Association of Fatigue and Ulnar Collateral Ligament Injury in Professional Baseball Pitchers

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Abstract

Little is known about the subclinical changes to the ulnar collateral ligament (UCL) throughout an entire competitive season. This knowledge gap is due to limitations of how physical workload measures are defined and collected. This study provides a proof of concept for the development of a novel measurement of physiological fatigue. It will further investigate whether there is an association between physiological workload and UCL injury probability.

This study collected demographic, environmental, performance and injury history information on 1,633 pitchers during the 2018 and 2019 seasons. Fatigue Adjusted Pitch Count was formulated and quantified from these measures. Time-to-event analysis was used on the 2018-2019 season data to validate the hypothesis that consistently elevated FAPC during a competitive season is an indicator of UCL injury risk. A Cox Proportional Hazards analysis found FAPC in its current version to have a weak, negative association with UCL injury. A posthoc inspection found FAPC to have a slightly stronger association with UCL injury than actual pitch count. Pitching status (starter versus reliever) was a finding of statistical and contextual relevance, warranting further research.

This study provides the initial steps towards the validation and potential adoption of this real-time, performance-based measure of fatigue. Further validation and refinement of the FAPC calculation can provide coaches, teams, and clinicians holistic, data-informed guidance for the surveillance of injury, maximizing sport-specific and overall health.

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1 Introduction

Major League Baseball injuries cost the league $700 million annually (S. Conte, Camp, and Dines 2016); pitchers account for half of all injuries annually. A quarter of these injuries arise from ulnar collateral ligament (UCL) tears of pitcher's elbows (S. A. Conte et al. 2015). Current knowledge finds professional pitchers at ten times the rate of ligament reconstructions annually compared to the general population (Hodgins et al. 2016). Pitchers who undergo ligament reconstruction often fail to return to previous performance levels and have shorter careers than pitchers who do not undergo ligament reconstruction (S. F. DeFroda et al. 2018; Liu et al. 2016; Whiteside et al. 2016; Zaremski et al. 2017). Little is known about the subclinical changes to the ligament throughout an entire season of competition. Also, ligament injury risk factors are poorly understood and studied (Birfer, Sonne, and Holmes 2019; Norton et al. 2018; Portney et al. 2019; Zaremski et al. 2018).

This project provides a novel and more comprehensive quantification towards measuring workloads found in overhead throwing sports. A vast number of previous literature in this domain is specific to non-throwing sports. It focuses on the lower body's measures, cardiovascular-derived exertions, leaving their results and their application towards baseball activity insufficient (Black et al. 2016).

1.1 Overview

Little is known about the subclinical changes to the ulnar collateral ligament (UCL) throughout an entire season of competition in baseball pitchers. This knowledge gap is primarily due to the limited scope and definition of fatigue-inducing workload expenditures that impact the UCL's health. Study design and statistical methodologies undertaken in previous research have also limited the applicability of their findings towards elbow injury mitigation efforts. Data is scarce in the younger, non-professional pitcher population, creating further uncertainties in this group to identify, mitigate, or manage ligament changes that could threaten future performance and productivity.

The relationship between internal, physiological predispositions and external, environmental risk factors responsible for fatigue-induced injury etiology is also poorly understood and unaccounted for in the literature. Baseball injury literature is limited due to this gap, which has been studied in other sports (Meeuwisse et al. 2007). Figure 1 provides a schematic of sports injury etiology inspired by a dynamic injury model, accounting for multiple risk factors, both intrinsic and extrinsic (Meeuwisse et al. 2007).

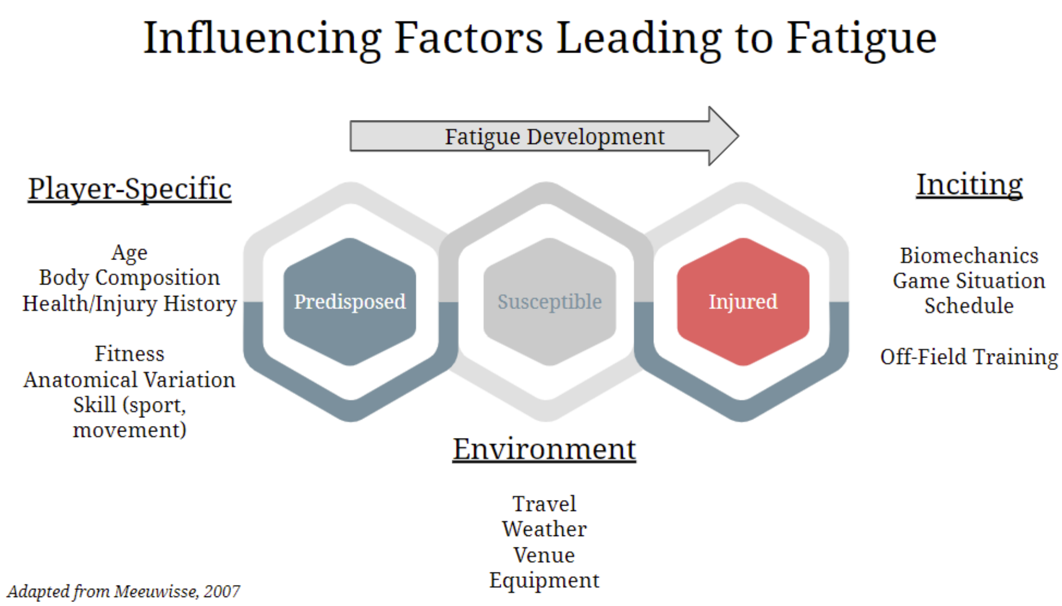


Figure 1: Dynamic Model of UCL Injury Risk Factors

This study looks to determine the association between physiological workload and UCL injury severity. A novel measurement is used and accounts for intrinsic risk factors such as age and injury history and repeated cycles of exposure to extrinsic risk factors that potentially lead to adaptations or maladaptations, many of which precede injury. This project offers the ability to accurately quantify the relationship between workload fatigue and ulnar collateral ligament injury in professional baseball pitchers during a season while also identifying the cumulative performance thresholds that lead up to UCL damage. This capability allows for further insights into how pitching's physical demands influence biomechanics, performance, and possible injury.

1.2 Epidemiology of Baseball Pitcher Elbow Injury

A quarter of all injuries sustained in Major League Baseball (MLB) in a given year are accounted for by ulnar collateral ligament (UCL) tears, and nearly a third of all pitchers on MLB rosters in 2018 had undergone ligament reconstruction (Camp et al. 2018; S. Conte, Camp, and Dines 2016). In pitchers, elbow injuries account for roughly 25% of injuries; they account for 16% of all baseball injuries (Posner et al. 2011). Pitchers who sustain a UCL tear and undergo surgical reconstruction on average miss 275 days due to the injury (Li et al. 2013). UCL tear has a prevalence of 13% across all professional baseball levels (Leland et al. 2019). Position players are also susceptible to UCL injury, with a 3% prevalence of UCL tear found in non-pitchers (S. A. Conte et al. 2015).

Amateur and youth pitchers have similar trends (Sakata et al. 2018). An incidence of 1.12 UCL tears per 10,000 athlete exposures was found in the collegiate pitcher population (Steven F. DeFroda et al. 2016), where athlete exposure is defined as participating in 1 practice or competition where a possible exposure to injury could occur, independent of time spent in activity (Dick, Agel, and Marshall 2007). In adolescents between the ages 9 and 14, a 5% incidence for all arm injuries in a recent 10-year prospective cohort study was found (Glenn

S. Fleisig et al. 2010). A recent systematic review of overhead upper extremity injuries in youths found an elbow injury incidence rate of 0.29-0.35 per 10,000 athlete exposures (Kraan et al. 2019). These trends have seen a steady rise over the last three decades. A previous study of community UCL reconstruction trends saw that the procedure rates increased 343% between 2003 and 2014 (Mahure et al. 2016), an abrupt leap in contrast to the previously mentioned study from Fleisig showing a 24% increase in procedure rates from 1994 to 2010 (Glenn S. Fleisig and Andrews 2012). Mahure Et al. also projected UCL reconstruction rates out 2025 and suggested that the incidence of UCL tears would increase to 14.6 per 100,000 in the late adolescent population (15 to 19 years of age).

With this injury burden comes a substantial financial cost to professional baseball teams. The 2015 season saw teams paying $695 million in total expenditures related to player injuries (Whiteside et al. 2016), increasing $116 million compared to the 2014 season. In the 2014 season, $253 million was spent on pitcher injuries alone, with half of these arising from elbow ligament injuries (Steven F. DeFroda et al. 2016). A previous prospective cohort study in youth sports found a mean medical cost per injury in baseball to be 532 dollars per injury (Knowles et al. 2007), highlighting the scope of the financial burden across all playing ages and levels.

1.3 Influencing Factors of UCL Injury

1.3.1 *Neuromuscular and Biomechanical Factors*

Muscle fatigue is hypothesized to be the primary instigator of these harmful mechanisms (Birfer, Sonne, and Holmes 2019). Muscle fatigue is the result of acute and chronic changes to central and peripheral mechanisms typically manifested as a decline in physical performance due to force production limitations (Enoka and Duchateau 2017; Norton et al. 2018; Zaremski et al. 2018). These changes then inspire adaptations in the biomechanical processes responsible for functional movement and performance, with kinetic and kinematic domains affected (Birfer, Sonne, and Holmes 2019; Brandon J. Erickson et al. 2017; B. J. Erickson et al. 2014; Zaremski et al. 2018; Makhni et al. 2014). Repeated microtrauma to the dynamic stabilizer muscles of the UCL produces laxity of the elbow joint (Brandon J. Erickson et al. 2017; B. J. Erickson et al. 2014; Zaremski et al. 2018). This laxity can lead to microtrauma to the UCL itself, which leads to a reduction in the tensile load that the ligament can withstand, escalating the risk of ligament failure and, ultimately, tears.

These declines affect both an athlete's force-generating processes (Sonne and Potvin 2016) and the neuromuscular functions related to sensorimotor integrity and proprioception (Jildeh et al. 2019). These functions are essential for sequencing and translating force through biomechanical movements, providing protective mechanisms against tissue damage, and supporting the endurance of these actions (Escamilla 2017; G. Fleisig et al. 2009; Wilk et al. 2014; Zaremski et al. 2018). These changes and their manifestations within pitching performance metrics towards a worsening of physical fatigue are supported in the literature (B. J. Erickson et al. 2014; Escamilla 2017; G. Fleisig et al. 2009; Makhni et al. 2014; Wilk et al. 2014; Zaremski et al. 2018). Studies using electromyography (EMG) as a method for measuring fatigue infer that changes in amplitude and frequency of EMG signal are a surrogate for fatigue (Oliver, Weimar, and Henning 2016; Pieter Clarys et al. 2010). These interpretations suggest that the measure of neuromuscular activity with EMG confirms its essential contribution to pitching mechanics (Peter N. Chalmers et al. 2017 May/Jun).

1.3.2 *Performance-related Factors*

The exact mechanisms and timing of possible fatigue-induced subclinical changes to ligament tissue remain unclear (Zaremski et al. 2018); the current application of performance metrics as indicators of injury produces inconsistent results Makhni et al. (2014). Common risk factors implicated in elbow injury include increased pitch velocities (Bushnell et al. 2010) and increased pitch counts and outings (Agresta, Krieg, and Freehill 2019; Norton et al. 2018). Pitch type and repertoire have also been identified as possible in-game factors related to an injury. The percentage of total fastballs thrown is positively correlated with UCL reconstruction in MLB pitchers; a 2% increase in UCL injury risk was found for every 1% increase in fastballs thrown (R. A. Keller et al. 2015). Compared to age-matched controls without an injury history, MLB pitchers who underwent UCL repair have higher average velocities on all pitch types thrown, controlling for pitch type frequency (Prodromo et al. 2016).

Similarly, rest between competitive appearances has shown to play a role in elbow injury incidence [Bakshi et al. (2020), 2020; Whiteside Et al., 2016]. Professional pitchers who underwent UCL reconstruction were found to have between 0.7 to 0.8 fewer days of rest between outings than matched controls with no injury history (Whiteside et al. 2016). Along with rest between competitive appearances, less time between each pitch thrown has shown to be associated with forearm muscle fatigue in one predictive model (Sonne and Keir 2016). Youth participants are found to have similar risk factors, with increased frequency of pitching for multiple teams with overlapping seasons and game participation as both a pitcher and catcher also associated with increased elbow injury risk (Glenn S. Fleisig et al. 2010; Kraan et al. 2019).

1.3.3 *Environmental Factors*

External, environmental risk factors responsible for injury etiology in the pitching setting are also poorly understood and unaccounted for (Bahr and Holme 2003; Meeuwisse et al. 2007). There is limited insight into how external factors, including travel, weather, and elevation, affect energy expenditures and performance, acutely or cumulatively. One previous cross-sectional, baseball-specific study found that pitchers from warm-weather climates were at higher risk of arm injury throughout a season than those from colder climates due to longer playing seasons and range of motion and strength deficits of the throwing arm (Kaplan et al. 2011). A study of Major League Baseball pitchers found that those from warm-weather climates had a higher frequency of UCL reconstructions than cold weather climates and were also younger at the time of reconstruction (Brandon J. Erickson et al. 2014). Competition-related heat illness in sports has been extensively reviewed and researched in high school sports in the United States (Howe and Boden 2007; Kerr et al. 2013). Baseball umpires have also been a population covered in this domain (Tsujita et al. 2001). Rates of exertional heat illness are lower in baseball compared to other outdoor sports. Still, they are determined by many factors, such as region, body mass index, and weather (Kerr et al. 2013).

Weather-related injury risk has also been researched in football, specific to the effects of cold weather in conjunction with the playing surface on leg injuries (Orchard and Powell 2003). Anterior cruciate ligament tears of the knee and other lower limb injuries are common in other cold-weather sports (Csapo et al. 2017). This phenomenon has not been rigorously researched in ligaments of the upper extremity or baseball. Likewise, extremes in elevation or elevation change over short periods have also been noted briefly in the literature as a risk factor for a team sports injury. Recent work has found that concussions in college football are sustained at a higher rate at higher elevations (Lynall et al. 2016); this finding is countered by a study in professional football players and concussion rate (Myer et al. 2014). Despite these conflicting results, physiological stress induced by increases in altitude can impact an athlete's performance and readiness (Woods et al. 2017) and is not currently understood or researched within the scope of baseball.

Beyond weather, the effects of travel between playing venues and the acute and cumulative effects of air travel, time zone change, as well as potential hours of rest have been shown to affect athlete health and physical readiness negatively. A recent study of National Basketball Association players found that short distance flights 'increase injury and impede performance' (Huyghe et al. 2018). Longer distance travel in professional rugby did not negatively influence performance or cause harm (Fuller, Taylor, and Raftery 2015). A 10-year retrospective study on sleep and travel in MLB found that teams with the circadian advantage, defined as '…how synchronized they were to their current time zone of play in relationship to the synchronization of their opponent,' performed better and had higher winning percentages in comparison to teams without this advantage (Winter et al. 2009).

This study provides firm baseball-specific conclusions in the professional player population; however, the effects of circadian advantage on injury susceptibility were not evaluated, further magnifying the absence of information about the acute and season-long road travel consequences of injury. The exposure as defined in this study seeks to supplant this deficiency in the current literature evaluating these extrinsic factors on performance and injury susceptibility on pitcher health.

Rule changes are also an external factor that can affect injury susceptibility. Recent MLB seasons have brought several rule changes affecting how injuries are sustained and captured. The addition of a separate injury list specific to concussion (Chatha et al. 2019), a rule to limit collisions at home plate (Green et al. 2019), and a reduction in the number of days a player can be placed on the non-concussion injury list ("4. 10-Day Injured List | Glossary | MLB.com," n.d.) are changes of note. Rules changes related to increasing the pace of play by reducing the amount of time allowed between pitches are proposed as having a significant, negative impact on pitchers' health and their ability to minimize fatigue during competition (Sonne and Keir 2016). In particular, using a 20-second pitch clock and the enforcement of a rule that gives a pitcher 12 seconds to throw a pitch after receiving the ball back from a catcher have been proposed as imposing increased demands on pitcher workloads (Sonne and Keir 2016). Another rule change that portends to a possible external factor leading to injury is the minimization of the number and duration of mound visits a coach can make throughout the game ("Mound Visit | Glossary," n.d.). This change can limit the amount of time a pitcher has for neuromuscular recovery during competition, increasing the potential for asymptomatic anatomical changes to the ligament.

Rule implementations that affect injury potential extend past those seen at the professional level. For youth-level pitching, Pitch Smart guidelines provided by MLB and USA

Baseball have been recently used to impart age-appropriate, data-informed injury prevention policy ("MLB | Pitch Smart," n.d.). Pitch count limits, shorter competitive seasons, limited use of breaking pitches, and a 3-month hiatus from overhead sports during a calendar year are all components included in the policy. Parents and coaches who are versed in understanding and implementing these rules have a lower probability of their child sustaining an arm injury (Zabawa and Alland 2019). Counter to the professional-level rule changes, this policy is geared towards maximizing rest and recovery and mitigating valgus forces on a ligament, which could lend it to a practical protocol towards optimizing pitcher arm health.

The recent phenomenon of focusing on the participation of one sport over all other possible options in youth baseball has been identified as the possible origin of the recent rise in soft tissue injury (Bell et al. 2018; Post, Struminger, and Hibberd 2020; Pytiak et al. 2017). A 2019 study using anonymous questionnaire data from high school-aged baseball players from 3 states found a 3.55-fold increase in the odds of high-specialization players reporting an upper extremity in their previous season of play, compared to their less-specialized peers (Post, Struminger, and Hibberd 2020). Specialization of a sport was defined as participation in a single sport for eight or more months during a calendar year. Meta-analyses (Post, Struminger, and Hibberd 2020; Pytiak et al. 2017) across multiple overhead sports at the youth level and a recent prospective study in youth baseball players reflect these findings (Arnold et al. 2019).

1.3.4 *Anatomical Factors*

Anatomically, the UCL is one component of soft tissue structures that provide the joint stability required in overhead throwing sports. The UCL is composed of 3 bundles. The anterior bundle provides valgus stability throughout the entire range of motion of a throw (Patel, n.d.), making it a primary focus of concern regarding fatigue. The mean length of the anterior bundle is 27 millimeters, with the mean width ranging from 5-8 mm (Hariri, n.d.).

The anterior bundle is further separated into two bands: the anterior and posterior. These bands provide direct support against joint displacement forces associated with pitching at different points of arm motion (Patel, n.d.).

Valgus stress can be significant, with forces up to 64 newton-meters of power generated with each pitch (Hariri, n.d.; Patel, n.d.; Slowik et al. 2019). With each pitch thrown, the UCL is subjected to these tensile stresses that tax the ligament to near failure. These stresses cause microscopic tears and attenuation of the anterior bundle of the UCL (Birfer, Sonne, and Holmes 2019; G. Fleisig et al. 2009; Hibberd, Brown, and Hoffer 2015; Patel, n.d.). As these forces accumulate, ligament degradation is accelerated, leading to adjacent soft tissue and musculoskeletal components of the joint sustaining these valgus forces due to this degradation (Hariri, n.d.; Patel, n.d.). As these adjacent structures fatigue from these additional stresses, the UCL is subjected to further structural insults, exacerbating the

$$stress \sim microtear \sim stretch \sim thickening$$

cascade to eventual ligament rupture (Birfer, Sonne, and Holmes 2019; Hariri, n.d.). These ruptures can occur at varying points along the ligament. Previous work found the most common site of a tear to be at the ligament's midsubstance, with ligament avulsions from the ulna distally and the medial epicondyle being other common sites of failure (Hariri, n.d.).

Influences of the glenohumeral (GH) joint on UCL injury risk are also reported in the literature. A total range of motion difference of 5 degrees or greater between dominant and non-dominant shoulder joints is associated with a 2.8-fold increase in elbow injury risk (Wilk et al. 2014). Other GH range of motion assessments, including horizontal adduction, have been compromised in pitchers with a previous UCL tear history (Garrison et al. 2012). Increased humeral torsion coinciding with decreased GH internal rotation of the throwing arm has also been a risk factor for elbow injury in pitchers (Noonan et al. 2016).

An association between increased UCL injury risk and higher body weight has been previously reported in professional pitchers (Peter N. Chalmers et al. 2016); using body mass index (BMI) as the exposure did not replicate this finding. Pitchers with higher BMI were found to manage better higher levels of pitching workload with positive performance results. Still, they did so at the risk of higher forces and velocities sustained by the elbow and UCL, increasing injury risk (Forsythe et al. 2017).

1.4 Treatment of UCL Injury

Treatment for tears varies and is based on the severity of the injury. Non-surgical options exist but are less-desired, given their lengthy timelines for a return to play and the uncertainty of a full recovery (Brandon J. Erickson et al. 2017; Rebolledo et al. 2017; Wilk et al. 2017). Early rehabilitation procedures, including stretching and strengthening exercises of the flexor-pronator muscles of the forearm along with pain and inflammation management along with rest, are often used in the athletic setting (Langer 2006). The use of a hinged external fixating brace or total joint immobilization are other conservative approaches to UCL tear treatment, albeit less common in overhead sports (Biz et al. 2019; Chauhan et al. 2019; Iloanya, Savoie, and O'Brien 2020). The use of platelet-rich plasma (PRP) has seen a surge in popularity in recent years as another means of non-operative management of UCL tears (Iloanya, Savoie, and O'Brien 2020). Its utility in baseball and with UCL tears remains questionable (Chauhan et al. 2019; Iloanya, Savoie, and O'Brien 2020); lengthier rehabilitation and a low percentage of players returning to play are standard (Chauhan et al. 2019).

While a UCL reconstruction is the most common and invasive treatment option for a UCL tear (Begly et al. 2018; Brandon J. Erickson et al. 2017; B. J. Erickson et al. 2014; Brandon J. Erickson et al. 2015b; Liu et al. 2016), the lesser-known primary repair procedure has seen an increase in utilization. This approach is frequently used for tears of lesser severity (Wilk et al. 2017). Post-surgical recovery and rehabilitation programs can vary in technique and intensity. A 10-12 month span from surgery to return to competition is commonplace but can extend to 24 months (B. J. Erickson et al. 2014; Ford et al. 2016; Jiang and Leland 2014; Liu et al. 2016). Undergoing these procedures involves the typical risks associated with surgery, such as extensive bleeding, infection, or neurology-related complications (Dwyer Et al., 2015; Ercole Et al., 2011]. Full returns to previous performance are not guaranteed. Those who have undergone reconstruction suffer on average a 30% decrease in overall performance, post-operatively, using earned run average as the comparison (Hodgins et al. 2016). Other studies researching return to performance measures post-ligament reconstruction found statistically significant decreases in performance post-operatively in innings pitched per season (58.7 ± 47.2 versus 77.4 ± 51.7, $p < 0.001$), strikeouts per season (45.6 ± 38.0 versus 58.2 ± 36.9, $p = 0.004$). Runs given up by innings pitched (0.641 ± 0.831 versus 0.552 ± 0.247) were also found to have worsened post-surgery, albeit not at a statistically significant level (Zaremski et al. 2017).

1.5 Gaps in Knowledge and Public Health Importance

Physiological workload has been established as a substantial precursor of UCL injury; few studies have provided a measure that offers the combination of extrinsic and intrinsic factors that dynamic models of sports injury etiology. Even fewer studies provide this exposure measurement at the pitch level. This work looks to provide an innovative deliverable to assist players, teams, and clinicians in monitoring performance-related fatigue and its link to UCL health. The application of this information can be beneficial in several ways beyond workload monitoring. This research can minimize financial costs and individual hardship related to the sustainment of a UCL injury, as pitching activity thresholds gleaned from this work can better inform workload management guidelines and prevent injuries before they occur. This research will further allow for better surveillance of individuals for potential harm, excessive participation in competition that negatively impacts health while also providing optimization of injury prevention protocols, further reducing injury risk. The quantification of the exposure in this fashion, using features that are readily accessible to professional and amateur baseball groups, can also provide much-needed guidance to younger age groups, supporting or even supplanting the recommendations supplied by Pitch Smart ("MLB | Pitch Smart," n.d.).

This contribution will disseminate results from a longitudinal cohort that is the first to collect multiple repeated workload measures accounting for forearm muscle fatigue during competition at all professional baseball levels. These efforts provide innovative and rigorous workload measures that better reflect the intensity and fatigue levels associated with competition while accounting for our population of interest's demographic features heretofore ignored. These contributions add to what is currently known about performance-based causes of ligament tears in pitchers in a novel and requisite fashion.

2 Objective

This proof of concept endeavors to contribute to the scholarship investigating fatigue-induced contributions to UCL injury by studying professional baseball pitchers across a season, collecting multiple workload-derived measures of fatigue with a novel calculation accounting for both intrinsic and extrinsic risk factors. The specific aim was to determine the effects of fatigue measures on a player's probability of UCL tear over a given season of MLB-level competition. We anticipate this work will explain the positive association between pitching workload and UCL tear probability and establish fatigue-adjusted pitch count as a predictive indicator of UCL failure. We hypothesize that UCL tears occur due to persistently elevated levels of arm fatigue across a competitive season, with higher levels of fatigue producing a shorter time to UCL failure. This increased risk is reflected in FAPC values over 1 for a single pitch. The cumulative difference between FAPC values and actual pitch count throughout an inning, game, or another time point higher than the true pitch count thrown in the given timeframe, expressed as a ratio, also indicates higher fatigue levels and an increased risk of UCL tear.

3 Methods

Previous work in this research space has used exposure and outcome data sources limited in depth and breadth. In particular, exposure definitions have been restricted to less informative metrics, such as innings pitched or aggregated variables, like total pitches thrown in a game. The influence and use of recent MLB-approved data sources that collect pitch-by-pitch information and its metadata have yet to be fully embraced in this space, further hampering the quality and validity of the conclusions previous work has provided. Similarly, injury data sources are scant; the data fields offered to the public or team non-medical staff are also strictly limited in breadth and depth. Publicly available information specifically for UCL tears has minimized this knowledge gap but remains incomplete compared to teams' data. In light of these limitations, we propose the data sources and methods that follow the study aim.

3.1 Study Population

The population for this aim was pitchers who threw in 10 or more plate appearances (PA) during each of the 2018 and 2019 baseball seasons at the MLB level, where pitch-tracking technology was used during game activities, indicates, and biographical data was available. Players who appeared in fewer than 10 PA total, in 9 or fewer PA with pitch-tracking technology, or did not have biographical information were excluded from this study. After applying the study criteria, 1,633 of 2,525 possible pitcher seasons were identified for further study; 121 injuries of the UCL were identified. Descriptive data for the study population stratified by injury status are presented below.

Table 1: Study Population Characteristics by Injury Status

Characteristic	Injury, N = 121	No Injury, N = 1,512
FAPC Value		
Mean (SD)	0.00 (0.12)	0.01 (0.13)
Range	-0.45, 0.75	-0.63, 1.04
FAPC Group		
Low	67 (55%)	815 (54%)
High	54 (45%)	697 (46%)
Birth Region		
USA	103 (85%)	1,155 (76%)
Foreign	18 (15%)	357 (24%)
Years Pro		
Mean (SD)	9.1 (4.4)	8.9 (4.4)
Range	2.0, 26.0	1.0, 31.0
Previous Injury		
Y	109 (90%)	1,227 (81%)
N	12 (9.9%)	285 (19%)
Age		
Mean (SD)	31 (4)	30 (4)
Range	21, 42	22, 47
BMI		
Mean (SD)	27.13 (2.14)	27.23 (2.38)
Range	21.15, 31.94	20.54, 39.75
Handedness		
R	90 (74%)	1,105 (73%)
L	31 (26%)	407 (27%)
Pitching Status		
RP	69 (57%)	1,137 (75%)
SP	52 (43%)	375 (25%)

3.2 Data Collection

3.2.1 *Event, Game, and Player Data*

The study data are output from TrackMan, https://trackmanbaseball.com/), a radar-based projectile tracking system used at the MLB and minor league professional levels. Pitch-specific metadata such as velocity, pitch type, and pitch movement components are included. TrackMan uses a proprietary tracking algorithm to collect relevant on-field data. TrackMan data is publicly available for MLB pitch data and selected minor league games by querying the MLB-StatsAPI interface (http://statsapi.mlb.com/api/v1.1/). Starting in 2019, MLB ball tracking hardware setups included TrackMan as a component of a more extensive game data tracking system, Statcast (http://mlb.com/glossary/statcast).

Data was collected using RStudio Version 1.3.1073 and the BaseballR package (https://github.com/BillPetti/baseballr; version 0.8.3). BaseballR provides functions that retrieve the relevant event, game, player, and pitch event information from MLB StatsAPI live data feed. Data elements available are supplied through the MLB Game Unified Master Baseball Object (tinyurl.com/5aps7yku). This data set consisted of 1,277,381 pitches thrown across 4,450 games. This data was collected between March and October of each season, consisting of matches from spring training, regular season, and playoff portions of a given season.

3.2.2 *Injury Data*

Injury data for MLB players were collected by querying the transactions tables provided through the MLB StatsAPI feed. All pitcher transaction information related to placement on the Disabled/Injury List (DL/IL) was queried for each season of interest. This information was further prepared only to include the injury of interest, using a text search for the following term combinations:

$$'ulnar\ collateral',\ 'forearm',\ 'flexor',\ 'UCL',\ 'Tommy\ John',\ 'elbow'$$

Text references to hip flexor injuries were excluded from the search. The earliest date of placement for an elbow-related injury was established as the time of the inciting event. Injuries that included either $'tear'$ or $'surgery'$ or $'Tommy\ John'$ in the transaction description were considered confirmed UCL tears. Injuries that did not have either of these words but otherwise satisfied inclusion criteria were assumed to be injuries arising from microtears of the ligament. Of the 121 MLB pitchers identified, three had confirmed tears, using the criteria mentioned above. Historical injury information for all players and any injury type that required placement on the DL/IL was also collected using the process mentioned above. This information was then dichotomized as a covariate of interest.

3.3 Study Design

An observational, retrospective assessment of time to injury in pitchers during the 2018 and 2019 baseball seasons was performed. This approach maximized the use of retrospective data towards validating previous descriptive studies and anecdotal evidence that allude to the relationship between fatigue and UCL tear. This assessment collected and studied repeated measures of our exposure (FAPC). This cohort of professional baseball pitchers was followed during the 2018 and 2019 seasons, noting the occurrence and time (days since the start of the season) of the outcome of interest: confirmed or presumed UCL tear based on DL/IL injury classification. A time-to-event design was applied to validate the hypothesis that high FAPC status is an indicator of UCL tear risk.

3.4 Outcome Measure

3.4.1 *Occurrence of Elbow Injury*

Injury occurrence was categorized as a dichotomous variable (0 - no, 1- yes) and is defined as the sustainment of an elbow injury that requires a placement on the DL/IL. Given the variability of how and if UCL tears are diagnosed and accurately reported, elbow injuries reported with the diagnosis keywords provided in Section XXX were considered a UCL injury. This rubric allowed for actual and evolving UCL injuries to be captured, as tears are often not explicitly noted as a tear. The date of the initial elbow injury was also collected.

3.5 Primary Exposure

3.5.1 *Fatigue Adjusted Pitch Count*

Much of the literature related to ligament tears in pitchers revolves around the relationship between stress, fatigue, and intensity components of throwing a ball and ligament integrity. This relationship is complicated and is driven by several intrinsic and extrinsic factors, many of which are poorly quantified using previous exposure ascertainment methods. The use of on-field performance metrics as indicators or surrogate measures for the kinematic and kinetic changes preceding fatigue or symptomatic pain indicates ligament injury remains controversial. This study provides a calculation of workload adjusted for fatigue to properly reflect performance-derived stress on the UCL, acutely and chronically.

Workload information was collected and defined using FAPC, a continuous measure that accounts for pitch count, the intensity of the game ('leverage index'), pitch velocity, pitch type, time of rest in between pitches thrown, and days of rest from competing. Briefly, the FAPC calculation is an extension and refinement of the lab-based modeling of fatigue and recovery rates of the forearm muscles performed by Sonne and Potvin (Sonne & Potvin, 2016) and further modeled by Sonne in the baseball setting.

FAPC represents the accumulation of physiological and anatomical fatigue sustained by the elbow joint of the throwing arm. FAPC is calculated and aggregated at the pitch level and summed across many longitudinal time points, such as by game and season to date. Percent differences between FAPC and actual pitch count during an outing will be calculated to standardize the exposure between starting pitchers and relief pitchers, given the differences in their roles and typical pitch counts. Additional FAPC details are provided in a succeeding section.

3.6 Covariates

Multiple game- and player-related intrinsic and extrinsic factors hypothesized to account for UCL tears were included in calculating the FAPC exposure. Additional variables noted in previous literature or anecdotally as UCL tear risk factors were included to support those included in the FAPC calculation in the analysis. These covariates are presented in Figure 2.

Covariate	Variable Type	Unit of Measurement
Age	continuous	years
Nationality	dichotomous	US/Foreign
Years Pro	continuous	years
Handedness	dichotomous	left/right
BMI	continuous	kg/m^2
Venue Travel	dichotomous	home/away
Previous Injury	dichotomous	yes/no
Venue Elevation	continuous	feet
Time Zone Change	ordinal	hours
Venue Temperature	continuous	degrees Fahrenheit
Player Team	dichotomous	AL/NL*
Venue, League	dichotomous	AL/NL*

AL: American League; NL: National League

Figure 2: Covariate Descriptions by Variable Type and Measurement Unit

All covariates were collected using the MLB StatsAPI methodology previously outlined. Player-relevant variables were pulled for each year from the MLB-provided biographical information tables at the start of each respective season. Years of professional playing experience was defined as the year a player initially signed a playing contract subtracted from the current season of play. BMI was calculated using the following formula:

$$BMI = (weight(lb)/height(in)^2) * 703$$

Like player covariate information, external covariate factors were accessed directly via StatsAPI and the respective game data tables. Time zone change was calculated for each player by taking the absolute value of the difference in time zone between their current and previous venue location. Covariate characteristics and Pearson correlations between covariates and injury status are presented in the table and plot below. In the graphical presentation of the correlations, blue denotes positive correlation, red a negative correlation. Widely, the correlations are found to be weak, with all having a Pearson r less than 0.1. The covariates for temperature and pitcher type (start versus relief outing) show the strongest correlations with injury status Pearson r of -0.059 and -0.0512, respectively; pitcher handedness is the strongest positive correlation with injury status (r = 0.0319).

Table 2: Internal Factor Covariate Characteristics

Characteristic	N = 1,633
FAPC Status	
Mean (SD)	0.01 (0.13)
Range	-0.63, 1.04
Birth Region	
USA	1,258 (77%)
Foreign	375 (23%)
Years Pro	
Mean (SD)	8.9 (4.4)
Range	1.0, 31.0
Previous Injury	
Y	1,336 (82%)
N	297 (18%)
Age	
Mean (SD)	30 (4)
Range	21, 47
BMI	
Mean (SD)	27.22 (2.36)
Range	20.54, 39.75
Handedness	
R	1,195 (73%)
L	438 (27%)
Pitching Status	
RP	1,206 (74%)
SP	427 (26%)

Table 3: External Factor Covariate Characteristics

Characteristic	N = 1,633
Team League	
NL	836 (51%)
AL	797 (49%)
Venue League	
NL	890 (55%)
AL	743 (45%)
Time Zone Change (hrs)	
0	1,260 (77%)
1	234 (14%)
2	85 (5.2%)
3	54 (3.3%)
Temp (F)	
Mean (SD)	72 (10)
Range	35, 107
Wind (mph)	
Mean (SD)	7.0 (4.9)
Range	0.0, 28.0
Elevation (ft)	
Mean (SD)	609 (1,069)
Range	4, 5,179

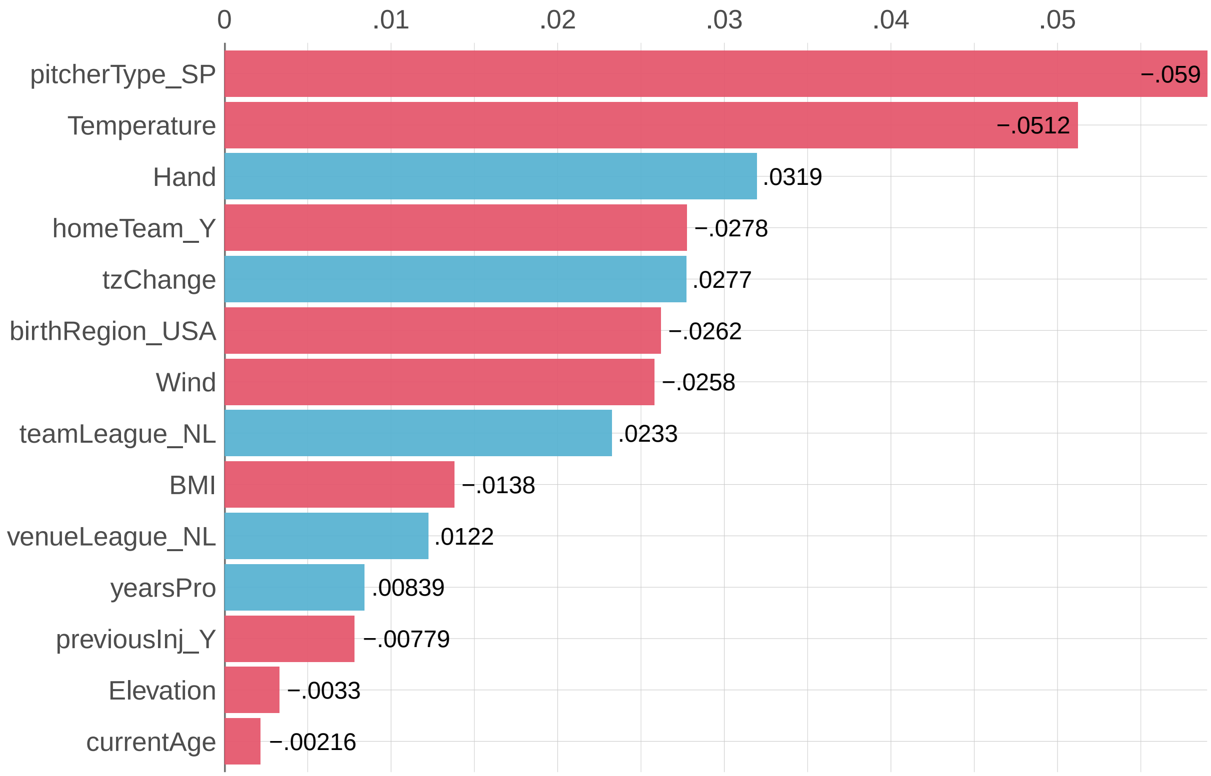


Figure 3: Pearson Correlations Between FAPC Status and Covariates

3.7 Analytic Methods

3.7.1 *FAPC Calculation*

After the collection of all pitch data, FAPC was calculated for each pitch. This calculation is performed as a multi-step process, starting with the fatigue unit (FU) initially developed by Sonne and Potvin (Sonne and Potvin 2016); a version of this calculation adapted for pitch level information seen below:

$$fatigueUnit = 0.11 * pitchPace(secs) * veloScale$$

A velocity scaling factor (veloScale) is added to fastball FU calculations. This value is the ratio of the velocity of the pitch thrown and the player's maximum fastball velocity attained in a given season. Next, a rest component is calculated (restScale), taking into account the number of days a player has had between appearances. Valgus stress related to the type of pitch thrown is then calculated (valgusScale) for each pitch and is derived from previous lab-based research performed by Fleisig (Fleisig Et al., 2006). Leverage Index values - the value of game situation stress when a pitch is thrown - were taken and adapted from previous public research (http://www.insidethebook.com/li.shtml). For scoring situations where values were not specifically provided, the leverage value closest to the number of runs ahead or behind was applied. This value is applied to the FAPC calculation as the percent change of the last pitch thrown (LI). The final FAPC form is provided below:

$$fatiguePitch = 1 + (fatigueUnit * restScale * valgusScale) + \Delta LI$$

FAPC is further transformed by taking the sum of FAPC divided by the total number of pitches thrown at the game level.

3.7.2 *Covariate Calculations*

Before initiating the analyses, all continuous covariates except for BMI were calculated as the percent change from the previous game of a given player. This approach was used to provide the context of the covariates relative to the changes in their environments and seasons. BMI was collected from a single preseason baseline measure of height and weight, preventing it from being calculated as change over time. All statistical analysis was performed using RStudio Version 1.3.1073 (R Foundation for Statistical Computing, Vienna, Austria.)

3.7.3 *Survival Analysis*

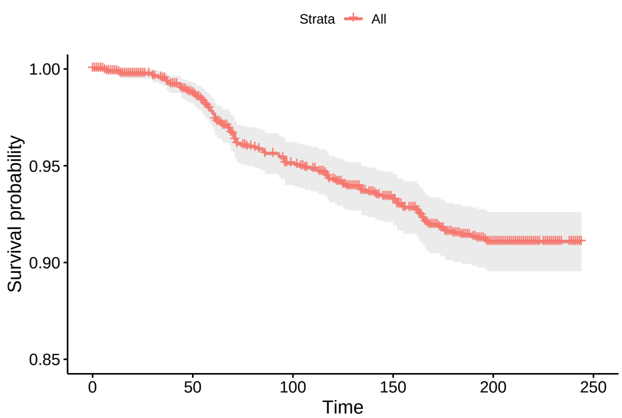
Kaplan-Meier (K-M) estimates of the probability of suffering an elbow injury given FAPC status were performed. This initial analysis was used to evaluate and visualize the effect of FAPC on injury probability independent of the covariates. FAPC was dichotomized, with the average cumulative FAPC determining FAPC status (high versus low).

A Cox Proportional Hazards analysis (CPH) was performed to identify the extent of the influence of FAPC on time to an elbow injury in concert with all covariates. The period at risk was defined as days of participation from the start of the season to either the inciting event or the end of the player's respective season. Overall, the study population contributed 372,485 person-days of observation. For the CPH model, all covariates were applied to the model and aggregated by taking the cumulative average for the entire observation period. Similar to the K-M analysis, dichotomized FAPC status was used in the model. Crude and adjusted hazard ratios with 95% confidence intervals (CI) were calculated, with a significance level set to a $p < 0.05$.

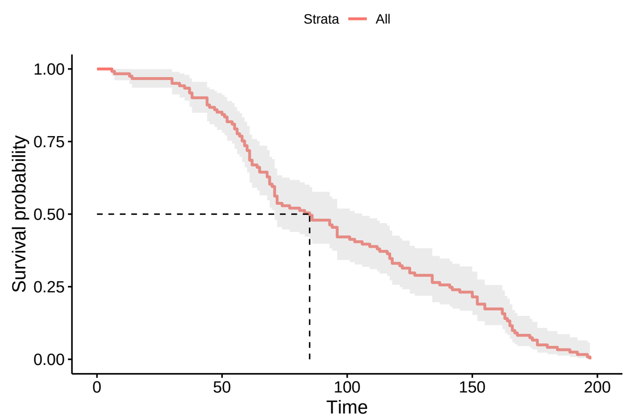
4 Results

4.1 Kaplan-Meier Analysis

Initial survival rates were estimated with a Kaplan-Meier (K-M) analysis. Results for time to injury for the entire cohort are shown in Figure 4a. The season-long probability of not sustaining an elbow injury in the study population was 91.1% (95% CI: 0.895-0.926). Additional objects specific to the injury cohort are provided in Figure 4b. The median survival rate for injured pitchers was 85 days (95% CI: 71-106).



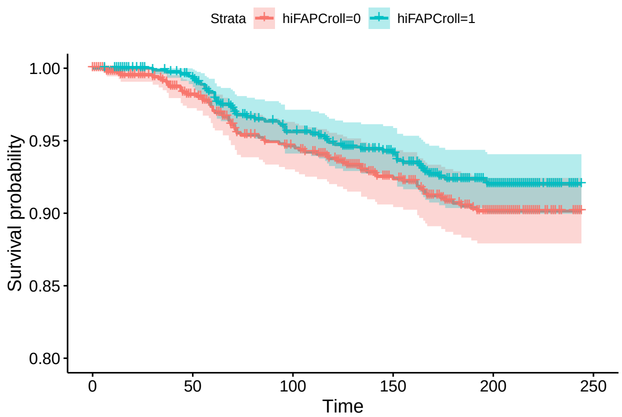
(a) Full Cohort



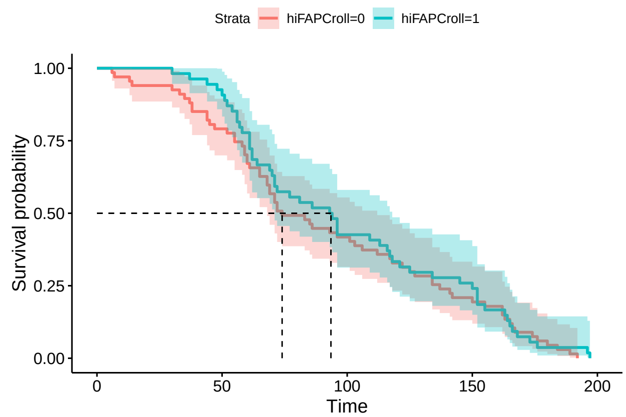
(b) Injured Cohort

Figure 4: Kaplan-Meier Results, Baseline

K-M evaluation of the effects of time to injury categorized by FAPC status was also undertaken; comparisons in the entire cohort (Figure 5a) and the injury cohort (Figure 5b) found little difference in survival status between the FAPC groups (High status: 92%, Low status: 90%). The median survival probability between the High and Low FAPC groups within the injury cohort was 93 and 74 days, respectively.



(a) Full Cohort



(b) Injured Cohort

Figure 5: Kaplan-Meier Results, FAPC Status

4.2 Cox Proportional Hazards Analysis

Descriptions of the injured and non-injured cohort covariates used in the hazard analysis are displayed in the ensuing figure. Of the 1,633 pitchers in the sample, 121 had a positive injury status. Each injury status group had a slightly higher portion of subjects with high FAPC status (55% injured group, 54% non-injured group, respectively). The injured group had a higher percentage of starting pitchers (43%) than the non-injured group. In terms of external factors, the injured group had a higher rate of subjects experiencing an absolute time zone change of 3 hours (6.6% versus 3.0%).

Table 4: Cox Analysis Internal Factors Across Injury Status

Characteristic	Injury, N = 121	No Injury, N = 1,512
rollFAPC		
Mean (SD)	0.00 (0.12)	0.01 (0.13)
Range	-0.45, 0.75	-0.63, 1.04
FAPC Status		
Low	67 (55%)	815 (54%)
High	54 (45%)	697 (46%)
Birth Region		
USA	103 (85%)	1,155 (76%)
Foreign	18 (15%)	357 (24%)
Years Pro		
Mean (SD)	9.1 (4.4)	8.9 (4.4)
Range	2.0, 26.0	1.0, 31.0
Previous Injury		
Y	109 (90%)	1,227 (81%)
N	12 (9.9%)	285 (19%)
Age		
Mean (SD)	31 (4)	30 (4)
Range	21, 42	22, 47
BMI		
Mean (SD)	27.13 (2.14)	27.23 (2.38)
Range	21.15, 31.94	20.54, 39.75
Handedness		
R	90 (74%)	1,105 (73%)
L	31 (26%)	407 (27%)
Pitching Status		
RP	69 (57%)	1,137 (75%)
SP	52 (43%)	375 (25%)

Table 5: Cox Analysis External Factors Across Injury Status

Characteristic	Injury, N = 121	No Injury, N = 1,512
Venue League		
NL	58 (48%)	832 (55%)
AL	63 (52%)	680 (45%)
Team League		
NL	52 (43%)	784 (52%)
AL	69 (57%)	728 (48%)
Home Game		
Y	57 (47%)	803 (53%)
N	64 (53%)	709 (47%)
Elevation		
Mean (SD)	1,059 (2,244)	983 (1,414)
Range	-49, 19,756	-49, 16,994
Temperature		
Mean (SD)	4.16 (4.09)	3.06 (3.50)
Range	-12.35, 16.62	-20.62, 41.21
Wind		
Mean (SD)	33 (53)	24 (38)
Range	-45, 287	-44, 676
Time Zone Change		
0	92 (76%)	1,168 (77%)
1	15 (12%)	219 (14%)
2	6 (5.0%)	79 (5.2%)
3	8 (6.6%)	46 (3.0%)

The assumption of proportionality was appraised with a Schoenfeld test. All variables except the temperature covariate (chi-sq: 4.683, $p = 0.03$) were statistically non-significant. Results of the global test were not statistically significant (chi-sq: 21.026, $p = 0.136$), confirming overall data proportionality.

The final results of the CPH model are presented in the following forest plot. Hazard ratios and their respective 95% confidence intervals are included along with the significance test result. The model was statistically significant globally ($p < 0.001$), with FAPC resulting in a hazard ratio (HR) of 0.85 (CI: 0.59-1.2). Pitcher type (HR: 1.89 [1.31-2.7]) and temperature (HR: 1.06 [1.02-1.1]) covariates provided significant results. Covariates of literature-confirmed, real-world significance with statistically significant trends were previous injury history (HR: 1.71 [0.92-3.2]) and age (HR: 1.09 [0.99-1.1]). Previous injury and age trends of association in the analysis reflected those found in previous UCL injury risk factors. In addition, the 'homeTeam' covariate, which denotes home versus away setting, trended towards a statistically significant covariate with real-world relevance.

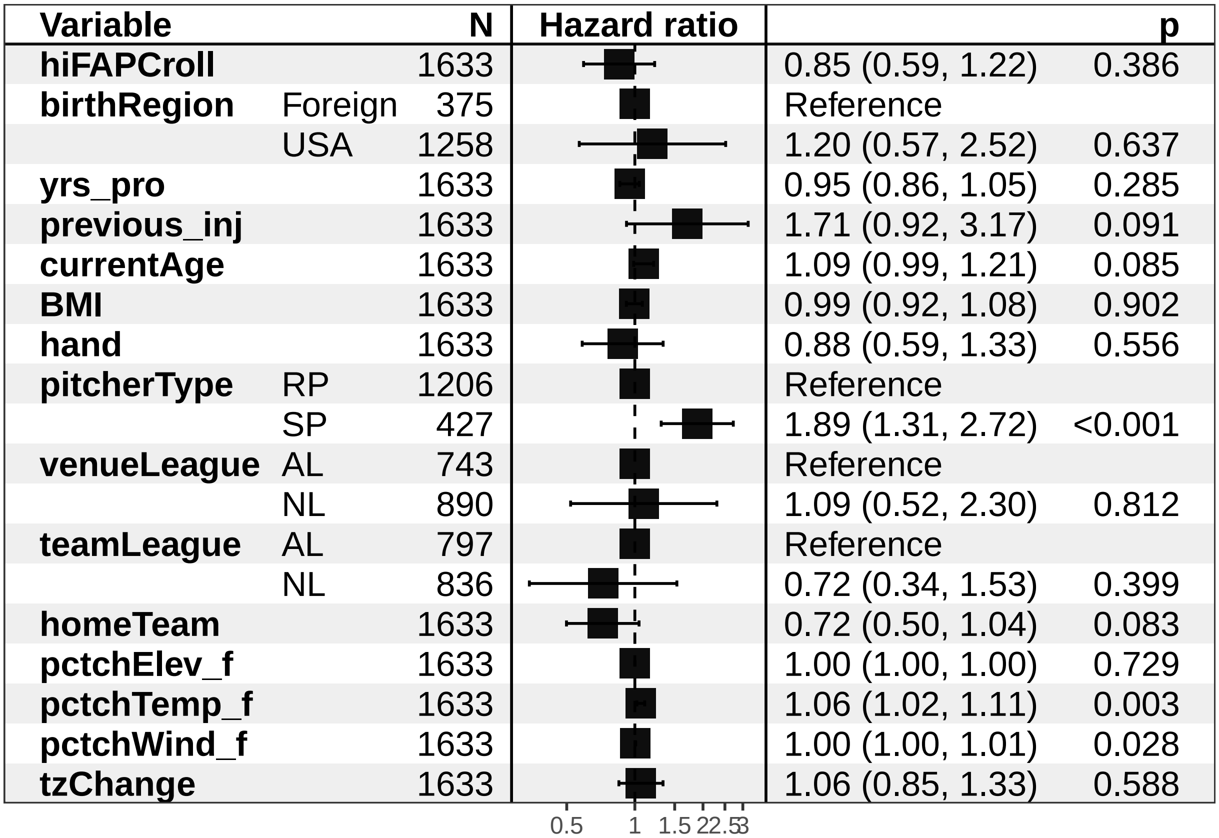


Figure 6: Forest Plot of Cox Proportional Hazards Analysis Results

4.3 Comparison of FAPC Versus Actual Pitch Count

As part of the exploration and development of FAPC as a valid measure of the effects of fatigue on UCL injury, a comparison of FAPC to actual pitch count (APC) was performed. APC is considered the 'gold standard' measure of workload and, tacitly, fatigue. Evaluation of FAPC against APC was conducted using tests of correlation and univariate and multivariate regression as a means to describe the initial discriminant and criterion validity of FAPC.

4.3.1 *Pearson Correlation*

Pearson correlations of the covariates against the percent change-adjusted APC metric are presented in the following plot. Associations with UCL injury were generally weak and ranged between 0.0592 (home/away team status) and -0.0532 (pitcher type). Blue denotes positive correlation, red a negative correlation.

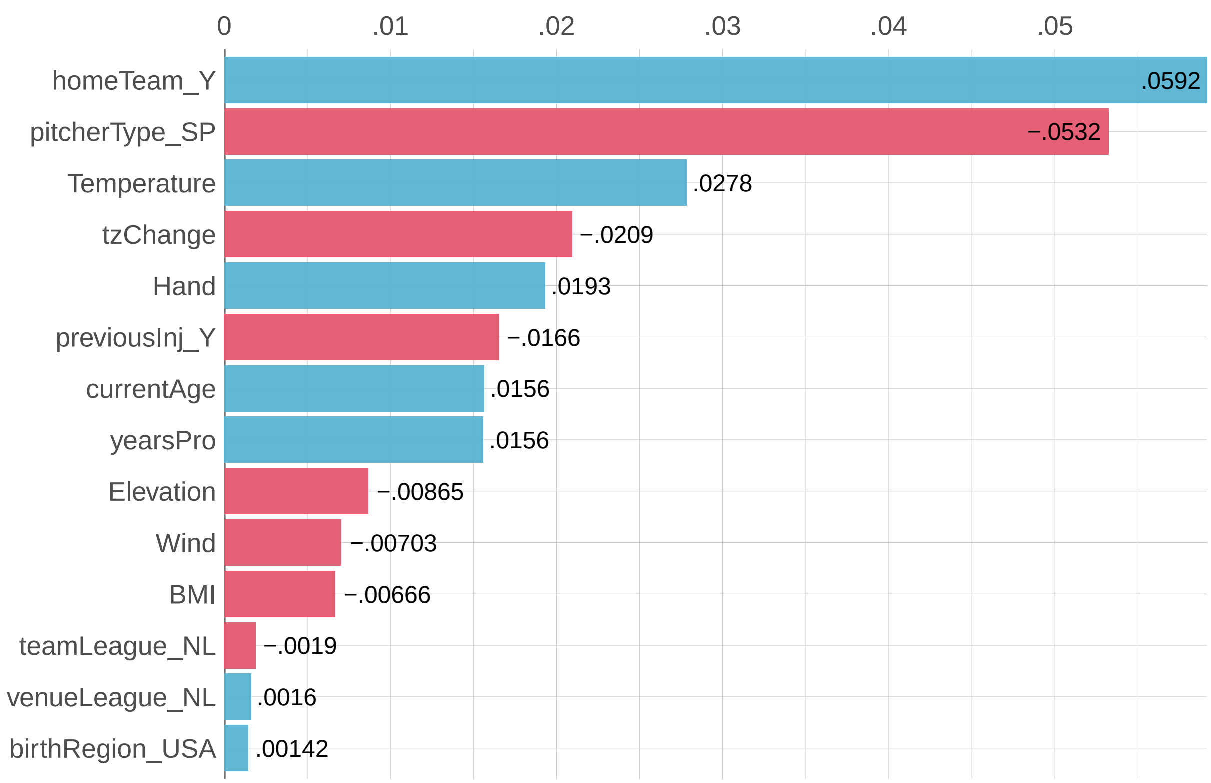


Figure 7: Pearson Correlations Between Actual Pitch Count and Covariates

4.3.2 *Univariate Logistic Regression*

Logistic regression was performed to provide estimates of the association of each measurement with injury probability. Table 4 provides univariate logistic regression results for the outcome and APC. APC regression estimate was -0.005, corresponding to an odds ratio of 0.995; this result was not statistically significant (p = 0.702).

Table 6: Univariate Logistic Regression of Injury Status, Actual Pitch Count

term	estimate	std.error	statistic	p.value	conf.low	conf.high
(Intercept)	-3.041	0.025	-121.513	0.000	-3.091	-2.993
pctavgPitch	-0.005	0.014	-0.383	0.702	-0.034	0.019

The following provides univariate logistic regression results for injury and FAPC. Improved statistical significance (p = 0.634) with a slightly stronger association with injury outcome is noted.

Table 7: Univariate Logistic Regression of Injury Status, Fatigue Adjusted Pitch Count

term	estimate	std.error	statistic	p.value	conf.low	conf.high
(Intercept)	-3.043	0.025	-123.802	0.000	-3.091	-2.995
rollFAPC	-0.089	0.188	-0.476	0.634	-0.469	0.256

4.3.3 ***Multivariate Logistic Regression***

Multivariate regression results for both APC (Figure XX) and FAPC (Table XX) predicting injury risk with all covariates modeled are presented below. Similar results with respect to overall strength of association of each exposure variable and injury and in direct comparison to one another is seen (APC estimate: -0.003 [-0.032, 0.022], p = 0.839; FAPC estimate: -0.063 [-0.46, 0.277], p = 0.736).

Table 8: Multivariate Logistic Regression of Injury Status, Actual Pitch Count

term	estimate	std.error	statistic	p.value	conf.low	conf.high
(Intercept)	-2.172	0.441	-4.926	0.000	-3.039	-1.310
pctavgPitch	-0.003	0.014	-0.203	0.839	-0.032	0.022
birthRegionUSA	0.235	0.105	2.233	0.026	0.030	0.442
yrs_pro	-0.034	0.014	-2.414	0.016	-0.062	-0.006
previous_inj	-0.029	0.071	-0.413	0.680	-0.167	0.112
currentAge	0.042	0.015	2.853	0.004	0.013	0.071
BMI	-0.060	0.011	-5.454	0.000	-0.082	-0.038
hand	-0.050	0.055	-0.902	0.367	-0.160	0.058
pitcherTypeSP	0.200	0.058	3.480	0.001	0.087	0.312
venueLeagueNL	0.101	0.097	1.050	0.294	-0.089	0.290
teamLeagueNL	-0.385	0.098	-3.943	0.000	-0.576	-0.193
homeTeam	-0.032	0.050	-0.642	0.521	-0.130	0.066
pctchElev_f	0.000	0.000	-4.658	0.000	0.000	0.000
pctchTemp_f	-0.037	0.006	-6.420	0.000	-0.049	-0.026
pctchWind_f	0.001	0.001	1.473	0.141	0.000	0.002
tzChange	0.025	0.033	0.748	0.454	-0.041	0.088

Table 9: Multivariate Logistic Regression of Injury Status, Fatigue Adjusted Pitch Count

term	estimate	std.error	statistic	p.value	conf.low	conf.high
(Intercept)	-2.172	0.441	-4.926	0.000	-3.039	-1.310
rollFAPC	-0.063	0.188	-0.338	0.736	-0.446	0.277
birthRegionUSA	0.235	0.105	2.235	0.025	0.030	0.442
yrs_pro	-0.034	0.014	-2.412	0.016	-0.062	-0.006
previous_inj	-0.029	0.071	-0.414	0.679	-0.167	0.112
currentAge	0.042	0.015	2.852	0.004	0.013	0.071
BMI	-0.060	0.011	-5.453	0.000	-0.082	-0.038
hand	-0.050	0.055	-0.909	0.363	-0.160	0.058
pitcherTypeSP	0.200	0.058	3.480	0.001	0.087	0.312
venueLeagueNL	0.101	0.097	1.050	0.294	-0.089	0.290
teamLeagueNL	-0.386	0.098	-3.945	0.000	-0.576	-0.193
homeTeam	-0.033	0.050	-0.652	0.514	-0.131	0.065
pctchElev_f	0.000	0.000	-4.657	0.000	0.000	0.000
pctchTemp_f	-0.037	0.006	-6.419	0.000	-0.049	-0.026
pctchWind_f	0.001	0.001	1.473	0.141	0.000	0.002
tzChange	0.025	0.033	0.747	0.455	-0.041	0.088

5 Discussion

The exploration of FAPC as a measurement of fatigue in this proof of concept study reflects the complexity of injury mechanisms and their relationship with their risk factors, known and unknown. In addition, this study has highlighted the complexity and vastness of the data available that could signal the elucidation of these injury mechanisms. These observations are underscored further by FAPC, providing small, incidental reflections of its possible association with UCL injury. The parallels between FAPC and actual pitch count did offer a small degree of validity to its calculation. The finding relating to the effect of pitch status (starting versus relieving) was a novel and robust outcome for this study, warranting further investigation and replication in separate research endeavors.

The covariates analyzed that have been previously researched show similar trends in comparison to previously reported findings. The CPH result seen with the previous injury covariate further supports prior research establishing it as a robust predictor of future injury. Age and years of professional experience results were not statistically significant in the analyses. However, their opposing direction of association with injury despite their interrelation suggests further investigation of their influence on injury risk. This effect could be possibly explained as a residual effect of high school and foreign player signings. For each, their entry into professional baseball starts earlier (between 16-18 years of age) than those signed out of college and can amass more years of experience at a younger age.

As mentioned, the effect of starting versus relief appearances on injury was substantial. The resulting inference that starting appearances have an influential role in determining elbow injury risk is evident but is not without further clarification. The effect of more time and pitches thrown in a game and thus an accumulation of valgus stress and fatigue puts those who start games at an increased probability of succumbing to fatigue. This fact has brought pitch counts into vogue, assuming that limiting the absolute number of throws to an arbitrary number can impart health benefits. The research into the effectiveness of pitch counts is copious and is primarily focused on youth-level participants (Glenn S. Fleisig and Andrews 2012; Yang et al. 2014; Zaremski et al. 2017). Counter to the obviousness of this result, the underlying contribution of rest to the FAPC calculation confounds this result; starting pitchers are provided multiple days off in between outings, which offers pitchers in this role to be wholly recovered before their next appearance ostensibly.

Individual routines for non-game day activities can vary widely. Still, the assumption that time away from competition as a starting pitcher provides an unlimited opportunity to rest should not be made possible by this result. Non-game activities and their corresponding workloads are not quantified in this design, making the FAPC calculator assumptions dubious in this situation. Starting a particular game also has a more significant number of low leverage situations than relief appearances, which can also minimize the effects of repeated throws, as they are performed in less-stressful game conditions.

BMI was not a substantial contributor to the results; the use of a single BMI measurement taken at the beginning of a season confounds this result. Given its status as a modifiable risk factor, the impact of changes in BMI on real-time injury risk lends it to be a particularly appealing avenue towards optimizing health and minimizing injury risk acutely. Increased BMI as a function of decreased physical health has been hypothesized to lead to increased injury risk in adolescent populations (Carter & Micheli, 2011), which corroborates its potential as a risk factor for injury. This point may not be as applicable in the study population of interest, given their increased lean muscle mass compared to the general population. This increased weight arising from skeletal muscle stands to minimize the utility of BMI to indicate poor health, given the use of body weight in its calculation. These population differences and the increased accessibility to devices that derive more exacting body mass characteristics beyond body weight lead to this risk factor considered as less fruitful of an approach to combat injury. BMI effects on injury risk in other sports have been thoroughly investigated, albeit with heterogeneous results. A common conclusion from this literature is that increases in BMI can increase lower extremity injury risk (Amoako, Nassim, and Keller July/August 2017).

No studies have been conducted in baseball, providing further dubiousness of BMI as a risk factor for an elbow injury.

Temperature changes predominantly drove environmental covariate contributions to the study results. Increased temperatures led to an elevated risk of an elbow injury and is a similar result seen across multiple outdoor sports. This previous research has been focused on injuries related to exertional heat stress (Kerr et al. 2013), which is of less concern in baseball given the multiple breaks between play and the ability for players to minimize time under hot conditions. Information on humidity levels was not available, which is a possible limiting factor of the integrity of this result. Weather changes could explain the role of temperature and changes in temperature on injury in the study context due to season. Early season movement from the warmer climates of spring training locations to destinations with lower temperatures could explain this result, more so than an effect of temperature on physiological fatigue and recovery patterns.

The increases in the average change in time zones reflected in this study are subtle and not statistically significant but reflect the work done by Fuller and Huyghe (Fuller, Taylor, and Raftery 2015; Huyghe et al. 2018). Its contribution to the study results demonstrates the impact of acute and frequent time zone change standards in baseball. Wearable devices tacitly reflect the importance of mitigating these effects to advance health by professional teams that monitor sleep hygiene. While this association did not reach statistical significance, its real-world relevance is substantial.

Team- and league-specific relationships on baseball injuries are not well researched or vetted, which fueled their inclusion in this study. Like the age: years professional relationship, the classification of a given team or its venue as American League (AL) or National League (NL) shows different effects. In terms of venue, the AL can boast the opening of new stadiums in recent years, which possibly add the benefit of updated clubhouse and exercise facilities, leading to more and better options to mitigate fatigue. Domed stadiums can also be a factor in the venue finding, as the depreciation of weather-related factors. Team effects show NL affiliation beneficial to elbow injury mitigation. The slight difference in duration of games by league is one avenue of possible explanation. Looking at both components of league effects, another avenue of future research would be the consideration of interleague play. Interleague games can acutely affect game situations and preparation for pitchers, whether it is AL pitchers required to hit in NL venue games or NL pitchers pitching to a lineup entirely dedicated to hitting via the addition of the designated hitter to hit for on the pitcher's behalf. AL venue games can thus add higher pitch counts and increase leverage for NL pitchers. This interaction is a unique component of baseball rules affecting fatigue accumulation and corresponding opportunities for in-game rest. Home versus away game settings have also seen scant investigation in the sports injury field, with few insights, obtained (Jones 2016) and have focused on the home field competitive advantage phenomenon. Previous discussions related to venue and time zone change effects apply to the debate of home-field completion; the influence of rest and familiarity of the environment may drive this result.

FAPC effects on elbow injury during the study opposed the a priori hypothesis that it would be a driving risk factor for UCL injury. The novelty of this measurement provides uncertainty of its interpretation, as does the formula. In particular, the baseline components of the procedure provided by Sonne and Potvin is a recent revelation; additional work by the author towards adding different game- and physiology-related variables is also not validated. Application of the Fatigue Unit components was inspired by literature and lab-based research; however, data available for this proof of concept are game-derived. The assumptions made of the integrity of the data possibly do reflect its ground truth. Decisions of how to quantitatively classify rest factors deserve further appraisal; lab-derived literature values also are impacted by the assumption lab efforts reflect game situations. The decision to apply these additional components to the original Fatigue Unit formula deserves further scrutiny. The magnitude of their influence on elbow anatomical changes and fatigue accumulation are unknown; a study of their direct association with injury could require their application as a covariate independent of the Fatigue Unit. FAPC trended similarly with pitch count, with a cursory indication that it shows a stronger association with injury probability. These effects are minuscule and are obscured by covariate selection and assumptions made during the study design.

The strengths of the approach taken in this study are manifold. Briefly, applying a novel calculation towards the elucidation of real-time fatigue changes in concert with literature-supported covariates provides a solid base to investigate these phenomena. The pursuit and application of previously unexplored external covariates in baseball injury that have been vetted in other sports also give the study's approach towards evaluating the fatigue and elbow injury association further attestation. The use of real-world, publicly available data also strengthens this research. The pursuit of these factors vetted by previous work from Meeuwisse and Bahr and myriad others lend credibility to the design of this study's work. Additionally, the potential for FAPC to be used to inform real-time changes to workload to maintain fatigue levels at a level below individual thresholds leading to changes in ligament integrity, strengthens FAPC's potential as a future tool for injury mitigation. FAPC's ability to reflect game situations while using a holistic array of performance factors familiar to medical and coaching staff benefits its adoption. The interpretation of factors as relative measures in contrast to the current utilization of absolute values adds further value to FAPC as an improved alternative to existing measures of fatigue. Additional pursuits by other investigators towards replication and validating the utility of FAPC as a method of risk factor evaluation strengthens the research community. These activities lead to downstream benefits across all baseball and elbow injury surveillance and mitigation activities.

Several limitations do potentially affect the fidelity and generalizability of the study outcomes. The scope of this study includes only two seasons of data, limiting the study sample. The ability to generalize the study results to other seasons, professional leagues, or amateur settings is contentious. Similarly, the population under review consisted of only professional pitchers who performed at stadiums with pitch-tracking technology, challenging the assumption that the internal validity of FAPC is achieved. Pitch tracking concerns related to the margin of error and calibration status of each system can also affect the accuracy of the pitch data.

The quality and comprehensiveness of injury information are unspecified and are dependent on a plethora of factors. The ability to verify that assessment data was accurately collected and that the diagnostic impression of the injury is correct cannot be demonstrated. With these limitations, the description of a specific injury as provided is assumed to be true. Considering that the inclusion criteria expanded to include all elbow injuries sustained captures sub-threshold, microscopic UCL tears could limit internal validity. The standards using the earliest date for DL/IL placement for the injury of interest assume any follow-up DL/IL placements are not separate injuries. Differences between single versus multiple elbow injuries for the period of interest are thus not captured. Injuries not requiring placement on the DL/IL, incidents not reported, and incidents not captured by the text search inclusion criteria all provide opportunities to introduce false positives and negatives to the dataset.

The components that comprise FAPC also pose issues towards its adoption as a comprehensive measure of fatigue. The scaling and application of the sub-components of the calculation applied alongside the fatigue unit calculation devised and evaluated by Sonne and Potvin warrants further scrutiny, both in the evaluation and validity of their respective measures.

The consideration and application of the factors intrinsic to an individual were hampered by limited access to such information; what information was available was static and measured during a narrow window of evaluation. The lack of repeated measurements of these modifiable intrinsic risk factors poses threats to the validity of the FAPC measure. Concerns with the calculation of BMI offer challenges for its utility and implementation. The use of lean muscle mass, body fat, and other health biomarkers as a covariate to pair with FAPC is an intriguing alternative to BMI if collected repeatedly throughout a season. The reliance on specially-trained coaches to manage this data and acquisition costs for these devices make this approach unrealistic for non-professional leagues and teams, making its inclusion and further application marginal.

The inability to capture and apply all physical activities on- and off-field pose a threat to the validity of FAPC as a direct measure of fatigue. Distance traveled within a game, and the engagement in strength activities to maintain and increase physiological well-being are factors relevant to the manifestation of fatigue and recovery that are unmeasured in this study. Player-specific measurements related to behavioral and subjective components of performance and competition are not collected. Rate of perceived exertion, personal evaluation of soreness, overall fatigue, mood, and feelings towards innate injury susceptibility are possible risk factors to study that could improve the integrity and robustness of the assumption that FAPC is associated with elbow injury risk.

Design-and analysis-related decisions bring forth criticism and skepticism. Merging of 2018 and 2019 data into a single dataset, while undertaken to maximize sample for a somewhat rare outcome, elicits questions about whether the seasons of interest are homogeneous. Previously mentioned rule changes also present an argument that this assumption does not hold. The choice of Kaplan-Meier and Cox Proportional Hazards approaches over other statistical approaches also impacts the interpretation of these results. Investigating different methods, such as frailty models, joint models for longitudinal and time to event data, and machine learning methods, are future avenues of exploration.

Future research directions that can further validate the FAPC concept should include further refinements to the definition and classification of an elbow injury to reflect the severity of the injury. The use of publicly available information on injury severity poses challenges, but the elucidation of severity can improve the sensitivity and specificity of FAPC. Improvement and validation of the FAPC calculation and the further vetting and improved selection of meaningful covariates to support the validity of FAPC values is another critical task to pursue. Continued evaluation and repeated measurements of modifiable risk factors should be appraised and emphasized in subsequent studies of fatigue and injury. Comparing FAPC to technology-driven measures of physiological changes is of particular importance. The correlation of FAPC to more invasive and less-available technology to amateur athletes allows for the dissemination and surveillance of changes in fatigue to a broader audience. Further adoption of a valid, reliable, and easy-to-use measure of changes in elbow injury potential can potentially lessen the impact of UCL injury on the youth population, a particularly vulnerable population for suffering long-term negative consequences of elbow injury.

This study has provided an innovative approach towards monitoring workload that can assist players, teams, and clinicians in maximizing sport-specific and overall health. The application of this information is beneficial in many ways relevant to the maintenance and dissemination of policies driven towards improving public health in the sports injury field. This research can minimize financial costs and individual hardship related to the sustainment of a UCL injury. Better-informed workload management guidelines based on this research and evaluation of acute fatigue manifestations will prevent injuries before they occur. This research will further allow for better surveillance of individuals for potential harm, excessive participation in competition that negatively impacts health while also providing optimization of injury prevention protocols, further reducing injury risk. The quantification of the exposure in this fashion, using features that are readily accessible to professional and amateur baseball groups, offers holistic, data-informed guidance for all age ranges who participate in baseball activities. The continued examination of the factors associated with UCL injury is paramount to understanding its genesis and the evolution of proper surveillance and mitigation protocols. The elucidation and application of insights established from the adoption of FAPC provide an opportunity to minimize the impairment elicited by UCL injury risk factors.

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