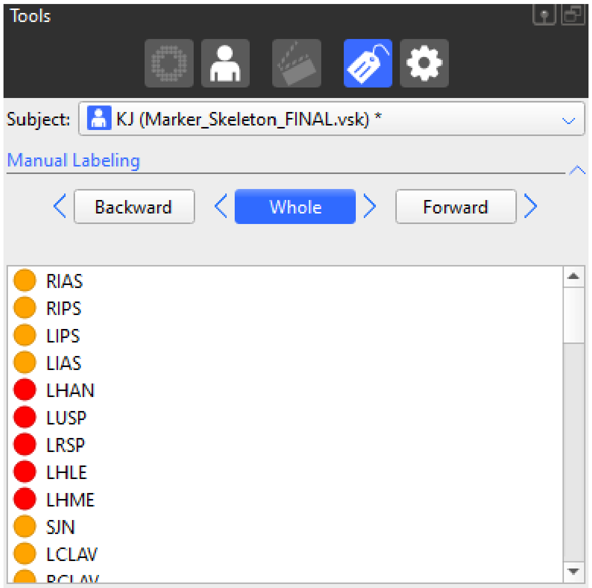
1. The first main step is to understand how to navigate around the software. The functions on the main buttons on the mouse will make the user's experience on Vicon Nexus much easier
    a. The **left mouse button** will allow the user to move and see the markers/skeleton on all different angles
    b. The **right mouse button** will zoom in and out
    c. Scrolling the **scroll wheel** will move the blue slider, changing what frame the user is looking at
    d. Holding the **scroll wheel** will allow the user to move the frame in a 2D view
2. The user should then start with the static poses and have the markers displayed in the 3D perspective.
    a. The figure below shows the anatomical static pose when no markers are labeled.
        i. 
3. **Press on the Label/Edit button under tools** (typically on the top right) to start.
    a. The figures below shows the main panel that the user will be on while marker labeling
        i. 

        ii.

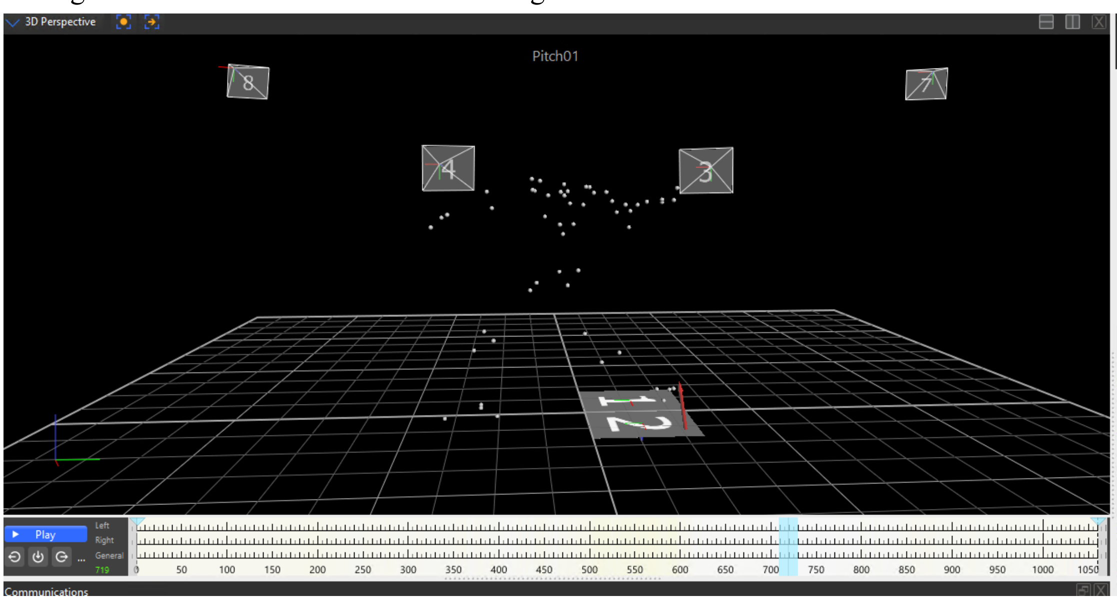
4. The subject should be the **.vsk file** of the marker skeleton.
5. If the .vsk file is not present, click the **Pipeline** button, which is the image that looks like a wheel, next to the label/edit button.
    a. Hit "**File Import" and "Import VSK"**



    b.
    c. Click the three dots next to Filename and find the .vsk file which contains the segments, the marker names that the team decided on
        i. *This is the for the marker template - for example, our team used KJ.vsk we developed*
    d. Then you hit the blue play button where the VSK file will be imported. Once this is finished, go back to the label/edit tab and the subject line should have the .vsk file.
6. Keep the manual labeling on "whole" to start shown below.

a. 

7. Click on the first marker name and start labeling based on the built marker set
   a. Start with the anatomical position.
8. **Label all the markers at least once.** Typically, it is easier to go to a frame where most if not all the markers are visible.
   a. The figure below shows the blue slider to drag in order to look at different frames

b. 

9. Once the markers are all labeled at least once, **unclick** the "auto advance selection" shown below and move the blue slider to the start of the trial. This is found **Underneath** the list of markers.

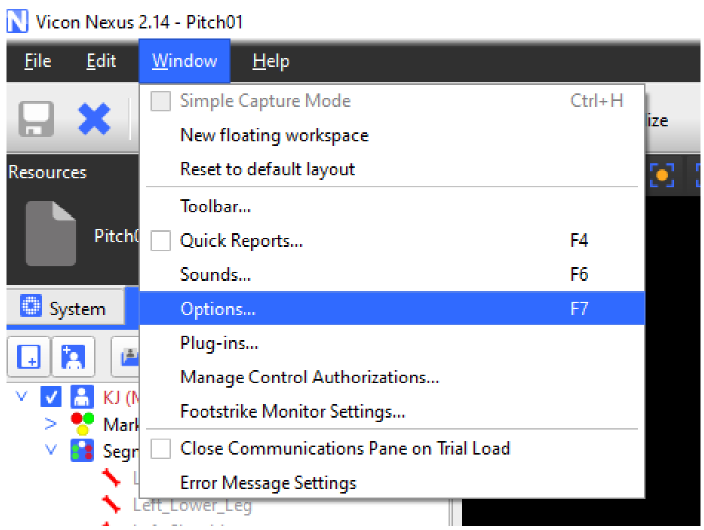
a. 

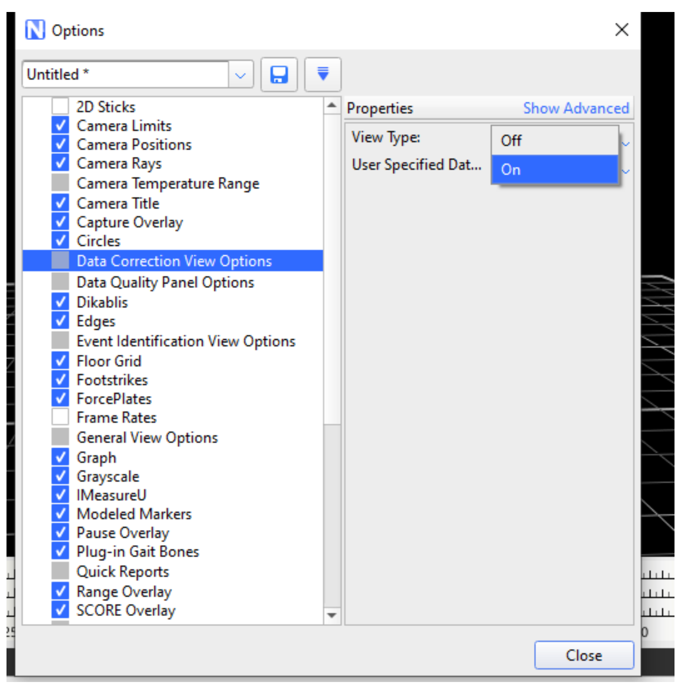
10. The next steps require the user to ensure that each marker is labeled frame by frame. The easiest method would be to continuously hit "**Find Next Unlabeled Trajectory**". This button will allow the program to go to the next unlabeled marker as shown below. Start at the first frame.

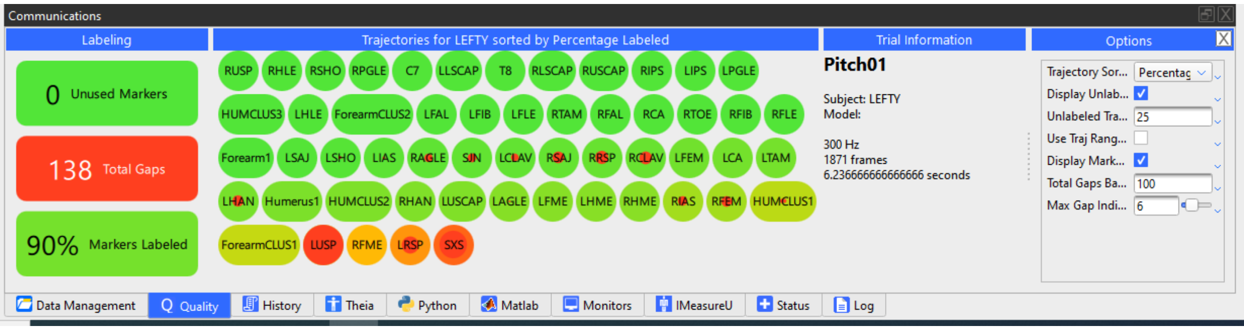
11. **On occasion,** it is important to note that there are times where the markers will switch. The user can try to use the **forward** or **backward** button in order to see if that resolves the issue

Gap Filling on Vicon Nexus

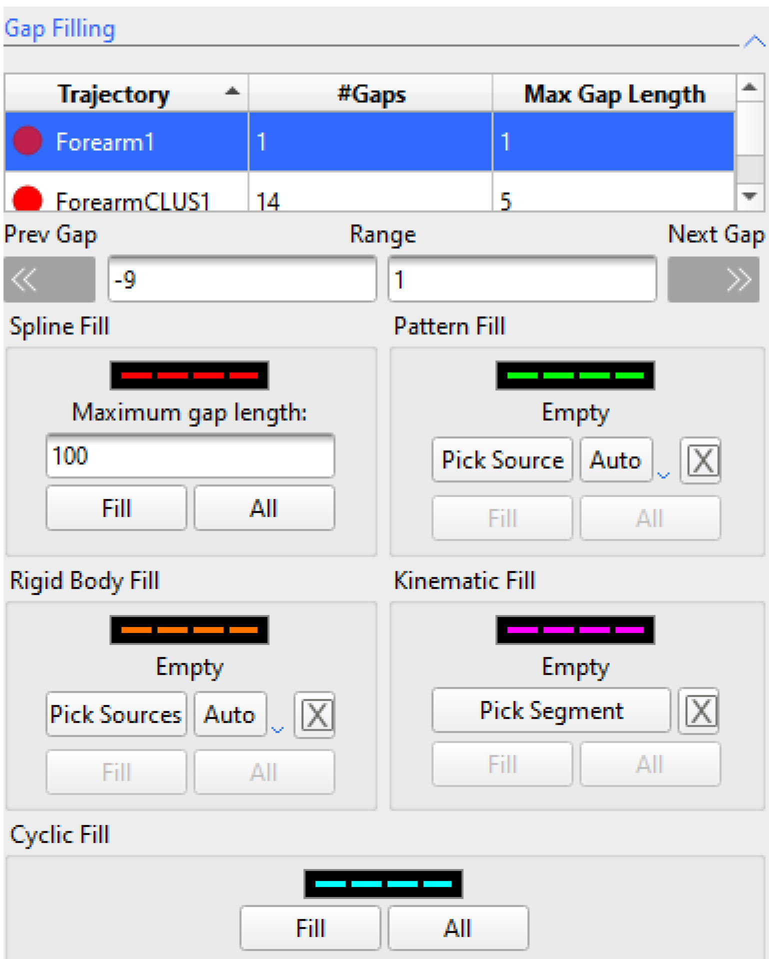
The next step in the post processing reconstruction would be to gap fill. Gap filling ensures that when the marker is not visible, it can be tracked by other further visible markers nearby, preferably those in the same segments or in the rigid body. The Vicon software was able to detect how many gaps there were in the quality section, allowing the team to map the marker to the nearest ones, giving the software a trajectory to follow.

1. The first step would be for the user to go to the top left and hit **Window**
    a. Hit **Options and turn the "Data Correction View Options" to ON**
        i. 

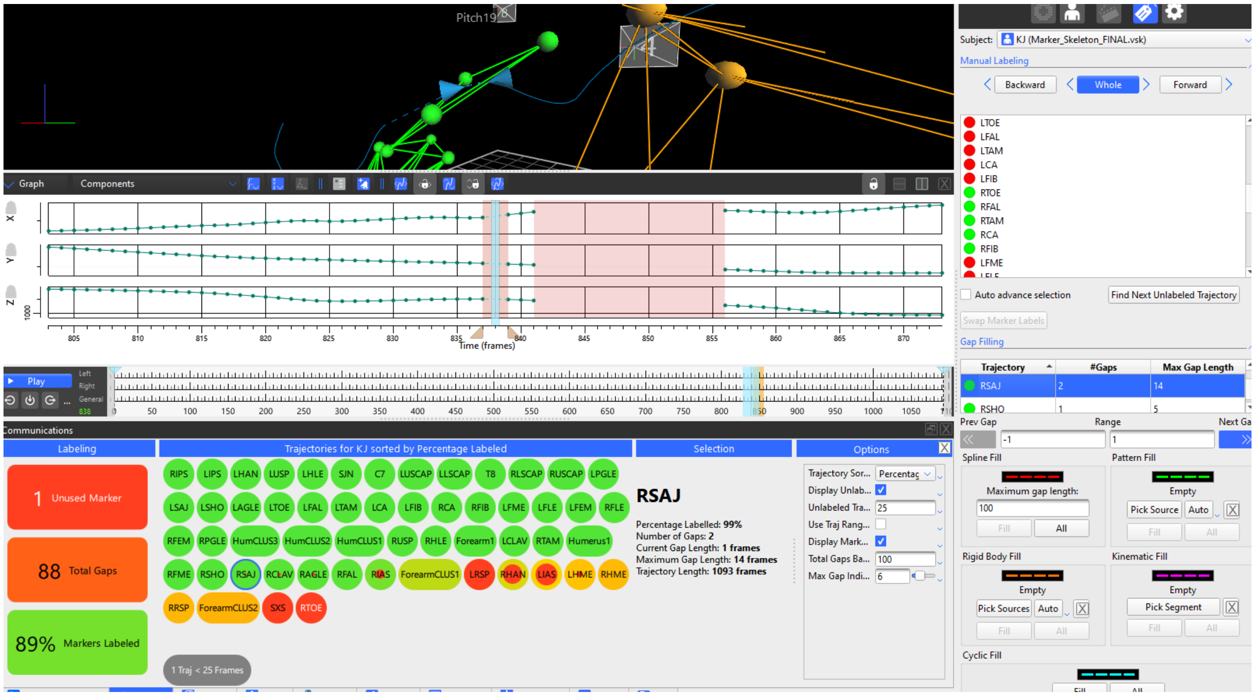
        ii. 

2. Hit **Quality** on the bottom set of tabs, and this should show the number of unused markers, total gaps, and the percentage of markers labeled. The main area of concentration would be the total of gaps it displays.
    a. 

3. The image below shows the main panel the user will be on for the gap filling process
    a.



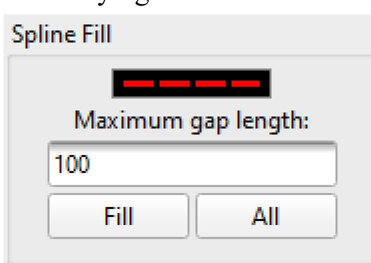
4. The maximum gap length default is set to 100 and can be set as that for the process
5. Under gap filling, there is a list of which markers have gaps under the **trajectory** column and how many gaps each has under **#Gaps**
    a. The user should go down this list



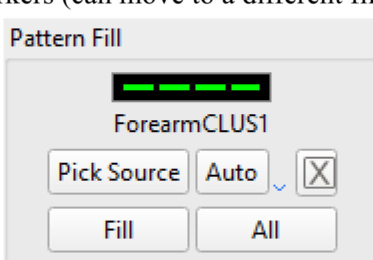
This graph shows the trajectory of the marker ^

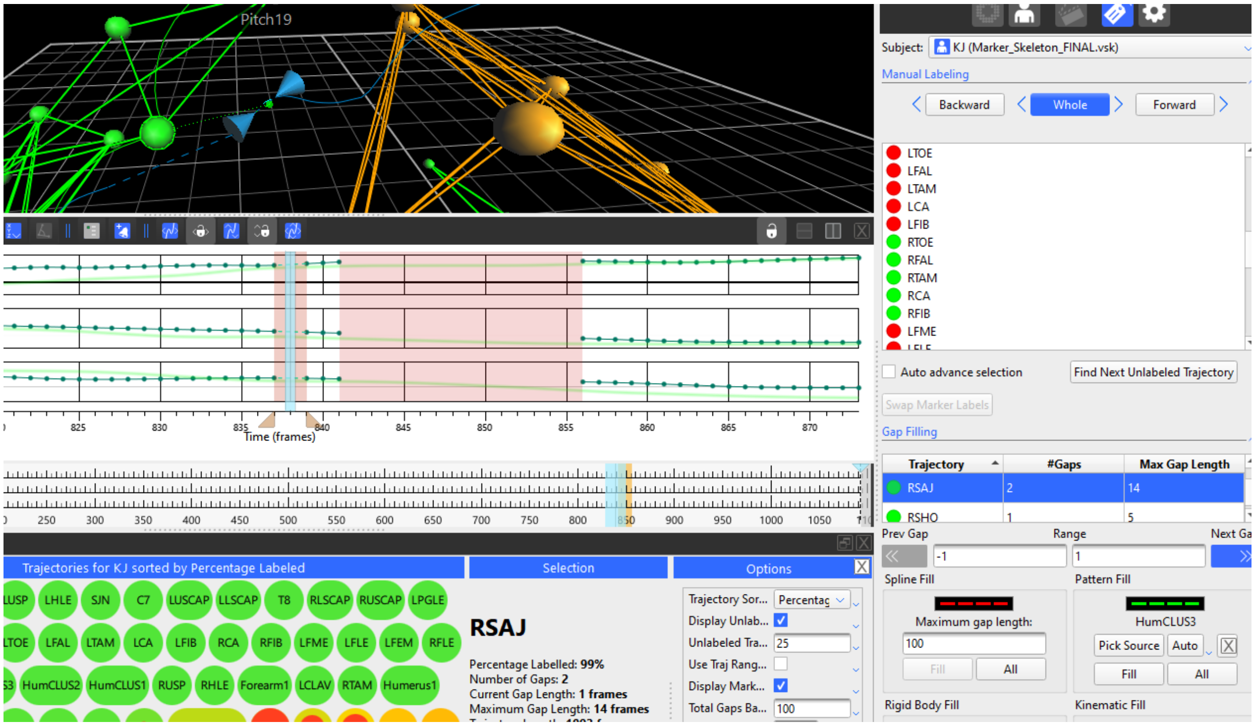
For each of these, you need to pick a "source" in the segment to reference it by

6. In order to actually gap fill, the user must be able to navigate under **Spline Fill, Pattern Fill, Rigid Body Fill, and Kinematic Fill**
7. The main ones used in this project are **Pattern Fill and Rigid Body Fill**
8. **Spline Fill** is used when you have frames that are all labeled with no gaps on either side of the gap the user is trying to fill

   a. 

9. **Pattern Fill** is when there is a suitable marker that follows a similar trajectory to the marker that has the gap. Typically the user should try to choose one marker that is on the same segment as the one marker trajectory trying to be filled. Once the "source" or marker is chosen, hit "fill" until the system stops the user or all the gaps are filled. If the system stops, then the user needs to pick new markers (can move to a different fill type).

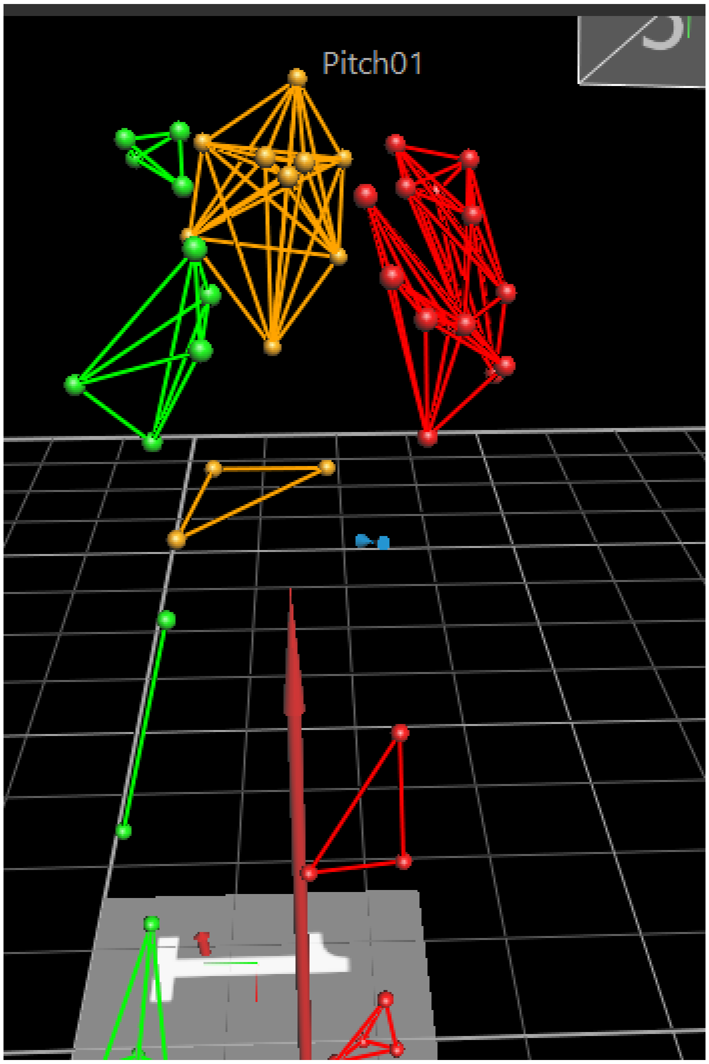
   a. 



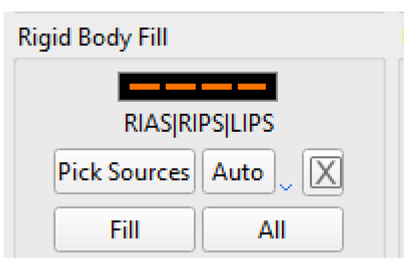
Example of using HumCLUS3 as a source for filling the RSAJ marker

- When you fill, it will move to the next gap in the marker trajectory
- CHECK the projected trajectory such that it follows a reasonable path

10. **Rigid Body Fill** is used where there are at least three other markers placed on a rigid body alongside the marker with the gaps. Typically, this is the thorax or the pelvis. Do the same thing as step nine, but instead choose three markers in the rigid body and hit fill until the system stops the user or all the gaps are filled. If the system stops, then the user needs to pick new markers (can move to a different fill type).

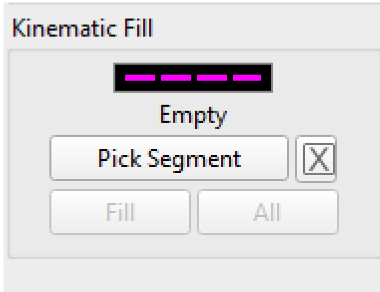


a.



b.

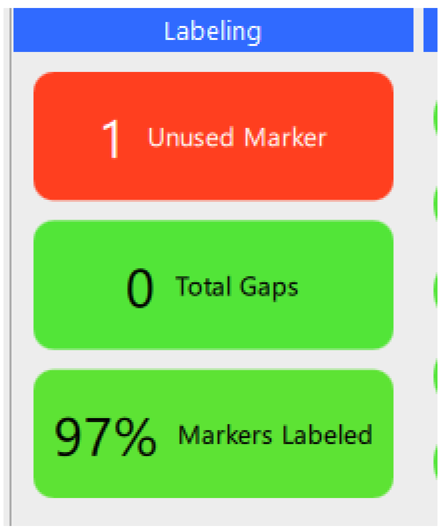
11. There is **Kinematic Fill,** where a segment is chosen and the information of the skeleton is used to fill the gaps. The kinematic fill pipeline needs to be run. This type of gap filling was not used.

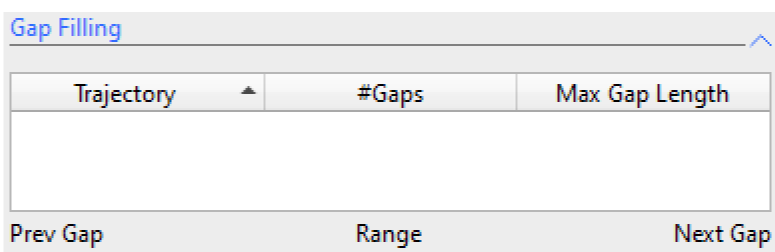
a. 

12. The **Cyclic Fill** is used for trials that have repetitive motions, such as running. This type of gap filling was not used.

    a. 

13. The user should continue to repeat, choosing mainly between pattern fill and rigid body fill until the total gap number is **zero.** The gap filling list should also be empty

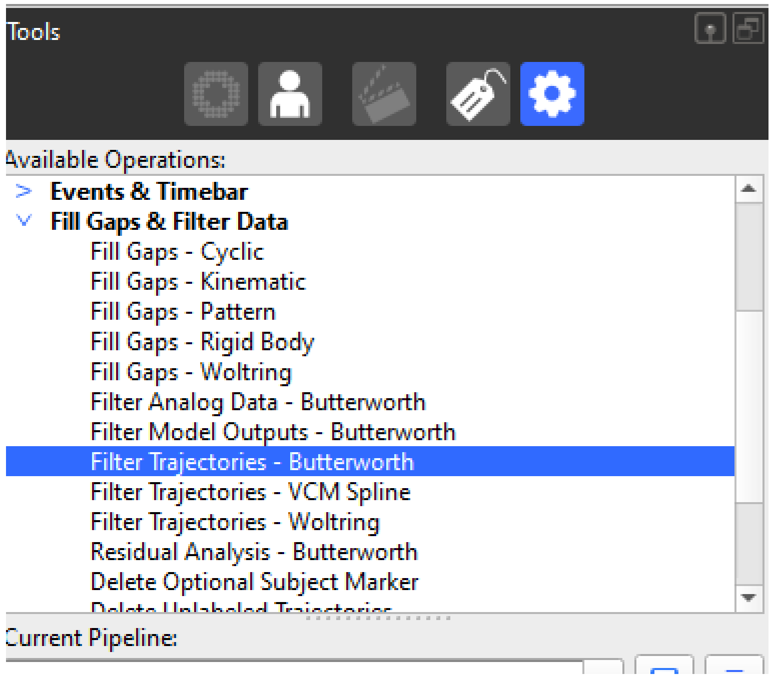
    a. 

    b. 

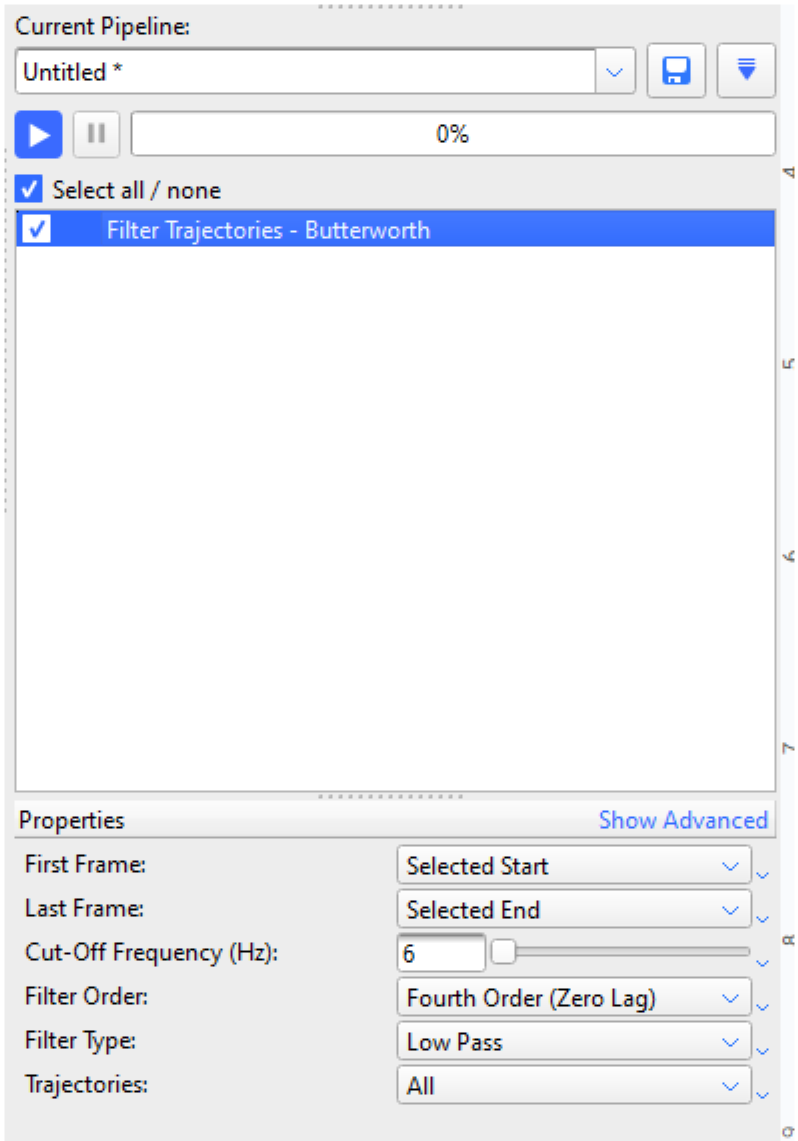
Filtering on Vicon Nexus

Filtering is the next step after gap filling. The process of filtering requires a pipeline operation which provides a smooth trajectory for the markers to follow, and is an essential step prior to starting the Visual3D software process. The pitch is filtered with a 20 Hz cut-off frequency and is a low pass filter.

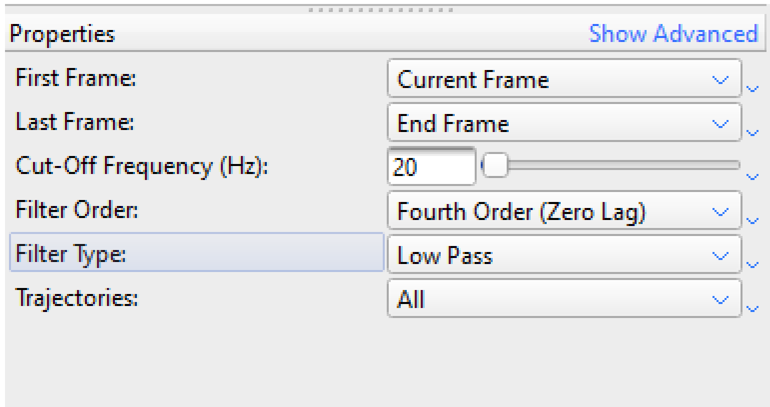
Once a pitch is filtered in Vicon, it cannot be filtered again. It is recommended to wait to filter the static poses until following the Visual 3D SOP.

1. Once the pitch has been completely gap filled, it is important for the user to go through all the frames and once more ensure that **ALL** markers are labeled.
2. The user should hit the pipeline tab once more (the same one to input the VSK file)
3. Hit "**Fill Gap & Filter Data**" and "**Filter Trajectories - Butterworth**"
   a. 

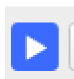
4. The figure below shows the properties tab that needs to be altered when you double click on the selected filter

5. 

   a.
   b. For this specific project, the team set the first frame to around where the pitcher **Starts** his throw and the last frame to the very end of the trial. The current frame selection is whatever frame the blue slider is on.
   c. Set the cut off frequency to **20Hz.**
   d. Keep the filter order to **Fourth Order (Zero Lag)**
   e. Set the Filter type to **Low Pass**
   f. Keep trajectories to **All**
   g. The figure below show the final alterations

i. 

6. Hit the blue play button and the filtering process will start.

   a. 

Once these steps are completed, the next steps include data extraction in the Visual3D software. These steps are found in Visual3D standard operating procedure.

Saving files

It should be saved as .c3d files among others, but .c3d is what is used for vis3d

These update automatically, so you can save copies prior to filtering for example to have back-ups

You can ignore all when closing out the system

Appendix L: Visual 3D Standard Operating Procedure

<u>Visual 3D Software SOP</u>

This SOP follows the necessary steps for using static motion capture poses to develop a skeletal model in Visual 3D and to export data via motion capture motion files. It should be noted that the motion capture software described in this SOP is Vicon Nexus 2.14. The SOP shows the steps to follow data exportation for joint angle, joint force, joint moment, segment velocity, and joint center paths, however, there are a multitude of other data types that can be explored using the Visual 3D software.

Exporting Anatomical Pose from Motion Capture Software

Prior to beginning any work in Visual 3D, the user must export a static pose to their respective lab drive. The steps for exporting are as follows:

1. **Choose one static pose to export** (during motion capture data collection, it is possible multiple different poses were performed, however, it does not matter which pose is selected for the Visual 3D process)
    a. Figure 1 shows images of two possible static poses performed during data collection (anatomical & chair pose)

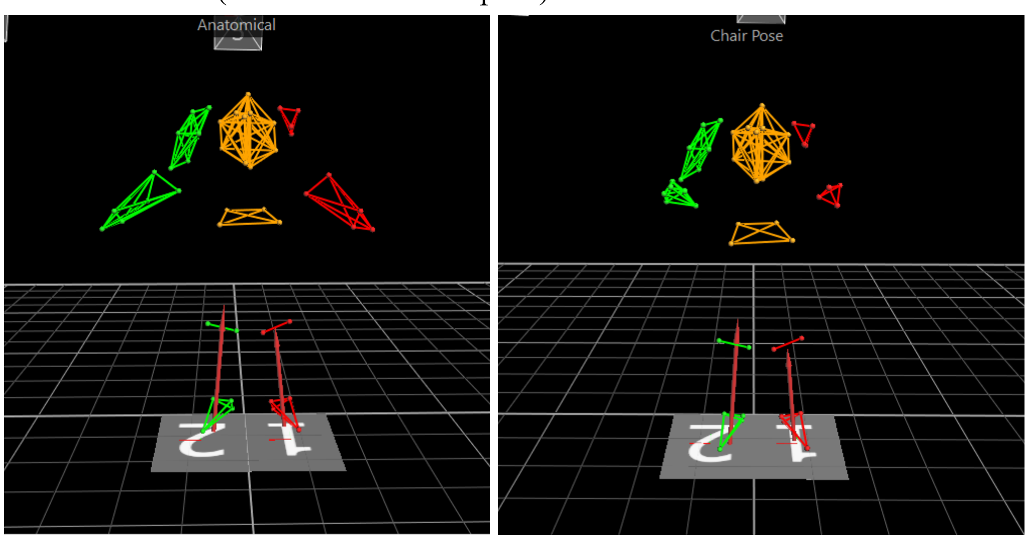


Figure 1: Anatomical and Chair Pose static calibration poses

2. Once a trial of a static pose is selected, **find a frame of the trial that has all markers visible**
    a. This step is extremely important, so it is best to count and ensure all the markers are visible so there are no issues with putting it into Visual 3D

3. **Trim the static pose to 1 frame**
    a. This can be done using the frame panel under the interface that shows the participant in a static pose. There are sliders with triangles at the bottom, and sliding them to the desired frame will trim the trial when saved (see Figure 2 for the panel)
    b. Figure 3 shows the frame panel once it has been trimmed to one frame

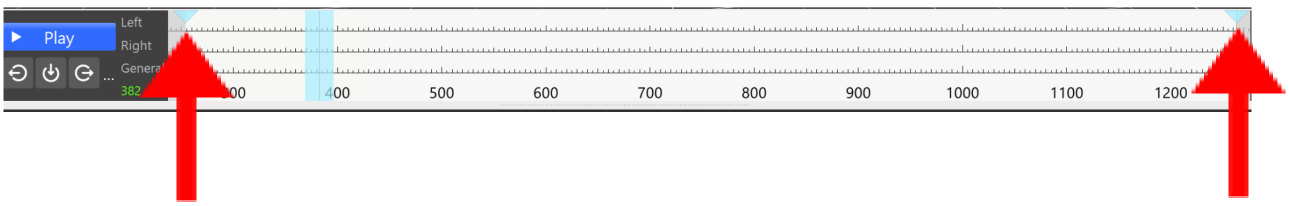


Figure 2: Frame panel in Vicon (the red arrows point to the sliders to use to trim the trial)

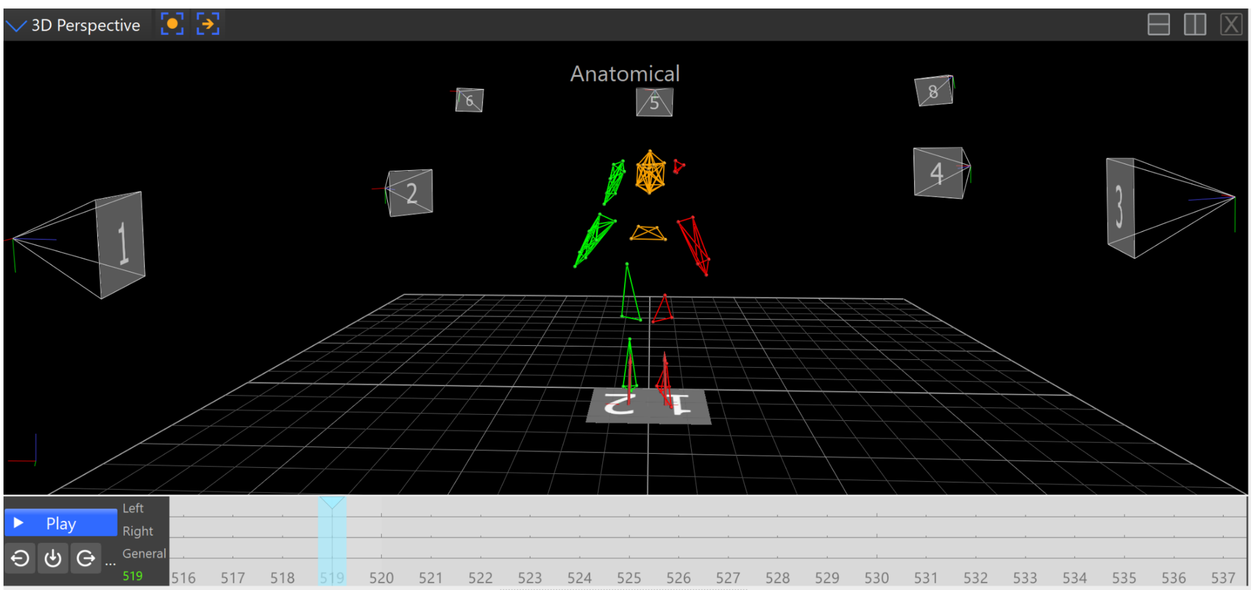


Figure 3: Frame panel shows what it looks like once the static pose is trimmed to one frame

4. **Filter data using a 20 Hz cutoff frequency, low pass filter**
    a. See Figure 4 to set up the filtering process correctly
    b. Ensure only the "Filter Trajectories- Butterworth" box is checked
    c. Note: The static pose can only be filtered once, so it is crucial to do it correctly and mark when it is complete so it is not filtered a second time
        i. A backup of each trial can be made if needed by right-clicking on the pitch in the directory and choosing the "backup" option

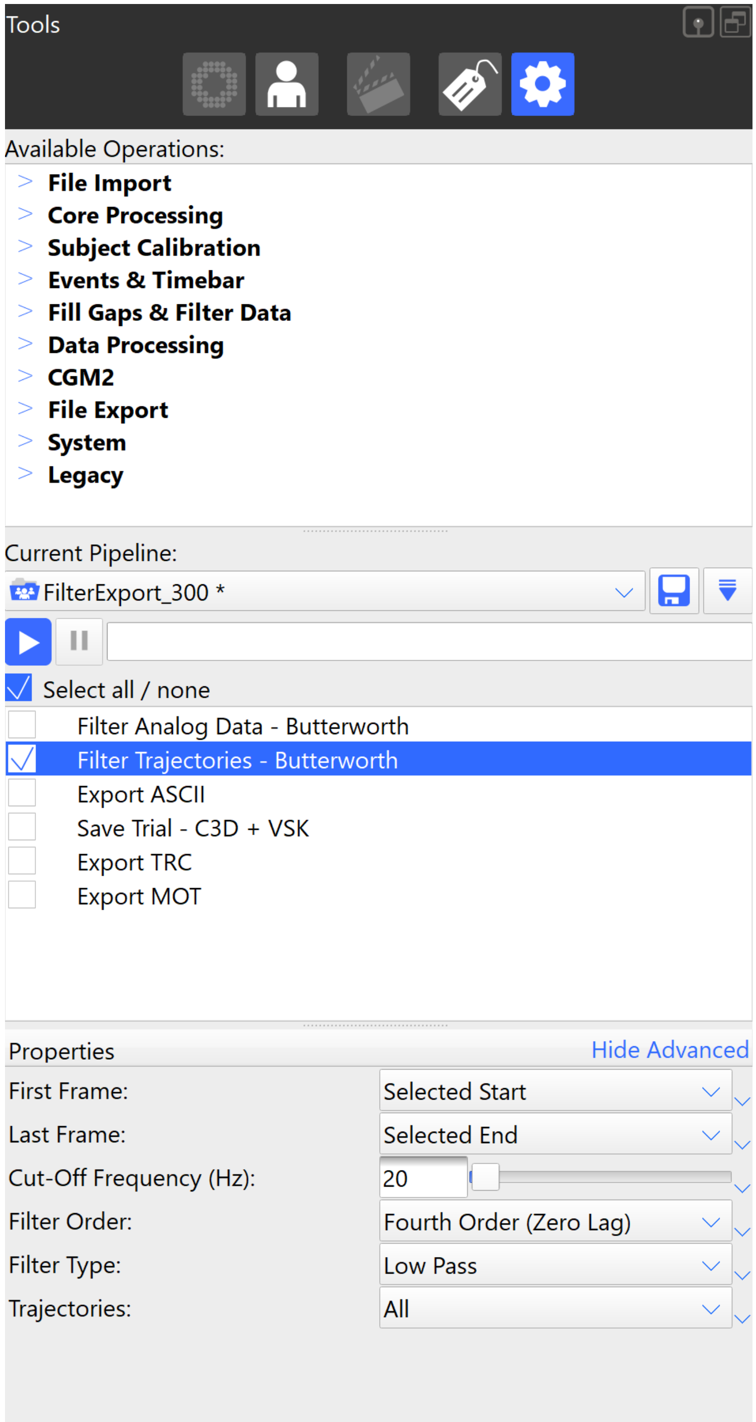


Figure 4: Proper inputs for filtering in Vicon

Importing Anatomical Pose into Visual 3D

1. **Open Visual 3D software**

a. Figure 5 shows the Visual 3D application icon (left) and what the interface should look like once opened (right)

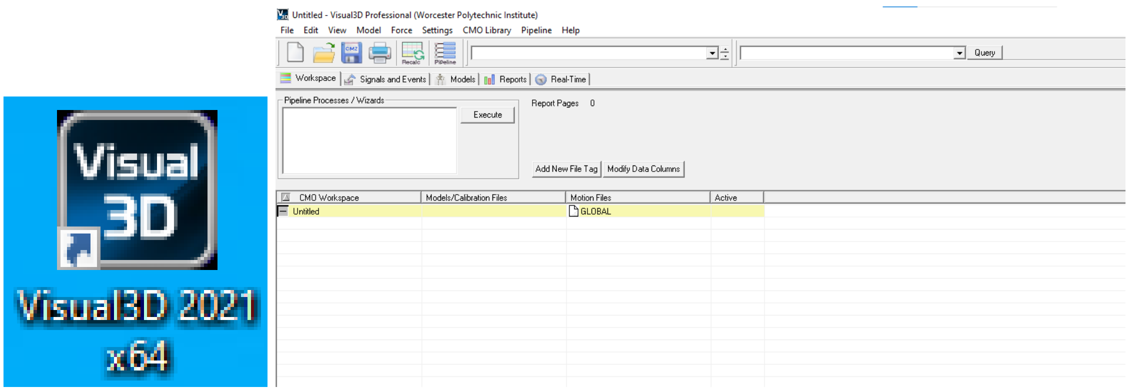


Figure 5: Visual 3D application (L) and interface appearance upon opening (R)

2. **Import static file**
    a. Select the "Model" tab in the top task bar
    b. Hover over "Create (Add Static Calibration File)"
    c. Select the first option: "Hybrid Model from C3D File"
    d. Locate the folder and the file of the static calibration file
        i. Should be a C3D file (i.e. Anatomical.c3d)
    e. Select "File" and click "Open"
    f. Figure 6 shows what Visual 3D automatically opens upon importing the static file
        i. Note: The markers are already labeled in Visual 3D (select one to have it highlighted and the marker name visible)
        ii. All of the markers should be visible as they were in Vicon

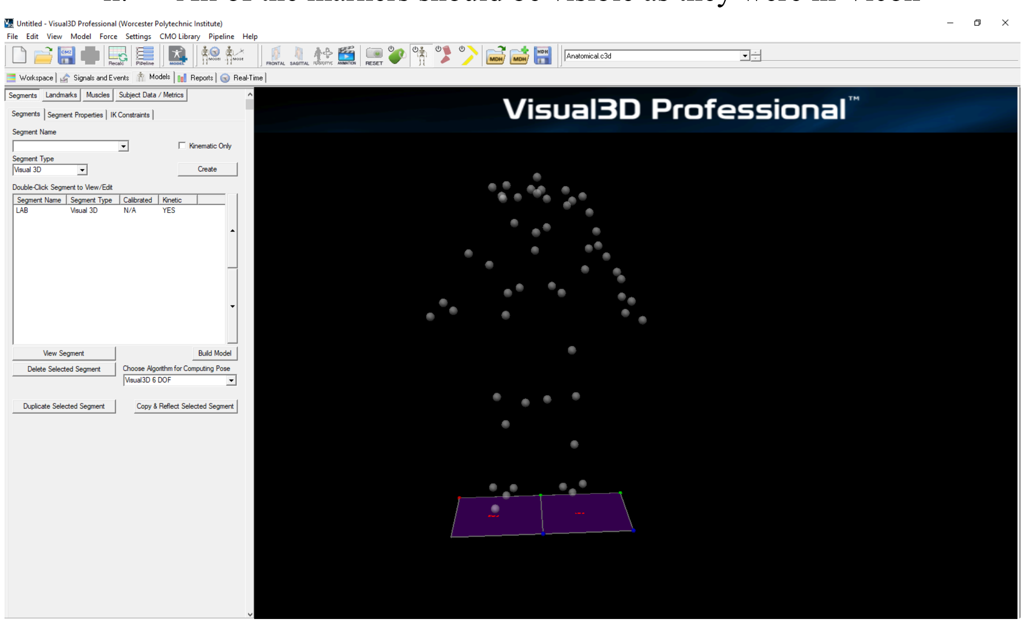


Figure 6: Interface once a static pose is imported (marker set from Vicon)

Build Skeletal Model in Visual 3D

The creation of the skeletal model in Visual 3D requires defining "landmarks" and using these landmarks to build "segments," until the model is completed. Prior to building any segments, it is important to input any known data into the "Subject Data / Metrics" tab. It is also reasonable to add more quantities to this section as the model is being built. Additionally, this is where Visual 3D will put any participant data that it calculates from anything that is entered for a landmark or segment.

1. **Enter preliminary metrics into "Subject Data / Metrics"**
   a. Navigate to the "Subject Data / Metric" tab (shown in Figure 7)

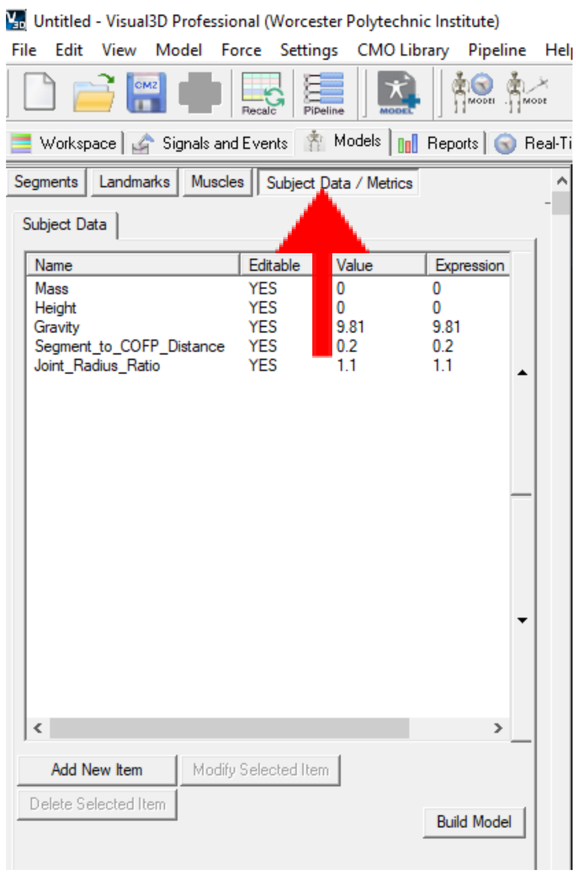


Figure 7: "Subject Data / Metric" tab shown by the red arrow

   b. Enter the participant's mass and height into the automatically generated category
      i. Double-click "mass" to edit the expression or click once and select the button that says "Modify Selected Item"
      ii. The units of mass are kilograms (kg) and the units of distance are meters (m)
         1. Be sure to input the metric with the proper units (this impacts data calculations)

iii. If the exact mass is unknown and force plates were used in the motion files, using Vicon the downward force in Newtons and dividing by the acceleration due to gravity can be used to represent the mass of the subject. An example is shown below:

$$\frac{764\ N}{9.81\ N/kg} = 77.88\ kg$$

2. **Enter radius values for motion capture markers**
   a. Remain on the “Subject Data / Metric” tab
   b. Select “Add New Item”
   c. Enter: “Large_Marker” for the name
   d. Enter: “0.007” into the “Value or Expression” space
      i. This is the radius value in meters for the larger marker
      ii. This is not the same size radius for all motion capture markers, so be sure to check the box or research to find the proper radius measurements
   e. Enter “Small_Marker” for the name
   f. Enter “0.00475” into the “Value or Expression” space
      i. This is the radius value in meters for the smaller marker
      ii. Similar to above, this value may vary or not be applicable if only one size marker was used
3. **Create the Pelvis segment**
   a. Navigate to the “Segments” tab
   b. In the drop-down menu under “Segment Name,” select “Pelvis”
   c. In the drop-down menu under “Segment Type,” select “CODA”
      i. CODA is a model that can be used to create the pelvis segment in Visual 3D, used by Charnwood Dynamics (Visual3D Wiki Documentation., n.d.).
   d. Select the “Create button”
   e. The Visual 3D software automatically selects the hip markers to align properly to make the pelvis. Ensure the markers (RIAS, LIAS, RIPS, LIPS) correspond with the correct Visual 3D position as shown in Figure 8 below.

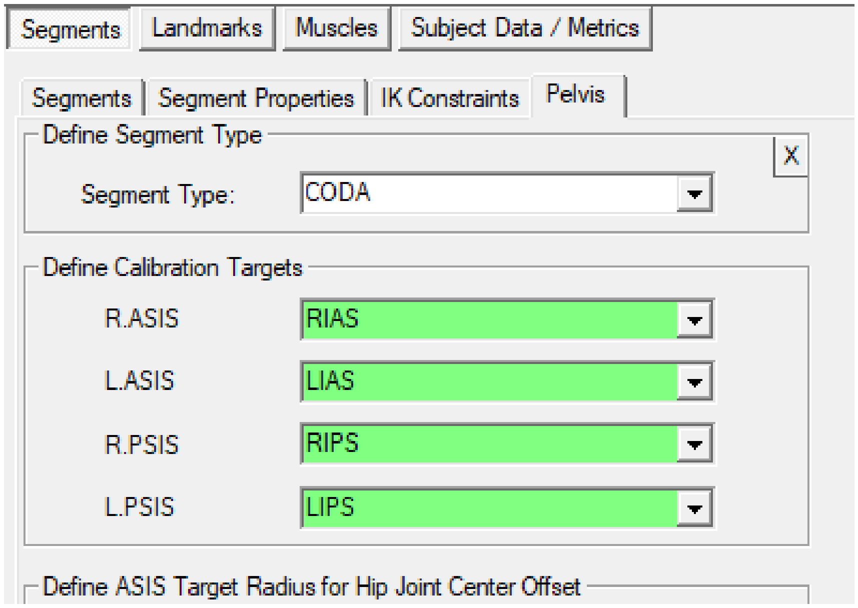


Figure 8: Pelvis markers used for calibration targets with correct correspondence (i.e. RIAS= R. ASIS)

f. Input "Large_Marker" in the space next to 'ASIS Target Radius
g. Uncheck the box "Use Calibration Targets for Track"
    i. Unchecking this box reveals the option to select every marker on the model
h. Select the same pelvis markers which are highlighted in green (Figure 7)
    i. Select RIAS, LIAS, RIPS, LIPS
i. The space next to "6DOF Cutoff Frequency" can remain at "0.0"
j. Select "Apply" and then select "Build Model"
    i. The Pelvis segment should appear on the model as shown in Figure 8 below
    ii. Ensure the coordinate system is orientated properly (shown in Figure 9)
        1. Red=x-axis, Green=y-axis, Blue=z-axis

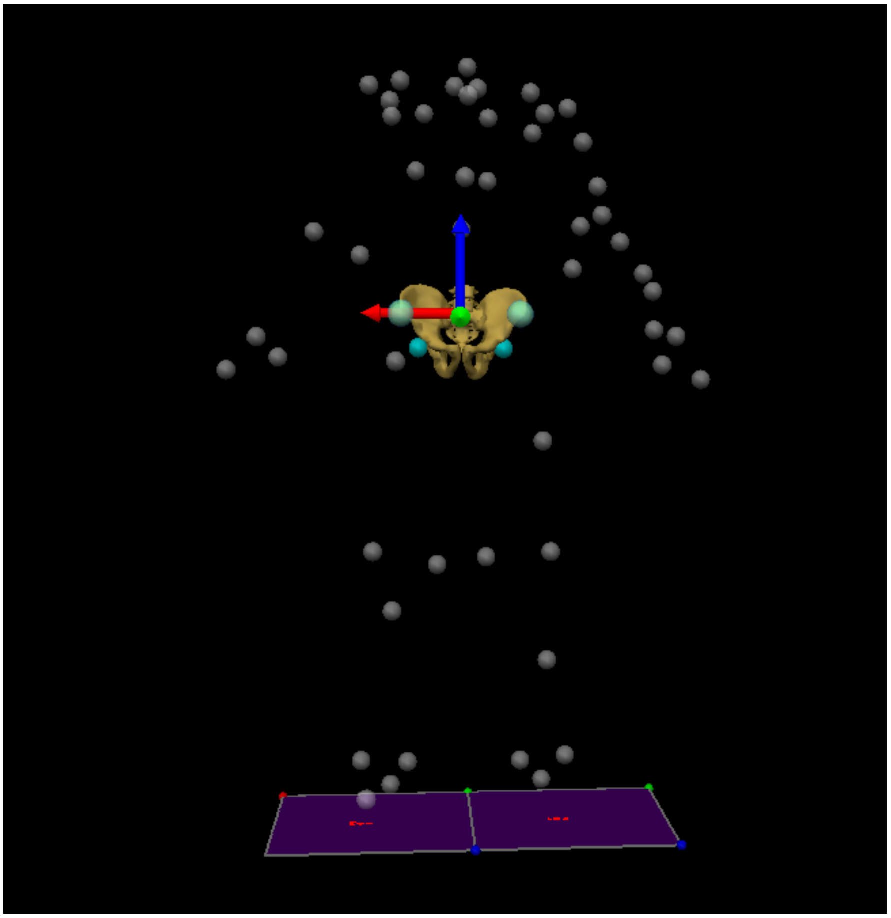


Figure 9: Pelvis segment on model

4. **Create right thigh segment**
    a. Navigate back to "Segments" tab
    b. In the drop down menu under "Segment Name," select "Right Thigh"
    c. In the drop down menu under "Segment Type," the type should be "Visual 3D"
    d. Select the "Create button"
    e. The inputs for the "Define Proximal Joint and Radius" section are as follows:
        i. Lateral: "None"
        ii. Joint Center: "RIGHT_HIP"
        iii. Medial: None
        iv. Radius (Meters): 0.5*DISTANCE(LEFT_HIP,RIGHT_HIP)
            1. Note: The joint centers for the left and right hip were automatically calculated by Visual 3D and inputted into the "subject data / metrics" tab
    f. The inputs for "Define Distal Joint and Radius" section are as follows:
        i. Lateral: "RFLE"
        ii. Joint center: should be grayed out and uneditable
        iii. Medial: "RFME"

    iv. Radius (meters): Uneditable

g. Nothing should be selected under the “Extra Target to Define Orientation (if needed)” section
h. Check the box next to “Use Calibration Targets for Tracking
i. “0.0” can remain in the box next to “6DOF Cutoff Frequency”
j. Select “Apply” and then select “Build Model”
    i. The right thigh should appear on the model

5. Create left thigh segment

a. Follow the same steps for the “right thigh” segment but for the left side
b. Navigate back to the “Segments” tab
c. In the drop-down menu under “Segment Name,” select “Left Thigh”
d. In the drop-down menu under “Segment Type,” the type should be “Visual 3D”
e. Select the “Create button”
f. The inputs for the “Define Proximal Joint and Radius” section are as follows:
    i. Lateral: “None”
    ii. Joint Center: “LEFT_HIP”
    iii. Medial: None
    iv. Radius (Meters): 0.5*DISTANCE(LEFT_HIP,RIGHT_HIP)
        1. Note: The joint centers for the left and right hip were automatically calculated by Visual 3D and inputted into the “subject data / metrics” tab.
        2. Specifically, Visual 3D uses Bell and Brand regression equations to automatically generate these values. The Bell and Brand regression equations were defined in research through in vivo medical imaging of pelvis samples and are widely used (Camomilla, V., et al., 2006).
        3. The formulas are the same for the right and left hip, aside from the left hip having a negative in the medial-lateral (ML), or transverse axis. The Bell and Brand regression equations are shown below for the ML, AP (anterior-posterior) and axial axes (Visual3D Wiki Documentation., n.d.).

RHJC: ML=0.36*ASIS_Distance, AP=-0.19*ASIS_Distance, Axial=-0.3*ASIS_Distance

LHJC: ML=-0.36*ASIS_Distance, AP=-0.19*ASIS_Distance, Axial=-0.3*ASIS_Distance

g. The inputs for the “Define Distal Joint and Radius” section are as follows:
    i. Lateral: “LFLE”
    ii. Joint Center: should be grayed out and uneditable

iii. Medial: "LFME"

iv. Radius (meters): Uneditable

h. Nothing should be selected under the "Extra Target to Define Orientation (if needed)" section

i. Check the box next to "Use Calibration Targets for Tracking"

j. "0.0" can remain in the box next to "6DOF Cutoff Frequency"

k. Select "Apply" and then select "Build Model"

i. The left thigh should appear on the model

1. Figure 10 shows what the model should look like after these steps

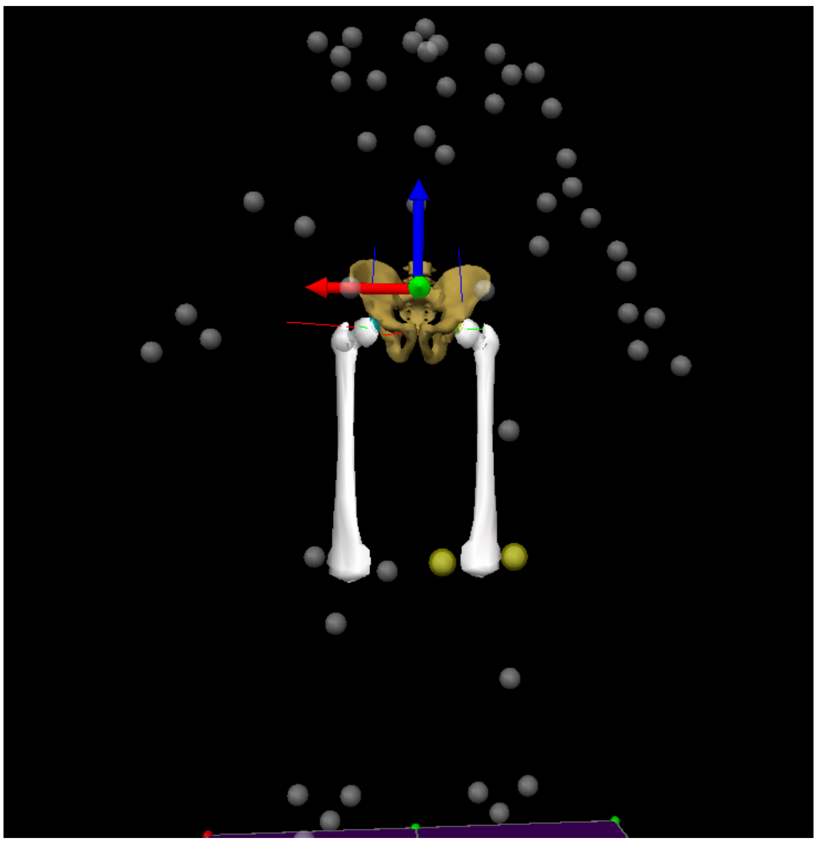


Figure 10: Skeletal model with the pelvis, right thigh, and left thigh

6. **Create right knee joint center**
   a. Navigate to the "Landmarks" tab shown in Figure 11

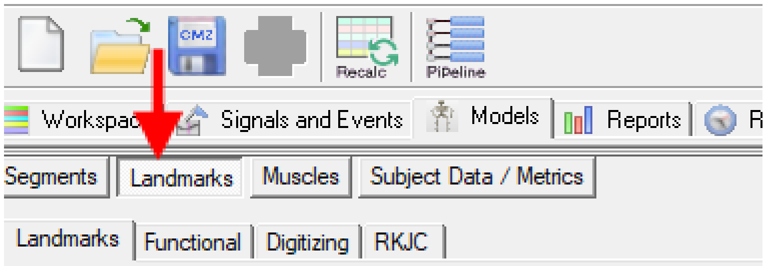


Figure 11: Landmarks tab used for creating joint centers

   b. Select the "Add New Landmark" button
   c. Input "RKJC" in the space next to "Landmark Name:"
   d. Under the "Define Orientation Using:" section, select "Existing Coordinate System"
   e. In the drop-down menu next to "Existing Coordinate System", select "Right Thigh"
   f. Under the "Landmark Offset from Start Point (Reference) or Segment Origin" section, select "Offset Using the Following ML/AP/AXIAL Offsets"
   g. The inputs for the "Offset Using the Following ML/AP/AXIAL Offsets" section are as follows:
      i. ML: 0.0
      ii. AP: 0.0
      iii. AXIAL: -1
   h. Select the "Offset by Percent" checkbox
   i. Do not select the "Calibration Only Landmark" checkbox
   j. Select "Apply"
      i. Figure 12 shows the proper inputs for the right knee joint center as an example

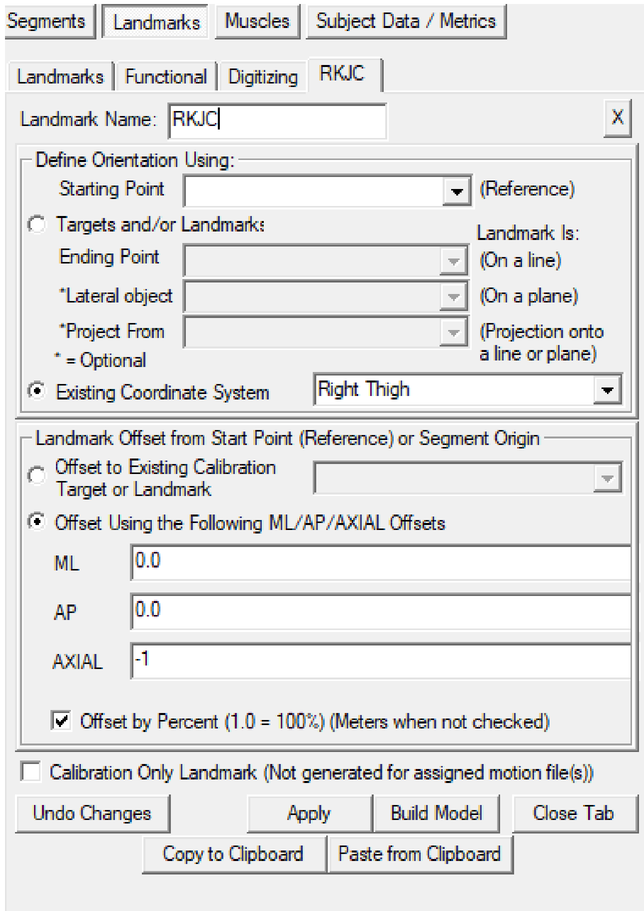


Figure 12: Proper inputs in landmarks tab for right knee joint center

ii. It should be noted that after each landmark is created, it will appear on the model with the chosen landmark name. In this case "RKJC" appears on the model as shown in Figure 13 below.

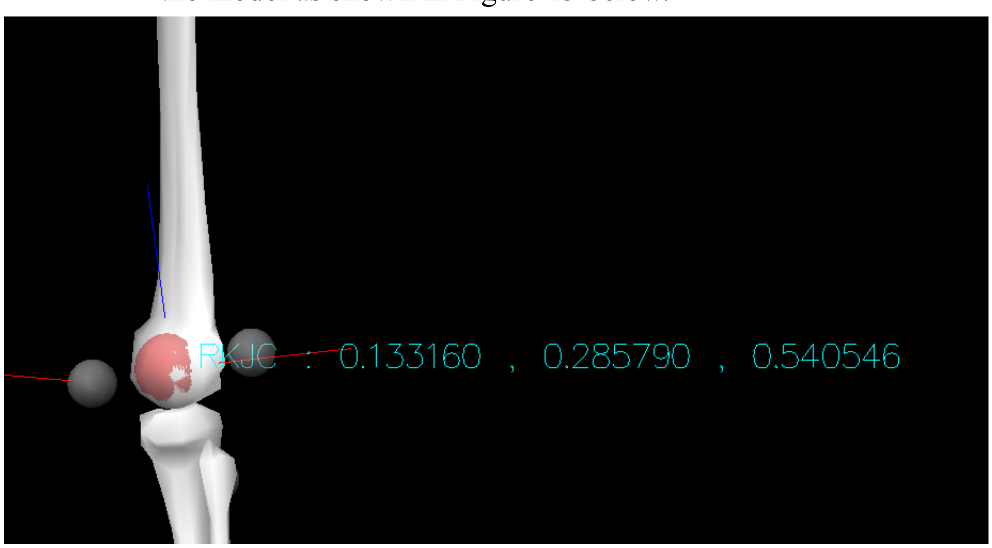


Figure 13: Joint center landmark "RKJC" for the right knee appears on the model once created

7. **Create right shank segment**
    a. Navigate to the “Segments” tab
    b. In the drop-down menu under “Segment Name,” select “Right Shank”
    c. In the drop-down menu under “Segment Type,” the type should be “Visual 3D”
    d. Select the “Create button”
    e. The inputs for the “Define Proximal Joint and Radius” section are as follows:
        i. Lateral: “None”
        ii. Joint Center: “RKJC”
        iii. Medial: None
        iv. Radius (Meters): RTH_DISTAL_RADIUS
            1. Note: This is the distal radius value for the right thigh, which was automatically calculated by Visual3D
    f. The inputs for the “Define Distal Joint and Radius” section are as follows:
        i. Lateral: “RFAL”
        ii. Joint Center: should be grayed out and uneditable
        iii. Medial: “RTAM”
        iv. Radius (meters): Uneditable
    g. Nothing should be selected under the “Extra Target to Define Orientation (if needed)” section
    h. Check the box next to “Use Calibration Targets for Tracking”
    i. “0.0” can remain in the box next to “6DOF Cutoff Frequency”
    j. Select “Apply” and then select “Build Model”
        i. The right shank should appear on the model
        ii. Use Figure 14 below to ensure the inputs are correct for the shank to be correctly built.

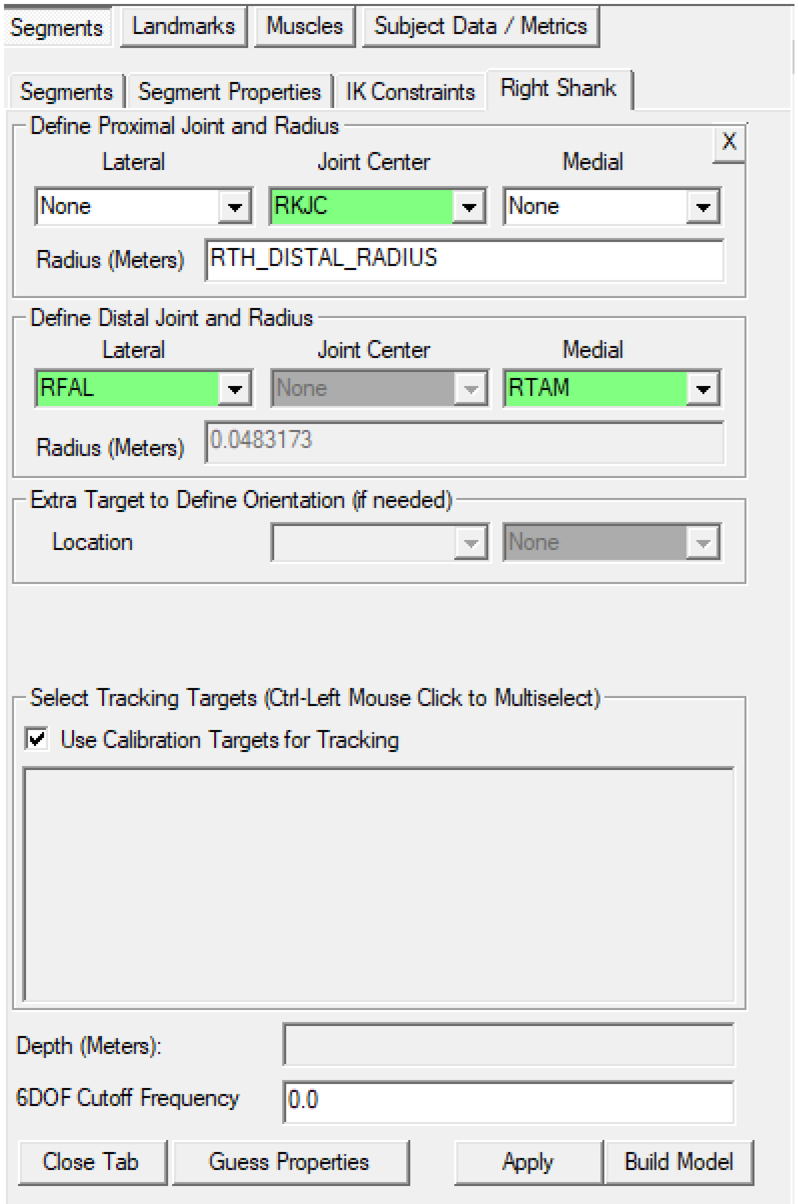


Figure 14: Segment inputs for building the right shank segment

8. **Create left knee joint center**
    a. Navigate back to the “Landmarks” tab
    b. Select the “Add New Landmark” button
    c. Input “LKJC” in the space next to “Landmark Name:”
    d. Under the “Define Orientation Using:” section, select “Existing Coordinate System”
    e. In the drop-down menu next to “Existing Coordinate System”, select “Left Thigh”
    f. Under the “Landmark Offset from Start Point (Reference) or Segment Origin” section, select “Offset Using the Following ML/AP/AXIAL Offsets”

g. The inputs for the "Offset Using the Following ML/AP/AXIAL Offsets" section are as follows:
    i. ML: 0.0
    ii. AP: 0.0
    iii. AXIAL: -1
h. Select the "Offset by Percent" checkbox
i. Do not select the "Calibration Only Landmark" checkbox
j. Select "Apply"

9. Create left shank segment

a. Navigate to the "Segments" tab
b. In the drop-down menu under "Segment Name," select "Left Shank"
c. In the drop-down menu under "Segment Type," the type should be "Visual 3D"
d. Select the "Create button"
e. The inputs for the "Define Proximal Joint and Radius" section are as follows:
    i. Lateral: "None"
    ii. Joint Center: "LKJC"
    iii. Medial: None
    iv. Radius (Meters): LTH_DISTAL_RADIUS
        1. Note: This is the distal radius value for the left thigh, which was automatically calculated by Visual3D
f. The inputs for the "Define Distal Joint and Radius" section are as follows:
    i. Lateral: "LFAL"
    ii. Joint Center: should be grayed out and uneditable
    iii. Medial: "LTAM"
    iv. Radius (meters): Uneditable
g. Nothing should be selected under the "Extra Target to Define Orientation (if needed)" section
h. Check the box next to "Use Calibration Targets for Tracking"
i. "0.0" can remain in the box next to "6DOF Cutoff Frequency"
j. Select "Apply" and then select "Build Model"
    i. The left shank should appear on the model

10. Create thorax landmarks

a. Navigate to the "Landmarks" tab
b. Create the first thorax landmark
    i. Select the "Add New Landmark" button
    ii. Input "Thorax_Prox" in the space next to "Landmark Name:"
    iii. Under the "Define Orientation Using:" section and next to "Starting Point", select "SJN"

iv. Under the "Define Orientation Using:" section, select "Targets and/or Landmark:"
v. Next to "Ending Point", select "C7"
vi. Under the "Landmark Offset from Start Point (Reference) or Segment Origin" section, select "Offset Using the Following ML/AP/AXIAL Offsets"
vii. The inputs for the "Offset Using the Following ML/AP/AXIAL Offsets" section are as follows:
    1. ML: 0.0
    2. AP: 0.0
    3. AXIAL: 0.5
viii. Select the "Offset by Percent" checkbox
ix. Select the "Calibration Only Landmark" checkbox
x. Select "Apply"

c. Create the second thorax landmark
    i. Return to the "Landmarks" tab
    ii. Select the "Add New Landmark" button
    iii. Input "Thorax_Dist" in the space next to "Landmark Name:"
    iv. Under the "Define Orientation Using:" section and next to "Starting Point", select "SXS"
    v. Under the "Define Orientation Using:" section, select "Targets and/or Landmark:"
    vi. Next to "Ending Point", select "T8"
    vii. Under the "Landmark Offset from Start Point (Reference) or Segment Origin" section, select "Offset Using the Following ML/AP/AXIAL Offsets"
    viii. The inputs for the "Offset Using the Following ML/AP/AXIAL Offsets" section are as follows:
        1. ML: uneditable
        2. AP: uneditable
        3. AXIAL: 0.5
    ix. Select the "Offset by Percent" checkbox
    x. Select the "Calibration Only Landmark" checkbox
    xi. Select "Apply"

d. Create the third thorax landmark
    i. Return to the "Landmarks" tab
    ii. Select the "Add New Landmark" button
    iii. Input "Thorax_AP" in the space next to "Landmark Name:"
    iv. Under the "Define Orientation Using:" section and next to "Starting Point", select "SJN"

    v. Under the “Define Orientation Using:” section, select “Targets and/or Landmark:”
    vi. Next to “Ending Point”, select “SXS”
    vii. Under the “Landmark Offset from Start Point (Reference) or Segment Origin” section, select “Offset Using the Following ML/AP/AXIAL Offsets”
    viii. The inputs for the “Offset Using the Following ML/AP/AXIAL Offsets” section are as follows:
        1. ML: uneditable
        2. AP: uneditable
        3. AXIAL: 0.5
    ix. Select the “Offset by Percent” checkbox
    x. Select the “Calibration Only Landmark” checkbox
    xi. Select “Apply”

11. Create thorax segment

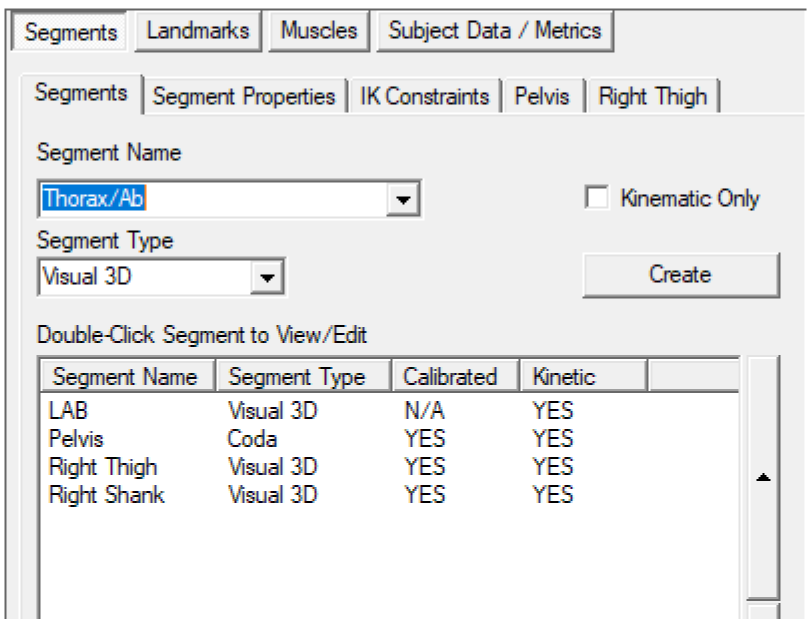


Figure 15: “Segments” tab for create Thorax/Ab segment

  a. Navigate to the “Segments” tab shown in Figure 15
  b. In the drop-down menu under “Segment Name,” select “Thorax/Ab”
  c. In the drop-down menu under “Segment Type,” the type should be “Visual 3D”
  d. Select the “Create button”
  e. The inputs for the “Define Proximal Joint and Radius” section are as follows:
    i. Lateral: “None”
    ii. Joint Center: “Thorax_Prox”
    iii. Medial: None
    iv. Radius (Meters): 0.5*DISTANCE(RSHO,LSHO)

1. Note: This is the distal radius value for the thorax which uses the two shoulder markers

f. The inputs for the "Define Distal Joint and Radius" section are as follows:
   i. Lateral: "None"
   ii. Joint Center: "Thorax-Dist"
   iii. Medial: "None"
   iv. Radius (meters): 0.5*DISTANCE(RSHO,LSHO)
g. Under the "Extra Target to Define Orientation (if needed)" section, select "Anterior" from the left drop-down menu next to "location"
h. For the right drop-down menu, select "Thorax_AP"
i. Ensure that "Use Calibration Tracking Targets" is unchecked
   i. Within this section, select "LAGLE," "LLSCAP," "LUSCAP," "SJIN," "SXS," "T8,"
j. In the space next to "Depth (Meters)" input "0.5*DISTANCE(C7,SJN)"
k. Select "Apply" and then select "Build Model"
   i. The thorax should appear on the model
      1. It should be noted that there is a slight error in the ribcage segment creation. Figure 16 shows what the thorax appears to look like at the time of building the segment. The thorax is assembled upside down, backward, and smaller than the proper body scale.

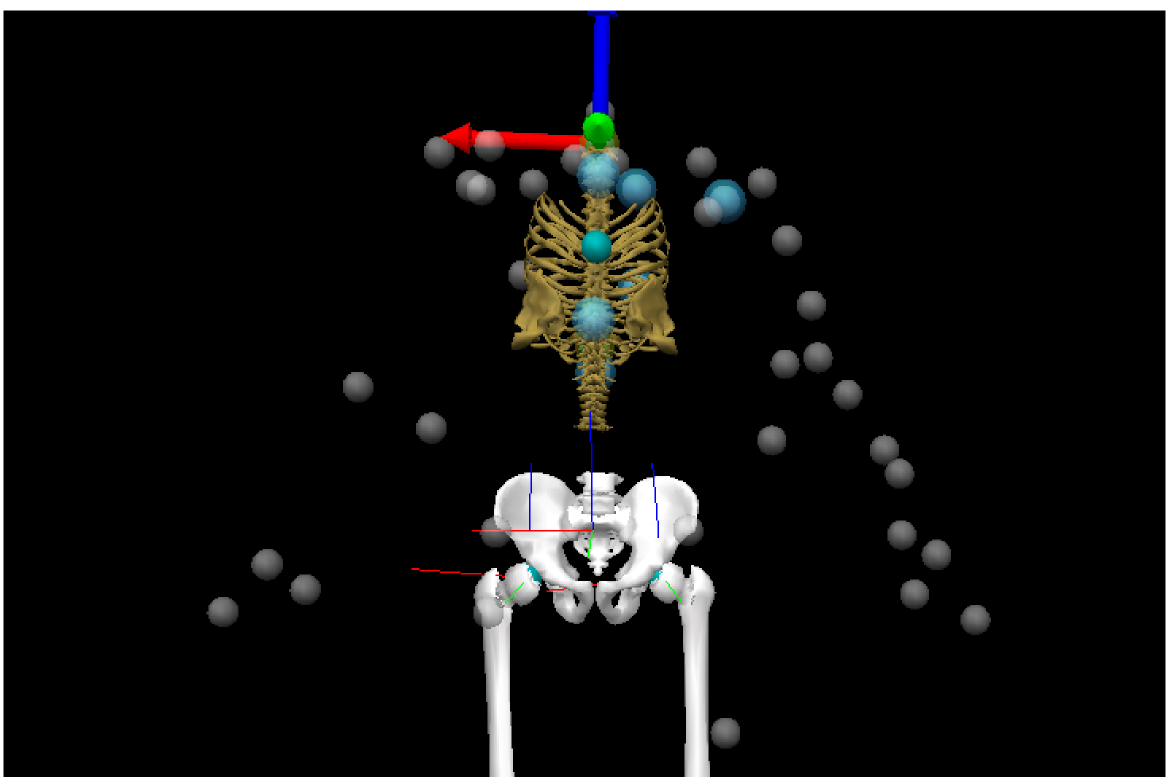


Figure 16: Difficulties with creating thorax segment (backward and upside down thorax)

12. Adjust thorax segment

a. Navigate to the "Segment Properties" tab

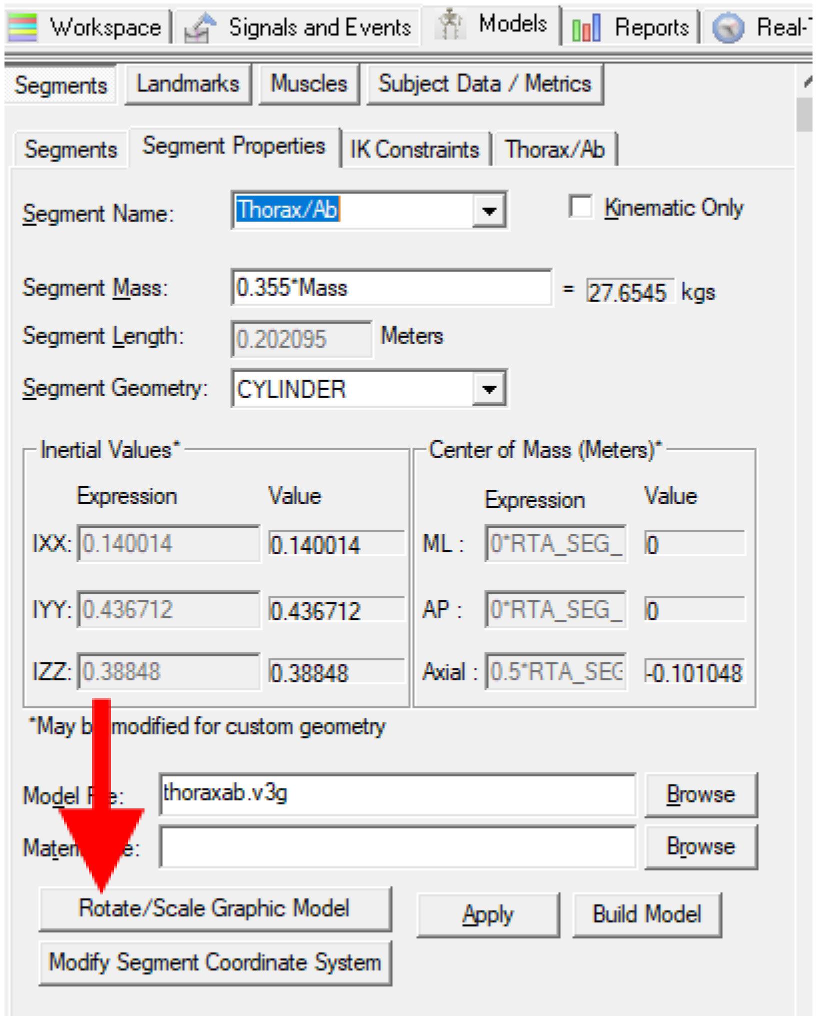


Figure 17: Segment properties interface, including the "Rotate/Scale Graphic Model" button

b. Select the button "Rotate/Scale Graphic Model" shown in Figure 17

c. Under the "Rotate" option, input "180" into the "Vertical Rotation" field

d. Now select the "move" option and input "65" into the "Move Up/Down" field

   i. It should be noted that this quantity will vary with every model and marker set so use the amount appropriate for the given model

e. Select the "scale" option and input "135" into each of the fields ("Scale Height," "Scale Width," and "Scale Depth")

   i. Similarly, these quantities vary depending on the model and the user should identify what amount of scaling works best

ii. Additionally, after the proper scaling amount is determined, the segment may need to be moved again to accommodate for this, and it also may need to be moved "Back/Forward" as well

iii. Figure 18 shows how the thorax should appear after these steps are completed

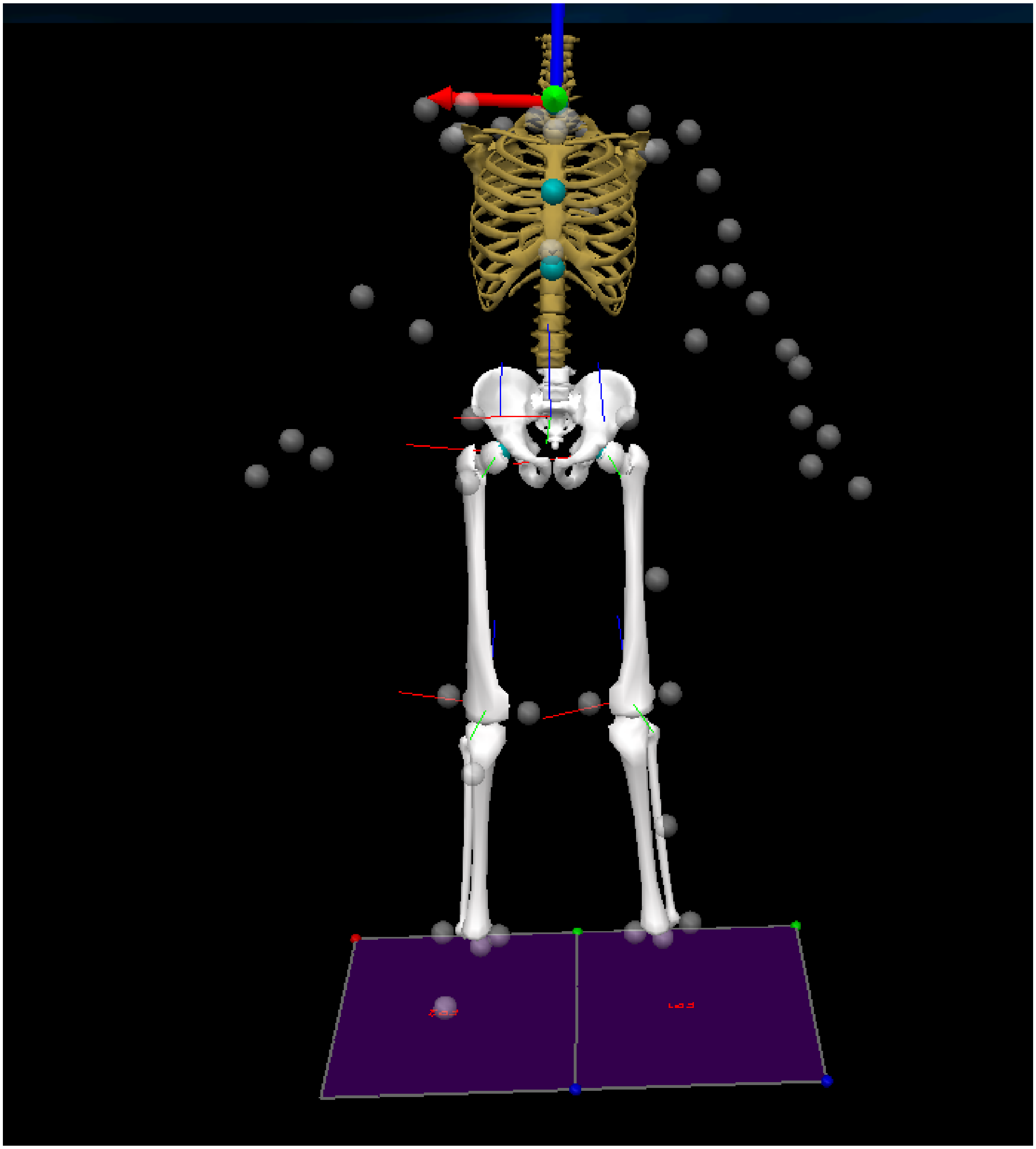


Figure 18: How the thorax segment should appear after proper scaling and moving

13. Create left shoulder joint center

a. Navigate to the “Landmarks” tab
b. Select the “Add New Landmark” button
c. Input “LSJC” in the space next to “Landmark Name:”
d. Under the “Define Orientation Using:” section, input “LPGLE” into the “Starting Point” field
e. Select “Targets and/or Landmark:” and select “LAGLE” from the drop-down options next to “Ending Point”
f. Under the “Landmark Offset from Start Point (Reference) or Segment Origin” section, select “Offset Using the Following ML/AP/AXIAL Offsets”
g. The inputs for the “Offset Using the Following ML/AP/AXIAL Offsets” section are as follows:
    i. ML: 0.0
    ii. AP: 0.0
    iii. AXIAL: 0.5
h. Select the “Offset by Percent” checkbox
i. Do not select the “Calibration Only Landmark” checkbox
j. Select “Apply”
    i. A blue marker should have just been applied to the left shoulder area, this represents the left shoulder joint center

14. Create left elbow joint center

a. Navigate to the “Landmarks” tab
b. Select the “Add New Landmark” button
c. Input “LEJC” in the space next to “Landmark Name:”
d. Under the “Define Orientation Using:” section, input “LHLE” into the “Starting Point” field
e. Select “Targets and/or Landmark:” and select “LHME” from the drop down options next to “Ending Point”
f. Under “Landmark Offset from Start Point (Reference) or Segment Origin” section, select “Offset Using the Following ML/AP/AXIAL Offsets”
g. The inputs for “Offset Using the Following ML/AP/AXIAL Offsets” section are as follows:
    i. ML: 0.0
    ii. AP: 0.0
    iii. AXIAL: 0.5
h. Select “Offset by Percent” checkbox
i. Do not select “Calibration Only Landmark” checkbox
j. Select “Apply”

i. A blue marker should have just been applied to the left elbow area, this represents the left elbow joint center

15. Enter value for left shoulder radius

a. Navigate to “Subject Data/Metrics” tab
b. Select “Add New Item”
c. In the name field enter “LShoulder”
d. In the “Value or Expression” field enter “0.0245”
    i. This is a radius value of the humeral head in meters, it was assumed from the results of a research study (Milner, G. R., & Boldsen, J. L., 2012)
e. Select “OK”

16. Create left upper arm segment

a. Navigate to “Segments” tab
b. In the drop down menu under “Segment Name,” select “Left Upper Arm”
c. In the drop down menu under “Segment Type,” the type should be “Visual 3D”
d. Select the “Create button”
e. The inputs for the “Define Proximal Joint and Radius” section are as follows:
    i. Lateral: “None”
    ii. Joint Center: “LSJC”
    iii. Medial: None
    iv. Radius (Meters): LShoulder
        1. Note: This is the shoulder radius value which was inputted in the previous step
f. The inputs for “Define Distal Joint and Radius” section are as follows:
    i. Lateral: “LHLE”
    ii. Joint center: “LEJC”
    iii. Medial: “None”
    iv. Radius (meters): Should be grayed out
g. “Extra Target to Define Orientation (if needed)” section should be grayed out, don’t select anything
h. Check “Use Calibration Tracking Targets” box
i. The “Depth (Meters)” input can remain at “0.0”
j. Select “Apply” and then select “Build Model”
    i. The left upper arm should appear on the model

17. Create right shoulder joint center

a. Navigate to “Landmarks” tab
b. Select “Add New Landmark” button

        i. Note: if you can't find it, try selecting a tab of a landmark you previously worked on, and close it out. This should bring you back to the "home" menu for the Landmarks tab
    c. Input "RSJC" in the space next to "Landmark Name:"
    d. Under the "Define Orientation Using:" section, input "RPGLE" into the "Starting Point" field
    e. Select "Targets and/or Landmark:" and select "RAGLE" from the drop down options next to "Ending Point"
    f. Under "Landmark Offset from Start Point (Reference) or Segment Origin" section, select "Offset Using the Following ML/AP/AXIAL Offsets"
    g. The inputs for "Offset Using the Following ML/AP/AXIAL Offsets" section are as follows:
        i. ML: 0.0
        ii. AP: 0.0
        iii. AXIAL: 0.5
    h. Select "Offset by Percent" checkbox
    i. Do not select "Calibration Only Landmark" checkbox
    j. Select "Apply"
        i. A blue marker should have just been applied to the right shoulder area, this represents the right shoulder joint center

18. Create right elbow joint center

    a. Navigate to "Landmarks" tab
    b. Select "Add New Landmark" button
    c. Input "REJC" in the space next to "Landmark Name:"
    d. Under the "Define Orientation Using:" section, input "RHLE" into the "Starting Point" field
    e. Select "Targets and/or Landmark:" and select "RHME" from the drop down options next to "Ending Point"
    f. Under "Landmark Offset from Start Point (Reference) or Segment Origin" section, select "Offset Using the Following ML/AP/AXIAL Offsets"
    g. The inputs for "Offset Using the Following ML/AP/AXIAL Offsets" section are as follows:
        i. ML: 0.0
        ii. AP: 0.0
        iii. AXIAL: 0.5
    h. Select "Offset by Percent" checkbox
    i. Do not select "Calibration Only Landmark" checkbox
    j. Select "Apply"

        i. A blue marker should have just been applied to the right elbow area, this represents the right elbow joint center

19. Enter value for right shoulder radius

a. Navigate to “Subject Data/Metrics” tab
b. Select “Add New Item”
c. In the name field enter “RShoulder”
d. In the “Value or Expression” field enter “0.0245”
    i. This is a radius value of the humeral head in meters, it was assumed from the results of a research study (Milner, G. R., & Boldsen, J. L., 2012)
e. Select “OK”

20. Create right upper arm segment

a. Navigate to “Segments” tab
b. In the drop down menu under “Segment Name,” select “Right Upper Arm”
c. In the drop down menu under “Segment Type,” the type should be “Visual 3D”
d. Select the “Create button”
e. The inputs for the “Define Proximal Joint and Radius” section are as follows:
    i. Lateral: “None”
    ii. Joint Center: “RSJC”
    iii. Medial: None
    iv. Radius (Meters): RShoulder
        1. Note: This is the shoulder radius value which was inputted in the previous step
f. The inputs for “Define Distal Joint and Radius” section are as follows:
    i. Lateral: “RHLE”
    ii. Joint center: “REJC”
    iii. Medial: “None”
    iv. Radius (meters): Should be grayed out
g. “Extra Target to Define Orientation (if needed)” section should be grayed out, don’t select anything
h. Check “Use Calibration Tracking Targets” box
i. The “Depth (Meters)” input can remain at “0.0”
j. Select “Apply” and then select “Build Model”
    i. The right upper arm should appear on the model

21. Create left wrist joint center

a. Navigate to “Landmarks” tab
b. Select “Add New Landmark” button
c. Input “LWJC” in the space next to “Landmark Name:”

d. Under the “Define Orientation Using:” section, input “LRSP” into the “Starting Point” field
e. Select “Targets and/or Landmark:” and select “LUSP” from the drop down options next to “Ending Point”
f. Under “Landmark Offset from Start Point (Reference) or Segment Origin” section, select “Offset Using the Following ML/AP/AXIAL Offsets”
g. The inputs for “Offset Using the Following ML/AP/AXIAL Offsets” section are as follows:
    i. ML: grayed out
    ii. AP: grayed out
    iii. AXIAL: 0.5
h. Select “Offset by Percent” checkbox
i. Do not select “Calibration Only Landmark” checkbox
j. Select “Apply”
    i. A blue marker should have just been applied to the left wrist area, this represents the left wrist joint center shown in Figure 19 (red arrow points to joint center)

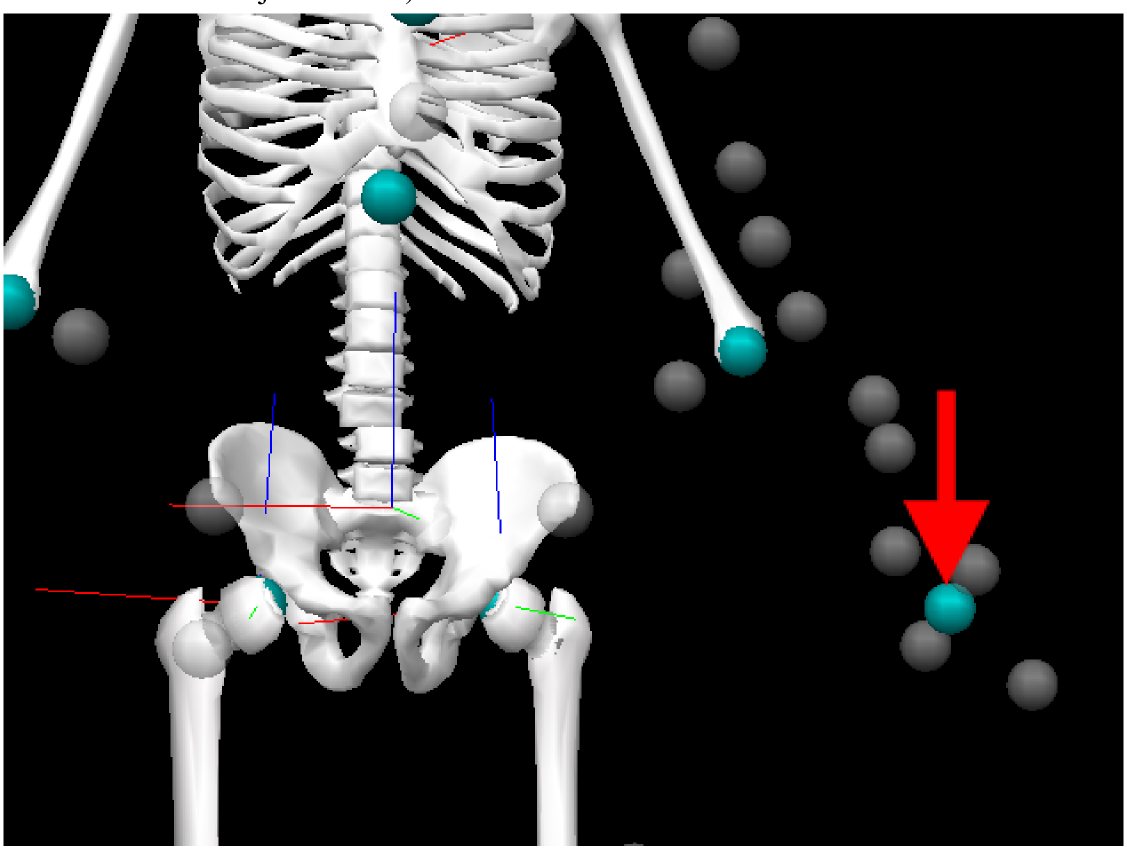


Figure 19: Image of model including the left wrist joint center denoted by the blue dot and red arrow

22. Create left elbow tracking joint center

a. Navigate to "Landmarks" tab
b. Select "Add New Landmark" button
c. Input "LEJC_Track" in the space next to "Landmark Name:"
d. Under the "Define Orientation Using:" section, select "Existing Coordinate System" and select "Left Upper Arm" from the dropdown
e. Under "Landmark Offset from Start Point (Reference) or Segment Origin" section, select "Offset Using the Following ML/AP/AXIAL Offsets"
f. The inputs for "Offset Using the Following ML/AP/AXIAL Offsets" section are as follows:
    i. ML: 0.0
    ii. AP: 0.0
    iii. AXIAL: -1
g. Select "Offset by Percent" checkbox
h. Do not select "Calibration Only Landmark" checkbox
i. Select "Apply"
    i. A blue marker should have just been applied to the left elbow area

23. Create left forearm segment

a. Navigate to "Segments" tab
b. In the drop down menu under "Segment Name," select "Left Forearm"
c. In the drop down menu under "Segment Type," the type should be "Visual 3D"
d. Select the "Create button"
e. The inputs for the "Define Proximal Joint and Radius" section are as follows:
    i. Lateral: "None"
    ii. Joint Center: "LEJC"
    iii. Medial: None
    iv. Radius (Meters): 0.5*DISTANCE(LHME,LHLE)
        1. Note: This is half the distance between the medial and lateral elbow markers respectively
f. The inputs for "Define Distal Joint and Radius" section are as follows:
    i. Lateral: "None"
    ii. Joint center: "LWJC"
    iii. Medial: "None"
    iv. Radius (meters): 0.5*DISTANCE(LUSP,LRSP)
g. The inputs for "Extra Target to Define Orientation (if needed)" section are as follows:
    i. Location: "Medial" (from left drop-down) and "LHME" (from right drop-down)
h. Do not check "Use Calibration Tracking Targets" box

        i. Within this section, select:“LEJC_Track”, “LRSP”, “LUSP”
   i. The “Depth (Meters)” input should be grayed out
   j. The 6DOF Cutoff Frequency can remain at “0.0”
   k. Select “Apply” and then select “Build Model”
        i. The left forearm should appear on the model
        ii. Ensure that the coordinate axis are pointing the same directions as other segments (corresponding with the colors for each axis)

24. Create right wrist joint center

a. Navigate to “Landmarks” tab
b. Select “Add New Landmark” button
c. Input “RWJC” in the space next to “Landmark Name:”
d. Under the “Define Orientation Using:” section, input “RRSP” into the “Starting Point” field
e. Select “Targets and/or Landmark:” and select “RUSP” from the drop down options next to “Ending Point”
f. Under “Landmark Offset from Start Point (Reference) or Segment Origin” section, select “Offset Using the Following ML/AP/AXIAL Offsets”
g. The inputs for “Offset Using the Following ML/AP/AXIAL Offsets” section are as follows:
    i. ML: grayed out
    ii. AP: grayed out
    iii. AXIAL: 0.5
h. Select “Offset by Percent” checkbox
i. Do not select “Calibration Only Landmark” checkbox
j. Select “Apply”
    i. A blue marker should have just been applied to the right wrist area, this represents the right wrist joint center

25. Create right elbow offset joint center

a. Navigate to “Landmarks” tab
b. Select “Add New Landmark” button
c. Input “REJC_Offset” in the space next to “Landmark Name:”
d. Under the “Define Orientation Using:” section, select “Existing Coordinate System” and select “Right Upper Arm” from the dropdown
e. Under “Landmark Offset from Start Point (Reference) or Segment Origin” section, select “Offset Using the Following ML/AP/AXIAL Offsets”
f. The inputs for “Offset Using the Following ML/AP/AXIAL Offsets” section are as follows:
    i. ML: 0.0

    ii. AP: 0.0
    iii. AXIAL: -1
g. Select “Offset by Percent” checkbox
h. Do not select “Calibration Only Landmark” checkbox
i. Select “Apply”
    i. A blue marker should have just been applied to the right elbow area

26. Create right forearm segment

a. Navigate to “Segments” tab
b. In the drop down menu under “Segment Name,” select “Right Forearm”
c. In the drop down menu under “Segment Type,” the type should be “Visual 3D”
d. Select the “Create button”
e. The inputs for the “Define Proximal Joint and Radius” section are as follows:
    i. Lateral: “None”
    ii. Joint Center: “REJC”
    iii. Medial: None
    iv. Radius (Meters): 0.5*DISTANCE(RHME,RHLE)
        1. Note: This is half the distance between the medial and lateral elbow markers respectively
f. The inputs for “Define Distal Joint and Radius” section are as follows:
    i. Lateral: “None”
    ii. Joint center: “RWJC”
    iii. Medial: “None”
    iv. Radius (meters): 0.5*DISTANCE(RUSP,RRSP)
g. The inputs for “Extra Target to Define Orientation (if needed)” section are as follows:
    i. Location: “Medial” (from left drop-down) and “RHME” (from right drop-down)
h. Do not check “Use Calibration Tracking Targets” box
    i. Within this section, select:“REJC_Offset”, “RRSP”, “RUSP”
i. The “Depth (Meters)” input should be grayed out
j. The 6DOF Cutoff Frequency can remain at “0.0”
k. Select “Apply” and then select “Build Model”
    i. The right forearm should appear on the model
    ii. Ensure that the coordinate axis are pointing the same directions as other segments (corresponding with the colors for each axis)

27. Create right ankle joint center

a. Navigate to “Landmarks” tab
b. Select “Add New Landmark” button

c. Input “RAJC” in the space next to “Landmark Name:”
d. Under the “Define Orientation Using:” section, select “Existing Coordinate System” and select “Right Shank” from the drop-down options
e. Under “Landmark Offset from Start Point (Reference) or Segment Origin” section, select “Offset Using the Following ML/AP/AXIAL Offsets”
f. The inputs for “Offset Using the Following ML/AP/AXIAL Offsets” section are as follows:
    i. ML: 0.0
    ii. AP: 0.0
    iii. AXIAL: -1
g. Select “Offset by Percent” checkbox
h. Do not select “Calibration Only Landmark” checkbox
i. Select “Apply”
    i. A blue marker should have just been applied to the left ankle area, this represents the left ankle joint center

28. Create right foot segment

a. Navigate to “Segments” tab
b. In the drop down menu under “Segment Name,” select “Right Foot”
c. In the drop down menu under “Segment Type,” the type should be “Visual 3D”
d. Select the “Create button”
e. The inputs for the “Define Proximal Joint and Radius” section are as follows:
    i. Lateral: “None”
    ii. Joint Center: “RAJC”
    iii. Medial: None
    iv. Radius (Meters): RSK_DISTAL_RADIUS
f. The inputs for “Define Distal Joint and Radius” section are as follows:
    i. Lateral: “None”
    ii. Joint center: “RTOE”
    iii. Medial: “None”
    iv. Radius (meters): RSK_DISTAL_RADIUS
g. The inputs for “Extra Target to Define Orientation (if needed)” section are as follows:
    i. Location: “Posterior” (from left drop-down) and “RCA” (from right drop-down)
h. Check “Use Calibration Tracking Targets” box
i. The “Depth (Meters)” input should be grayed out
j. The 6DOF Cutoff Frequency can remain at “0.0”
k. Select “Apply” and then select “Build Model”
    i. The right forearm should appear on the model

ii. Note: Only the right foot can be created using this marker set because the left toe marker was removed because the pitchers drag their toe while pitching. This markerset in this SOP is based off of a left-handed pitcher, so the left foot segment cannot be created. In a right-handed pitcher scenario, the right foot would not be included in the model.
iii. At this point, the model is complete and should appear as it does in Figure 20 below

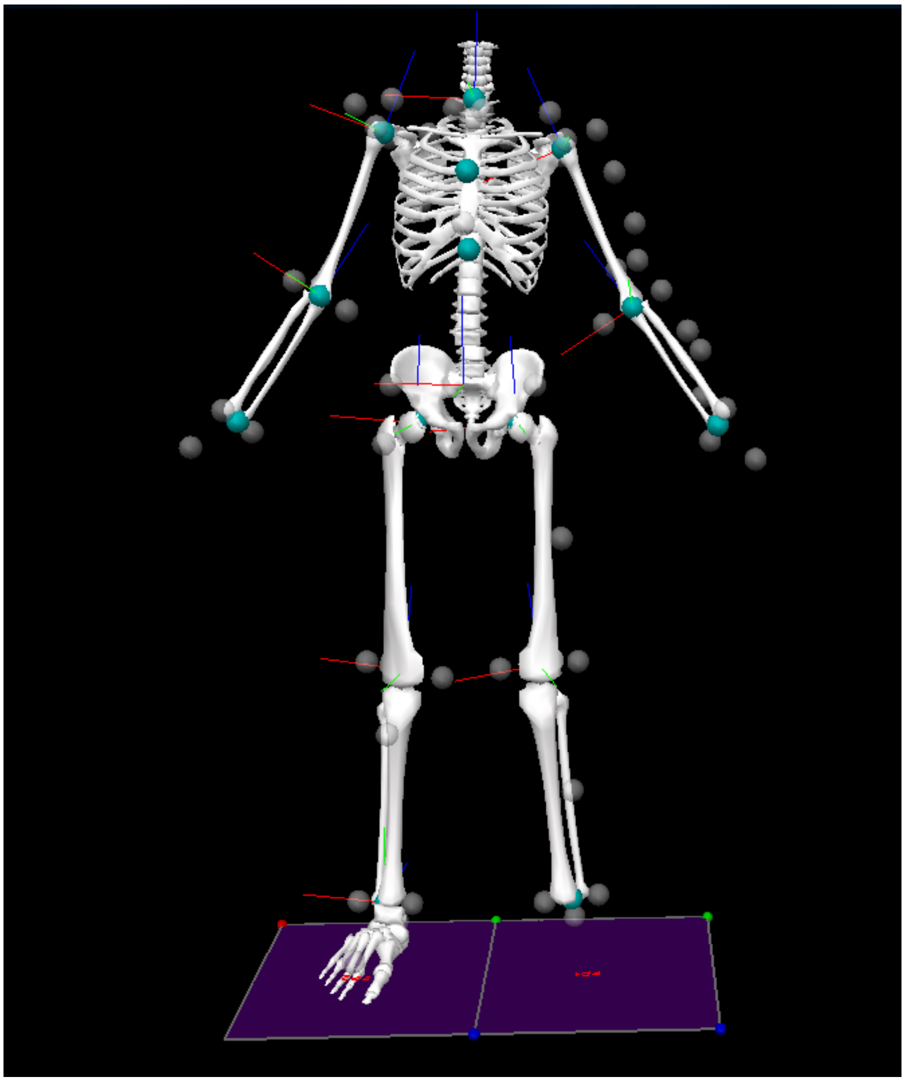


Figure 20: Final model created in this tutorial

Exporting Motion Data Visual 3D

Once the Visual 3D model is complete, the model can be used to apply the motion files from motion capture and export kinematic and dynamic data such as joint angles, forces, moments, and many other useful data types depending on the application. This section will cover the steps of running the motion files on the model and exporting several data types.

1. **Import Motion Files to Visual 3D**
   a. Return to the "Workspace" shown by following the button in Figure 21

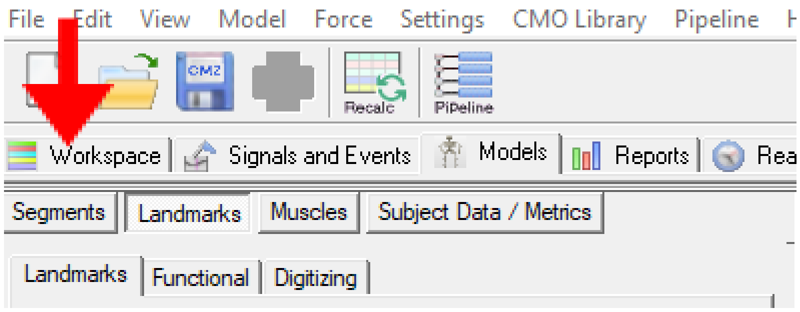


Figure 21: Workspace button

   b. Select "File", then "Open/Add…" as shown in Figure 22

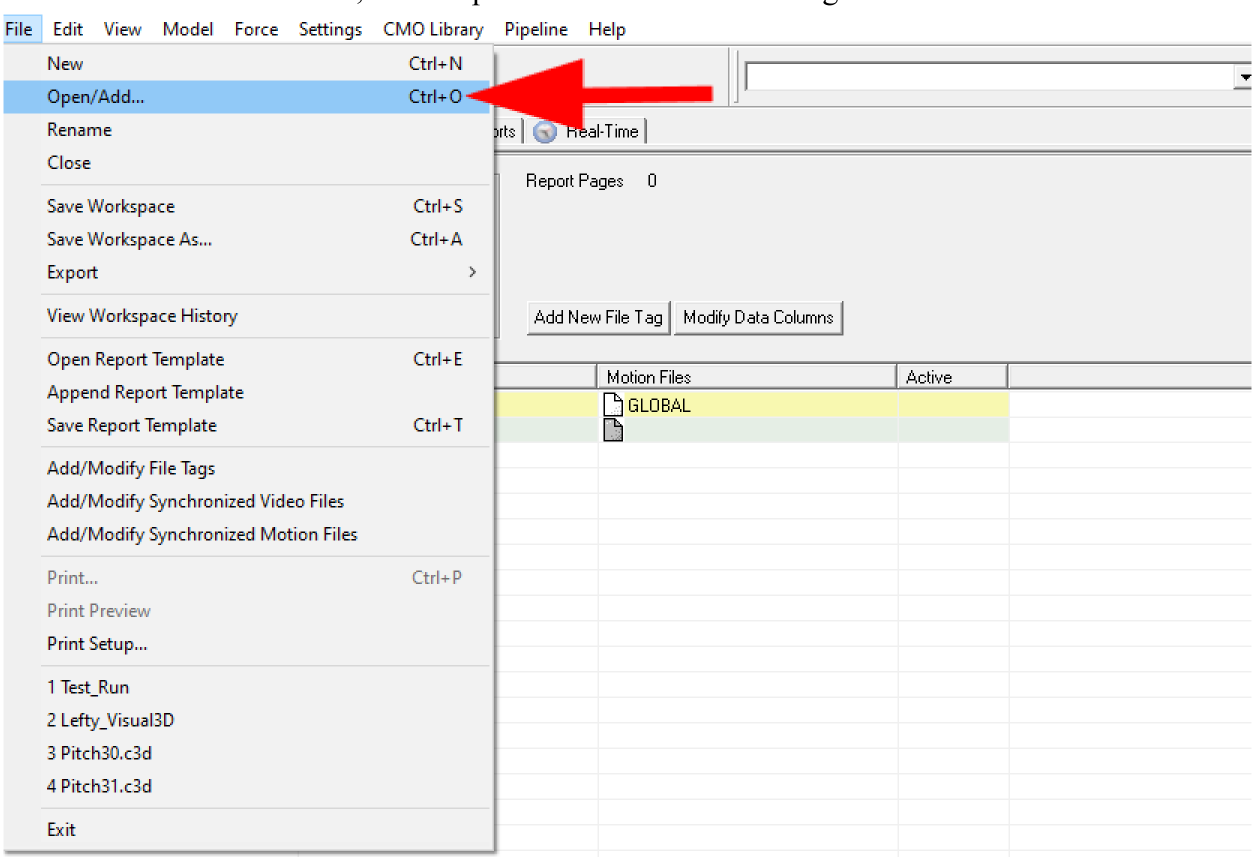


Figure 22: "Open/Add…" button to select for desired motion files

   c. A pop-up shown in Figure 23 will appear, select "Insert new files into your currently open workspace"

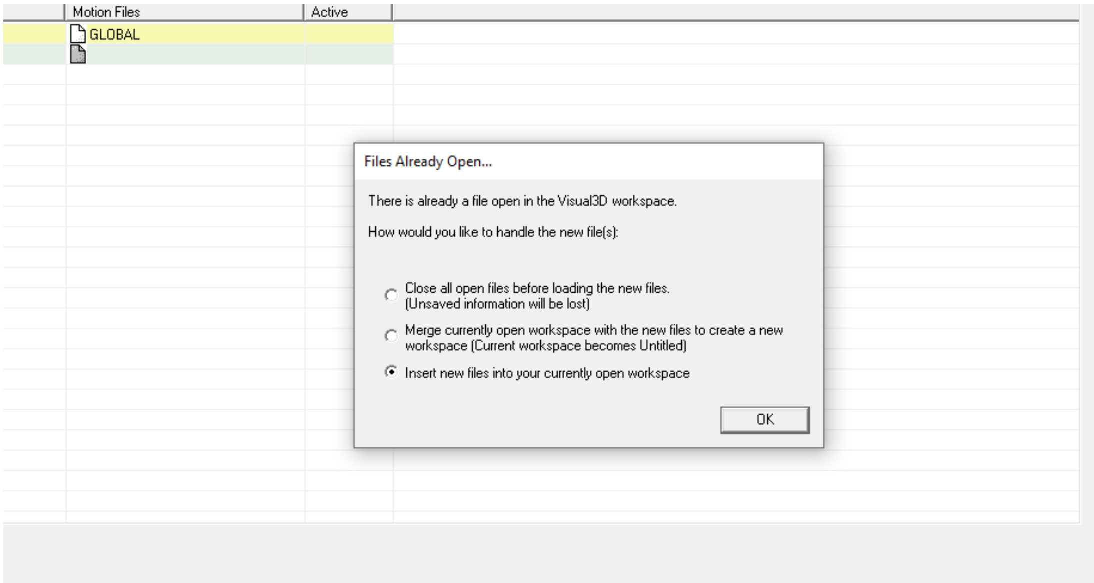


Figure 23: Pop-up options when adding files to workspace

d. From here, Visual 3D will allow you to navigate to your folder with your motion files
e. Select one or multiple motion files to import
   i. To select multiple at once, hold the "Ctrl" key and click each file or click and drag to highlight all the pitches
   ii. The files should be "C3D" file types
f. Select "Open" button at the bottom
   i. All of the selected motion files should appear within the workspace as shown in Figure 24

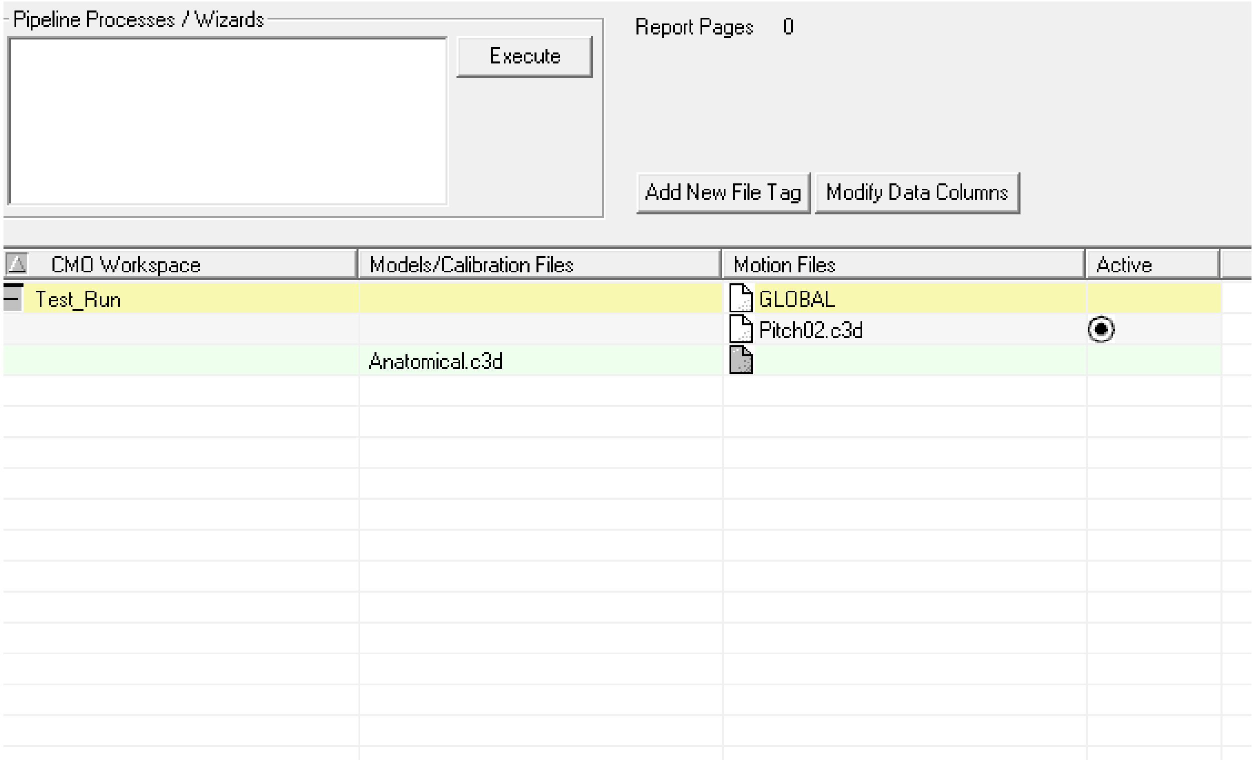


Figure 24: Workspace view once motion files are imported

g. Select "Model" tab and then "Assign Model to Motion Files"
   i. This essentially is telling the software to use the selected motion files with the model in the workspace

h. Select or highlight all the motion file checkboxes that are needed for the model as shown in Figure 25

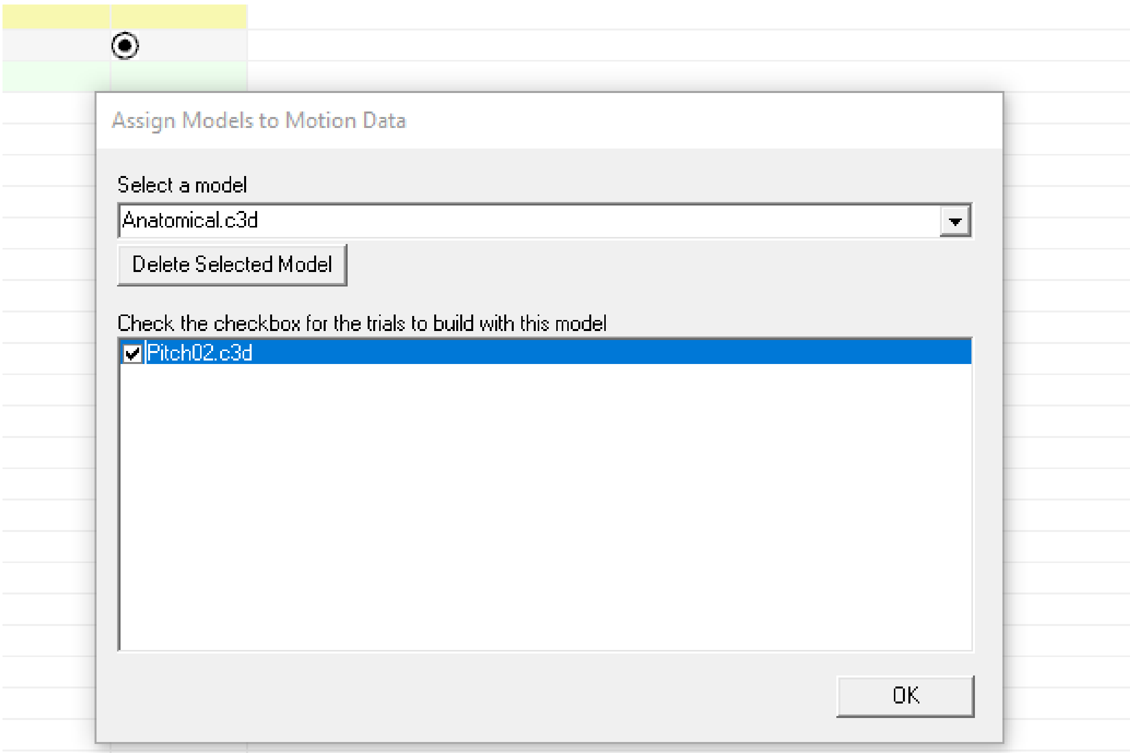


Figure 25: Selecting motion files for the model to be assigned to

i. Select "OK"

j. Double click on the specific motion file to export data from first

   i. The interface should now appear as it does in Figure 26. At this point, the user has the option to play the motion file on the model using the "Play" button in the bottom left corner. Additionally, the video can be played at different speeds, and Visual 3D shows the current frame it is on, as well as the total frames.

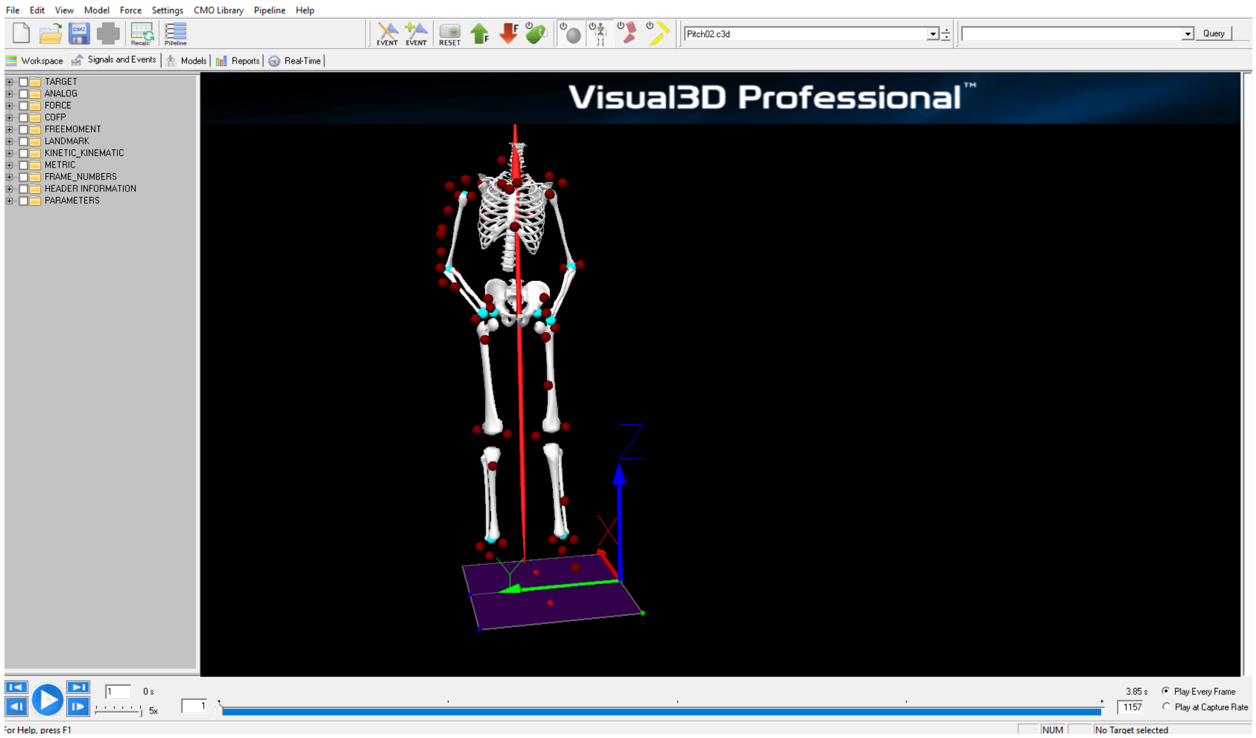


Figure 26: Motion file player on Visual 3D

2. **Export joint angle data**
   a. Select "Model" tab and then "Compute Model Based Data"
   b. Under "Data Name", create a name for the data exportation
      i. i.e. "RightArmAngle"
   c. Ensure "ORIGINAL" is selected for the "Folder"
   d. Under "Model Based Item Properties" select "Joint_Angle"
      i. This is the full list of data that can exported from Visual 3D
   e. "Normalization" section should be grayed out
   f. Under "Segment" select "Right Forearm"
   g. Under "Reference Segment" select "Right Upper Arm"
   h. Under "Cardan Sequence" select "ML-AP-AXIAL"
      i. Figure 27 shows a summary of all the inputs. These specific inputs can be used to determine the max external rotation of the right arm. The meaning of this data is further explained in the section "Understanding Data Types Exported."

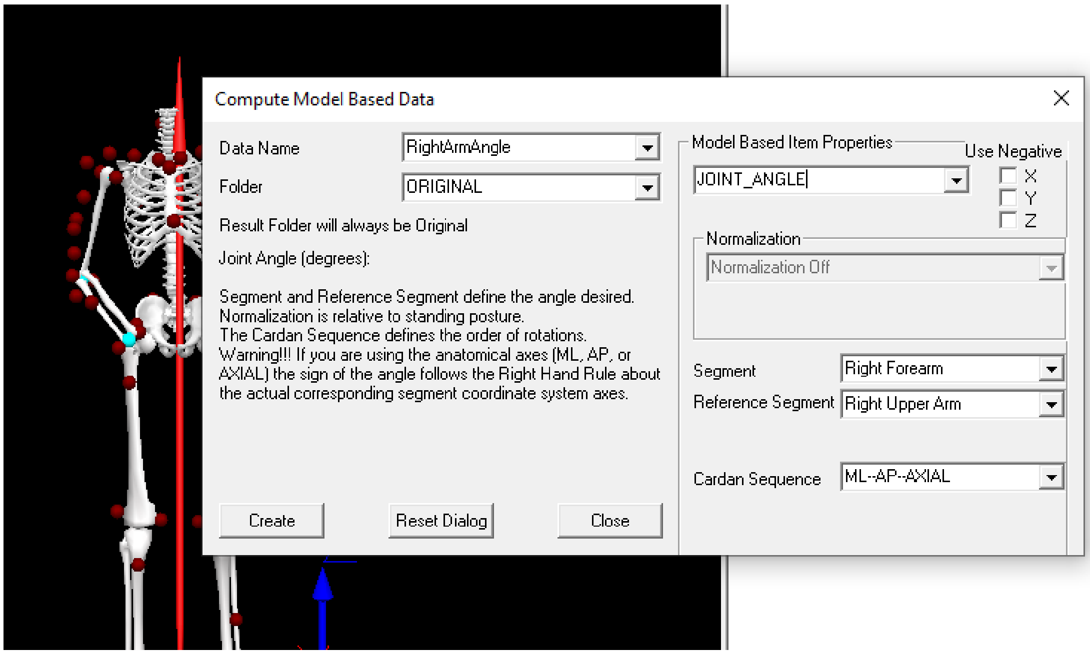


Figure 27: Inputs for Right Arm Angle Data

i. When all fields are selected, select "Create"

j. To view the data, select "LINK_MODEL_BASED" from the side tree options, then "ORIGINAL", and the previously created data file should be there as shown in Figure 28

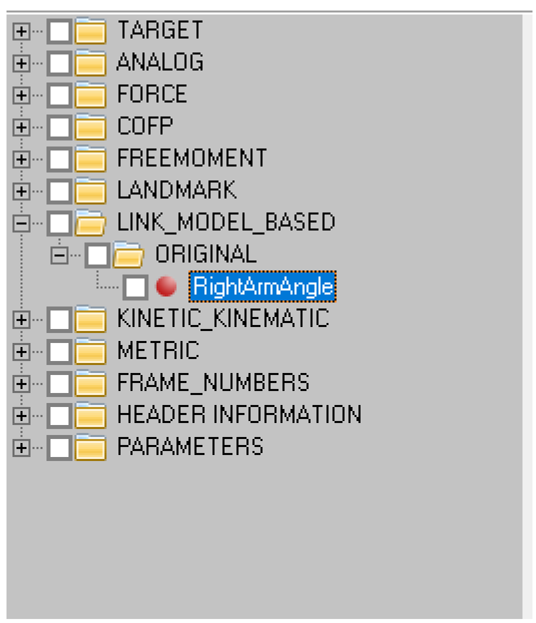


Figure 28: Location of data post-exporting

k. Clicking on the data will pull up a "Data View" tab including a "Data Graph", "Data Values" and "Signal Processing History"

l. To export the data, select the "Data Values" tab and select the "Export ASCII" button shown in Figure 29

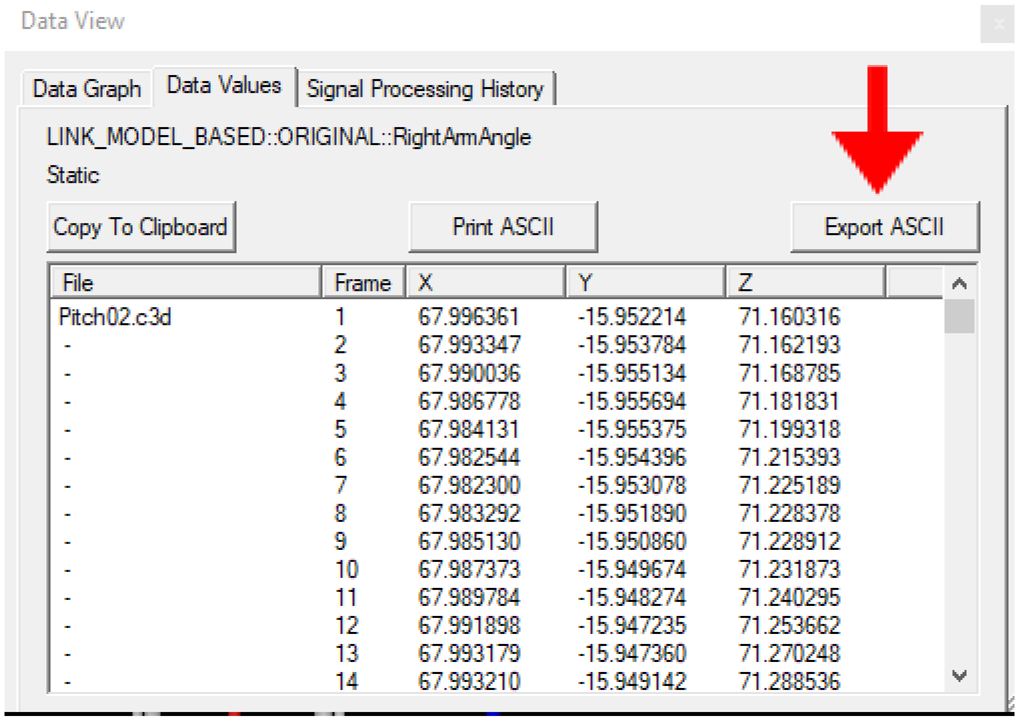


Figure 29: Data values tab including the "Export ASCII" button which should be used to export data

m. From here, the data will be saved as a (*.txt) file to the folder of the user choosing
n. See the final section of this document to understand the meaning of all the exported data

3. **Export joint force data**
   a. Figure 30 shows the inputs for exporting joint force data of the left elbow
      i. Use the left elbow as the "Joint/(segment)" and use the left upper arm as the "Resolution Coordinate System"

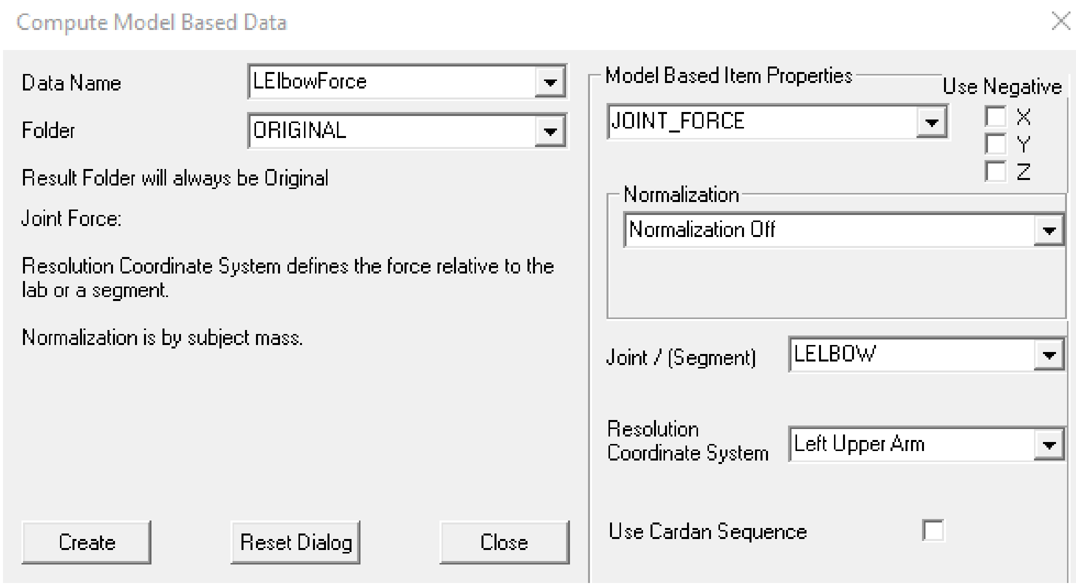


Figure 30: Joint force data input

4. **Export joint force data**
    a. Figure 31 shows the inputs for exporting joint moment data of the left elbow
        i. Use the left elbow as the "Joint/(segment)" and use the left upper arm as the "Resolution Coordinate System"

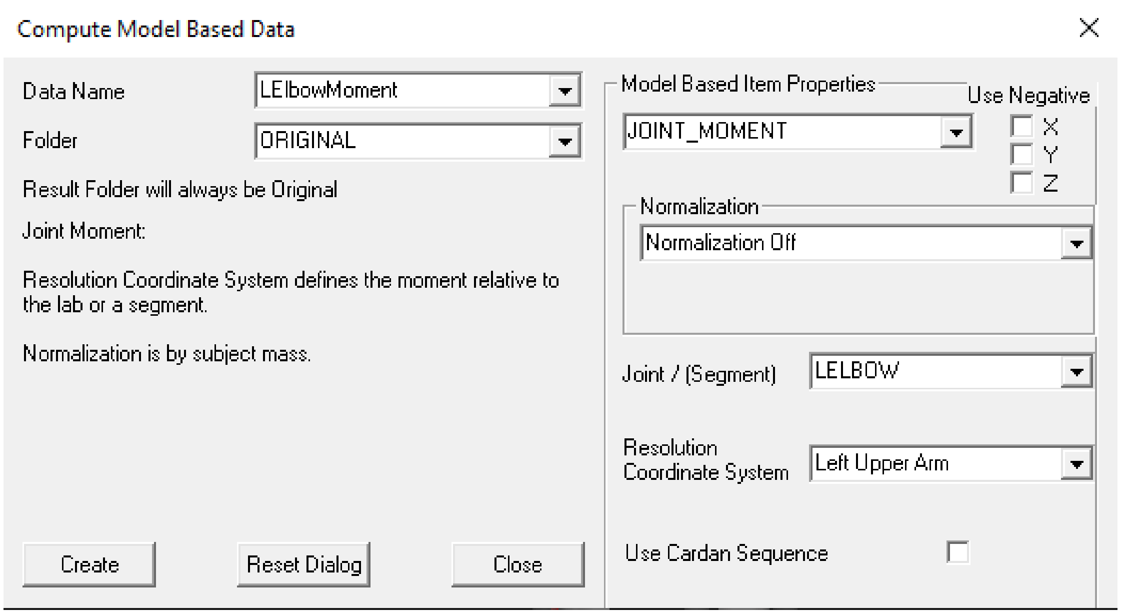


Figure 31: Joint moment data input

5. **Export target path data**
    a. Figure 32 shows the inputs for exporting target path data for the left elbow joint center

i. Use the left elbow joint center (LEJC) as the "Target" and use "LAB" as the "Reference Segment" and "Resolution Coordinate System"

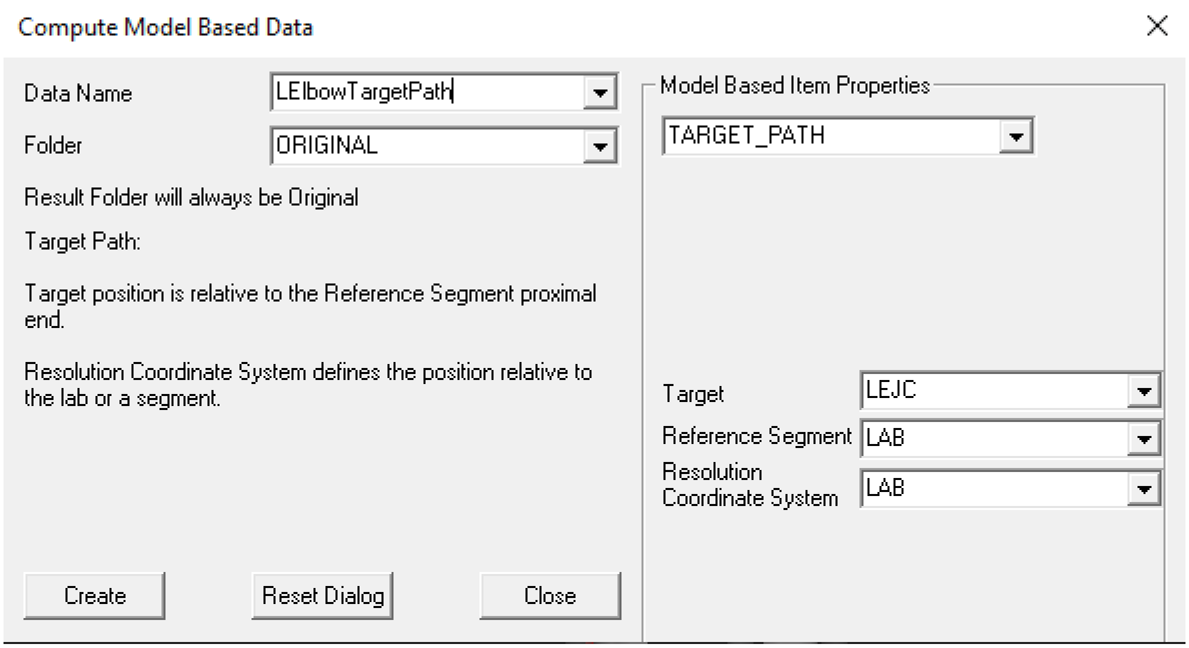
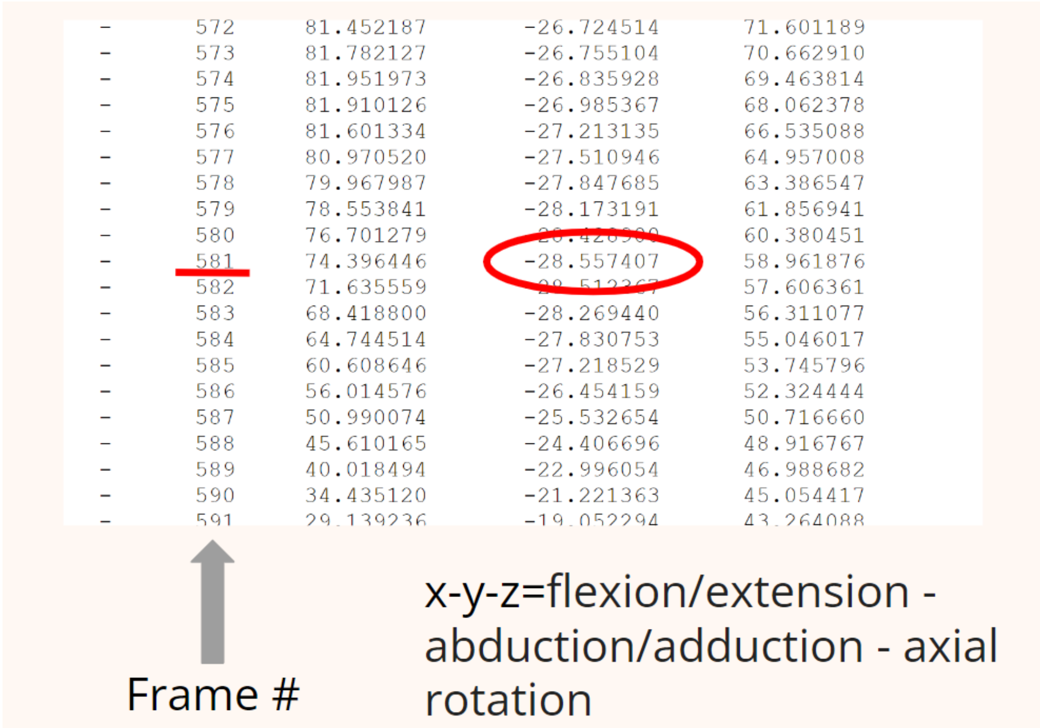


Figure 32: Joint center target path inputs

Understanding Data Types Exported

Joint Angle Data

Visual 3D can calculate joint angles of motion files, resulting in a default Cardan sequence of x-y-z. More specifically, when calculating joint angles, the software outputs three columns of data, corresponding to x-y-z, or in the case of joint angles, flexion/extension-abduction/adduction-axial rotation respectively. Figure 33 shows the data output for joint angle with the inputs explained in the previous section. The figure clearly shows the frame number of the motion file on the left, and the right three columns are joint angles corresponding to the data types previously explained. In this example, the data was exported on the throwing forearm with respect to the throwing upper arm. With this data, the max external rotation angle can be determined with the throwing arm. As shown in Figure 33, using the largest number in the abduction/adduction column (second column), disregarding the negative sign, the angle can be determined. In this example, the largest number is 28.557 degrees, as circled in the figure. Subtracting this number from 180 degrees gives the final value of maximum external rotation of 151.443 degrees.



-	572	81.452187	-26.724514	71.601189
-	573	81.782127	-26.755104	70.662910
-	574	81.951973	-26.835928	69.463814
-	575	81.910126	-26.985367	68.062378
-	576	81.601334	-27.213135	66.535088
-	577	80.970520	-27.510946	64.957008
-	578	79.967987	-27.847685	63.386547
-	579	78.553841	-28.173191	61.856941
-	580	76.701279	[illegible]	60.380451
-	581	74.396446	-28.557407	58.961876
-	582	71.635559	-28.512367	57.606361
-	583	68.418800	-28.269440	56.311077
-	584	64.744514	-27.830753	55.046017
-	585	60.608646	-27.218529	53.745796
-	586	56.014576	-26.454159	52.324444
-	587	50.990074	-25.532654	50.716660
-	588	45.610165	-24.406696	48.916767
-	589	40.018494	-22.996054	46.988682
-	590	34.435120	-21.221363	45.054417
-	591	29.139236	-19.052294	43.264088

Figure 33: Throwing arm joint angles, with angle used to calculate max external rotation circled

Joint Force and Moment Data

Visual 3D also can export data on the joint's forces and moments. Similarly to the joint angle data, the results will output three columns of data corresponding to the forces and moments in the x-y-z directions. This data can be used to further analyze the biomechanics of the specific motion.

Target Path Data

Visual 3D also has the ability to calculate the target path data of all the markers and the joint center markers. In this case, and in the input figure in the previous section, the target path was determined for the left elbow joint center. This data can be valuable for understanding how a given location or landmark changes throughout a specific motion, or its average across several of the same motion.

References

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Milner, G. R., & Boldsen, J. L. (2012). Humeral and femoral head diameters in recent white American skeletons. *Journal of Forensic Sciences*, *57*(1), 35–40. https://doi.org/10.1111/j.1556-4029.2011.01953.x

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