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Epidemiology and Prediction of Injuries in the National Football League (NFL)

By

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Doctor of Philosophy

Epidemiology

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B.A., University of Chicago, 2008
M.P.H., Emory University, 2013

Advisor: Cecile Janssens, Ph.D.

An abstract of

A dissertation submitted to the Faculty of the
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in partial fulfillment of the requirements for the degree of
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Abstract

Epidemiology and Prediction of Injuries in the National Football League (NFL)

By Zachary O. Binney

American football is the most popular sport in the U.S.; over a million high school students play it every year. It also has high injury rates. In the National Football League (NFL) the reported in-game injury rate is at least three times that of any other major U.S. professional sport. Yet the literature on NFL injuries has major gaps, including a lack of descriptive epidemiology, few assessments of rule changes designed to reduce injuries, and an inability to predict which players are most likely to get injured. This dissertation used a prospectively-collected database of reported NFL injuries from 2007-2016 to address these gaps.

In **Aim 1** we calculated NFL injury rates and investigated their associations with an array of potential risk factors. Over two-thirds of player-seasons resulted in an injury. Injury rates were higher among older players, those with longer injury histories, heavier players, and on certain types of artificial turf. While injury rates did rise over time, it appeared a majority of the rise was due to better reporting.

In **Aim 2** we assessed whether the NFL's 2011 collective bargaining agreement (CBA), which restricted practice times, affected the number of NFL injuries. Some had expressed concerns that the restrictions would worsen player conditioning and increase injury risk. To investigate this we split injuries by those likely and unlikely to be affected by poor conditioning and observed their changes pre- and post-CBA. After accounting for a pre-CBA increase in injuries, we found little evidence for an increase in injuries following the 2011 CBA.

In **Aim 3** we used publicly-available data on established NFL injury risk factors to develop prediction models for the 1-seaon risk of missing one or more games due to any injury or a lower extremity (LE) muscle injury. In all models discrimination and calibration were poor, and they were unable to predict NFL injuries in a way that would be useful for NFL players or teams.

This work identified some new possible risk factors (specific brands of artificial turf) and suggested some common explanations for increased injuries such as short rest and practice restrictions may be overstated.

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Chapter 1: Introduction and Literature Review

I. Introduction to Football

American or gridiron football, hereafter referred to as "football," is the most popular professional sport in the U.S.: in a recent Harris Poll asking 1,510 people who reported following at least one sport to pick their favorite from 21 options, the professional-level National Football League (NFL) held the top spot and college football ranked third (1). The sport is played with 11 men from each of two teams squaring off on a field 100 yards long (with a 10-yard "end zone" appended to each end) and 55 1/3 yards wide (2). The object of the game is to accumulate points by moving the ball – an oblong leather spheroid that, at the professional level, is 11 inches long and 2 feet in circumference at its widest point – either into the opponent's end zone (6 points plus an opportunity for 1 or 2 bonus points) or by kicking it through yellow uprights at the back edge of the opponent's end zone (3 points) (2). The ball can be moved either by handing it to a player who runs with it, or by throwing it to a player who catches and subsequently tries to run with it.

Football is played in games 60 minutes long (though with breaks in play this is typically 3-3.5 hours), divided into four 15-minute quarters. The game is further subdivided into plays – segments of action 5-15 seconds long where one team (the "offense") tries to move the ball "up the field" (toward their opponent's end zone) and the other (the "defense") tries to stop them by tackling them. Teams have four chances to either move the ball at least ten yards up the field, whereupon their four chances reset, or "punt" the ball away by dropkicking it downfield to the other team. After a punt, score, or turnover (a play where the defense gains possession of the football from the offense), the teams typically switch roles (the team on offense goes on defense, and vice versa). There are 40-second rest periods between plays, though the offense may decide to take less time to rest. In addition to offense and defense, there is a third group of players called "special teams" – these players are used for plays that involve kicking the ball (punts and "kickoffs" that occur at the start of each half or after one team scores in order to hand the ball to the other team). Players typically play on either offense or defense, but any player could be on special teams.

On offense and defense, there are 8 basic types of players. On offense, quarterbacks (QBs) are responsible for organizing each play and either handing the ball off to a runner or throwing it to a receiver to try and move the ball up the field. There are special rules to protect them from injuries and are not hit as often as other players. Running backs (RBs) most often get handed the football by the QB and try to run it up the field before getting knocked down, though they may also catch the football or "pass block" (try and prevent defenders from reaching and knocking down the QB before he can get rid of the football). Wide receivers (WRs) most often run up the field and try to catch the ball from the QB, then either get knocked down immediately or run further toward the opponent's end zone before scoring or being knocked down. Tight ends (TEs) are similar to WRs but are used more often for pass blocking. Offensive linemen (OLs) are 5 men who stand in front of the QB and either "run block" (try and push defenders forward to allow a runner to move the ball up the field) or pass block, depending on the type of play. On defense, defensive linemen (DLs) stand a few inches from the OLs and try and force their way past them to knock down whoever is holding the football (typically a runner or the QB). Linebackers (LBs) stand behind the DLs and have a variety of tasks in trying to stop the offense from moving the ball depending on the type of play. Defensive backs (DBs) play even deeper down the field and typically shadow the offense's receivers to stop them from catching the football.

Football is an inherently physical, chaotic, and high-speed game. There are 22 men on the field for each play – 11 trying to move the ball up the field and 11 trying to physically stop them. Offensive players will push, shove, and ram into defenders in an effort to move the ball further toward their opponent's end zone. Defenders also push and shove, but in addition they tackle (violently knock down) whichever offensive player has the ball in order to end the play. Injuries occur with regularity in both practices and games (3) and, given the physically taxing nature of the game, they happen frequently even without any physical contact between players (4-7).

II. Who Plays Football

As noted above, football is the most popular sport in the U.S., and that is reflected in the number of athletes playing it. In the 2013-14 school year, the National Federation of State High School Associations (NFSHSA) counted 14,262 high schools with boys' 11-player football programs, comprising 1,093,234 athletes (8). The National Collegiate Athletic Association (NCAA) reported 70,147 men's college football players in 2013 (9). In 2015, 1,979 players were listed on an NFL game-day roster for at least one regular season game, with a few hundred additional players on practice squads or training camps(10). These numbers, along with the intense public interest and economic impact of the sport, underscore the importance of studying injuries among football players.

III. Football Injuries – Descriptive Epidemiology and Injury Surveillance

Much attention, particularly in recent years, has been given to the topic of concussions and head injuries in football (11-16). By contrast, relatively little has been written about general musculoskeletal trauma, which comprise the vast majority of football injuries (17); most studies in this realm focus on specific injuries and/or use case series from individual treatment centers or teams rather than taking an overarching approach.

We begin Section III with a discussion of general descriptive injury studies and surveillance efforts at different levels of play. We then move into the more robust literature on specific injury types in the NFL and a brief discussion of the concussion literature. In the next section (Section IV) we will delve into analytic epidemiology and the factors affecting football injury risk.

A. General Football Injury Studies – High School and Younger

A 1991 review of five high school football epidemiology studies from 1979-1983 found that 51% of injuries occurred during training/practices, with contact sessions being 4.7 times more likely to produce injuries. 50% of injuries were to the lower extremities, with 36% to the knee; 30% of injuries were to the upper extremities. 40% of injuries were strains or sprains, 25% contusions/bruises, 10% fractures, 15% dislocations, and 5% concussions (18). All these data points are consistent with more recent, higher-quality, nationally-representative data discussed below.

The best data we have for this level of play may come from the High School Sports-Related Injury Surveillance Study, also sometimes referred to as High School – Reporting Information Online (RIO). The study was conducted among a nationally-representative sample of 100 high schools and included any injury known to, and subsequently reported by, the high school's certified athletic trainer(s) (ATCs). A 2006 analysis in the *Morbidity and Mortality Weekly Report* (MMWR) from the Centers for Disease Control and Prevention (CDC) for the 2005-06 school year found an overall injury rate of 4.36 injuries per 1,000 athlete-exposures (AE, commonly defined as 1 player participating in a practice or game) (19). The study also found this rate was the highest of 9 sports studied, and the rate for games (12.09/1,000 AEs) was nearly 5 times that of practices (2.54/1,000 AEs). About 45% of injuries resulted in 1-6 days out, while roughly 20% led to players being out for 3 weeks or more. A second analysis of these data reported in the 2007 *American Journal of Sports Medicine* (AJSM) found similar figures: 4.36, 2.56, and 12.04 per 1,000 AEs overall, during practice, and during games, respectively (7).

Updated data from this same study for the 2012-13 school year show similar results: 3.87 injuries per 1,000 AEs overall, 12.53 during games and 2.08 during practice (20). These numbers corresponded to 616,209 boys' football injuries nationwide. This report also included a wealth of additional information, including: 38-39% of injuries were sprains or strains and 25% concussions; excluding concussions, knee, ankle, hand/wrist, and shoulder injuries were the most common, respectively; 34% of injuries led to less than a week lost from practices and games; 10.2% of injuries required surgery; 9% were recurrent injuries; 25% occurred in the preseason while 69.5% occurred during the regular season; 58% of practice injuries occurred 1-2 hours into practice; and 51% of injuries occurred in the act of tackling and 26% during blocking (20). The 2007 *AJSM* analysis of the 2005-06 school year data provided some additional details on injury mechanism: 57% of practice and 77% of game injuries occurred from contact with another player; 18% and 5% were non-contact (overuse) injuries; 40% and 62% occurred on running plays; and offensive players suffered 56% and 52.5% of practice and game injuries (vs. 37% and 39% defensive players, with the remainder unknown or special teams) (7).

Another *MMWR* article published in 2011 used data from the National Electronic Injury Surveillance System – All Injury Program (NEISS-AIP) from 2001-2009 (11). It looked at all sports- and recreation-related injuries resulting in visits to a nationally representative sample of emergency departments (EDs), although the study's primary focus was on traumatic brain injuries (TBIs). This study estimated there were 351,562 ± 47,448 football-related ED visits in kids 19 and younger; 7.2% (25,376) of these visits were for TBIs. Football was found to be the number one source of sports-related TBI ED visits for boys 10-14, 15-19, and 19 and younger overall.

It is important to note that these injury rate estimates are very sensitive to the case definition of an "injury." For example, the studies cited above all used some variation on a definition that required "restriction of the…athlete's participation for one or more days beyond the day of injury" (20). A 2-year prospective study of 210 team- and 4,092 player-seasons from 13 youth leagues across 6 states that captured all injuries regardless of time loss found an overall injury rate of 10.3 per 1,000 AEs – nearly *triple* the values outlined above (21)! The majority of studies for youth and other levels of football seem to use the more restrictive definition, but it's always important when interpreting a study and putting it in the context of other research to understand the exact case definition that was used.

Over the last 40 years or so there have been a host of other local or state-level studies on high school football injuries, but none of these provides the nationally-representative data available from NEISS-AIP or RIO and so they will only be reviewed briefly. The North Carolina High School Athletic Injury Study, a prospective cohort, followed 3,323 high school football players from 1996-99 (22). It found an overall injury rate of 3.54 per 1,000 AEs (95% CI: 3.31-3.78), which is slightly lower than the estimates from RIO; 52% of injuries occurred while tackling or blocking, and 59% occurred on running plays (22). The injury rate was 9x higher for games versus practices (15.7 vs. 1.7 per 1,000 AEs) (22). A study of 717 high school football players in Oklahoma City found injury rates of 3.20 (95% CI: 2.7-3.8) per 1,000 AEs overall (1.31 (0.9-1.7) in practices and 13.12 (10.4-16.0) in games) (23). There were 132 injuries; 62% of injuries were to the lower body, primarily the ankle and knee; 9% were shoulder injuries; 6% were concussions; 54% of injuries were sprains or strains; 36% were non-contact; 60% occurred during a game; and 58% resulted in >= 1 game missed (10% >= 3 games) (23). In a study by the same group of 646 Oklahoma City middle school students found rates of 0.94 per 1,000 AEs for practices and 8.84 for games, a similar ratio but both lower than in high school (24). The distribution of 64 injuries was mostly similar, with a few notable exceptions: no concussions; only 39% of injuries to the lower body; and 30% of injuries to the hand/finger/wrist (24). A 1983 study of 1,877 injuries treated at the University of Alabama-Birmingham (UAB) from 1976-79 found sprains (32%) and bruises (25%) were the most common injuries, with concussions comprising only 1%; the majority of injuries (70%) were to offensive players, and roughly 2/3 occurred during practices (25). Among 100 Texas high schools in 1989 covering 4,399 varsity football players, there were 2,228 injuries (most commonly knee and ankle injuries) and a calculated incidence rate of 0.003 injuries per student-hour of athletic exposure (26), which is not out of line with the RIO data. Among 20 Atlanta-area high schools, researchers found higher injury rates (79.9 per 10,000 AEs) among schools with <1,600 students vs. larger schools (46.6 per 10,000 AEs); these rates are both somewhat above the national estimates from RIO of 38.7 injuries per 10,000 AEs (27). Among 678 9-14 year olds in central Michigan on 33 football teams in 2000 and 2001, there were 259 injuries; about 2/3 were in practice, 64% were classified as "mild," and both practice and game injuries increased with rising grade level (28). In 87 California high schools in the 2001 and 2002 seasons, there were 9.3 injuries per 10,000 "player-hours" (no further definition was given) and 8.4 per 100 "session-hours" during a game or practice (29); assuming 3 player-hours per AE, these figures are somewhat lower than the national RIO estimates (0.93x3 = 2.79 vs. 3.87 per 1,000 AEs) (20, 29), but it's difficult to make any confident comparison without more details on the calculation of the denominators in this study. In addition, this study found higher injury rates during games and higher rates for mobile offensive and defensive backfielders vs. more static linemen (29). There were also other similar studies in Oklahoma in 1978 (30) and South Carolina in 1982 (31).

B. General Football Injury Studies – College

1. NCAA ISS Data

The literature on general college football injury is more robust than that for either high school or professional players. This may be due in part to the NCAA's robust Injury Surveillance System (NCAA ISS), which has been around since 1982 and has been used for a number of research studies (32). In all studies using the ISS, an athletic-exposure (AE) is defined as 1 student athlete participating in a practice or competition in which they were exposed to injury; an "injury" was defined as an event that "(1) occurred as a result of participation in an organized intercollegiate practice or competition *and* (2) required medical attention by a team certified athletic trainer or physician *and* (3) resulted in restriction of the student-athlete's participation or performance for 1 or more calendar days beyond the day of injury" (32). Time loss and return to play (RTP) estimates were based off the time it took the player to return to a level allowing competition participation (32).

Data are entered from selected institutions by ATCs. Unfortunately, participation in the NCAA ISS is voluntary, so these are not nationally-representative data. Participating schools were selected by the following process: each year, a letter is sent to the institution's head ATC asking him/her to choose 1 primary and any number of secondary sports to report data for in each of the fall, spring, and summer seasons; all primary requests are chosen for the NCAA ISS and secondary requests are accepted until 15% of schools with a given sports program are accounted for; athletic trainers are given detailed instructions and data reporting forms (or, now, web-based log-ins (33)) and asked to provide data on injuries as they occurred and exposures (practices, competitions, participants) weekly from the first day of the preseason (including 15-day spring practices for football) to the end of any relevant postseason; ATCs responsible for each sport were give a "small monetary stipend" if their data were of sufficient quality to make it into the national data (32). No individually-identifiable information – only an institutional identifier – is included in the forms sent to the NCAA ISS, so injuries cannot be tracked longitudinally across players (32). Despite the limitations imposed by voluntary participation and anonymized data, these studies provide our best known estimates of injury risks and rates in college football and are outlined in the table below:

Table 1.1. College football injury studies using the NCAA ISS.

Study	Population	Injury Risk/Rate Estimates	Dimensions of Variation	Other Notes
Shankar et al, *J Athl Train*, 2007 (7)	2005-06 academic year 55/68 schools who volunteered to provide data that actually provided data for >90% of expected competitions and activity weeks (e.g. practices, spring camps); 27 (11%) from DI, 7 (5%) from DII, 21 (9%) from DIII programs; 621 varsity NCAA football programs exist overall 3,459 injuries (1,330 in competition; 2,129 in practice)	8.61/1,000 AEs overall 5.77/1,000 AEs practice 40.23/1,000 AEs competition	Game vs. Practice: 61.5% of injuries in practice, but competition rate 7x higher Injury Type, Competition/Practice: 39%/25% sprain, 34%/25% strain, 19%/10% contusion, 7%/7% concussion, 5%/4% fracture, 16%/29% unknown Injury Location: Lower leg/ankle/foot (20.5%), Hip/thigh (17.3%), Knee (16.4%), Shoulder (13.2%), Torso/spine/neck (10.6%) RTP: ~50% in 1-6 days, ~40% in >= 7 days, ~7.5% season/career ending, 2% unknown Injury Mechanism, Competition/Practice: 75%/41% contact with player, 8%/7% contact with field, 16%/35% non-contact or overuse; 56%/47% tackling, 35%/38% blocking, 9%/11% fallen/stepped on Play Type, Competition/Practice: 42%/26% running, 29%/25% passing, 12%/4% punt or kickoff, 0%/6% conditioning, 15%/26% "general play", 1%/3% unknown	Overall rates roughly double those for HS football (competition 3x higher)

			Position (Competition Only): 47% offense, 43% defense, 9% ST; 14% OL, 12% RB, 12% WR, 5% QB, 4% TE; 16% DL, 14% DB, 13% LB	
Dick et al, *J Athl Train*, 2007 (34)	1988-89 through 2003-04 academic years 19% and 18%, on average, of schools with football programs provided data in fall and spring each year; somewhat more DIII than DI or DII schools participated 30,797 game, 42,355 fall practice, and 10,943 spring practice injuries 17,911 games, 128,395 practices	Overall: 35.9/1,000 AEs game, 3.80/1,000 AEs fall practice, 9.62/1,000 AEs spring practice (~5.0,1,000 AEs overall practice) 2003-04: 32.4/1,000 AEs game; 4.1/1,000 AEs fall practice; 7.9/1,000 AEs spring practice Game rate generally varied 32-34/1,000 AEs, spring practice dropped from 9-10 to around 8/1000 AEs over time	Game vs. Practice: 66.2% of injuries in practice, but competition rate ~7x higher Injury Location, Game/Fall/Spring: 55/51/56% lower extremity, 23/20/23% upper extremity, 12/10/10% head/neck, 10/13/12% trunk Most Common Injuries: Knee internal derangement, ankle sprain, upper leg strain, concussion (~45/38% of all injuries in games/fall practices; full details in Table 6) Injury Mechanism, Game/Fall/Spring: 78/57/59% player contact; 5/5/6% other contact; 9/29/22% non-contact; 8/10/3% unknown RTP: 27/25/34% required 10+ days to return Position (weighted by avg. # players): 20% RB, 18% QB, 16% LB, 14% WR, 12% DB, 11% DL, 10% OL (wgt=6); (no TE category); concussions even more disproportionately common for QB	Much more detail for knee and shoulder injuries not extracted here because they pertain to specific injuries rather than a general overview

Kerr et al, *MMWR*, 2015 (33)	2009-10 to 2013-14 academic years 25 NCAA championship sports National estimates generated using inverse selection probabilities stratified by sport, division, and academic year; then "adjusted for potential underreporting" 8,680 injuries in men's football 899,321 AEs in men's football	9.2 (95% CI 9.0-9.4) per 1,000 AEs overall 39.9 per 1,000 AEs competition 5.8 per 1,000 AEs practice	Game vs. Practice: 57.7% of injuries in practice, but competition rate ~7x higher (highest of any sport in study) RTP: ~28/22% of game/practice injuries required >= 7 days to return to full participation	4th highest overall injury rate after men's wrestling (13.1), women's gymnastics (10.4), men's ice hockey (9.5) Football had highest # injuries overall due to more participants
Hootman et al, *J Athl Train*, 2007 (35)	1988-89 through 2003-04 academic years	35.9/1,000 AEs game, 3.8/1,000 AEs fall practice, 9.6/1,000 AEs spring practice (same data as Dick et al 2007)	-	Ankle sprains: 0.83 (fall) and 1.34 (spring) per 1,000 AEs ACLs: 0.18 and 0.33 per 1,000 AEs Concussions: 0.37 and 0.54 per 1,000 AEs

Summarizing the table above, we find fairly consistent estimates for overall injury rates in college football: approximately 8.6-9.2 injuries per 1,000 AEs during overall, approximately 40 injuries per 1,000 AEs during games, and approximately 5.8 per 1,000 AEs during practices (with substantially higher AEs in the spring than fall, 9.6 vs. 3.8 injuries per 1,000 AEs, although this could be explained by other factors as expanded upon below). Game injury rates were consistently about 7 times higher than practice rates, though practices accounted for 58-67% of injuries overall. In terms of RTP, comparisons are a bit more difficult due to the use of different return time cutpoints and how season/career-ending injuries were treated, but it appears either around 30% (33, 34) or almost 50% (7) of injuries kept players out at least a week. The most common injuries, generally speaking, are to the lower extremities, with knee and ankle injuries particularly common; however, exact percentages are very sensitive to the specific categorizations chosen by a research group, making direct comparisons difficult. After weighting according to the number of players typically at each position, the two studies including positional breakdowns roughly agree that defenders account for a lower proportion of injuries than offensive players (approximately 38-43% vs. 47-51% after accounting for 9% of injuries to ST players), as well as that injuries are roughly evenly spread across defenders. On the offense, OLs appeared to be a bit less likely to be injured than other positions, with RBs and WRs (more mobile positions) a bit higher. After weighting, the two studies also roughly agreed on the proportion of injuries to QBs.

2. *Big 10 Conference ISS (B10 ISS) Data*

There is one other noteworthy general injury study that did not use the NCAA ISS. In the 2004 issue of *AJSM*, Albright et al used data from the Big 10 Conference's own ISS (B10 ISS) (4). The Big 10 data are different than those reported to the NCAA ISS. The study's overarching goal was to analyze the difference in injury rates between fall and spring practices – spring demonstrating higher rates – and assess whether new NCAA spring practice restrictions issued before the 1998 season reduced that disparity. The authors conducted two separate analyses: the first used data from the 1992-93 through 1996-97 academic years, and the second the 1998-99 to 2000-01 academic years. In both cases the data were provided by ATCs and included a full roster, daily logs of practices and games, and "all reportable injuries" (defined differently from the NCAA ISS: "evidence of tissue damage, as determined by the clinical signs of erythema, warmth, tenderness, swelling, or abnormal laxity, and the inability of the player to return to practice that day" plus all concussions, fractures, and dental injuries) (4). Team-seasons were only included if they had data for the fall and spring. In the first analysis, 44/55 (80%) team-seasons were included. This analysis found injury rates of 19.8 per 1,000 AEs in spring practices and 10.6 per 1,000 AEs for fall practices (4); these figures are, notably, about twice as high as the same estimates from the NCAA ISS (33), though the B10 ISS only includes Division I (higher-level) schools with stronger competition and better players, which could explain at least part of this difference. The researchers then stratified practice intensity into contact ("routine weekday practice and may include periods of full-contact scrimmage", but has restrictions such as no "piling on"), limited contact ("contact but at a lesser degree of intensity and/or duration than is normal for the team" including no contact), and scrimmages (game-like conditions) (4). They found injury rates of 14.5, 5.8, and 5.7 per 1,000 AEs, meaning, interestingly, injury rates for the mid-level contact practices were higher than either limited-contact practices or scrimmages (4).

In their second analysis, the group used similar data from 1998-99 through 2000-01, but with two added data elements: position and string. Positions were defined as "line" (OL and DL), "skill" (WR, RB, DB), "linebacker/tight end" (LB and TE), and "special teams" (ST); quarterbacks seemed to be excluded (4). "String" was defined fairly typically as "starters", "substitutes", and "non-players," though it was not explicitly stated who assigned these designations and whether they could change over the course of the year. In these later years, all 33/33 possible team seasons were reported (100%). Furthermore, the NCAA had instituted rules to curb the intensity of spring practices in an effort to prevent injuries. Fall injury rates dropped from 10.6 to 5.2 per 1,000 AEs, while spring rates dropped proportionally less from 19.8 to 16.4 per 1,000 AEs (4); these rates are still about 50% above the corresponding NCAA ISS rates (34). The injury rates were 7.4, 8.3, and 19.5 per 1,000 AEs for contact, limited contact, and scrimmage practices, respectively; this makes more sense intuitively but stands in contrast to the data reported for the earlier period (4). The data for this time period is also broken down by injury type but uses different categories than the earlier years, making comparisons difficult.

The analyses also revealed that 66% of fall and 60% of spring injuries resulted in 0-7 days lost (4), which is in line with the NCAA ISS data. Leg injuries, especially ankle and knee injuries, were the most common practice injuries, followed by shoulder/arm and head/neck/scalp, with injury rate estimates per 1,000 AEs for each of these injuries for both fall and spring practices (though we will not get into those details here) (4). Once again, these data are also in line with analyses of the NCAA ISS. When broken down by practice type, in the older years scrimmages had the lowest injury rates, while in 1998-99 to 2000-01 they were highest (4). I am not sure what explains that, but perhaps it is also the result of eliminating selection bias in the later years. Finally, non-players had higher injury rates (18.6 and 6.3 per 1,000 AEs in the spring and fall, respectively) than starters (15.9 and 4.9) and substitutes (14.9 and 4.3) (4); this finding, however, could be easily explained by confounding by "injury-proneness" (i.e. players who get hurt easily – or are hurt – are more likely to be classified as non-players; this could be considered a type of confounding by indication and presents a separate difficult methodological challenge).

3. Other College Data

There are several other papers that used more limited datasets that merit a briefer discussion. The most important of these is the 2007 study by Brophy et al that analyzed data from the NFL combine – an inviteonly workout and medical examination event for elite college football players with a shot at playing in the NFL. They analyzed the medical records from the New York Giants for combine players from 1987-2000 (36). This yielded interesting data on the combined toll of injuries by the time pro-caliber players complete their college careers: among 5,047 records, there were an average of 2.45 musculoskeletal diagnoses and 0.53 procedures per player (36) – these figures could be considered prevalences if we permanently assign a diagnosis or procedure to an individual (i.e. no recovery). The most common diagnoses were ankle sprains (0.29 per player), "burners" (nerve injuries) (0.17), wrist/hand non-fractures (0.17), medial collateral ligament (MCL) knee injuries (0.16), and AC joint shoulder injuries (0.16). The most common procedures were menisectomy in the knee (0.10), knee arthroscopy (0.08), ACL reconstruction (0.06), and shoulder stabilization (0.05) (36). Overall, 284 (5.63%) of players were given a "reject" grade by the Giants medical staff at the combine; this varied from 0.62% of kickers to, interestingly, 7.71% of OLs despite their generally lower injury rates (7, 34) and middle-of-the-pack diagnosis and procedure prevalences (36). Perhaps there is a higher medical threshold for these players at the combine.

Three other papers merit a brief mention. In a 1979 study of data collected during the 1976 season for 5 college teams that compared injury rates for 12 drills plus practice games, agility drills had the lowest rates (1 injury per 47,138 minutes of exposure) while practice games had the highest (1 per 1,009 minutes) (37). This seems in line with NCAA ISS data. In a 2016 study that looked at 3 seasons of football and club rugby at Ohio State University, overall football injury rates were 4.9 per 1,000 AEs (38), substantially below the NCAA ISS data and national estimates; game and practice-specific injury rates were commensurately lower. The authors did find, however, a similar IDR for games vs. practices (6.5, 95% CI 4.5-9.3) (38). They also found that most injuries occurred during player contact and that knee, ankle, and head injuries were some of the most frequent (38), which is consistent with the NCAA ISS. Finally, a 2013 article by Iguchi et al reviewed data on the college football team at Doshisha University in Kyoto, Japan from 2007-2009, and found game and practice injury rates of 32.7 per 1,000 AEs and 10.9 per 1,000 AEs, respectively (39). The practice rates are higher than the NCAA ISS, while the game rate is somewhat lower – there are likely many differences between Japanese and U.S. college football players and systems to explain this, though.

4. *Synthesis*

The best descriptive data on college football injuries comes from the NCAA ISS, although these data cannot be taken as nationally-representative due to the voluntary nature of reporting. Several studies found consistent estimates for overall injury rates in college football: approximately 8.6-9.2 injuries per 1,000 AEs overall, approximately 40 injuries per 1,000 AEs during games, and approximately 5.8 per 1,000 AEs during practices (with substantially higher rates in the spring than fall – 9.6 vs. 3.8 injuries per 1,000 AEs – although this could be explained by other factors) (7, 33, 34). Game injury rates were consistently about 7 times higher than practice rates, though practices accounted for 58-67% of injuries overall because of their greater frequency. Return to play (RTP) estimates are more variable, partly due to the use of different cutpoints for return categories; either around 30% (33, 34) or almost 50% (7) of injuries kept players out at least a week. The most common injuries are to the lower extremities, with knee and ankle injuries particularly common; however, exact percentages are very sensitive to the specific categorizations chosen by a research group. After weighting for the number of players typically at each position, the two studies including positional breakdowns roughly agree that defenders account for a lower proportion of injuries than offensive players (approximately 38-43% vs. 47-51% after accounting for 9% of injuries to ST players), as well as that injuries are roughly evenly spread across defenders. On the offense, OLs appeared to be a bit less likely to be injured than other positions, with RBs and WRs (more mobile positions) a bit higher. A number of other smaller-scale studies have provided data consistent with these estimates. Lastly, an analysis of college players at the NFL Combine provides injury prevalence estimates for these elite players after a full college career: an average of 2.45 musculoskeletal diagnoses and 0.53 procedures per player, with the most common being ankle sprains (0.29 per player), "burners" (nerve injuries) (0.17), wrist/hand non-fractures (0.17), medial collateral ligament (MCL) knee injuries (0.16), and AC joint shoulder injuries (0.16) (36).

C. General Football Injury Studies – NFL

1. NFL Injury Surveillance System (NFL ISS)

Although the NFL has had its own Injury Surveillance System (NFL ISS) since 1980 (40, 41), it has not been used for broad-based investigations into injury risks and rates. Most studies using these data are focused on specific types of injuries such as ulnar collateral ligament (UCL) injuries or triceps tendon tears (42-48). Broad-based, general descriptive injury epidemiology and surveillance results from the NFL ISS are lacking. The reasons for that are unclear but may involve data access and research approval issues. In the absence of access to NFL ISS data, an alternative source of data is the official NFL injury reports.

One recent report from Harvard Law School counted overall injuries in the NFL ISS. In 2014-15 (the most recent 2 years available for all injuries) there were 3,553 injuries in regular season games and 737 in regular season practices (82.8% of injuries occurred during games) (41). Assuming 92 athlete exposures per game (46-man game-day roster x 2) and 256 games per regular season, this translates to 3,553/(256 x 2 x 92) x 1,000 = 75.4 injuries per 1,000 AEs in games. There were 737 injuries in regular season practices over the same time period (41). If we assume 4 practices per week, 61 athlete exposures per practice (53-man active roster + 8-man practice squad), 32 teams, 17 weeks, and 2 seasons, this translates to 737/(61 x 32 x 17 x 4 x 2) = 2.8 injuries per 1,000 AEs in regular season practices. The combined game and practice regular season injury rate would then be 13.7 per 1,000 AEs. The report only provides data on one specific injury: concussions, and only for regular season games (practices are reported as combined pre- and regular season). The regular season game rate for concussions, using similar calculations to the above, was 350/(256 x 2 x 92) x 1,000 = 7.4 per 1,000 AEs in 2015-16 (the most recent two years available). This translates to ~0.68

concussions per game. Although it provides benchmarks for overall injury rates, the report did not stratify by any factors that may affect injuries.

These numbers can be compared with the results of another NFL ISS-based study, which reported 20,639 and 3,479 injuries in regular season games and practices, respectively, over 15 seasons (49). 85.6% of injuries occurred in games, similar to the 82.8% from the Harvard study. Using the same method we used above we can also estimate injury rates from these counts. For games: 20,639/(256 x 15 x 92) x 1,000 = 58.4 injuries per 1,000 AEs (vs. 75.4 from 2014-15 in the Harvard study (41)). For practices: 3,479/(61 x 32 x 17 x 4 x 15) x 1,000 = 1.7 injuries per 1,000 AEs (vs. 2.8 in the Harvard study (41)). These numbers are lower than the estimates from the Harvard study (41), which isn't surprising as the number of injuries recorded is known to have risen over time. Unfortunately, because of the different time periods we cannot make a direct comparison. The Harvard study should be considered the gold standard because it provides data that can be limited to more recent years.

One other general epidemiology study used the NFL ISS to ascertain all injuries from 1988-2008, although the analysis focused on kicking positions (placekickers and punters) (50). The NFL ISS defined an injury as "significant and reportable if it resulted in premature cessation of at least 1 practice, game, or training event….football injuries that were treated in a delayed fashion, even if not associated with premature cessation of play, were also reported" (50). Data were entered by each team's senior ATC and updated daily with treatment and practice and competition limitations until the player fully returned from that injury (50). Injuries during team-sanctioned activities in the preseason (including organized team activities (OTAs) in the spring and training camp), regular season, and post-season were included. Injury rates were calculated using AEs as a denominator, with 1 AE being a single game or practice for one player. Over the 20-year study period, there were 488 injuries (24 per year) and 264 kickers on NFL rosters (50). Unsurprisingly, 4 of the top 5 injuries were in the leg/pelvis area: adductor strains (54), hamstring strains (50), quadriceps strains (30), and lumbosacral sprains/strains (29). These injuries resulted in a mean of about 1.5-5.0 weeks lost, but the ranges indicate the data were heavily left-skewed (50). Concussions were the third most common injury (31), but they resulted in a mean of only 3 days lost (50). Overall, 72% of injuries were to the lower extremities and a further 17% to the head/neck/spine (50). 49% of injuries were to muscles and tendons, and 17% to ligaments. 62% of injuries occurred during games, with the game injury rate over 9x higher than the practice rate (17.7 vs. 1.91 injuries per 1,000 AEs) (50). 32% of injuries were caused by contact (54% non-contact and 14% unknown), but this figure was 46% during games (beating out non-contact injuries at 43%); 42% of injuries overall occurred during kicking, with others occurring while tackling, blocking, or in other situations (50). Punters and placekickers exhibited similar injury profiles. This study provides a great example of the kind of descriptive epidemiology that the NFL ISS is capable of providing, but its utility is limited by being restricted to placekickers and punters.

2. NFL Injury Report Data

As noted above, in the absence of NFL ISS data, the best source the public is left with are the NFL's official injury reports. These are League-mandated public reports that all 32 teams put out each week of "any player hampered by an injury (17)." In concert with the injured/reserve (IR) and physically unable to perform (PUP) lists for longer-term injuries (>=6 weeks away from practice and >=8 away from games) (51), these reports provide a list of all NFL players suffering the effects of an injury at any given time. The reports have several limitations. First, the definition of "injury" is somewhat unclear. Second, the reported data are limited to player name, position, team, practice status (full/limited/no participation), the likelihood of playing in the team's next game (probable, questionable, doubtful, out), and injury location (e.g. ankle, knee, arm, illness) (17). However, there is no universal structured nomenclature of injury location and teams vary in the level of detail they provide. Third, information on specifics of the injury, the player's injury history, injury severity, or when or how the injury occurred (game vs. practice) is not available (17) though sometimes additional details can be garnered from interviews or other sources. Finally, there is substantial variability in how much information teams report, which may allow them to manipulate who exactly appears on an injury report and how much information is revealed about a given injury (3, 17, 52). A more thorough discussion of the limitations of the NFL's injury report appears below in Chapter 2. Even with all of these limitations, however, the injury report remains the best available public injury information available by a wide margin.

Lawrence and colleagues presented a comprehensive analysis of these data in their 2015 article published in the *Orthopedic Journal of Sports Medicine* (17). The authors prospectively collected weekly injury report data for the 2012-13 and 2013-14 regular seasons (presumably excluding injuries sustained during training camp, preseason, or the postseason) (17). They defined an "injury" as any event in an official injury report (53). They counted new injuries as any entry that did not appear the previous week (17). As they did not know exactly when an injury occurred (a player appearing on the week 7 injury report could have been hurt in the game in week 6 or the practices between weeks 6 and 7), they assumed that every injury occurred in the prior game (17). This was based on other NFL studies that showed a substantial majority (>80%) of injuries occurring in games rather than practices, though these (41, 47, 54, 55) run counter to the data from college and high school football (7) that shows a majority of injuries during practices. They calculated "injury rates" using three different denominators: 1.) team-games (TG, 2 TGs per game played), 2.) team-game positions (TGP, TG x the typical number of positions [overall or of a given type] in a game, and 3.) athletes at risk (AAR, TG x 11 players on the field at any given time) (17). The first two could reasonably be called injury rates with "game" or "game-position" as measures of time. The interpretation of these measures is not straightforward, though; both measures could be interpreted as rates for recurrent diseases with an instantaneous recovery time, since injured players are always immediately replaced by someone else at the same position. The third denominator (AAR), as defined in this study, is redundant at best (it is defined in the article's Table 1 to be the TG measure divided by 11 (17)) and difficult to interpret at worst. Because of its redundancy and lack of value as an individual player risk (it assumes the same player is at risk the entire game, and different players have vastly different levels of exposure when they're at risk for injury during games and practices), I will not use any of the AAR measures in this review. The study did not use AEs as a denominator in any analysis.

The study ultimately included 984 TGs, 961 (97.7%) of which had at least one injury; there were 4,284 injuries in 1,172 players (3.7 injuries per player injured), translating to 4.35 injuries per TG or 8.71 injuries per game overall (17). If we make an assumption of 46 athlete-exposures – the size of the active game-day NFL roster – per TG, this would translate to a game injury rate of 4,284 injuries/(984 TGs x 46 athletes per TG x 82.8% of injuries in games) (41) = 78.4 injuries per 1,000 AEs, much higher than that for college and similar to what was found in the Harvard NFL ISS study (41). If we factor in 4 additional practices per week with the 61 athletes per practice (53-man active roster + 8-man practice squad), we would get 4,284 injuries in 984 x 46 game AEs + 4 x 61 x 984 practice AEs = 15.0 injuries per 1,000 AEs overall. This is about 50% above our best estimates for the college football injury rate (7, 33, 34) and is comparable with what a research team analyzing New York Giants training camp data reported (17.3 per 1,000 AEs overall) as well as the Harvard Law School study (13.7 per 1,000 AEs) (3). It may still be an overestimate from back-of-the-envelope calculations, however, especially since training camp injury rates may be higher than those for the regular season due to survivor bias.

The fact that the calculated game and overall injury rates are similar between studies based on public injury report data and the NFL ISS (17, 41) might give us more confidence in using the public data despite its known limitations. However, a closer reading of the numbers raises some eyebrows: the public injury reports counted 4,284 regular season injuries from 2012-13 through 2013-14, but the NFL ISS over this same time counted just 3,406 (17, 41). This difference is in the opposite direction of what would be expected if the NFL ISS were more thorough. Lawrence et al defined a new injury as any injury that was not present the previous week (they did not specify if or how they accounted for byes) (17); this may have led to over-counting of recurrent injuries as new injuries, which might explain some (but not nearly all) of the difference. Another difference might be in whether players who were on IR the entire season counted in either of these studies.

61.9% of injuries were to lower extremities, with knee (17.8%) and ankle (12.4%) injuries most common; 18.0% were to upper extremities, with the majority being shoulder injuries (8.4%); 10.2% were head and neck and 7.8% were "axial" injuries (back, ribs, abdomen, other) (17). After accounting for the number of players at each position, WRs (30.28 (95% CI: 27.90-32.82) injuries per 100 TGP), TEs (27.44 (24.26-30.91)), and DBs (23.60 (22.11-25.17)) had the highest injury rates, while QBs (12.09 (10.02-14.47)) and kickers/punters (4.88 (3.60-6.47)) had the lowest. Although I have concerns (as outlined above) about the appropriateness, calculation and interpretation of the TGP and AAR measures, this study provides invaluable raw data on the number of injuries suffered and players injured over the course of two NFL seasons, as well as how those injuries break down by position and injury location. The descriptive injury location data from the study's Figure 1 is particularly useful. Also, even if the TGP measures are difficult to interpret in isolation, in comparison to each other they show us that positions experiencing common high-velocity contact (WRs, TEs, DBs) are more subject to injury than those who aren't (QBs, kickers, punters).

A later extension of this study stratified data on the most common injuries by a range of game-level variables (56). Concussions appeared somewhat more frequent in away games and colder temperatures. Knee injuries were somewhat more common in higher temperatures. Ankle injuries were more common in lower temperatures but less common with 3+-hour time zone changes. Hamstring injuries were progressively less frequent as the season drags on; more common with less rest; less common at away games; and somewhat less frequent in colder games. Shoulder injuries were less common with 3+-hour time zone changes and more common on grass than artificial turf.

3. Single Team Data

In addition to the NFL ISS, more detailed injury data than that available to the public is also held by individual NFL teams. Teams are often reticent to disclose this information due to the competitive advantage it provides, but clinicians and researchers who work for these teams have sometimes managed to secure access to it for academic research purposes. One group working with the New York Giants has been particularly productive (3, 36, 57, 58).

Brophy et al (2007) analyzed injury prevalence for players assessed by the New York Giants at NFL combine from 1987-2000 was already discussed above in the NCAA section (36). The data included medical grades (A+ to F) given by the Giants' medical staff; an A+ was no injury history, an A was a minor injury treated successfully without surgery, a B was multiple injuries or a successful surgery, a D was a player with an injury likely to recur, and an F meant to reject adding to the player to the team because of injury concerns (36). Overall, 70.1% of players received an A or B and 5.6% received an F/reject grade (36). Brophy devised and executed a process to code and categorize all diagnosis and procedure information by himself to reduce misclassification. Among 5,047 players evaluated at the Combine, there were an average of 2.45 musculoskeletal diagnoses and 0.53 procedures per player (36) – these figures could be considered prevalences if we permanently assign a diagnosis or procedure to an individual (i.e. no recovery). The most common diagnoses were ankle sprains (0.29 per player), "burners" (nerve injuries) (0.17), wrist/hand non-fractures (0.17), medial collateral ligament (MCL) knee injuries (0.16), and AC joint shoulder injuries (0.16). The most common procedures were menisectomy in the knee (0.10), knee arthroscopy (0.08), ACL reconstruction (0.06), and shoulder stabilization (0.05) (36). Overall, 284 (5.63%) of players were given a F/reject grade by the Giants medical staff at the combine; this varied from 0.62% of kickers to, interestingly, 7.71% of OLs despite their generally lower injury rates (3, 7, 34) and middle-of-the-pack diagnosis and procedure prevalences (36). Only about 60% of these players went on the play in the NFL, though, so these prevalences are probably not indicative of these measures in the NFL.

Feeley et al also used New York Giants data collected prospectively during training camps from 1998 to 2007 to assess injury rates in the run-up to the regular season. An injury was defined as "an event that occurred as a result of participation in an organized practice or game, required medical attention by an athletic trainer or physician, and resulted in restriction of the athlete's participation for at least 1 day beyond the day of injury"(3). All injuries were diagnosed and classified by one of the paper's authors using a unique categorization system. Players who joined any time during training camp were included, leading to an open cohort where players had differing degrees of exposure (3), necessitating the calculation of rates with AE denominators. Players with any injury at the start of training camp or who were missing any data were excluded (3); this restricts generalizability to only healthy players and is arguably inappropriate because, for example, a player with a nagging ankle sprain wouldn't be considered "at risk" for a shoulder labrum tear. It is unclear if players were eligible for multiple injuries (but they should have been). Injury severity was measured as the number of days a player was out (unable to perform any team activities during practice) or limited (able to only perform individual drills). The number of AEs was estimated based on the "total number of athletes in camp at any time minus the number of athletes who were out and limited" (3); it is unclear whether this was calculated each day or based on the overall average. Risk ratios (RRs) were calculated (3), but if we considered injuries per AE to be an incidence rate, these would technically be IDRs. There were 728 injuries and 42,030 AEs during the study period, for an overall incidence rate of 17.3 per 1,000 AEs (3). The rate for preseason games was roughly 5x higher than for practices (64.7 vs 12.7 per 1,000 AEs). On average these injuries resulted in 6.4 days missed, with an even split between "out" and "limited" days (3) – though the mean is misleading because the days missed measure is likely heavily right skewed. Injury rates peaked in weeks 1 and 2 of training camp (21.2 and 28.1 per 1,000 AEs, respectively, vs. 11.5 in week 3 and 5.4 in week 5); this is suggestive of an injury-prone group getting hurt (and possibly cut) early, with heartier players – who also may have been more likely to make the team in the first place – being present in greater numbers in later weeks (3). This survivor bias needs to be accounted for in any analysis of NFL injuries over the course of a season. Injuries were also more severe in weeks 1 and 2, though this may be confounded by the quality of the player that was getting hurt. The most common injuries were knee sprains (2.12 and 10.84 per 1,000 AEs in practices and games, respectively), hamstring strains (1.79 and 4.07), ankle sprains (1.10 and 6.78), and all contusions (0.92 and 12.47) (3). Although these are data are only for one team during training camp and preseason, it comprises the best comprehensive estimates we have from a single study for NFL injury *rates* broken out by type.

The rates stratified by position do not make sense as they are all far lower than the overall rates, which may indicate a calculation error. That said, defensive players were slightly more likely to get hurt than offensive players (2.2 vs. 2.0 injuries per 1,000 AEs). Consistent with other studies, highly mobile positions prone to violent collisions once again had the highest injury rates (TEs 2.7 per 1,000 AEs, WRs 2.3, DBs 2.6, LBs 2.3); the relatively-protected QBs (1.2) and punters/kickers (0.7) had the lowest rates (3).

In an earlier 1988 study, Nicholas et al reviewed the medical records of the New York Titans/Jets from 1960-1985 (59). The authors used the American Medical Association's (AMA's) *Standard Nomenclature of Athletic Injuries* to classify injuries (59). The study focused only on "significant" and "major" injuries causing athletes to miss >= 2 or 8 consecutive regular-season games (or by judgement of the team physician if the injury occurred in the latter part of the season), respectively; other injuries were outside the study's scope (59). The analytic dataset only included injuries during regular season games, not practices. The study found, over 373 games and 55,643 plays, 331 significant and 130 major injuries; these convert to 89 and 35 significant and major injuries per 100 games, respectively. If we were to translate these to the common denominator of 1,000 AEs (player-games), assuming 22 AEs per game (a questionable assumption), we get 40.5 and 15.9 significant and major injuries per 1,000 AEs. This is somewhat below the game estimate of 64.7 per 1,000 AEs reported in the Feeley et al study (3). However, Feeley's study included minor injuries and was performed only in preseason games, where injury rates might be expected to be higher due to survivor bias. If we define an exposure as a single play rather than a snap and make the assumption of 22 AEs per snap (a more solid assumption for snaps than for games, since a snap is a closed cohort while a game is not), then the rate becomes 0.27 significant and 0.11 injuries per 1,000 AEs. About 76% of significant injuries were to lower extremities, with 39% to the knee alone; these figures were 78% and 58% for major injuries (59). These figures are in line with those of other studies.

4. *Review of NFL Injury Studies*

In 2014, Makhni et al reviewed different dimensions of and patterns within the medical literature around the Big Four U.S. sports leagues – the NFL, National Basketball Association (NBA), Major League Baseball (MLB), and National Hockey League (NHL) (60). Any original research article providing data from professional athletes on a medical topic (injury or otherwise) was included; articles were identified using "broad search terms" (e.g. for the NFL, "NFL", "National Football League", and "Professional football") and searching of reference lists (60). The study identified 211 NFL injury studies, second only to MLB with 216 and well ahead of the NBA (34) and NHL (75) (60). Only about half of NFL articles appeared in "sports-focused" journals such as *AJSM (60).* Approximately half of all articles addressed orthopedic (e.g. injuries) and nonorthopedic (e.g. cardiovascular disease) outcomes (60) – the latter type are not included in the current review. Among 102 orthopedic articles addressing injuries at various sites, 28% focused on the knee or lower leg, 18% on the spine, and 16% on the shoulder or elbow; these numbers reflect the frequency and severity of injuries in the NFL (60). Among nonorthopedic studies, 30% focused on neurology and another 30% on cardiovascular disease, underscoring the medical concerns of players during and after their playing days (60).

Highlighting the growing importance of and interest in studying NFL injuries, the number of studies has increased substantially from under 30 from 2000-2004 to almost 80 from 2010-2012; the 2010-2012 period also saw the NFL take the top spot in number of studies away from MLB by a nearly 2-to-1 margin (60).

5. Synthesis

There has been limited descriptive epidemiology done on injuries to NFL players, especially relative to the work that's been done in NCAA and even high school football. The best all-injury, NFL-wide study we have come from the Harvard Law School report using the NFL's ISS (41). From this report, which only gave injury counts, we can estimate regular season overall/game/practice injury rates to be 13.7/75.4/2.8 per 1,000 AEs in 2014-15. Although it provides excellent benchmarks for overall injury rates, the report did not stratify by any factors that may affect injuries.

These data are similar to a study of public injury report data over the two-year period 2012-13 (17, 56), from which we calculated injury rates of 15.0 per 1,000 AEs overall and 78.4 per 1,000 AEs in games (17). This study also showed that, consistent with high school and college data, the most common NFL injuries were knee, ankle, hamstring, and shoulder injuries, as well as concussions (3, 17). These League-wide studies, however, only looked at how injuries varied by position (17); and time within the season, rest, travel variables, altitude, and weather (56). They neglect some other dimensions of interest (e.g. calendar time, age) that we seek to address. Additionally, these studies counted about 25% more injuries than the NFL ISS study did, and the reason is unclear.

Researchers accessing the New York Giants' training camp data provide us with another data point for injury rates: 17.3 injuries per 1,000 AEs overall, 64.7 in preseason games and 12.7 in practices (3). The preseason game rate is lower than the regular season game rate, but the practice rates are much higher; these make sense as players tend to play less time each in preseason games while practices are more intense and survivor bias has yet to take hold. The Giants data also stratified by position but the rates must have been calculated incorrectly as they are all far lower than the overall rate. Additionally, all these data are only for the preseason and only for a single team – and, while this is a different time period, one that has ranked dead last each of the last three years in Footballoutsiders.com's adjusted games lost (AGL) metric of how badly the team was damaged by injuries (61).

Specific Aim 1 will attempt to fill in some of these large descriptive epidemiology gaps.

D. Specific Football Injury Studies – NFL

A number of NFL ISS-based studies examined data pertaining to specific injuries. We briefly review these studies in Table 3.2 below. The table is limited to NFL ISS studies that included a count or injury rate for their target injury type, as well as a small number of additional studies. Also included are injury estimates from two general NFL injury studies using public injury reports from 2012-13 to 2013-14 (17) and a single team's data from 1998-2007 (3) to allow comparisons with the NFL ISS analyses. To get injury-specific rates from the public injury report study, we take the percent of all injuries in each category and multiply by the rate for all injuries calculated using the methodology described elsewhere in this paper (15.0 per 1,000 AEs). To get injury-specific rates for the single team data, we take the number of each injury reported in that paper, divide it by the total AEs reported in the paper (42,030) and multiply by 1,000.

Table 1.2. Specific Injury Studies from the NFL Injury Surveillance System.

General Injury Type	Specific Injury Type	Study	Population	Time	Injury Risk/Rate Estimates	Correlated Factors
<u>Knee</u>: Injury reports – 2.7 per 1,000 AEs Single team – 2.9 per 1,000 AEs (knee sprains)	ACL tears	Bradley et al, *Arthroscopy*, 2002 (62)	NFL ISS; pre-season through post-season	1994-1998	In 5 years, 209 ACL tears ~2,100 knee injuries overall, ~1,155 knee sprains	<u>Game vs. Practice:</u> 142/209 in games <u>Time (Month):</u> most practice injuries in July, more game injuries in August before flattening across regular season <u>Turf:</u> proportions commensurate with proportions of practices and games that take place on each turf <u>Position:</u> RBs higher, QBs and TEs lower <u>Play Type:</u> 31.7% occur on ST plays, suggesting they are higher risk
		Carey et al, *AJSM*, 2006 (63)	Injury reports/game summaries/player profiles; RBs and WRs only	1998-2002	33 injuries to 31 players → ~6 per year	21% did not RTP "Power rating" dropped significantly post-injury vs. control players
		Eisenstein et al, *Ortho J Sports Med*, 2016 (64)	Public websites/post-game summaries; pre-season through post-season	2013-2014	92 injuries to 90 players → 46 per season	More likely to RTP: in-season, non-ST play, round 1-3 draft pick (i.e. better players) <u>Position:</u> highest 2-season incidence in WRs (5.3%), DL (4.6%), LB (4.0%), OL (2.9%)

	Read et al, *AJSM*, 2017 (65)	Public injury reports, websites, newspapers *Defensive players only*	2006-2012	39 injuries overall in 7 seasons	
	Secrist et al, *Orthop J Sports Med*, 2016 (66)	Public injury reports, websites, newspapers	2010-2013	219 injuries in 4 seasons	
Knee Articular Cartilage	Brophy et al, *J Knee Surg*, 2009 (67)	"League database"	1992-2006	118 cases → 8 per season	Position: ~ ½ of injuries in "linemen"
Chrondral lesions with microfracture surgery	Steadman et al, *J Knee Surg*, 2003 (68)		1986-1997	25 surgeries overall in 12 seasons	
LCL injury	Bushnell et al, *AJSM*, 2010 (69)	NFL ISS	1994-2004	88 injuries → 8 per season 9 isolated LCL tears	7/9 from direct blow to knee
MCL sprain	Hershman et al, *AJSM*, 2012 (70)	NFL ISS *Game injuries only* Grass and FieldTurf only	2000-2009	0.16 per team-game → ~3.4 per 1,000 AEs	Turf: IDR 1.03 (0.88-1.21)
ACL sprain	Hershman et al, *AJSM*, 2012 (70)	NFL ISS *Game injuries only* Grass and FieldTurf only	2000-2009	0.05 per team-game → ~1.0 per 1,000 AEs	Turf: IDR 1.67 (1.30-2.15)
Knee sprains	Hershman et al, *AJSM*, 2012 (70)	NFL ISS *Game injuries only* Grass and FieldTurf only	2000-2009	0.285 per team-game → ~6.2 per 1,000 AEs	Turf: IDR 1.22 (1.09-1.36)

	Knee sprains	Orchard et al, *Med Sci Sports Exercise*, 2003 (48)	NFL ISS *Game injuries only*	1989-1998	5.5 knee sprains per team-season; 3.9 "significant" (>7d lost) knee sprains; 3.2 MCL, 0.9 ACLs per team-season	<u>Turf:</u> rates ~20% lower on grass vs. AstroTurf <u>Temperature:</u> rates ~20-30% lower for ACLs/sig knee sprains, no difference MCLs in cold temps (<70 vs. >70) on grass; rates ~20-30% lower in cold across the board on AstroTurf <u>Precipitation:</u> no big differences wet vs. dry overall
<u>Ankle:</u> Injury reports – 1.9 per 1,000 AEs	Ankle sprain	Hershman et al, *AJSM*, 2012 (70)	NFL ISS *Game injuries only* Grass and FieldTurf only	2000-2009	0.28 per team-game → ~6.0 per 1,000 AEs 0.12 inversion, 0.14 eversion per team-game	<u>Turf:</u> IDR 1.31 (1.12-1.54) for eversion sprains, 1.08 (0.91-1.29) for inversion
Single team – 1.7 per 1,000 AEs (sprains)	Ankle sprains	Orchard et al, *Med Sci Sports Exercise*, 2003 (48)	NFL ISS *Game injuries only*	1989-1998	5.1 knee sprains per team-season; 2.6 "significant" (>7d lost) ankle sprains; 2.1 inversion, 2.4 eversion per team-season	<u>Turf:</u> rates ~20-30% lower on grass vs. AstroTurf, and worse in domes <u>Temperature:</u> fewer inversions, significant sprains in cold games on turf but not grass <u>Precipitation:</u> rates ~20-25% lower for wet vs. dry games, mostly in cold weather, on grass
<u>Foot:</u> Injury reports – 0.6 per 1,000 AEs	Jones fracture	Low et al, *J Surg Orthop Adv*, 2004 (71)	NFL ISS	1996-2001	17 injuries overall in 6 seasons	
	Lisfranc injuries	McHale et al, *AJSM*, 2016 (72)	Injury reports/game summaries/player profiles	2000-2010	33 injuries overall in 11 seasons	<u>Position:</u> even offense-defense split

Single team – 0.8 per 1,000 AEs (sprains)						
Achilles: Injury reports – 0.1 per 1,000 AEs Single team – 0.6 per 1,000 AEs (strains)	Achilles ruptures	Krill et al, *Phys Sportsmed*, 2017 (73)	Public websites, newspapers; regular season through post-season	2009-2016	44 injuries overall in 8 seasons	Position: 72.7% to defensive players Time of Season: 72.7% in first 8 games of regular season Turf: 1.00 per team-game on grass vs. 1.08 on turf
	Achilles ruptures	Parekh et al, *Foot Ankle Spec*, 2009 (74)	Injury reports/game summaries/player profiles	1997-2002	31 injuries overall in 6 seasons, 29 players 0.015% per player per game → 0.15 per 1,000 AEs in games	Games vs. Practices: 25/31 (81%) in games Time of Game: 70% in first half Position: most common in DTs (vs. DE, OL, DB, LB, etc.) Time of Season: even spread Turf: no differences reported Weather: no differences reported, but data not clear
Kidney: Unavailable	Kidney	Brophy et al, *AJSM*, 2008 (75)	NFL ISS	1986-2004	52 cases → 2.7 per season Overall 0.012 per 1,000 AEs Games 0.055 per 1,000 AEs Practices 0.0005 per 1,000 AEs	49/52 contact-related 42 contusions, 6 lacerations Position: RBs, WRs more common
Hand/Thumb/Finger: Injury reports – 0.54 per 1,000 AEs	Hand, Thumb, and Finger	Mall et al, *AJSM*, 2008 (55)	NFL ISS; pre-season through post-season	1996-2005	1,385 (307/414/664) hand/thumb/finger injuries	Most common injuries: metacarpal fx (241), finger dislocation (232), finger fx

Single team – N/A					0.13/0.18/0.29 per 1,000 AEs → 0.60 overall	(196), thumb fx (135), thumb UCL (60) 53% occur from blocking or tackling >90% from contact Game vs. Practice: only 62% in games (74% thumb, 54% fingers); 2.63/0.26 per 1,000 AEs in games/practices
Elbow: Injury reports – 0.33 per 1,000 AEs Single team – 0.24 per 1,000 AEs (elbow sprains)	Elbow	Carlisle et al, *AJSM*, 2008 (54)	NFL ISS; pre-season through post-season	1996-2005	494 injuries → 0.21 per 1,000 AEs 179 were sprains, 56 bruises, 44 dislocations and subluxations	>95% contact-related Game vs. Practice: 69% in games. Of elbow/forearm/wrist, 1.93/0.11 per 1,000 AEs in games/practices Position: most common in OL/DL
	UCL injury	Dodson et al, *J Shoulder Elbow Surg*, 2010 (42)	NFL ISS; training camp through post-season *QBs only*	1994-2008	10 injuries → < 1 per year	All on throwing arm 7/10 from being tackled
	Acute elbow injuries	Kenter et al, *J Shoulder Elbow Surg*, 2000 (76)	NFL ISS	1991-1996	91 injuries overall; sprains most common, followed by dislocation / subluxation	67% in games
Forearm: Injury reports – 0.04 per 1,000 AEs Single team – N/A	Forearm	Carlisle et al, *AJSM*, 2008 (54)	NFL ISS; pre-season through post-season	1996-2005	108 injuries → 0.05 per 1,000 AEs 84 fx	>95% contact-related Game vs. Practice: 77% in games. Of elbow/forearm/wrist, 1.93/0.11 per 1,000 AEs in games/practices

						Position: most common among DBs
Wrist: Injury reports – 0.21 per 1,000 AEs Single team – N/A	Wrist	Carlisle et al, *AJSM*, 2008 (54)	NFL ISS; pre-season through post-season	1996-2005	257 injuries → 0.11 per 1,000 AEs 160 sprains, 43 fx, 23 dislocations and subluxations	>95% contact-related Game vs. Practice: 81% in games. Of elbow/forearm/wrist, 1.93/0.11 per 1,000 AEs in games/practices Position: surprisingly even across positions except QB, so positions RBs probably at highest risk
Shoulder: Injury reports – 1.3 per 1,000 AEs Single team – 1.2 per 1,000 AEs (shoulder sprains)	Shoulder	Chambers et al, *AJSM*, 2016 (49)	NFL ISS; pre-season through post-season	2000-2014	1,524 overall in 15 seasons 1,231 in regular season → 0.5 per 1,000 AEs 1,106/125 → 3.1/0.06 per 1,000 AEs in games/practices	856 (41.3% sprains), 453 (21.9%) strains Games vs. Practices: 89.8% of regular season injuries in games vs. practices (73.5% if include pre- and post-season)
	AC Joint Injuries (distal clavicle contusion, sprains, separations, inflammation)	Lynch et al, *AJSM*, 2013 (47)	NFL ISS; pre-season through post-season	2000-2011	2,486 shoulder injuries (8.2% of total); 29.2% of those (727) AC joint → 2.61 per 1,000 AEs 89% AC sprains; of known type, 64/24/12% type I/II/III 30,304 all-type injuries	Position: ST *highest* rate (7.6 per 1,000 player-games), then QBs (7.4); WR (4.1); OL/DL lowest (1.8) Turf: IDR for turf 0.79 (0.67-0.92), so grass higher Games vs. Practices: 81.5% of injuries in games Play Type: no difference between running/passing plays

	Superior Labrum Anterior-Posterior (SLAP) tears	Chambers et al, *AJSM*, 2016 (49)	NFL ISS; pre-season through post-season	2000-2014	65 overall in 15 seasons 37 in regular season → 0.016 per 1,000 AEs 0.01/0.001 per 1,000 AEs in games/practices	88.6% during contact (75% with other player) Games vs. Practices: 35/37 (95%) in games in regular season; 44/65 (67.7%) overall Position: OL seems to be at higher risk (18 tears vs. 9 each for DL and DB), with WRs (4 tears) and RBs (1 tear) at lower risks
	Shoulder	Kelly et al, *AJSM*, 2004 (46)	NFL ISS; pre-season through post-season Only injuries with >= 2 days limited included *QBs only*	1980-2001	17.9 per 1,000 AEs in games	82.3% contact injuries, ~70% while being tackled Most common were deltoid contusions, rotator cuff, dislocation/separation
	Middle Third Clavicle Fractures	Morgan et al, *AJSM*, 2010 (77)	NFL ISS; pre-season through post-season	2003-2007	19 injuries overall in 5 seasons	Games vs. Practices: 12/19 occurred in games; 5/7 practice injuries in preseason
Hamstring: Injury reports – 1.3 per 1,000 AEs Single team – 2.0 per 1,000 AEs	Hamstring strain	Elliott et al, *AJSM*, 2011 (78)	NFL ISS; pre-season through post-season Only injuries with >= 2 days limited included	1989-1998	1,716 injuries 0.77 per 1,000 AEs overall; 2.7/0.47 in games/practices	81.5% noncontact (88% practice, 73% game), mainly sprinting; this varied by position, with contact more common for linemen Games vs. Practices: majority (52.7%) occur in *practices* Time of Season: most practice injuries occur in preseason (0.82 vs. 0.18 per 1,000 AEs)

						<u>Position:</u> rates highest for WR, DB; lowest for QB/TE/OL <u>Play Type:</u> 0.79/1.55/3.27 for runs/passes/STs; most ST injuries on kicking vs. receiving team
<u>Hip:</u> Injury reports – 0.5 per 1,000 AEs Single team – 0.7 per 1,000 AEs	"Hip or groin injuries"	Feeley et al, *AJSM*, 2008 (79)	NFL ISS; pre-season through post-season	1997-2006	738 injuries overall in 10 seasons, of which 268 strains and 237 contusions	Vast majority are contact injuries <u>Position:</u> injuries most severe for OL/DL
<u>Triceps:</u> Injury reports – 0.02 per 1,000 AEs	Triceps tendon ruptures	Finstein et al, *Ortho J Sports Med*, 2015 (43)	NFL ISS; surgical injuries only	2000-2009	37 injuries overall in 10 seasons	<u>Games vs. Practices:</u> 68% during games <u>Position:</u> 31/37 (84%) were linemen, even split OL/DL
Single team –N/A	Triceps tendon ruptures	Mair et al, *AJSM*, 2004 (80)	NFL ISS	1991-1996	21 injuries overall in 6 seasons; 19 players 11 total, 10 partial ruptures	"Most" occurred while blocking with elbows extended; 4/19 from blow or fall <u>Position:</u> 15/19 were linemen
<u>Quadriceps:</u> Injury reports – 0.7 per 1,000 AEs Single team – 0.7 per 1,000 AEs	Rectus femoris avulsion	Gamradt et al, *AJSM*, 2009 (81)	NFL ISS	1986-2006	11 injuries overall in 20 seasons	<u>Games vs. Practices:</u> 7/11 in games

<u>Face:</u> Injury reports – 0.1 per 1,000 AEs Single team – N/A	Eye (orbital fractures)	Williams et al, *AJSM*, 2001 (82)	NFL ISS; pre-season through post-season	1980-1997	41 injuries overall in 18 seasons; 29 orbital fx, 12 zygomatic arch fx	<u>Mechanism:</u> all contact, 14/19 w known mechanism suffered an eye poke and remainder blunt trauma <u>Position:</u> OLs at highest risk
<u>Back:</u> Injury reports – 0.7 per 1,000 AEs Single team – 1.2 per 1,000 AEs (lumbar strain)	Disc herniations	Gray et al, *Spine*, 2013 (83)	NFL ISS	2000-2012	275 injuries overall in 13 seasons ; 1.1 per 10,000 AEs 74% lumbar, mostly lower 13% of 1,984 overall spine injuries; 28% of lumbar and 5-6% of other spine injuries Nerve injuries most common in cervical, muscle in thoracic/lumbar	17% non-contact, 25% unknown; among contact injuries, a majority blocking and tackling rather than being tackled/blocked Position breakdown given, but only counts rather than rates
<u>Neck:</u> Injury reports – 0.4 per 1,000 AEs (incl. stingers)	Lumbar disc herniation	Hsu WK, *Spine*, 2010 (84)	Injury reports / newspapers / press releases	1979-2008	137 injuries overall in 30 seasons	
Single team – 0.7 per 1,000 AEs (cervical strain)	Lumbar disc herniation with discectomy	Savage et al, *Clin J Sports Med*, 2010 (84)	Injury reports / newspapers / press releases *QB/WR/TE/RB only*	1986-2008	23 injuries overall in 23 seasons	
<u>Ribs:</u>	Cervical disc herniation	Hsu WK, *Spine*, 2011 (85)	Injury reports / newspapers / press releases	1979-2008	99 injuries overall in 30 seasons	
Injury reports – 0.3 per 1,000 AEs Single team – N/A	Spine and axial skeleton (includes ribs, pelvis)	Mall et al, *AJSM*, 2012 (86)	NFL ISS; pre-season through post-season	2000-2011	0.93/3.55/0.41 per 1,000 AEs overall/games/practices 44.7% cervical, 30.9% lumbar, 10%	>90% of cervical injuries from contact; ~80% for lumbar, pelvis/sacrum/coccyx

					sacrum/coccyx/pelvis, 9% unknown, 4% thoracic/ribs, 0.6% spinal cord 24.9% strains, 21.4% nerve injuries (45.9% of cervical), 12% sprain, 11% disc 31,338 all-type injuries	Games vs. Practices: ~80% in games; game rate 3.55 per 1,000 AEs vs. 0.41 in practices Mechanism: Cervical injuries 32.5% blocking, 24% tackling; lumbar 20.8% non-contact, 18.6% blocking; sacrum/coccyx/pelvis similar to lumbar
Concussions:	Concussion	Deubert et al, Harvard report, 2017 (41)	NFL ISS; pre-season through regular season	2009-2016	1,951 concussions overall in 8 seasons → 1.1 per 1,000 AEs	
Injury reports – 1.1 per 1,000 AEs (head/concussion) Single team – 0.5 per 1,000 AEs	Concussion	Teramoto et al, *Ortho J Sports Med*, 2015 (87)	*Frontline* Concussion Watch blog; pre-season through regular season	2012-2014	437 concussions overall in 3 seasons	Style of Play: more offensive concussions in West Coast Offense (3 per team-season) than Air Coryell (1.6) or other (2.2); no defensive difference in 3-4 vs. 4-3 (2.0 vs. 2.2)

It is important to note the concussions section of the above chart is substantially abbreviated; there are many studies looking at NFL concussion incidence, but we restricted our analysis to the most recent high-quality study available (Deubert et al) and one unique study investigating differences by offensive and defensive schemes (Teramoto et al).

E. Football Injury Surveillance Systems

There are injury surveillance systems in high school, college, and professional football. The High School – Reporting Information Online (RIO) (88) takes detailed injury reports from ATCs using a sample of 100 high schools nationwide and weights injury counts to get national estimates. These data have been used in several studies (7, 19, 20).

At the college level similar data are provided by the NCAA Injury Surveillance System (NCAA ISS, which extends beyond football and has been operating since 1982) (32). Data are entered from selected institutions by ATCs. Participation in the NCAA ISS is voluntary, and so the data are not nationally-representative. No individually-identifiable information – only an institutional identifier – is included in the forms sent to the NCAA ISS, so injuries cannot be tracked longitudinally (32).

The NCAA ISS has been used in a large number of studies, all of which share a few useful commonalities. In all studies using the ISS an athletic-exposure (AE) is defined as 1 student athlete participating in a practice or competition in which they were exposed to injury, and an "injury" was defined as an event that "(1) occurred as a result of participation in an organized intercollegiate practice or competition *and* (2) required medical attention by a team certified athletic trainer or physician *and* (3) resulted in restriction of the student-athlete's participation or performance for 1 or more calendar days beyond the day of injury" (32). Time loss and return to play (RTP) estimates are based off the time it took the player to return to a level allowing competition participation (32).

The NFL has its own Injury Surveillance System (NFL ISS) that has been around since 1980 but has improved and expanded substantially in recent years (40, 41). The system was first converted into electronic format in 2011 as a pilot with 5 teams and expanded to all 32 teams in 2012 (41). In 2013, the system expanded to become an "electronic medical record" (EMR) in an 8-team pilot that expanded to all 32 teams in 2014, however the advantages of the EMR in terms of data collection or integration remain unclear (41). Like the high school and college systems, detailed information about each injury is input by the teams' athletic trainers. The definition of an "injury" has also varied in recent years, expanding in 2015 from injuries that resulted in time lost from practices or games (or were a fracture, concussion, dental injury, or anything requiring intravenous fluids or special equipment such as a brace) to include non-time-loss injuries, as well

(41). Unlike systems at lower levels, the NFL ISS also tracks information on all medical care, including surgeries, that players receive for these injuries (41).

These surveillance systems represent the most broad-based source of overall injury counts and rates at each level of football. They also tend to contain information about injury circumstances that is extremely useful for descriptive, associative, and predictive epidemiology. Although sometimes, but not always, more specific sources – such as single teams – may offer more details on individual injuries. While obtaining RIO and NCAA ISS data is relatively easy, the NFL ISS is more restricted and its research uses are usually limited to narrow NFL-approved projects. Most studies using NFL ISS data are focused on specific types of injuries such as ulnar collateral ligament (UCL) injuries or triceps tendon tears (42-48). Broad-based, general descriptive injury epidemiology and surveillance results from the NFL ISS are lacking.

IV. Football Injuries – Analytic Epidemiology and Factors Influencing/Predicting Injuries

The purpose of this section of the review is to identify key potential predictors of injury risk to consider in our model for specific aim 3. A review of the literature relevant for this goal follows:

A. Age

There is broad consensus both in the NFL and other sports that older athletes are at higher risk for various injuries (89-93). However, little research has been done in this field with NFL players specifically (93). In American football more generally, studies of youth have shown that older age is associated with greater injury risk (18, 22, 24), but at this level the effects of age may be explained by differences in level of competition (22), athlete size, and speed of play. This is consistent with findings that age is only associated with increases in game, not practice, injury rates (22), and that after controlling for experience, race, BMI, grip strength, injury history, and coaching experience, age was independently associated only with fractures (24).

Although studies of youth football injuries are probably not applicable to NFL players, relevant data may be found in other professional sports. In a study of all regular season matches from 1992-99 using the Australian Football League's (AFL) own ISS, Orchard et al investigated a number of risk factors for hamstring, quadriceps, or calf muscle strains (92). Using logistic regression on 83,503 player-matches (1,607 individual players), and adjusting for height, weight, BMI, previous relevant injury, competition level, date and time of match, and weather conditions, older age (dichotomized to > 23 years and <= 23 years) was associated with 1.34 times higher odds of a hamstring strain (95% CI: 1.14-1.57) and 2.59 times higher odds of a calf strain (95% CI: 1.75-3.83) (92). Older age was not significantly associated with quadriceps injuries, but actual model estimates were not provided. A major limitation of the study was the use of a binary age variable, which does not allow conclusions about the longitudinal effects of aging on player injury risk.

One further consideration is that the effects of aging on injury risk can be difficult to assess in an open cohort such as the NFL, where survivor bias can influence the results because: 1.) only heartier players with a lower baseline injury risk survive to play in their later years in the NFL, and 2.) positions that get hit and injured less, and thus have longer careers (e.g. QBs and kickers), are disproportionately represented in older age groups. One method to control for this and properly estimate the effect of aging in subsets of players who play to certain ages would be to use closed cohorts of players who survive to a certain age in the NFL (e.g. only those players who played to 30 years or later) and then look at injury risks and rates in those cohorts as they age up to the minimum level specified for the cohort (e.g. 30 years).

In summary, the effect of aging on injury risk in the NFL is widely-accepted but has not yet been rigorously analyzed in the academic literature.

B. Prior Injuries

With the possible exception of age, prior injury history is arguably the most-accepted risk factor for injuries in the NFL, though once again analyses specific to the NFL are lacking (93, 94). A review of some of the key studies in football follows:

Table 1.3. Review of Studies Investigating Prior Injuries as Risk Factor for Football Injuries.

Study	Population	Outcome(s)	Exposure(s) (Prior Injury Definitions)	Analysis Design and Associations	Other Notes
Knowles et al 2009 (22)	North Carolina High School Athletic Injury Study (prospective cohort), 1996-1999 N=3,323 high school football players, 3,948 player-seasons	Injury rate (per 1,000 AEs)	"Prior injury in football included the following injuries: knee, ankle, shoulder, wrist, elbow, fracture, concussion, and heat-related injury"	IRR 1.9 (95% CI: 1.5-2.4), adjusting for age, BMI, playing experience, grade, coach experience, competition level, multi-sport participation Held for both games and practices IRRs were especially high for same-site prior injuries for knee (2.7), ankle (5.2), and shoulder (10.2)	Unsure how you can adjust for both grade and age, since the two will be practically collinear in high school
Turbeville et al 2003, middle school (24)	N=646 players from 9 middle schools in Oklahoma City in the 1998-99 seasons	Injury causing player to miss >=1 game or practice, or concussion w/ altered consciousness	Injury in prior season that kept player out for >= 1 game	5% of players had injury the previous year 6/5% of players with/without previous injury history experienced an incident injury (p=0.78)	
Turbeville et al 2003, high school (23)	N=717 players from 8 high schools in Oklahoma City in the 1998-99 seasons	Injury causing player to miss >=1 game or practice, or concussion w/ altered consciousness	Injury in prior season that kept player out for >= 1 game	15% of players had injury the previous year 29/14% of players with/without previous injury history experienced an incident injury (p=0.001) OR 1.83 (95% CI 1.09-3.07) adjusting for age, BMI, position, grip strength, school, coach experience, player experience	
McHugh et al 2007 (95)	N=125 players on two high school varsity football teams from 2003-05 Balance training intervention study; 107 player-seasons and 15,543 AEs preintervention, 175 and 27,778 postintervention	Incident noncontact inversion ankle sprain rate (per 1,000 AEs) as defined by ATCs	"Previous ankle sprain"	2.85 per 1,000 AEs with vs. 0.86 without prior ankle sprain pre-intervention, 1.29 vs. 0.43 post-intervention Holds when stratify over BMI	Think this is the same/similar population as Tyler et al

Tyler et al 2006 (6)	N=152 athletes from 2 schools observed for 1 (N=117), 2 (25), or 3 (10) seasons	Incident noncontact ankle sprain (per 1,000 AEs)	"Previous ankle sprain"	2.65 per 1,000 AEs vs. 0.41 without prior ankle sprain Holds when stratify over BMI	Think this is the same/similar population as McHugh et al
Brophy et al 2008 and 2009 (57, 58)	NFL-caliber college players assessed by New York Giants at 1987-2000 Combines (N=5,047)	Playing >= 1 game in the NFL; Career length (games)	Combine medical grades: no/minor injury with recovery, incomplete recovery/likely recurrence, reject	Playing >= 1 game: 80%/39%/8% with increasing category of exposure Mean career length: ~54/~20/3 games with increasing category of exposure Results varied by position	Did not predict injury risk, just likelihood of playing and number of games. Differences shrank over time as treatment / recovery techniques improve
Brophy et al 2011	NFL-caliber college players assessed by New York Giants at 1987-2000 Combines who went on to play >= 1 game (N=2,845) 42 with history of shoulder stabilization at Combine pair-matched by position, draft year and round to players without other major injuries or surgeries	Career length (years, games, games started)	History of shoulder stabilization at NFL combine	Games: mean 77 vs. 56 but median 36 vs. 36 for controls/cases (p=0.03); Kaplan-Meier (KM) curves show significantly better survival in controls (p=0.04) Games started: 45 vs. 29 mean, 48 vs. 7 median (p=0.06) Years: 6.9 vs. 5.2 mean, 6.5 vs. 4.0 median (p=0.01) Significant for linemen + linebackers (N=20 cases), n.s. for others (N=22)	Did not predict injury risk, just career length; however, may the two may be correlated because injuries can shorten careers
Schroeder et al 2014 (96)	NFL-caliber college players assessed by one team at 2003-11 Combines (N=2,965) N=143 with previous cervical spine injury, 93 of whom were drafted and matched to 134 controls on position and draft age/year/round	Career length (years, games, games started)	"…Previous cervical spine injury [was] determined on the basis of athlete interviews, injury history, treating spine surgeon notes, operative reports (where applicable), and imaging reports"	Games: mean 55.6 vs. 42.1 for controls/cases (p=0.01); Games started: 30.9 vs. 22.8 mean (p=0.08) Years: 4.6 vs. 3.7 mean (p=0.01)	Did not predict injury risk, just career length; however, may the two may be correlated because injuries can shorten careers
Guskiewicz et al 2003 (97)	2,509 NCAA football players from 25 schools in	Incident concussion rate (per 1,000 AEs)	Number of previous concussions (self-reported); unclear if only from before study began	Rate ratios: 1.4 (95% CI: 1.0-2.1), 2.8 (1.6-4.8), 3.4 (1.8-6.5) for players reporting 0, 1, 2, >=3 prior concussions (adjusting for BMI,	

	prospective cohort study, 1999-2001			academic year, years of experience, Division, position)
Williams et al 2017 (98)	365 NCAA football players from two Division I programs, 2007-2011	Incident and subsequent injury rates per 10,000 AEs	Incident injury during this study period	Rate ratios: 1.4 (95% CI 1.1-1.9) for subsequent vs. initial injuries; rates continued rising until 4th injury Head/neck/face injuries especially high (IDR 2.0 (1.1-3.5))

As shown in Table 4.1, the strongest evidence for prior injuries as a predictor of any future injuries comes from multiple studies of high school football players (22, 23) in North Carolina and Oklahoma; the Oklahoma association did not hold in middle school players (24). There is also evidence from high school players that previous injuries are associated with noncontact ankle sprain injury rates (6, 95), and there are similar data from college football for concussions and all injuries combined (97, 98). At the NFL level, the relationship between previous injuries and future injury risk hasn't been explicitly studied for all injuries; this represents an important knowledge gap that Specific Aim 3 will address. There is some evidence from single-team NFL Combine records that players with substantial college injury histories are less likely to play in the NFL and, if they do make it, to have shorter careers (57, 58, 96, 99); while these shorter careers could be evidence of injury issues, the association with injury risk itself was never assessed. There could also be selection bias from a sort of self-fulfilling prophecy where a substantial injury history prevents a player from being given a chance to succeed in the NFL.

C. Anthropometrics

1. *Athlete Size (BMI)*

Player size, most often quantified as body mass index (BMI), is a third possible predictor of NFL injuries. It is hypothesized mechanism of association is typically that impact forces are magnified for larger players, increasing injury risk (93). The association between athlete size and injuries has been heavily studied across many sports, yet the relationship remains unclear (93). The data for the association between BMI and injury risk in the NFL are, once again, limited. Data from college football might be applicable, especially if the schools are in Division I; studies have shown that incoming Division I freshmen are comparable to NFL players in various size measures (100). Data on the player size-injury association is limited in this population as well, however. While substantial research on this issue is available in youth football (high school especially), these data may not be relevant for the NFL because of the vast size differences between these populations; they are presented in the current review for completeness.

Table 1.4. Football studies investigating the association between BMI and injuries.

Study	Population	Outcome(s)	Exposure(s) (Body size measures)	Analysis Design and Associations	Other Notes
Gomez et al 1998 (101)	215 high school **linemen** at 10 public high schools in San Antonio with willing athletic trainers Prospective cohort during 2-week pre- and 10-week regular season	Injury rates per 1,000 hrs playing time Injuries as defined and reported by ATCs Playing time from population averages from ATCs (1.2 hrs/practice, 6 min per quarter in game)	BMI, m/kg^2 Skinfold (millimeters) at chest, abdomen, thigh; used to calculate "body density", % body fat, and lean body mass (weight x (1-% body fat))	Crude: substantial increases in injury risk with rising body weight, BMI, and lean body mass After adjusting for age, playing level, and other body measures, BMI retained a significant association (but strength not given)	Most common injuries were ankle sprains (22.1%) and MCL sprains (11.6%)
Kaplan et al 1995 (102)	98 high school players from two public high schools in Miami	Injury rates (per player-season) Injuries as defined and reported by ATCs Practice times were given (2-4h, ~80 practices) but not used	BMI, m/kg^2 Skinfold (millimeters) at triceps, subscapula	Crude: significantly higher risks for BMIs >95th %ile and across tertiles of BMI; similar results for body weight >90kg and skinfold tertiles In multiple linear regression, only body weight significant, but coefficients not reported and unclear what was adjusted for	A lot of missing and confusing information; study may not be particularly rigorous Did not adjust for position?
Knowles et al 2009 (22)	North Carolina High School Athletic Injury Study (prospective cohort), 1996-1999 N=3,323 high school football players, 3,948 player-seasons	Injury rate (per 1,000 AEs) Injury defined as the result of participating in a high school sport that limited participation beyond day of injury or required medical attention AEs calculated by summing games and practices x number players	BMI-for-age, categorized into Underweight, Normal, Risk of overweight, and Overweight	After adjusting for age, experience, coach experience, competition level, and prior injury, IRR for overweight vs. normal was significantly and substantially elevated (1.9, 95% CI 1.2-2.9); no other substantial associations Did *not* adjust for position	Unsure how you can adjust for both grade and age, since the two will be practically collinear in high school Did not seem to adjust for position

Malina et al 2006 (28)	678 youth football players (9-14 years old), 33 teams, 2 Michigan communities, 2000-01 seasons	Injury rates per 1,000 AEs and risks per 100 athletes Injuries as reported by ATCs according to NATA definition	BMI, m/kg^2	In 6th grade and above, no crude or adjusted association between BMI and dichotomous injury status	
McHugh et al 2007 (95)	N=125 players on two high school varsity football teams from 2003-05 Balance training intervention study; 107 player-seasons and 15,543 AEs preintervention, 175 and 27,778 postintervention	Incident noncontact inversion ankle sprain rate (per 1,000 AEs) as defined by ATCs	BMI-for-age, m/kg^2,categorized into Underweight (<=5th %ile), Normal (>5th to <85th %ile), Risk of overweight (85th to <95th%ile), and Overweight (>= 95th %ile)	Before a balance intervention that was the main focus of the study, higher BMI was associated with a substantially higher risk of a noncontact ankle sprain among those with a previous ankle sprain, but no other consistent relationships were observed	Think this is the same/similar population as Tyler et al
Prager et al 1989 (103)	598 players in 4 high school football teams in Peoria, IL from 1982-85; 251 total injuries	Dichotomous player injured/not injured	Quetelet index	No correlation in body size between injured and non-injured players	Old paper, was unable to access beyond abstract, many things unknown
Turbeville et al 2003, middle school (24)	N=646 players from 9 middle schools in Oklahoma City in the 1998-99 seasons	Injury causing player to miss >=1 game or practice, or concussion w/ altered consciousness Player categorized as injured or non-injured	BMI, m/kg^2	Crude: no association between BMI and dichotomous injury status (injured 22.9 m/kg^2, non-injured 23.9 m/kg^2) Adjusted: after adjusting for experience, age, grip strength, prior injury, and coach experience, no association between BMI and injury status (but OR not given)	
Turbeville et al 2003, high school (23)	N=717 players from 8 high schools in Oklahoma City in the 1998-99 seasons	Injury causing player to miss >=1 game or practice, or concussion w/ altered consciousness Player categorized as injured or non-injured	BMI, m/kg^2	Crude: median BMI among injured players 27.2 vs. 24.1 among non-injured players (p=0.001) Adjusted: after adjusting for position, injury history, age, and other variables, no longer significant (OR not given)	

Tyler et al 2006 (6)	N=152 athletes from 2 schools observed for 1 (N=117), 2 (25), or 3 (10) seasons	Incident noncontact inversion ankle sprain rate (per 1,000 AEs) as defined by ATCs	BMI-for-age, m/kg^2,categorized into Underweight (<=5th %ile), Normal (>5th to <85th %ile), Risk of overweight (85th to <95th%ile), and Overweight (>= 95th %ile)	Crude: incidence rose from 0.5 to 1.05 to 2.03 injuries per 1,000 AEs for normal, at risk, and overweight players, though 95% CIs overlapped considerably; increased risk was especially pronounced for overweight players with previous ankle sprains No adjusted analyses	Think this is the same/similar population as McHugh et al

Overall the data show a mixed association between player size (BMI) and injury risk. Among the nine studies outlined above, four found substantial crude associations between higher BMI and overall injury risk (22, 23, 101, 102) while another two (from the same population) found associations with inversion ankle sprains, especially for those with a previous ankle sprain (6, 95). The remaining three found no crude association (24, 28, 103). Only two found a significant association after adjusting for other relevant risk factors (22, 101), and only one of these adjusted for position (by looking solely at linemen) (101). Position is extremely important to adjust for, as BMI varies by position (for example, a WR or DB versus a lineman in terms of BMI, abdominal fat, lean mass, or other metrics) (100, 104-106), as does injury risk (7, 17, 22-24, 47, 50, 86, 103, 105, 107-110). It could be, for example, that higher BMI raises a DL's or OL's injury risk, but that is masked by their lack of high-speed collisions relative to WRs, TEs, and DBs. Any association between BMI and injury risk is also likely to vary by position given their substantially different body compositions. Overall, none of these studies has provided conclusive evidence for an association between BMI and injury risk even in youth football; meanwhile, the evidence for college and the NFL is virtually nonexistent (at least in the academic literature).

It should also be noted that BMI, while a very common measure of athlete size and a proxy for impact forces, may not be the best metric to use when studying injury risk – some studies have suggested that abdominal circumference or other abdominal measures may be a better (if less commonly used and harder to measure) predictor (104, 111). Elite athletes are also often outliers in BMI, especially in football: for example, incoming freshmen at a Division I college football program had BMIs that would classify them as overweight or obese, but their body fat percentages were considered within normal range (100). This means that associations discovered in this population should not be generalized outside this group and, at worst, means BMI isn't measuring what we typically think of it measuring in elite athletes (though it still may be useful as a proxy/predictor of injury risk due to increased size and forces on the body).

It may be useful to consider two possible effects of BMI on injury risk: internal and external. "Internal" applies to an individual-level effect associated with the increased force and wear and tear both in his daily life or on the field (for example, the wear and tear on a 290- vs. 350-pound lineman's knees from getting up and out of his stance). "External" refers to a population-level effect stemming from the greater forces encountered in collisions with other players (for example, the difference between being tackled by a 290- versus 350-pound opponent).

Is Player BMI Changing?

One key point to address in this section is whether player size is changing over time. Players getting bigger, faster, and stronger as a contributor to rising injuries over time is a common refrain at the high school, college, and professional levels; here we're focusing on just the bigger aspect, but even here the evidence is somewhat mixed. A simple linear regression analysis of height, weight, and body fat percentage of professional football players from 1942-2011 found statistically significant increases in weight for "mixed offensive backs" (QBs and RBs, 0.362 kg/year) and "mixed linemen" (0.427 kg/year); nearly all other regression coefficients were positive but not statistically significant (112). The same study found college athletes also grew substantially over time (112). A study of 1,712 college athletes at the 1999-2001 and 2008-10 NFL combines who were drafted the same year found significant differences in weight between the two groups, but the differences varied by position (DBs, defensive tackles, WRs, and QBs got heavier, while centers, offensive tackles, and TEs got lighter) (113). A comparison of Division I player sizes reported by strength and conditioning coaches in 2000 with a prior study from 1987 found that weights had risen about 5-9 kg, but again the differences varied substantially by position (114). These results need to be viewed with caution because the data for the 2000 estimates were limited to 12 returned surveys; which represents approximately 10% of survey invitations. Another study of Division I college teams found that the average height, weight, and BMI estimates among football, basketball, baseball, and tennis players had all increased from the 1950s to 2000s, with the biggest gains in football, especially for offensive and defensive linemen (115). On the other hand, a study that compared the 2011 New York Giants to 3 other studies of NFL players from 1998-2009 found no significant differences in the sizes of players over this 13-year period, though the sample size was small especially after stratifying by position (116). Overall, the evidence does suggest that players are getting bigger, with some additional evidence for faster and stronger coming from comparisons of NFL Combine performance measures over time showing improvements to measures such as 40-yard dash times and repetitions of the bench press (113, 114).

2. *Other Anthropometric Measures*

A number of physical attributes besides athlete size have been linked to injury risk. For the lower extremities, a 2003 review investigated aerobic fitness, joint laxity, muscle tightness, range of motion in the knee and ankle, limb dominance, muscle strength, muscle imbalance, reaction time, limb girth, postural ability, anatomical alignment, and foot morphology, though many of these associations are unclear or have conflicting results in the literature (93). A more updated review of injury risk screening tools found that joint laxity, lower hamstring-to-quadriceps ratio, decreased hip range of motion, knee hyperextension, differences in knee abduction movement across legs, hip adduction-to-abduction strength ratio, plantar flexor strength, and postural sway were all associated with various kinds of leg injuries (90). A larger alpha angle in the hip joint, indicating more severe cam-type femoroacetabular impingement (FAI), was correlated with hip and groin pain among players at the NFL Combine, though this was not further correlated with actual injury risk. On the negative side, a 2013 study found isokinetic concentric quadriceps and hamstring strength measures conducted at the NFL Combine were not significantly associated with the risk of a hamstring injury in the players' rookie years (117). Unfortunately, the data we will be using for this project will not include many of these anthropometric measures, so we will stop this section of the review here.

D. Games vs. Practices

1. Games vs. Practices Overall

Multiple studies have provided conclusive data that injury rates for football games/competitions are much higher than those for practices. This isn't surprising given the increased violence, contact, and collisions in games. Roughly 10.8% (2005-06 school year) to 12.4% (2012-13 school year) of injuries in high school football came in non-contact situations (7, 20); estimates of this figure for college football ranged from 17.9% from 1988-89 to 2003-04 (34) to 27.8% in 2005-06 (7). A summary of some of the largest, most broadly representative studies providing data on this topic are summarized below. Several other studies have calculated similar rate ratios, but because they fell in these ranges and were from more restricted populations (e.g. single school or city), we have excluded them from the table below.

Table 1.5. Estimates of game vs. practice injury rate ratios.

Competition Level	Incidence Rate Ratio (IRR), Games/Competitions vs. Practices, All Injuries
High School (7, 19, 20, 22)	4.70, 4.76, 6.02, 9.24
College (7, 33-35)	6.82, 6.97, 9.45
NFL (3, 41, 49)	5.09 (preseason), 26.9 (regular season), 34.5 (regular season)

Overall we see that injury rates in games are roughly 5-9x those of practices except in the NFL regular season where the ratio jumps to 25-35x! In high school and college the estimates are remarkably consistent, with most clustering around a 5-7x higher rate. The one estimate we have for the NFL preseason is also in this range, but once we get into the regular season the ratios spike. Of note, our NFL regular season numbers required estimation of AEs using a new method developed for this dissertation that may not be comparable with the other studies that directly reported game and practice rates. Whether the true value in the NFL is 5x, 9x, or 30x may not be as important as simply recognizing that game injury rates are greatly elevated over those for practices.

Of note, there is evidence that these IRRs vary substantially by type of injury – for example, in college football shoulder injuries have a 5-6x higher game-vs.-practice IRR than knee injuries (34). However, a more thorough investigation of this issue is beyond the scope of this project.

One limitation worth noting is the data for our dissertation do not allow us to differentiate between game and practice rates. This is a product of needing to know *exactly* when an injury occurred rather than the week in order to get these estimates, which either requires cross-referencing public injury reports with play-by-play data to identify major injuries (118) or accessing the NFL ISS (40), which the League holds close to the vest. Public injury report data only tells you the week an injury occurred, not whether it occurred in a game or practice. These details may be gleaned on a case-by-case basis from media reports, but this is a very time-intensive data collection method.

2. Practice Intensity

Just as games have higher injury rates than practices overall, it's possible that more "intense" (i.e. contact-heavy) practices have higher injury rates than less "intense" ones. Unfortunately, data on the relative injury rates for different types of practices is harder to get than that for games vs. practices because, put simply, you need even *more* detailed information about when the injury occurred (i.e. the type of practice).

The most detailed study we could locate on this issue is Albright et al's 2004 analysis of the Big 10 Conference's ISS for college football injuries (4). This study has been discussed and critiqued in detail both above and in the next section, so here we'll simply focus on the numbers. The researchers stratified practice intensity into contact ("routine weekday practice and may include periods of full-contact scrimmage", but has restrictions such as no "piling on"), limited contact ("contact but at a lesser degree of intensity and/or duration than is normal for the team" including no contact), and scrimmages (game-like conditions); they also used more detailed categories for the second time period they investigated prospectively (1998-99 through 2000-01 seasons) (4). These more detailed categories were laid out in new conference practice rules before the 1998-99 season. A modified summary of their results is below:

Table 1.6. Estimates of injury rates by practice time, Big 10 Conference, 1992-1996 and 1998-2000 seasons.

Time Period	Season	Practice Type	Injury Rate per 1,000 AEs
1992-93 to 1996-97	Fall	Limited contact	4.2
		Contact	13.7
		Scrimmage	3.5
	Spring	Limited contact	10.4
		Contact	18.8
		Scrimmage	8.4
1998-99 to 2000-01	Fall	Limited contact	2.7
		Contact	5.3
		Scrimmage	16.2
	Spring	Limited contact	12.3
		Contact	17.5
		Scrimmage	22.3
1998-99 to 2000-01	Spring	Helmets only	5.8
		Full pads/no tackle	20.8
		Full pads/tackling	15.3
		Spring game	14.3
		Other scrimmage	26.5

These results are a bit confusing and internally contradictory. In the later period of the study, injury rates showed a distinct dose-response relationship with practice intensity in both fall and spring, with "limited contact" practices the lowest and game-like "scrimmages" the highest. In the early period, "contact" practices still had higher injury rates than "limited contact" practices, but scrimmages were lower than both. In the more detailed analysis of spring practices, the lightest-intensity practices ("helmets only") had the lowest injury rates and scrimmages the highest, but within full-padded practices those with more contact ("tackling") had *lower* injury rates than those without tackling (and the 95% confidence intervals did not overlap). Generally, these data do seem to show that more intense practices have higher injury rates, but we are at a loss to explain the low injury rates for scrimmages in the early period or the full padded tackling inversion in the second period. Our best guess is that this is due to some differences in how practices were classified between the two periods, but the article does not provide explicit details to back up that hypothesis (4). Another study of a single college football team over 4 seasons found significant correlations between injuries and exposure to full-contact practices and games or scrimmages in both the pre-season and regular season (119).

Considering this evidence together with the fact that, as discussed in the previous section, the vast majority of football injuries come from some form of contact, we think there is at least moderate evidence for higher injury rates in more intense and contact-driven practices. Unfortunately, we could not find any data that addressed this question specifically for NFL players, though we think the data above from Division I college football should generalize pretty well to that population. Unfortunately, we will not be able to address this question in our analyses, either, due to insufficient information on the timing of injuries and breakdown of practices.

3. Seasonal Variation (Spring vs. Fall Practices)

Multiple analyses from the NCAA ISS and other sources have shown that, in college, spring practices have 2-3x higher injury rates than fall practices (4, 34, 35). Many explanations have been put forth for this difference, but one major one has gone basically untested: survivor bias. Spring practices are shorter, so while injury-prone players have a chance to get hurt early in the course of both fall and spring practices, fall has more practices later with heartier players to reduce its overall injury rate.

One of the most thorough treatments of this topic appears in the 2004 issue of *AJSM*, where Albright et al used data from the Big 10 Conference's ISS (B10 ISS) (4) to analyze the difference in injury rates between fall and spring practices and assess whether new NCAA spring practice restrictions issued before the 1998 season reduced that disparity. They conducted two separate analyses: the first used data from the 1992-93 through 1996-97 academic years, and the second the 1998-99 to 2000-01 academic years; 44/55 (80%) team-seasons were included in the first period and 33/33 (100%) in the second. This analysis found injury rates of 19.8 per 1,000 AEs in spring practices and 10.6 per 1,000 AEs for fall practices (4); these figures are, notably, about twice as high as the same estimates from the NCAA ISS (33), though the B10 ISS only includes Division I (higher-level) schools with stronger competition and better players, which could explain at least part of this difference. This corresponds to an incidence density ratio (IDR) of 1.9 (95% CI 1.7-2.0) for spring vs. fall practices. They also calculate an "etiologic fraction" (EF) that is really an "excess risk" (ER, or the incidence density difference (IDD) where spring is the exposed divided by the rate in the spring) translated to a "number of excess cases/injuries" (ER x # of spring injuries): 469 additional injuries in the spring were "attributed" to an amorphous "spring risk factor" ([19.8-10.6]/19.8 x 1,007 spring injuries) (4). They provide similar calculations for several specific injury types, with IDRs ranging from 2.0 (1.6-3.2) for acromioclavicular (AC) joint sprains in the shoulder to 3.0 (2.4-7.0) for anterior cruciate ligament (ACL) injuries in the knee. The researchers then stratified practice intensity into contact ("routine weekday practice and may include periods of full-contact scrimmage", but has restrictions such as no "piling on"), limited contact ("contact but at a lesser degree of intensity and/or duration than is normal for the team" including no contact), and scrimmages (game-like conditions) (4). They found IDRs for spring vs. fall of 1.4 (1.2-2.5), 2.5 (2.1-2.8), and 2.4 (2.1-2.8), respectively – all elevated, but with the mid-level "contact" practices demonstrating the lowest IDR. In their second analysis, the group used similar data from 1998-99 through 2000-01, but with two added dimensions collected: position and string. Furthermore, the NCAA had instituted rules to curb the intensity of spring practices in an effort to prevent injuries. Fall injury rates dropped from 10.6 to 5.2 per 1,000 AEs, while spring rates dropped proportionally less from 19.8 to 16.4 per 1,000 AEs (4); these rates are still about 50% above the corresponding NCAA ISS rates (34). Commensurate with this, IDRs rose to 3.2 (2.9-3.5) for all practices, rose to 4.5 (3.7-5.4) for limited contact practices, rose to 3.3 (2.9-3.8) for contact practices, but dropped to 1.4 (1.1-1.7) for scrimmages. The elevated IDRs held across all categories of position and string except for ST players; it also held across categories of RTP time (0-7, 8-21, and 22+ days lost). The data for this time period is broken down by injury type but uses different categories than the earlier years, making comparisons difficult.

The authors interpret these findings as the NCAA rule changes not having their intended effect of closing the fall-spring injury rate gap (though I assume their actual goal was to reduce spring injuries, not just close the gap, otherwise the NCAA could have legislated that all coaches bring lead pipes to hit players with at fall practices) (4). Considering the fact that although spring practice injury rates dropped, fall practice injury rates dropped more (perhaps driven partly by the elimination of selection bias in moving from 80% of team-seasons reported in the old period to 100% in the new period), I would have to agree that this analysis does not support the NCAA's rule changes having the hypothesized effect. *However*, they neglect to address survivor bias as a possible explanation for the elevated injury rate in the spring. To control for this, a better analysis might have been to compare the first X practices of each type (e.g. contact, limited contact) in the fall and spring and inspect the IDRs – if they're closer to 1.0, survivor bias could explain the difference.

In summary, multiple analyses have demonstrated a crude difference in injury rates between fall and spring practices, but none has sufficiently controlled for survivor bias.

E. Play Type

Do certain types of plays, such as runs up the middle or long pass plays, put players at greater risk for injuries? We have some data breaking down injuries by type of play, but unfortunately the data on any association(s) between play types and injury rate are scarce.

High School RIO tells us that, for example, 51.2% of injuries in 2012-13 were associated with tackling, so perhaps plays less likely to involve a tackle – such as sideline passing routes – might have lower injury rates, but we do not have the direct data to support that (20). Shankar et al break down 2005-06 RIO data and find that, among game injuries, 62.1% occurred on running plays and just 20.0% on passing plays (for practices the numbers were in a similar ratio, 40.1% and 14.9%, respectively). In college games these numbers were closer but still substantially different from one another at 42.2% on rushing plays and 28.7% on passing plays (for college practices, interestingly, the numbers were nearly identical at 25.8% and 24.3%). While we cannot calculate the rates for running vs. passing plays without knowing the number of each type of plays, what we can do is figure out the percentage of all plays that would have to be runs if the injury *rate* per play were equal and make a decision about whether that's plausible. For example, for high school games, for the injury rates to be equal for running and passing plays while producing the 62.1% to 20.0% breakdown, running plays would have to outnumber passing plays by 62.1%/20.0% = 3.1-fold, meaning passing plays would only be 1/(3.1+1) = 24.4% of high school football plays. This is a purely subjective judgment, but that number seems *far* too low, suggesting that in high school running plays do indeed have a higher injury rate than passing plays. For college, pass plays would have to be 40.5% of all plays using a similar calculation, which also seems low and suggests running plays do carry greater injury rates – though maybe with a smaller differential than in high school. On the other hand, you have a study from NFL analyst Brian Burke that used injury play-by-play data (a sub-sample of injuries that stopped play and/or were otherwise severe enough to be recorded in game log data) that found that from 2000-2010 about 1.6% of rushing and 1.5% of passing plays had an injury (118). All of these studies have flaws or require assumptions of questionable validity, but it seems like the balance of evidence suggests running plays are slightly to moderately more dangerous than passing plays (or at least that passing plays aren't *less* safe).

To directly calculate rates by type of play we would need to know on which kind of play each injury occurred – which is collected in some surveillance systems such as RIO and the NCAA ISS, as well as the NFL ISS – and the number of plays of that type overall that occurred – which is not, to our knowledge, available at the high school level but is in college and the NFL. At the NFL level, in particular, there are some databases that capture information on rushes vs. passing plays or even more granular play data (120). These data, if it were able to be linked with data on what types of plays each injury occurred during (such as might be found in the NFL ISS), would provide powerful data to tease out whether certain play types actually have a higher injury rate than others. While we do not have access to data on individual injuries via the NFL ISS, we will try and address this question by comparing team injury rates to the percent of their plays that were rushes or passes over the course of an entire season in Specific Aim 1.

Kickoff Returns and Special Teams Plays

The NFL has said that special teams plays – in particular kickoffs and kickoff returns – have the highest rate of injury and has taken many steps to try and reduce injuries on these plays specifically, with some success (121, 122). The hypothesis is that the high speed cuts and collisions by virtually all players on kickoffs leads to higher injury rates. There is some data to bear this out: for example, in the Brian Burke article referenced above, he found 2.0% of kickoffs had an injury recorded in the play-by-play data vs. 1.5%

of passing and 1.6% of running plays (punts were actually a bit lower at 1.3%) (118). Shankar et al found that 7.7% and 4.0% of game injuries occurred on kickoffs in college and high school football (vs. 4.3% and 2.1%, respectively, on punts) – these figures translate to 9.3% and 4.5% of injuries occurring on known running/passing/punt/kickoff plays (7). Assuming 9.5 kickoffs per game (118) out of an average of about 130 plays per game, kickoffs account for about 7.3% of plays in the NFL. If we assume a similar percentage in college, then it looks like kickoffs may indeed have an elevated injury rate in the NCAA, as well. Taken together these data suggest kickoffs may be especially dangerous, but a direct investigation involving all injuries where the precise timing of each injury is known has yet to be done. Unfortunately, once again, the data we will be using for this dissertation do not allow us to identify the type of play during which an injury occurred. As a side note, efforts to reduce injuries in the NFL that focus solely on kickoffs because they're the plays with the highest injury rate are misguided because kickoffs are less than 10% of plays games (and even less in practices) – the vast majority of injuries have and will continue to occur outside of kickoffs.

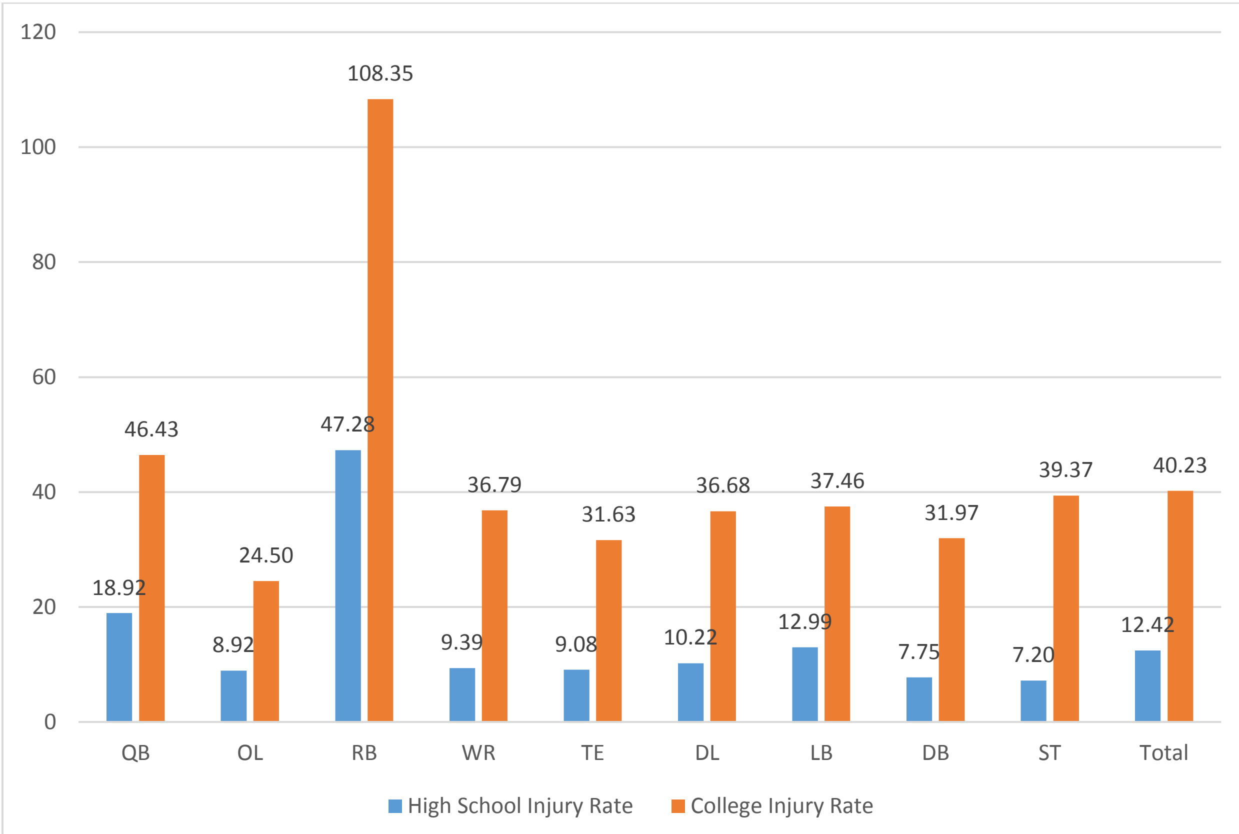
F. Position

Position is, if not *the* most common, one of the top two or three most common dimensions of variation for studies to investigate with respect to football injuries. Dozens of studies have compared injury rates and risks for OLs, DLs, QBs, RBs, LBs, DBs, TEs, and WRs (7, 17, 22-24, 34, 47, 50, 86, 103, 105, 107-110) (these references are an incomplete list). Instead of going through each of these studies individually, we chose to focus on a handful of high-quality national surveillance-type studies to investigate how injuries vary by position. We will focus on game rather than practice injuries since this is where most studies have focused their attention and it's also where differences are most likely to be apparent.

Among high school and college football players, Shankar et al provide positional game injury estimates using High School RIO (high school) and the NCAA ISS (college) (7). This study has already been examined in more detail above. In short, the paper provides numbers of injuries broken down by position for both college and high school football for the 2005-06 academic year. The RIO data are weighted to be nationally representative, while the college data are simply the raw numbers from the schools participating in the NCAA ISS for football that year. To get injury rates per 1,000 AEs we can first estimate the total number of game AEs provided in the paper (21,386,004 for high school after national weighting and 29,782) after excluding AEs from players with unknown positions (1.1% in college, 3.1% in high school). We must then distribute these AEs across players, which requires assuming a breakdown of AEs by position in games: we assumed 1 QB, 5 OLs, 1 RB, 3 WRs, 1 TE, 4 DLs, 3 LBs, 4 DBs, and 2 STs (a kicker and punter) per game since these are the most common personnel groupings on offense and defense, and we split the total AEs in these ratios. It is important to note here that our actual rate estimates are *extremely* sensitive to this choice of breakdown; this is especially true for RBs, who look much more in line with other positions if we assume they account for

2 AEs rather than 1 AE per game. But assuming these assumptions are valid, we can now simply divide the number of injuries given in the paper by our estimated positional breakdown of AEs:

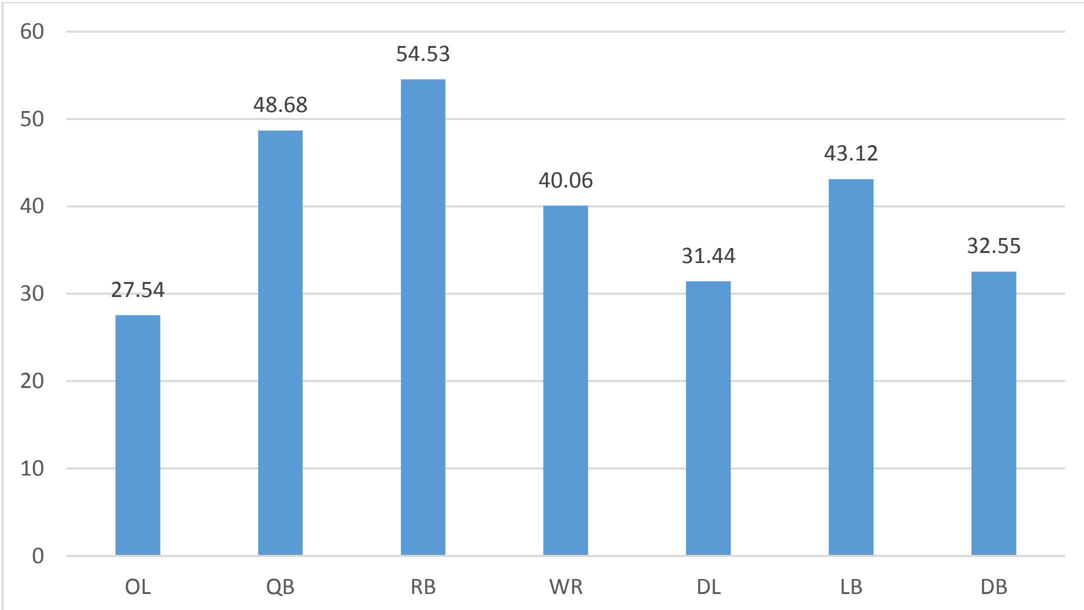
Figure 1.1. Calculated Game Injury Rates per 1,000 AEs by Position, HS RIO and NCAA ISS Data, Shankar et al 2007.



We see that RBs stand out as having by far the highest injury rates in both high school and college, by a substantial margin (though, as noted above, this may be an artifact of our allocation scheme for AEs rather than a real difference in risk). Even if we assume 2 AEs rather than 1, though, they retain the highest injury rates, albeit by a much slimmer margin. Interestingly, QBs had the next highest injury rates, which is somewhat unexpected given that they typically experience fewer collisions than other players. However, they are also actively involved in virtually every play, perhaps putting them at greater risk for overuse injuries. OLs are on the low end in both high school and college, but especially the latter. TEs and DBs form the second lowest tier, while WRs, DLs, and LBs cluster together pretty closely. Special teams players are an odd case that's difficult to sort out – we assumed there are two "true" ST players per game (the kicker and punter), which may hold in high school better than college – the latter may have more players who play strictly special teams, while in high school most ST players will also be on offense or defense, skewing our estimated rate here for college upwards.

Dick et al provide another data point. Using 16 years of NCAA ISS from 1988-89 through 2003-04, they calculated the percent of *game* injuries for each position adjusted for the frequency of that position (i.e. a team typically fields 1 QB but 4 DLs) (34). The authors say they simply took the percent of game injuries for each position and then divided them by the position weights (e.g. QB = 1, DL = 4, OL = 6, etc.) – however, I do not think that's correct, since the percentages below still sum to 100% (well, 99.9%). I think what they mean they did is they took the total *number* of injuries for each position, divided by the weights for each position, and then calculated a percent of those total weighted injuries for each position. Regardless, this breakdown shows RBs (19.6% of weighted injuries) and QBs (17.5%) have the highest weighted share of injuries – and, by extension, should have the highest injury rates and risks, as well. LBs and WRs/TEs form the next tier at around 14-15%, followed by DBs and DLs at 11-12% and OLs at 10%. We can back-calculate game injury rates from these numbers using the weights and the total number of game injuries (30,797), sum of the player weights (22), and total number of games (17,911) (34). First we calculate a *weighted number of injuries at each position* using the equation $\boldsymbol{Weighted\ percent * \ Weight * 30,797}$. Then, to get the *true number of injuries for each position*, we multiply each of those weighted numbers by $\frac{\mathbf{30{,}797}}{\boldsymbol{Sum\ of\ Weighted\ injuries}\mathbf{=87287.7}} \boldsymbol{= 2.834}$. Then, to get injury rates per 1,000 games we simply divide by $\boldsymbol{Total\ games\ (17,911) * Positions\ per\ game\ (weight)}$. However, we have to apply one final correction, since the weights only sum to 22 positions per game but the data tells us that on average the NCAA ISS reported an overall game injury rate of 35.90 per 1,000 AEs = $\frac{30{,}797\ injuries}{17{,}911\ games} * \frac{1\ game}{X\ AEs} * \mathbf{1{,}000}$, where solving for X gives us 47.98 AEs (i.e. players) per game. Therefore we will need to multiply our estimates by 22/47.98 to ensure we get an overall rate in line with what Dick et al calculated (note, this simple correction is imprecise and flawed since the number of players rotated in and out – and thus who are exposed for a given game – varies by position). For example, for offensive linemen we have (30,797*9.9%*6/2.834)/17,911*6*1,000 = 27.54 injuries per 1,000 games. Our calculated rates for each position are below:

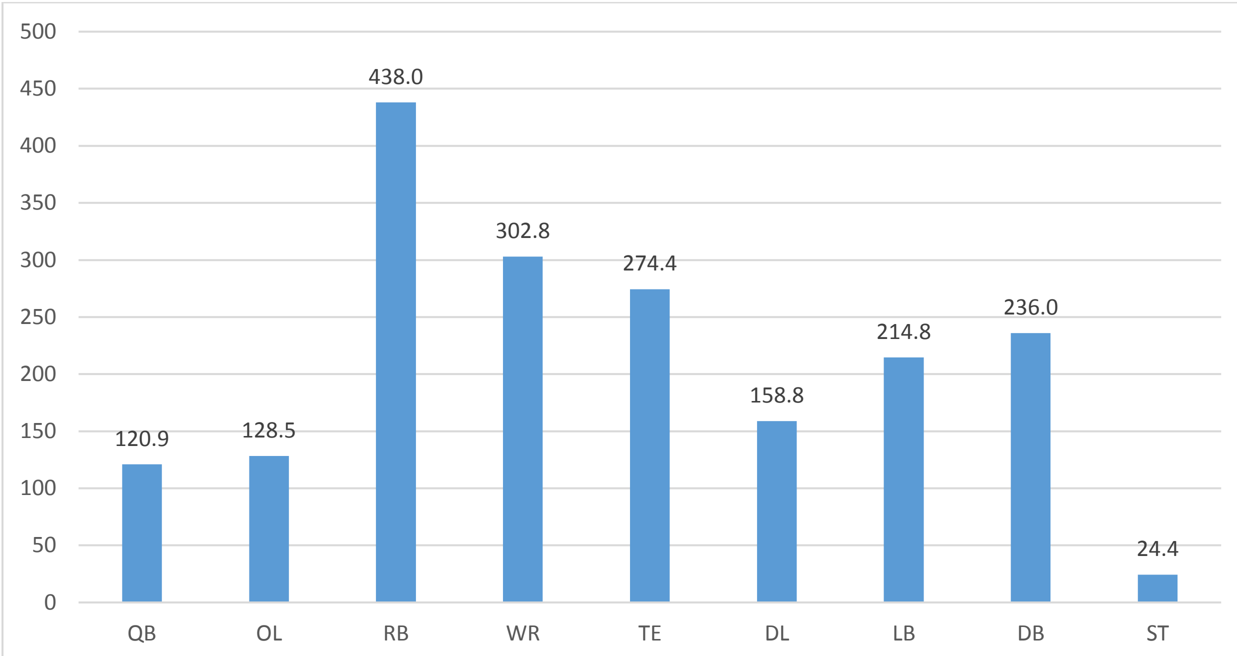
Figure 1.2. Calculated Game Injury Rates per 1,000 AEs by Position, NCAA ISS Data, Dick et al 2007.



These results are fairly similar to Shankar et al, though the gap between RBs and everyone else is much less – this is driven by Dick et al giving them a weight of 2 while above we gave them a weight of 1. If that discrepancy were fixed our estimated game rates would be quite close. Everything else lines up fairly closely, although Dick et al did not separate out TEs.

Finally, let's take a look at some NFL data from Lawrence et al (17). Importantly, the data in this study are from injuries that occurred *in or outside of* games, but they are all *assumed* to have occurred during a game (i.e. no AEs are accumulated for practices). Once again, this study has already been described and critiqued in detail above, so we'll just focus here on the positional breakdowns. Although Lawrence et al provide their own estimates of injury rates per 100 "team game positions" (TGP) by position (# injuries/Total TGPs for position x 100, where total TGPs = 964 games in the data*Y players per position on a typical game play), to improve comparability with Shankar et al we'll apply the same methodology here to calculate rates from the raw numbers of injuries and AEs. We'll simply take the numbers of injuries reported by position and divide by 964 games in the data x the number of players at each position on the field for a typical play, already given above. Here's what we see:

Figure 1.3. Calculated Game Injury Rates per 1,000 AEs by Position, NFL Data, Lawrence et al 2015.



As noted above, the numerators here are injuries that occur at any time but the denominators are only games, which inflates all these estimates relative to other studies that looked at in-game injuries only. Regardless, though, RBs once again top the list by a substantial margin. WRs and TEs form the next tier; LBs are somewhat lower than we saw in the last two studies, forming their own tier with DBs. Linemen on both sides form a lower risk stratum, with OLs at particularly low risk as we saw in other studies. The biggest difference is QBs are now one of the *least* likely positions to get hurt, which is more in line with our a priori thinking.

None of these studies or calculations is perfect, they all rely on some assumptions of questionable validity, and they sometimes disagree with each other. What we can synthesize from all this, though, is that injury rates *do* vary substantially by position, with more mobile positions such as RBs *in general* exhibiting higher injury rates. In Specific Aim 1 we will attempt to calculate rigorous rate and risk breakdowns by position beyond that which has appeared in the literature so far and been described above.

G. Rest

The optimal rest time between football games is a subject of great debate. What is the balance between full recovery and getting "rusty" or deconditioned? The studies on this in American football are limited.

The main study looking at this question so far used public NFL injury data from the 2012-2013 seasons that split rest by long (10-15 days), short (4 days), and normal (6-8 days) periods found no substantial association between rest and concussions, ankle injuries, or shoulder injuries (56). There was a small association between shorter rest periods and fewer knee injuries, but the confidence interval was wide (56). Hamstring injuries, however, showed ~30% higher rates with shorter rest and ~30% lower rates with longer rest versus a normal rest period (56). Hamstring injuries are soft tissue (muscle) injuries and might be expected to the most impacted by extra or shortened rest.

One other biomarker study is worth mentioning. A study at the University of Connecticut took blood from 28 players before, 18-20 hours after, and 42-44 hours after a single game (123). They found temporary rises in markers of muscle tissue damage; although these had returned to pre-game levels by two days post-game, pre-game levels of these markers were still above normal ranges, indicating soft tissue injuries likely carry over game-to-game (123). This suggests that even rest periods on the short end in the NFL (4 days) may allow time for certain biomarkers to return to normal, though whether you have 4, 7, or 10 days to rest may make only a modest difference, if any at all, in terms of your injury risk.

H. Game-Day Conditions

1. Altitude

One research group (Myer et al) looking at public injury data for the 2012-13 seasons found statistically significantly fewer concussions (OR 0.70, 95% CI 0.50-0.94) for NFL stadiums at "higher altitudes", defined as being >= 644 feet above sea level (the median elevation of NFL stadiums) (124). The physiological theory behind this is that as elevation increases atmospheric pressure decreases, causing the brain to swell and leaving less room for it to move around and bang against the inside of the skull (124, 125). However, other studies have questioned these results. Some have pointed out the proposed physiological mechanism is unknown to have a meaningful effect under ~1,000 m (>3,000 feet), and there is only a single NFL stadium over that altitude (Denver) (125). A separate research group investigating public injury data over the same timeframe as Myer et al split stadiums into quartiles by altitude but found no consistent associations between that and concussions or knee, ankle, hamstring, and shoulder injuries (56). A study of 21 Division I NCAA football programs found statistically significantly *greater* concussion rates at higher altitudes by splitting both at the median and by quartile (126). A meta analysis of this question in contact sports found no association between altitude and concussion incidence (127).

Overall, there is no compelling evidence for an effect of altitude on concussions or other injuries in the NFL. Especially concerning is the fact that Myer's findings do not seem to be robust to other altitude categorization schemes (quartiles vs. a median split) (56, 124). However, it may be interesting to look at Denver's (the only true "high altitude" NFL stadium, physiologically speaking) injury patterns in more detail.

2. Precipitation

Field conditions can have a major impact on injury rates in football, particularly lower extremity injuries. Wet or snowy fields, for example, have less traction than dry fields, leading to more slipping but fewer hard cuts putting extreme torsion on leg joints (128). Yet studies investigating this question directly in football are relatively limited. In addition to the traction and torsion mechanism mentioned above, precipitation conditions may also impact injury rates by altering game plans (e.g. by causing a team to shift to more running rather than passing plays). We know of no study that has successfully teased out these effects, however.

The most direct investigation into the effect of precipitation on injury rates in the NFL is a 2003 study focusing on knee and ankle sprains from 1989-1998 using data from the NFL ISS. They split games into wet and dry days (any vs. no precipitation in the game city). Dome stadiums were excluded from the analysis, and all results were stratified by natural grass vs. artificial turf in open stadiums. The study found a 46% greater rate of ACL injuries in wet games on grass (95% CI 0.98-2.18), but a 39% lower rate in wet games on artificial turf (95% CI 0.34-1.09); no substantial difference for knee sprains overall was found on either turf type (48). There was a 24% lower rate of ankle sprains in wet vs. dry games on grass (95% CI 0.61-0.94), but no such difference was observed on artificial turf (48). The study also stratified by "hot" (maximum daily temperature 70+ F) and "cold" days. Although the study did not present a direct comparison for wet/cold and dry/cold days, we can calculate differences from their wet/cold vs. dry/hot and dry/cold vs. dry/hot ratios. On natural grass, ACL sprains had a 25% higher rate when wet on cold days and a 74% higher rate when wet on hot days (48). Knee sprains overall did not show a substantial difference on either hot or cold days (48). Ankle sprains were just 12% lower on wet days when hot but 36% lower for wet and cold vs. dry and cold days (48). This relationship carried over to both inversion and eversion sprains. On artificial turf, the difference in ACL rates was driven entirely by a 54% decrease on hot and wet days vs. hot and dry days; wet and dry days in cold temperatures were almost identical (48). Consistent with the all-temperature results, no substantial differences were seen on artificial turf for knee sprains overall or ankle sprains overall in cold or hot days (48). Summarizing, we have the following findings: an effect of precipitation on ACL injuries and ankle sprains that varies by turf and also possibly temperature, but no effect on knee sprains overall.

One study of the Australian Football League (AFL) from 1992-98 found high water evaporation in the month before and low rainfall in the year before a match were associated with greater risk of ACL injuries (RRs 2.80 and 1.93, respectively). Although these are rather distal exposure measures, they provide modest evidence that dryer turf is worse for ACL injuries, possibly because of greater shoe-surface traction (128). Another study from the same group that included the 1999 season and adjusted for various intrinsic player factors found similar results (129).

Overall, there is substantial evidence for some sort of precipitation effect on lower extremity injuries, though the studies on this topic are old and, in the NFL, limited in number. The effect seems to be, in general, for wet games to be associated with no difference in or fewer lower extremity injuries than dry games. This question could benefit from additional, updated investigations, however.

3. Temperature

In addition to precipitation, temperature is another weather factor that may impact injury rates through, for example, fatigue, conditioning, muscle tightness, or dehydration (130). This area has seen more NFL studies than precipitation, but there remains ample room for further research.

An investigation of public NFL injury reports from the 2012-2013 seasons that split mean game-day temperature into quartiles (roughly <=50 F, 51-62 F, 63-69 F, 70+ F) found more concussions and ankle injuries in colder temperatures (especially the lowest quartile) (56). However, there were more knee injuries in the warmest quartile and more hamstring injuries in the two warmest quartiles; shoulder injuries did not exhibit any consistent trend (56).

Another investigation into the effect of temperature on injury rates in the NFL is a 2003 study focusing on knee and ankle sprains from 1989-1998 using data from the NFL ISS. The authors dichotomized games into “hot” (maximum daily temperature 70+ F) and “cold” days and also stratified by whether there was precipitation (wet) or not (dry) and turf type (natural grass vs. artificial turf). Dome games were excluded. On natural grass the study found a 31% lower rate of ACL sprains (95% CI 0.47-1.03) and 17% lower rate of eversion ankle sprains (95% CI 0.65-1.06) on cold days, but no substantial effect on knee sprains or ankle sprains overall (48). On artificial turf, the study found a 29% lower rate of knee sprains overall (95% CI 0.58-0.88) and 50% fewer ACL sprains, as well as a 39% lower rate of inversion ankle sprains (95% CI 0.45-0.82) on cold days (48). When stratifying by precipitation on natural grass, the reduction in ACL sprains was seen in both types but was stronger on wet days; the change in eversion ankle sprains was similar for wet and dry days (48). Ankle sprains overall were 26% lower on cold and wet days than hot and wet days (48). On artificial turf, knee and ankle inversion sprains were lower for cold days regardless of precipitation (48). Summarizing, knee and ankle sprains were less common when it was cold; this effect varied by turf type but not by meaningfully by precipitation.

A study of the Australian Football League (AFL) from 1992-1998 categorized their teams into “warmer” or “cooler” climates. This study found more concussions (IDR 1.24, 0.89-1.71), knee injuries (IDR 1.18, 1.06-1.31) (especially MCL and knee cartilage injuries), and ankle injuries (IDR 1.17, 1.00-1.37) in warmer climates (131). There was a tendency towards fewer Achilles injuries in warmer climates (IDR 0.70, 0.47-1.03), however (131). Overall, injury rates were 5% higher in warmer climates (131). This same study sought to compare these results to a similar analysis for European (UEFA) soccer teams. That analysis found fewer concussions and knee injuries in warmer climates, along with fewer shoulder injuries; it also found no substantial difference in Achilles injuries, though ankle injuries remained elevated (131). Overall, injury rates were 14% lower for soccer teams in warmer climates (131). It is difficult to reconcile these sets of results into a coherent effect of temperature, though that may be due to differential effects by sport. The AFL results may be expected to more closely mimic the NFL than soccer would. Additionally, the authors here attempt to interpret these differences not as causal effects of temperature per se, but rather as an effect of the different kinds of grasses that grow in these climates (131).

One study of a single British rugby club's in-game injuries found nearly 50% higher rates (182 vs. 126 per 1,000 player-hours) in summer than winter games (132). The increase appeared relatively consistent over injury site and type, with the notable exception of shoulder injuries (132). This could be evidence of higher injury rates in higher temperatures. However, the study leveraged a change in the season of play from 1993-1995 (winter) to 1996-1999 (summer) from the team's league. This was a clever study design, but such a change could have included a number of other extraneous effects, such as altered training schedules, that impacted injuries.

In summary, we see a consistent association between warmer temperatures and more injuries across the NFL, AFL, and rugby, though not soccer. However, these studies often used imprecise measures of temperature (such as season or climate) or categorized temperatures into a handful of groups that make little biological or physiological sense. There is a need for studies that consider temperature on a continuous scale to tease out broader trends and possible thresholds where injury risk increase or decrease.

As a sidenote, in all studies seeking to estimate a causal effect of temperature it is critical to control for the time point within the season. However, this is often difficult as time in season and temperature may be tightly correlated (in the NFL, later games being colder). One solution might be to look at teams, such as those on the west coast, with relatively invariant climates. To our knowledge no study has tried to tease out these effects in this way in the NFL.

4. *Turf*

The effects of artificial turf versus natural grass surfaces is one of the most frequently investigated aspects of sports injuries. The greater stiffness of many artificial turfs may increase impact forces on the leg and foot, while greater friction at the shoe-surface interface can also result in greater injury-causing forces when an athletes stops, starts, or cuts (93, 133). Studies have been addressing this question since shortly after the first generation of Astroturf was rolled out in 1965 (134, 135). However, because of the evolution in artificial surfaces since then, only more recent studies may be relevant to today's NFL injuries (45). What follows is a brief review of some of the most relevant literature from professional and college football since 2000.

<u>NFL Studies:</u>

A study from the NFL Injury and Safety Panel that used the 2000-2009 NFL ISS game injuries compared injury rates for ankle and knee sprains on natural grass versus one particular type of newer-generation artificial infill surface (FieldTurf) (45). The authors found higher rates of knee sprains (IDR 1.22) on

FieldTurf; there was virtually no difference for MCL injuries (IDR 1.03) but a major increase in ACL injuries (IDR 1.67) (45). Ankle sprains exhibited an identical increase (IDR 1.22 for FieldTurf vs. grass), with a larger difference in eversion ("high") sprains (IDR 1.31) than inversion ("low") sprains (IDR 1.08) (45).

Another study of 2012-2013 public NFL injury reports that compared natural grass to all artificial surfaces found no differences in concussions or hamstring injuries, but higher (~40%) rates of shoulder injuries and modestly (~10%) lower rates of knee and ankle injuries on natural grass (56). A similar study of 219 ACL tears from 2010-2013 found no substantial difference between grass and turf fields (136). Another study of in-game Achilles ruptures from NFL public injury reports from 2009-2016 found no substantial difference between games played on turf vs. natural grass (1.08 vs. 1.00 per 100 team-games) (73).

An older study using 1989-1998 NFL ISS data found ~20% lower rates of knee sprains, especially MCL sprains, on natural grass versus artificial turf in both domes and open stadiums with artificial turf (48). A similar effect (~20-30% lower on grass) was seen for ankle sprains, including for both the inversion ("low") and eversion ("high") types (48).

<u>College Football Studies:</u>

The NCAA ISS has issued several studies on artificial turf. One study using 2004-05 to 2008-09 NCAA ISS data (5 seasons) found ACL tear rates of 1.73 vs. 1.24 per 10,000 AEs on artificial vs. grass playing surfaces (137, 138). Another study using the NCAA's ISS from the 2004-05 to 2008-09 seasons found "turf toe" injuries – essentially a sprain or fracture to the big toe – had rates over twice as high on artificial turf vs. natural grass (0.87 vs. 0.47 per 10,000 AEs) (108). A similar study of high ankle sprains also found elevated rates of those injuries on 3rd-generation "fill" turf vs. natural grass (0.29 vs. 0.22 per 1,000 AEs) (109).

Another study of 24 Division I football programs that did not use the NCAA ISP found lower rates of overall injuries, minor injuries, and severe injuries on FieldTurf versus natural grass (139). However, this study was funded by FieldTurf, and data on individual injury types – placed in an Appendix – were not available at the time of this writing (September 14, 2017) due to journal site maintenance. The study does state no significant differences were found for knee, shoulder, or head injuries (139).

A study of a single Big 10 NCAA football program from the 2007-2009 seasons found higher overall rates of game injuries on artificial turf vs. grass (172.0 vs. 51.6 per 10,000 AEs), but in practices the trend was reversed (20.0 vs. 28.8 per 10,000 AEs) (140).

<u>Systematic Reviews:</u>

A systematic review from 2015 of the effect of turf vs. grass on ACL injuries in football players found four studies reporting an increased rate of between 10 and 92% versus one with a 25% decreased rate on turf

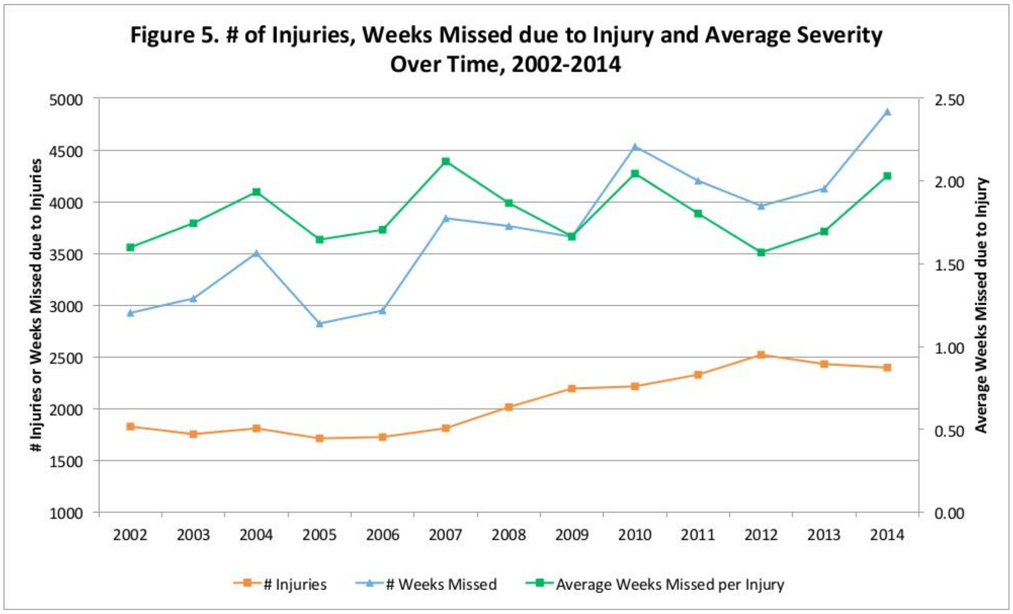
(141). The one study that showed a (non-significant) decrease of 25% was funded by Field Turf (139). These articles were not combined in any kind of meta-analysis, but the largest studies reported increased rates of 40% and 68% (141). Another 2011 systematic review of injuries in soccer, rugby, and football that reviewed 11 papers comprising 20 player cohorts concluded there was good evidence for higher rates of ankle injuries (IDRs 0.7-5.2) but inconsistent evidence for knee and other injuries (133). Both systematic reviews included some of the individual studies mentioned above.

I. Calendar Time (Years/Seasons)

A handful of analyses have investigated how NFL injuries have varied over time in recent years. However, it remains an open question how much of this increase is a true increase in the injury dangers of football and how much is increased reporting or, in the case of concussions especially, better recognition of injuries in recent years (35). The latter could be considered a form of diagnosis bias if our goal is to identify underlying changes in injury rates from across seasons. The increasing revenue, sky-high television ratings, ballooning media coverage in the social networking age, and rising popularity of fantasy football all create a constant and expanding pressure for information on and scrutiny of players' injury issues, which can be hard to tease out from true increases over time.

One way to separate these two issues might be to look at injury severity. Injuries resulting in players missing substantial time are less subject to increasing reporting or diagnostic pressure than more minor or nagging injuries. An analysis of an earlier version of this dissertation's dataset (public NFL injury reports) revealed an increase in the number of reported injuries from roughly 2007-2012 (2000-06 and 2012-14 were relatively flat) while the average severity in weeks missed of injuries remained relatively unchanged (142). This provides evidence for a true increase in the underlying injury rate rather than increased reporting, which would be expected to drive average injury severity down.

Figure 1.4. NFL injury counts and severity over time, Binney 2015.



Other data from the NFL's ISS paints a different picture. A 2012 report from Edgeworth Economics on NFL ISS data provided by the NFLPA found no substantial change of injury counts through 2009 before a small spike in 2010 and a much larger increase in 2011 (143). These increases were almost entirely in "Minor" injuries that resulted in less than 8 days missed (143). This suggests two things. First, what increases there were were due largely to better identification or reporting of minor injuries. Second, the NFL public injury reports displayed increases during a time (2007-2009) when the NFL's own internal counts were *not* increasing, suggesting the increases in that timeframe were due to better reporting and not a true rise in the underlying rate.

More recent NFL ISS data mimics and extends these findings. Deubert et al's Harvard report also found a jump – in both game and practice injuries from the preseason and regular season – from 2010 to 2011, though this was only by about 300 injuries rather than 1,500 reported by Edgewood (41). They did not stratify by severity. There was then another spike of roughly 200 injuries in the preseason and 450 in the regular season from 2013-2014 before the numbers eased off a bit in 2015 (41). In general, the Harvard report found increases in injuries over time, but they weren't steady: there were instead large jumps to a "new normal" in 2011 and 2014. This sort of pattern suggests sudden changes – such as new reporting regulations or rule changes – are more responsible for observed increases than some sort of gradual, continuing change over time such as increasing media attention or heavier players. It also does not reflect the pattern observed in public injury report data over the same time period, suggesting some differences between the NFL ISS and public reports (142). Nonetheless, all these studies agree a greater number of injuries are being reported and counted in more recent years, though the explanatory mechanism remains unclear.

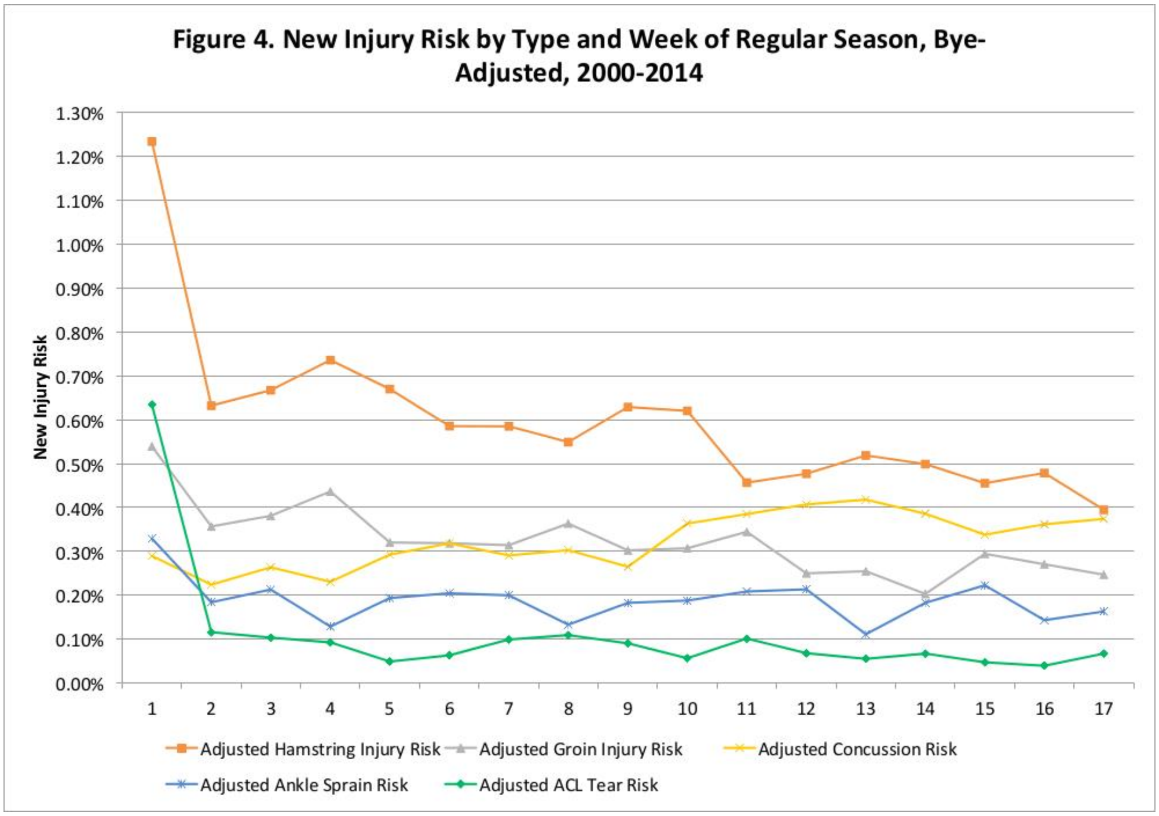
One non-NFL study, from college football, merits mentioning. Dick et al studied data from the NCAA ISP from 1988-2004 and found no substantial changes in game or fall practice injury rates, though spring practice rates did appear to decrease from 1997-2004 (34). Division I NCAA football would likely be a good control for teasing out the impact of increasing attention and reporting in the NFL as their ISS is less subject to that while the sport has been subject to similar increasing attention. Unfortunately, the early time period of this study limits the lessons we can draw from it for our more recent data.

J. Within-Season Time (Weeks)

In addition to variation across seasons, several analyses have looked at how injuries vary *within* a season from week-to-week. Any observed trend over time in a season needs to consider the survivor effect as a likely explanation: "frailer" players are likely to get injured earlier in the season, leaving a heartier group with lower baseline injury risk in the season's later weeks. Regardless of the causal mechanism, these analyses provide us with good descriptive data for how observed injury rates vary over the course of a season.

An analysis of an earlier version of this dissertation's dataset (public NFL injury reports) found the risk of any new injury did not vary substantially as the season dragged on, but there was substantial variation by injury type (142). Concussions became more common later in the season, while soft tissue injuries like hamstring and groin injuries became less common – soft tissue injuries are where we might expect survivor bias to exert a stronger downward force on incidence in later weeks (142). Ankle sprains and ACL tears remained relatively flat from week to week (142).

Figure 1.5. NFL injury risk by week and injury type, Binney 2015.



The 2012 Edgeworth Economics report, meanwhile, found relatively flat injury counts through the first half of the regular season before a modest (~10%) decrease from week 10-17 (143). The report also looked at concussions specifically and did find an increase over the course of the season, though it was inconsistent in the latest weeks (143).

There are several other NFL studies that looked at this issue. Lawrence et al looked at public injury report data for the 2012 and 2013 NFL seasons and found there were higher rates of concussions in the last 12 vs. the first 4 games; lower rates of hamstring injuries in later weeks; and somewhat higher rates of shoulder injuries in the last 12 vs. the first 4 games (56). The study found no discernible difference in ankle or knee injuries over the course of the season (56). Another analysis of NFL ISS data from 1989-1998 found lower rates of ACL tears in November-January (approximately weeks 9-17) vs. July-October (approximately preseason through week 8) but did not look at other injuries over in-season time (48). In a study of Achilles tendon ruptures using public injury report data, Krill et al found lower rates of ruptures in each subsequent 4-game stretch of the regular season, dropping from 1.7 to 0.5 per 100 team-games (73).

One other study from rugby merits a brief mention. In a study of New Zealand rugby players during the 1993 season, Alsop et al found a gradual drop in injuries over the course of a 19-week (women) or 25-week (men) season (144). The changes did vary by injury type, with lower leg/foot injuries decreasing but trunk injuries increasing over the course of the season (144).

Overall, there is clear evidence that injury rates vary for at least some types of injuries over the course of the season, and this relationship warrants further investigation. To determine any causal effect of this progression through the season, however, would necessitate further controlling for environmental factors that change as the season progresses, such as temperature and precipitation.

K. Coach Experience

It is likely that coaches exert at least some influence over injury rates in the NFL as they set, among other things, practice schedules (including duration and intensity) and drills. More experienced coaches may have more refined practice regimens and a better feel for player health management, leading to lower injury rates. On the other hand, more experienced coaches tend to be older, and perhaps younger/less experienced coaches will approach practices with a less intense, "old school" attitude given the ever-increasing recognition of the injury toll in the NFL. Unfortunately, prior research into the effects of coaches on injury rates in football is limited. What evidence exists comes from high school and youth football and is largely centered around concussions. A brief review of that evidence follows.

A study of 3,323 high school football players over 3,948 athlete-seasons in North Carolina from 1996-1999 measured "coach experience, qualifications, and training" on a 5-point scale (yes/no to 1+ years playing experience, 1+ year sport-specific coaching experience, college degree, coaching class, and current first aid or CPR certification) where 1-2 was low, 3 medium, and 4-5 high (22). This study found no substantial difference in overall injury rates or practice injury rates across coach experience categories (22). However, *when an injury occurred*, medium and high levels of coaching experience were associated with 68% and 59% reductions in the odds of that injury being "severe" (3+ weeks prevented from football participation), respectively (22). These percentages shrank to 41% and 51% after adjusting for player variables (age, playing experience, BMI, prior injury history) and competition level (22). Older studies also demonstrated lower football injury rates for teams with more experienced coaches and larger coaching staffs (18).

Another study from Washington state focusing on concussions found that the least experienced coaches (1-5 years) were more likely to be aware of their athletes' concussions (6/6, 100%) than those with 6+ years of experience (52/89, 58%) (145). However, the association between coach experience and concussion rate was not investigated.

A study investigating the league-level impact of two injury-reduction programs (Heads Up Football (HUF) and Pop Warner practice contact restrictions (PW)) instituted in 2012 studied 2,108 players ages 5-15 during the 2014 season from 10 leagues that received either HUF only (4), HUF and the Pop Warner restrictions (2), or neither (4). The study found 63% (95% CI 47-74%) and 87% (95% CI 79-92%) lower *practice* injury rates in the HUF and HUF+PW groups versus the non-HUF group, respectively; there was a similar reduction for concussions (67%, 89% decrease to 2% increase) in the HUF+PW group but not in the HUF group (146). Game injury rates were 75% (95% CI 56-85%) lower in the HUF+PW group; game concussion rates were 54% lower but with much uncertainty (95% CI 87% decrease to 66% increase) (146). This study could be construed as providing evidence that coach education can help to reduce practice injury rates, but top-down practice contact restrictions appear more effective and consistent. However, the lack of data from before the rules were introduced severely limits the conclusions we can draw from it. Additionally, this study assumed all coaches were similarly impacted by the educational efforts as the exposure was measured at the league level and did not control for any other covariates.

The effect of coaches on injury rates generally is understudied and merits further investigation. Almost nothing is known to date about their effect in the NFL. The best analyses would be able to zero in on practice injuries, as this is likely where coaches have their strongest impact. If a subset of coaches can be found where age and experience are not too collinear, it may also be worth controlling for age to tease out what aspects of older and more experienced coaches may be impacting injury rates.

L. Travel

Travel can impact a team in many ways. Although they have traveling medical and training staffs, when on the road teams are away from their homes and parts of their routines, their locker rooms, their normal training and practice facilities, and they may also have to deal with a time change. Any of these could be reasonably expected to impact injury rates, though the literature to date in football is very limited.

One study of public NFL injury report data from the 2012-2013 seasons compared various injury rates per team-game for teams at home to those traveling under or over 627 miles (the median travel distance for road teams) (56). This study found greater rates of concussions and shoulder injuries for away teams, but no substantial differences between those traveling short or long distances (56). As these are both often contact injuries, such a similarity might be expected. Hamstring injuries, which are typically non-contact muscle strains, had lower rates for away teams, but again exhibited no difference based on distance traveled (56). Knee and ankle injuries exhibited no discernible trend, though ankle injuries did exhibit a roughly 20% higher rate for teams that had to travel a long distance (56).

This same study also looked at body clock differences, operationalized as a 3+ time-zone shift versus a 0, 1, or 2-zone shift. This comparison yielded no substantial differences in concussions or hamstring injuries, but shoulder, knee, and ankle injuries were all *lower* for teams with a greater time shift (56). This runs counter to our expectation given the well-known handicap in winning percentage and some performance metrics west coast teams traveling to the east coast face (147).

Overall there is more we do not know than what we do know about travel and NFL injuries, though what data we do have does not suggest a detrimental effect of traveling on injuries.

M. Pre-season Conditioning

The new collective bargaining agreement (CBA) between the NFL and its players' union negotiated following a pre-season lockout in 2011 put substantial restrictions on offseason workout, overall practice, and contact/padded practices for NFL teams (148). These regulations were implemented to improve player safety and reduce practice injuries (148-150). However, some have argued that they have had the opposite effect by worsening player conditioning and limiting access to team medical and training resources, thus leaving players more susceptible to injuries than before (151-155). It's possible both sides have a point.

There is a substantial body of research linking high training loads with increased risk of injuries, particularly soft tissue injuries (156, 157). However, there is a growing body of literature suggesting that too little training – a low "chronic workload" – is also a predictor of increased injury risk; indeed, high training loads results in a host of physiologic changes that are associated with lower injury (156, 157). Out of this was born the more recent idea of the "acute:chronic workload ratio," wherein a high chronic workload is necessary to achieve fitness and maximize competitive performance but too high an acute workload over a short period can lead to fatigue overwhelming fitness and increasing injury risk (156). The goal is to find a "sweet spot" between undertraining and overtraining that leaves athletes both equipped to perform at a high level and resistant to injuries.

What is unknown and virtually unstudied in the academic literature is whether the NFL's requirements, including a large slate of full-contact practices – provided this appropriate level of conditioning before and/or after the 2011 CBA.

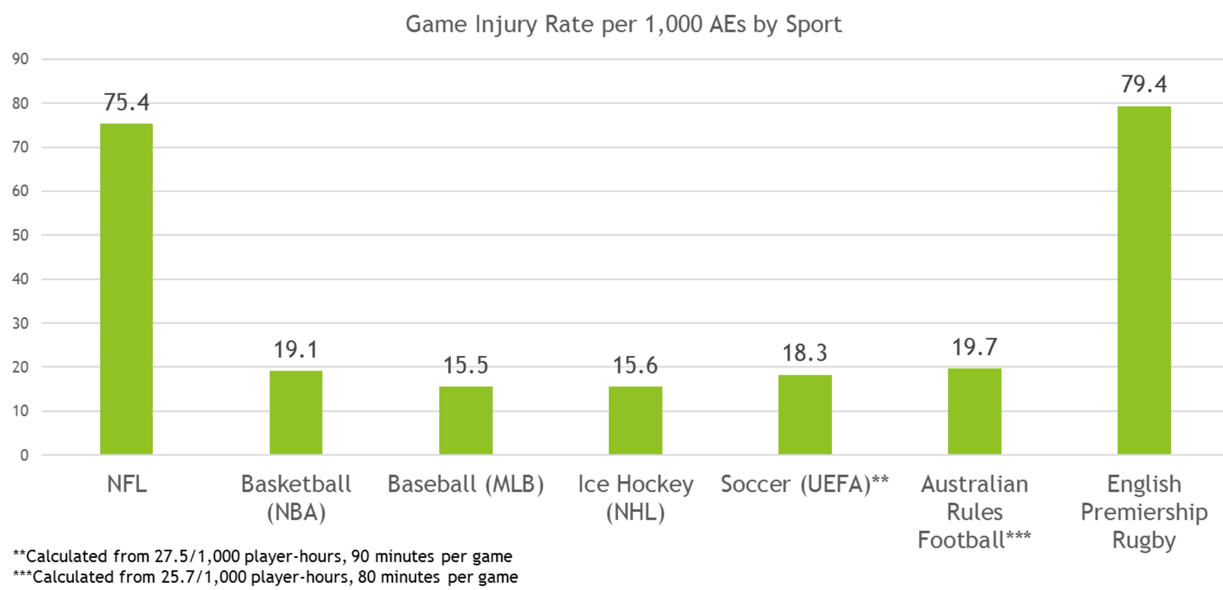
N. Synthesis

Our review identified a handful of factors that have been clearly shown to impact football injury rates, though several others exhibit sufficient plausibility to merit further investigation. The strongest evidence is for higher rates in games, on kickoff and punt plays, among those with injury histories, for those who play more mobile positions, on dryer surfaces, in higher temperatures, and on artificial turf. Age, rest, year, week of season, coach experience, and travel, and player conditioning all merit further investigation. Specific Aims 1 and 3 of this dissertation will attempt to fill in some of these knowledge gaps.

V. Injury Risks and Rates in Football vs. Other Sports

It may also be instructive to see how injury rates in the NFL compare to other professional sports. There is a wide-ranging belief that the NFL has the highest injury rates of the major North American sports, but by how much? Because game injury rates tend to be easier to calculate (and more available across studies) than those incorporating practices, we'll focus on those. All numbers are provided as a rate per 1,000 "athlete-exposures" (AE), defined as 1 athlete participating in a practice or game.

Figure 1.6. Game injury rates per 1,000 AEs across sports.



The best available estimate of overall NFL injuries comes from a 2017 report from Harvard Law School that used NFL Injury Surveillance System (ISS) data. In 2014-15 (the most recent 2 years available for all injuries) there were 3,553 injuries in regular season games and 737 in regular season practices (82.8% of injuries in games) (41). Assuming 92 athlete exposures per game (46-man game-day roster x 2) and 256 games per regular season, this translates to 3,553/(256 x 2 x 92) x 1,000 = **75.4 injuries per 1,000 AEs in games in the NFL**. This translates to an average of about 7 injuries in any given game. There were 737 injuries in regular season practices over the same time period (41). If we assume 4 practices per week, 61 athlete exposures per practice (53-man active roster + 8-man practice squad), 32 teams, 17 weeks, and 2 seasons, this translates to 737/(61 x 32 x 17 x 4 x 2) = 2.8 injuries per 1,000 AEs in regular season practices. The combined game and practice regular season injury rate would then be 13.7 per 1,000 AEs.

What about the other of the "Big 4" North American sports? For MLB, the Harvard report began with data from MLB's Healthy Injury and Tracking System (HITS) that showed 2,988 injuries in the 2011-12 seasons across spring training, the regular season, and postseason (41, 158). Since ~71.7% of those games would have been in the regular season, we can assume 2,142 regular season injuries. Other data reveal 138,085 regular season player-games in 2011-12 (159), translating to a game injury rate of 15.5 per 1,000 AEs (41). In the NBA, Drakos et al used data from the NBA Trainers Association database to estimate a rate of 19.1 injuries per 1,000 AEs in regular season games from the 1988-89 through 2004-05 seasons (160). Due to the age of these data and the fact that it did not come from a modern EMR system, this is likely something of an underestimate of the true NBA injury rate. In the NHL, McKay et al used data from the Athlete Health and Management System (AHMS) to estimate a regular season game injury rate of 15.6 per 1,000 AEs from the 2006-07 to 2011-12 seasons (161). **The NFL thus has roughly 4-5 times the in-game injury rate of the NBA, MLB, and NHL.**

What about other international sports? For soccer, MLS data is unfortunately limited and old, but better data is available from the Union of European Football Associations (UEFA). From 2001-2008, Ekstrand et al estimated 27.5 injuries per 1,000 hours of match play (162). At 90 minutes per game for most players, this translates to approximately 27.5 / 1.5 hours = 18.3 injuries per 1,000 AEs in UEFA games. (More recent data from the 2014 UEFA Report on injuries reported 23.2 injuries per 1,000 hours of match play in 2013-14, translating to 15.5 injuries per 1,000 AEs). For Australian Rules Football, Orchard et al estimated a game injury rate of 25.7 per 1,000 hours from 1997-2000 (163). At 80 minutes per game, this translates to approximately 25.7 / 1.33 hours = 19.7 per 1,000 AEs. Due to its age, this number may also, like the NBA's, be a substantial underestimate. **The NFL has roughly 4 times the in-game injury rate of soccer and Australian rules football.**

There is one sport, however, that competes with the NFL: rugby. One study of the highest level of English rugby found a game injury rate of 91.4 per 1,000 player-hours from 1,534 injuries in 420 matches from the 2002-03 to 2003-04 seasons (164). In this league there are 15 players per team with up to 8 replacements; if we assume the maximum played in each game (23 x 2 = 46), this would translate to 1,534 injuries / (420 matches x 46 players per match) = 79.4 injuries per 1,000 AEs in English Premiership rugby games. A systematic review of 15 men's senior rugby studies found an overall game injury rate of 81 per 1,000 player-hours (95% CI 63-105) (165). If we take the same ratio of AEs to player-hours as in the English Premiership study, this would translate to 70.4 injuries per 1,000 AEs in games (95% CI: 54.7-91.2). Additionally, a comparison of football and club rugby teams at Ohio State University from 2012-2014 found game injury rates of 23.4 per 1,000 AEs for football and 39.6 per 1,000 AEs for club rugby (38) – though this football rate was lower than the 35-40 per 1,000 AEs reported in other college studies (7, 34). In the end, **it seems likely that at similar levels of competition rugby has game injury rates at least similar to, if not higher than, the NFL.**

Speaking of rugby, a common question is with the lack of protective gear, how do head injury rates in rugby compare to the NFL? Despite a higher overall injury rate, concussion incidence in the English Premiership rugby study was only 4.4 per 1,000 player-hours – this is much lower than the 7.4 per 1,000 AEs calculated from the Harvard Law Study (41, 164). Although these numbers aren't directly comparable - the average NFL player plays far less than an hour per game - meaning an NFL estimate of concussion incidence per 1,000 player-hours is likely >> 7.4 vs. 4.4 in English rugby. Part of that difference may be that the rugby study is from a time when less attention was paid to concussions, depressing that rate artificially. Additionally, a comparison of football and club rugby teams at Ohio State from 2012-2014 found game concussion rates of 4.4 per 1,000 AEs for football and 9.6 per 1,000 AEs for club rugby (38). In summary, the NFL has fewer injuries overall than rugby – but it's less clear for concussions specifically.

Chapter 2: Specific Aims, Data Sources, and Methods Overview

I. Overview and Specific Aims

American football is the most popular professional sport in the U.S.: in a recent Harris Poll asking 1,510 people who reported following at least one sport to pick their favorite from 21 options, the professional-level National Football League (NFL) held the top spot and college football ranked third (1). This popularity is reflected in the number of athletes playing it: in the 2013-14 school year there were 14,262 high schools with boys' 11-player football programs, comprising 1,093,234 athletes (8); the National Collegiate Athletic Association (NCAA) reported 70,147 men's college football players in 2013 (9); and in 2015, 1,979 players were listed on an NFL game-day roster for at least one regular season game, with a few hundred additional players on practice squads or training camps (10). Football is also an inherently physical, chaotic, and violent game. There are 22 men on the field for each play – 11 trying to move the ball up the field and 11 trying to physically stop them. Offensive players will push, shove, and ram into defenders in an effort to move the ball further toward their opponent's end zone. Defenders also push and shove, but in addition they tackle (violently knock down) whichever offensive player has the ball in order to end the play. Injuries occur with regularity in both practices and games in the NFL –and, given the physically taxing nature of the game, injuries happen frequently even without any physical contact between players (4-7). The injury rate is approximately 15-18 injuries per 1,000 athlete-exposures (3, 17, 41) (AE, a single athlete's participation in a game or practice) overall, with much higher rates in games (75.4 per 1,000 AEs) (3, 41). These rates are approximately 5 times higher than those for high school football (7, 20), approximately 1.5-2 times higher than those for college football (7, 33, 34), higher than those for any college sport (21), and higher than Major League Baseball (MLB), the National Basketball Association (NBA), and the National Hockey League (NHL) (160, 161, 166). These numbers, along with the intense public interest and economic impact of the sport, underscore the importance of studying the injuries among football players.

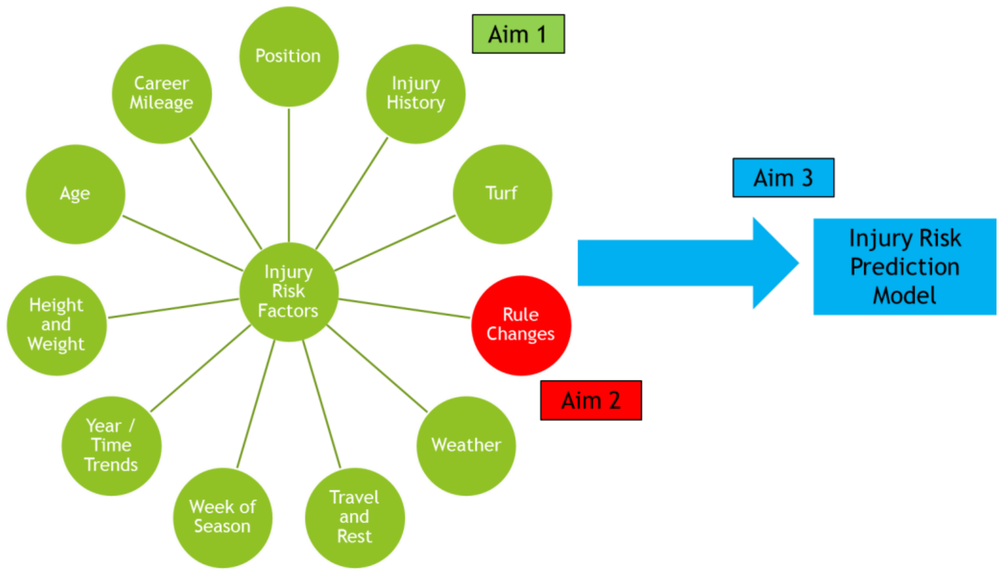
The academic literature on NFL injuries, however, is sparse in some areas, including descriptive epidemiology. Aim 1 will attempt to fill this gap by investigating the associations between injuries and a range of factors such as position, weather, weight, and age. We will then take a deeper dive on one specific risk factor – a rule change the League and players' union undertook to limit injury rates in Aim 2. Finally, we sought to see whether these risk factors could be used to identify and predict which players are at highest risk for an injury. A schematic of how the aims fit together is provided in Figure 2. A more detailed discussion of the three specific aims is below:

> **Aim 1:** <u>Describe the epidemiology of injuries among NFL players from 2007-2015</u> using publicly available injury report data that have been compiled by Footballoutsiders.com. We will calculate rates, 1-season risks, and end-season prevalences for any injury and by injury type (e.g. ACL tear, ankle sprain, concussion). We will also investigate how these rates vary by person (chronological age, career snap count, position), place (team, head coach, game climate, turf type), and time (variation within a season, variation over time between seasons).

Aim 2: We will investigate the effects of the 2011 collective bargaining agreement (CBA)'s practice limitations on injury risks among NFL players. The new CBA limited offseason practice times, which some have claimed leads to more poorly-conditioned players and greater injury risk and others have suggested might lead to fewer injuries due to extra rest and fewer practices in which to get hurt. We will investigate these hypotheses in conditioning-dependent and non-conditioning dependent injuries to tease out effect pathways, controlling for temporal trends in injury risk as well as other injury-relevant factors.

Aim 3: We will develop models for predicting the 1-season risk of missing any games due to injury among NFL players. The models will include age, height, weight, previous injury history, and other relevant predictors and will be stratified by position. Models will be created using logistic regression with GEEs and assessed on discrimination and calibration in a validation cohort from the 2015-2016 NFL seasons.

Figure 2.1. Dissertation Aim Schematic.



II. Cross-Aim Methods

A. Data Sources

FootballOutsiders.com (FO) (167) has agreed to let us use their database of NFL injuries and other NFL player data from 2000-2015. The injury database includes information from the injury report (player name, position, team, injury type), duration, history, player body mass index (BMI), age, and many other relevant variables. There are over 30,000 unique injuries (30,186 through 2014) and >30,000 individual player-seasons (31,184 through 2014) in FO's database. We are free to publish our findings from these data as long as it is offered to FO for publication first.

1. *Study Design and Data Collection Methods*

We collected data relevant to injury description and prediction at multiple levels. We will primarily focus on player-season-level injury predictors, but some relevant data from the team-season, game-, and season-level were also be collected. Injury data were collected at the player-week level. These data were linked to the most granular player-week-level data. The primary unit of analysis will vary by specific aim and within specific aim 1.

General Player-Season-level Data: FO has compiled a database of all player-seasons in the NFL since at least the year 2000 with a lot of basic information – age, position, team, games and snaps played, height, weight, body mass index (BMI), and various physical characteristics such as 40-yard dash time collected at the NFL Combine. These data could best be described as a cohort study with mixed timing of data collection (prospective since the site began cataloging each piece of data, retrospective before that). These data have been cleaned and analyzed by multiple editors at FO and are used for all of the site's published analyses, including those appearing on ESPN and in their popular Football Outsiders Almanac series (168).

Injury Player-week-level data: In 2007, FO began prospectively collecting data from regular-season NFL injury reports. That information included player name, team, year, week of season, and a description with a "reasonable degree of specificity" of the type of injury (53) – sometimes additional details about the injury are also gleaned from player or team interviews or other sources. The data could best be described as a cohort study with mixed timing of data collection (prospective for 2007 and later, retrospective before that). Data on weekly injury reports has been gathered prospectively every year since 2007 by FO interns under the supervision of a series of FO editors (Bill Barnwell, then Danny Tuccitto, currently Scott Kacsmar). The interns are different every year, leading to the potential for variations in data quality. Compounding that concern is that data for the 2000-2006 seasons were collected retrospectively, which may be associated with a difference in data quality between these two periods.

Team-Season, Game-, and Season-level data: Various other data sources were collated with this player-level data for all analyses. These data include team-season-level data on head coaches, schedules, stadium type (dome vs. outdoors), stadium turf (natural vs. artificial) and play type breakdowns from a combination of FO, pro-football-reference.com (PFR) (120), the NFL's website, and team websites. Game-level weather data came from Weather Underground (169). Season-level data on new rules (e.g. moving the kickoff up 5 yards, banning hits on defenseless receivers, spring practice limitations) were be abstracted from the NFL's website and media coverage of all changes.

2. *Study Population*

General Player data: These data are available for all players who were on a regular season NFL 53-man roster or 8- to 10-man practice squad, including some who never appeared in an NFL regular season game. There may also be additional players in the data, but these were not collected in a way that allows them to be well-defined. As they are only of peripheral interest for our project, they will be excluded from all analyses.

Injury data: These data are available for all players who were eligible to appear on a regular season injury report: all players on the 53-man roster or 8- to 10-man practice squad at any time during the regular season, or players who were put on the injured/reserve (IR), physically unable to perform (PUP), or non-football injury (NFI) lists prior to the regular season. There may also be additional players in the data, but these were not collected in a way that allows them to be well-defined. As they are only of peripheral interest for our project, they will be excluded from all analyses.

Team-Season, Game-, and Season-level data: These data were available for all or virtually all team-seasons and games in the NFL since the year 2000. We were able to link them to every player-season in our data.

<u>We define our **study population** and **target population** as only players who appeared in at least one regular-season NFL game over the course of their career</u>. Any player-seasons that do not meet this criterion will be excluded from the FO player and injury data. We make this restriction for three reasons: 1. It controls for any changes in the type of players FO may have tracked over the last 15 years since at minimum they have always tracked this group; 2. It focuses our analysis on the group that could best be defined as at-risk for an NFL injury, and; 3. It is the group for whom descriptive statistics and predictive models will be most relevant. The drawback is this will not allow us to generalize to players who may only appear in an NFL training camp or be briefly on a regular season roster, but we feel that the other considerations outweigh this minor concern.

B. Limitations and Methodologic Challenges

There are a variety of limitations to the data described above, as well as other general methodologic issues in sports injury epidemiology that we are likely to encounter. These challenges are briefly reviewed below:

1. *Limitations Inherent to Injury Report Data*

Defining an Injury

A detailed case definition is important epidemiologically to avoid misclassification of outcomes. In football injury studies, there is some variation in the case definition of injury. In a study using the NFL ISS, Brophy et al defined injuries as "significant and reportable if it resulted in premature cessation of at least 1 practice, game, or training event. Additionally, football injuries that were treated in a delayed fashion, even if not associated with premature cessation of play, were also reported" (50). Interestingly, another study using the NFL ISS data had a somewhat different injury definition: "An injury is reportable when 1 or more of the following conditions exist: (1) any injury for which the player was removed from the session or missed 1 day after the injury; (2) any fracture, regardless of time loss; (3) any concussion, regardless of time loss; (4) any dental injury, regardless of time loss; and (5) any heat-related problem, regardless of time loss" (45). In a study using the Big 10 Conference's ISS, an injury "required evidence of tissue damage, as determined by the clinical signs of erythema, warmth, tenderness, swelling, or abnormal laxity, and the inability of the player to return to practice that day. In addition, all concussions (regardless of time loss), fractures, and dental injuries were reportable" (4). The NCAA ISS defines an injury as "one that (1) occurred as a result of participation in an organized intercollegiate practice or competition and (2) required medical attention by a team certified athletic trainer or physician and (3) resulted in restriction of the student-athlete's participation or performance for 1 or more calendar days beyond the day of injury. If an off day followed the injury event, athletic trainers were asked to assess whether the injured athlete would have been able to participate…include[s] any dental injury occurring in an organized practice or game, regardless of time loss" (32). While these definitions exhibit some variation, they revolve around a couple central themes: any physical incident that makes a player unable to participate in some portion of a practice or game, plus a few specific categories of incidents that should always be reported. Beyond that core, though, there is some substantial variation: medical attention from an ATC or physician may be required, the player may have been required to be limited beyond the day of the injury, clinical signs of or treatment for an injury might be enough in some cases, and so on.

In our analysis we will be using data from the NFL injury report, and so we are reliant on their definition of an injury. These are League-mandated public reports that all 32 teams put out each week of "any player hampered by an injury (17)." In concert with the injured/reserve (IR) and physically unable to perform (PUP) lists for longer-term injuries (>=6 weeks away from practice and >=8 away from games) (51) and the non-football injury list for other issues that cost players playing time, these reports provide a list of all NFL players suffering the effects of an injury at any given time. The definition of "injury" for the injury report is rather muddled (emphasis added) (53):

> **All players with significant or noteworthy injuries** must be listed on the report, even if the player takes all the reps in practice, and even if the team is certain that he will play in the upcoming game. **This is especially true of key players and those players whose injuries have been covered extensively by the media**. … A

> player who **misses a game due to injury or a player who does not finish a game due to injury must be included on the Injury Report** each day of the following week…

"Significant or noteworthy injuries" is subject to different interpretations by different teams. The second emphasized sentence also suggests that it may be acceptable to have differential reporting thresholds for different players depending on skill and media scrutiny, which muddles the definition of "injury" and "injured player" even further. The only clearly delineated requirement is to include players whose injuries cost them well-defined chunks of in-game playing time, but there are many instances where an injury may just limit a player in practice or force them to be used less in games while still playing in all four quarters.

This lack of a strict, consistent case definition could lead to misclassification of players as injured or non-injured, though in most cases this will be non-differential – the one case in which it could certainly be differential is when stratifying the data by team or team-season, when different training and coaching staffs could tend to report borderline injuries in different ways. Even if this misclassification is non-differential, though, it could still bias our estimates in specific aim 2 and degrade the quality of our prediction model in aim 3. This misclassification is likely to be minimized if we restrict our analyses to injuries that resulted in players missing >= 1 regular season game, since these injuries will virtually always appear on the injury report – the League gets very suspicious if a player who normally play sits out a game without a reported injury or disciplinary problem. Also, it should be noted that the League is able to levy penalties against teams who abuse the injury report, which likely places a cap on the severity of the misclassification in injury report data.

<u>Teams Manipulating the Injury Report</u>

The imprecise definition of an injury as outlined above gives teams opportunities to modify the injury report for competitive advantage, either through the decision of whether to list the player at all or in determining how much information to reveal about their injury (3, 17, 52). This is especially a problem for top quality players, who could either be kept off the injury report to force opponents to prepare for them as if they were healthy or put on with inflated issues to lull teams into a false sense of security. The New York Jets were fined for doing the former with QB Brett Favre in 2009, while the Cowboys were investigated for the same with QB Tony Romo in 2014 (52). However, this problem is not limited to top quality players. The vagaries of the "likelihood of playing" categories of "probable," "questionable," and "doubtful" – especially the first two – lend themselves to different applications by different teams. For example, in 2015 the percent of players listed as questionable who played that week ranged from 30.8% (4/13, Pittsburgh) to 84.7% (50/59, Cleveland); the NFL average was 62.4% (61). This may not be a problem if it's just year-to-year variation, but often the same teams (unless they change coaching staffs) are consistent offenders from year to year: 6 of the bottom 10 in questionable playing percentage repeated from 2014 to 2015, while Miami and Cleveland were in the bottom 3 both years (61). 5 of the bottom 8 in number of "probable" players also repeated from 2014 to 2015 (61).

This can lead to misclassification of truly injured players as non-injured or vice versa and could bias results in the same ways as a loose injury case definition could. It may be possible to develop corrections based on past data on team-head coach injury reporting trends, but at least for the initial analyses it will be sufficient to stick to the injury report and interpret injury risks and rates as conditional on the injury being reported. Also, it should be noted that the League is able to levy penalties against teams who egregiously abuse the injury report, which likely places a cap on the severity of the misclassification in injury report data.

One additional issue is worth discussing. One might think from its name and private, in-house nature that the NFL ISS would be less subject to this kind of misclassification. However, we find it unlikely that this would be the case: the League could easily correlate injuries reported to its ISS with public injury reports, and if it found substantial differences could levy heavy fines against the offenders. We find it likely that the NFL ISS suffers from the same sorts of competitive manipulation problems the public injury reports do, though that would be a very interesting ancillary analysis beyond the scope of this dissertation.

Limited Information of Circumstances Around Injury

The data in the injury reports are limited to player name, position, team, practice status (full/limited/no participation), the likelihood that they will play in the team's next game (probable, questionable, doubtful, out), and injury location (e.g. ankle, knee, arm, illness) (17). Potentially important but unavailable data points include: 1. Whether the injury occurred in a game vs. a practice, 2. The mechanism of the injury (contact vs. non-contact, contact with another player vs. the field), 3. The activity that led to the injury (blocking vs. tackling vs. conditioning vs. other), and 4. If a game injury, the type of play the injury occurred on (running vs. passing vs. kick/punt return). Indeed, all we know is that if a player first appears on an injury report in week 7, they were either injured during the team's prior (week 6) game or a practice in the interceding period (early part of week 7). This injury circumstance information is available in surveillance systems such as High School RIO (20), the NCAA ISS (32, 34), and the NFL ISS (50).

This lack of information restricts us from conducting any analyses using these variables, even though they may be of interest. For example, we will not be able to calculate injury rates for practices vs. games, a stratification which is commonly reported in other injury studies – though we may be able to estimate stratified rates using data from college or previous smaller NFL studies. We also will not be able to answer questions such as whether running or passing plays are more risky; the percent of injuries that are non-contact or whether they have increased over time; and whether rule changes to reduce injuries on kickoffs have accomplished what they intended. Without gaining access to the NFL ISS data or linking our data with another source such as NFL play-by-play data, we will simply have to work around these limitations in our analysis.

How Big Are These Problems? – Quantifying Bias

If we consider the NFL's ISS to be the gold standard for NFL injury reporting, we can attempt to replicate several published studies on specific types of injuries, such as AC joint shoulder sprains, in our injury report data to see how far off our estimates might be. Our ability to quantify this bias will be limited because gold standard data are only available for a subset of injuries, but it will give us a good starting point for quantifying potential bias in our risk and rate estimates in specific aim 1.

2. *Limitations with the FO Injury Data*

Variations in Data Quality Across Years

The FO injury data are subject to several additional sources of potential variation in quality: 1. Different interns collecting data each year, 2. Three different editors leading the effort since 2007, and 3. Retrospective data collection prior to 2007 but prospective data collection thereafter. This could lead to systematic differences across years regarding which players and injuries are included in the data, complicating our efforts to make comparisons over time. Our decision to restrict our population to players who played at least one regular season game in their career will substantially mitigate the issue of variation in which players are included in the data (while admittedly restricting generalizability beyond those players). Our decision to restrict analysis to 2007 and later also eliminates any differences from retrospective versus prospective reporting. As an ancillary analysis, in concert with FO staff we may try to develop corrections for earlier years if it becomes apparent that that is appropriate (e.g. if we find substantial mismatches between historical injured/reserve (IR) data from NFL transaction reports and the FO injury database in earlier years).

In addition to these sources of variation, there is also a more general issue: with the rise of fantasy football, internet sports journalism, and other trends, injury data has become more accessible, rich, and detailed over time. What in 2001 may have been a vague "knee" injury could today be a grade 2 right MCL sprain. NFL injury reports, as noted above, typically only provide a high-level categorization such as "knee" or "ankle"; additional information has to come from team news conferences or other media reports. We could crudely quantify this trend by calculating the percent of injuries with such enhanced information over the last 15 years. The corrections that implies, however, are not straightforward but may provide an avenue for future investigation. Can we assume a similar proportion of injuries went entirely unreported? Can we estimate probabilities for vague injuries from earlier years? Could we triangulate these percentages with previously published data on specific injuries from the NFL ISS to apply corrections for earlier years on those specific injuries (or could we broaden those corrections to other injuries)?

Offseason, Training Camp, and Preseason Injuries – the "Week 1 Tag"

As noted above, the FO injury report data are organized by player-week. An injury marked as first occurring in "week 7" either occurred during the week 6 game or a practice in week 7. However, any injury first listed in "week 1" could be one that: 1. Occurred in a preseason game; 2. Occurred in a practice at any time throughout training camp or the preseason; 3. Occurred in spring minicamps; 4. Occurred at any other time in the offseason; 5. Is a "hold-over" injury from last season, or 6. Occurred in a practice during week 1. Further complicating matters, no injuries that happened in training camp or preseason from which the player recovered fully prior to week 1 of the regular season is included in our data, though we could correct for this issue using previously published training camp data (79). These issues make it difficult to provide any valid risk or rate estimates specific to the offseason, spring practices, training camp, or preseason. It also means the "week 1" injury numbers and rates will appear much higher than those for other weeks, but these differences should be disregarded. The "week 1" injury reports *can* be included in calculating rates at the full-season or higher levels, however.

No Postseason (Playoff) Injuries

A smaller issue is that we are also ignoring postseason injury rates, since these teams and players are systematically different from teams that do not make the postseason in many ways that could affect injury risks and rates. These data were collected by FO, but only for more recent years and with somewhat more variability than the regular season data.

3. *Methodologic Challenge: Categorizing Injuries*

There are hundreds of International Classification of Diseases version 9 (ICD-9) – and even more ICD-10 – codes that can be used to describe sports injuries. These individual codes are far too granular to create useful categories for studying sports injuries on the population level, as epidemiologists typically want to do. At the same time, simply categorizing an injury as "leg" or "head" is often too broad to draw meaningful conclusions. Where is the sweet spot in the middle?

Different football injury researchers have come to different conclusions on this question. Some have created their own injury categorization schemes for specific studies or strings of studies (3, 36, 170). Others have appealed to authorities such as the AMA's *Standard Nomenclature of Athletic Injuries* (59). Some are at the mercy of categorizations imposed by their data sources (e.g. surveillance systems such as High School RIO, the NCAA ISS, and the NFL ISS) – though that doesn't stop them from commonly wrapping multiple injury types up into broader categories for ease of analysis or interpretation (7, 34, 50). Our situation is closest to, though not exactly the same as, this third class of studies.

For this dissertation, when classifying injuries we are primarily restricted by the data in the NFL injury reports. These data are supposed to include a fairly specific injury location (e.g. ankle, knee, arm, illness) (17). However, no universal structured classification schema exists, and the level of detail available about an injury can vary widely. The NFL provides only the following guidance (emphasis added) (53):

> **Injuries must be identified with a reasonable degree of specificity** in terms that are meaningful to coaches, other club officials, the media, and the public. For example, leg injuries must be specified as ankle,

> knee, thigh or calf. Arm injuries must be identified as a shoulder, elbow, wrist, hand, or muscle injury. Listing an injury simply as "leg," "arm," "upper body," or some other vague description is not acceptable. **For quarterbacks, kickers, and punters, the report must designate "left" or "right" if the injury is to the arm/hand of a quarterback or the leg/foot of a kicker or punter**.

"Reasonable degree of specificity" here is subject to uncertainty, and the exact threshold can clearly vary by position and injury. However, for us there is also another wrinkle: frequently additional details can be garnered from media interviews or other sources, and FO has regularly tried to gather that information. Thus, for example, while the 2015 official injury report for Jaguars defensive lineman Dante Fowler may specify him as going on IR with a "knee" injury, his injury is more correctly coded in our data as a "Knee – ACL tear." This information is not always available, however – it tends to be more easily available for recent injuries, more severe injuries, and higher-profile players. Even when it is available, we cannot be certain how often FO has captured it. Thus a true medial collateral ligament (MCL) knee sprain could be coded in our data as "Knee," "Knee Sprain," or "Knee – MCL Sprain," and it's difficult to predict which it will be. Particularly at granular levels, then, we run the risk of substantial misclassification by injury type. On the other hand, the more granular categories – such as ACL tears and high ankle sprains – can be important to consider and differentiate from more general "knee" or "ankle" injuries.

To address this issue we propose a two-tier injury classification system: one more granular tier incorporating some of the additional data collected by FO, and a second higher-level anatomical tier that more closely aligns with the NFL's injury report requirements and is expected to reduce the misclassification that occurs at the more granular level. Our proposed scheme is below; of note, the granular category is condensed from 380 different injury descriptions in the FO data after cleaning (before that it was over 1,600):

Table 2.1. Injury categorization schema.

Granular Injury Type (51 categories)	Condensed Injury Type (39 categories)
Abdomen	Abdomen
Achilles	Achilles
Ankle – High Ankle Sprain	Ankle
Ankle – Other	
Ankle – Sprain	
Arm – Broken	Arm
Arm – Other	
Back	Back
Biceps	Biceps
Buttocks	Buttocks
Calf	Calf
Chest	Chest
Elbow	Elbow
Eye	Eye
Face	Face
Finger	Finger
Foot – Broken	Foot
Foot – Lisfranc	
Foot – Other	
Toe – Other	Toe
Toe - Turf Toe	
Groin	Groin
Hamstring	Hamstring
Hand	Hand
Head – Concussion	Head
Head – Other	
Heart	Heart
Hip	Hip
Illness	Illness
Knee – ACL	Knee
Knee – Other	
Knee – Sprain	
Knee - Tear, non-ACL	
Leg – Broken	Leg
Leg – Other	
Lung	Lung
Neck	Neck
Non-Injury	NFI
Other	Other
Pectoral	Pectoral

Pelvis	Pelvis
Quadriceps	Quadriceps
Ribs	Ribs
Shoulder – Other	Shoulder
Shoulder – Tear	
Spine	Spine
Thigh	Thigh
Thumb	Thumb
Triceps	Triceps
Unknown	Unknown
Wrist	Wrist

4. *Methodologic Challenge: Calculating Injury Risks and Rates*

Football and other sports injury studies have a variety of ways for calculating measures of disease frequency:

<u>Injury Rates</u>

Generally speaking, an incidence rate for sports injuries could be written as $\frac{\#\ of\ injuries}{Total\ athlete{-}time\ at\ risk\ for\ the\ injuries\ in\ the\ numerator}$. The numerator in this ratio is calculated as the number of injuries among players who played at least 1 regular season game in their career, with adjustments for training camp to account for injuries that did not last to the regular season. The calculations for the denominator are more complex. Sometimes actual hours of athlete participation in athletic activity putting them at risk for injury are measured or can be estimated (29). More often, however, broader categories of time such as athlete-game, athlete-practice, athlete-exposure (AE, defined as 1 athlete participating in one game or practice), or team-game (defined as 1 team playing 1 game) are used (17, 171). In the football injury literature, athlete-exposure (AE) is the most common unit used for incidence rates (3, 4, 7, 34, 50, 171). This is the unit we will use when calculating incidence rates for this dissertation. AEs will be calculated by summing up the number of player-games and the approximate number of practices multiplied by the number of players from our target population participating in those practices (the 53-man roster as an approximation).

This method may underestimate true injury rates because it does not account for injured players missing practice on a day-to-day basis, thus inflating the denominator. It also may inappropriately count some players who make the 53-man rosters but never played a regular-season game – and who thus wouldn't be in the numerator – in the denominator, biasing our estimate upwards. In addition, it fails to account for the fact that different players will have different levels of participation and work in practice – in one practice a starting cornerback may make dozens of quick accelerations and cuts while a backup QB will make virtually none.

Their "true exposure" to injury risk is going to be different, but our AEs will count them each as 1 in the denominator.

Risks

The primary time period for risks in our analysis is a single season (i.e., we most commonly ask "what is the risk of player X suffering Y injury over the course of the season?). A season is defined as the beginning of training camp through the end of the regular season, excluding the postseason. The general formula for injury risk is: $\frac{\#\ of\ athletes\ injured}{\#\ of\ athletes\ at\ risk\ for\ injury\ at\ the\ start\ of\ a\ season}$ (171). The numerator is defined as the number of players suffering an injury that impacts them in the regular season (either by occurring in the regular season, placing them on IR, or occurring in training camp but evident into the regular season) who are included in the denominator. The denominator for an all-injury/specific injury risk is all players without any injury/that specific injury at the beginning of a season. All injuries will be treated as potentially recurrent between seasons (i.e. having a hamstring injury two seasons ago doesn't exclude you from the denominator for the current season). We will also assume all players are healthy at the beginning of training camp unless they are on the PUP list – which is specifically for players entering training camp with an injury (51).

As mentioned above, NFL players over the course of a season are an open but stable-dynamic cohort – as players get injured, other players enter the roster to replace them. This can be accounted for in injury rates but is harder to address in 1-season injury risks (171). For 1-season injury risks, we assume all non-PUP players are healthy by the start of training camp and propose the following denominator: all players with >= 1 regular season game in their career who are on a team's week 1 53-man roster, plus any player with >= 1 regular season game who was put on IR for the entire season. This counts players who would have been at risk for injury in the regular season had they survived that long, as well as their non-injured replacements who have an entire regular season – and, if they were on the week 1 53-man roster, very likely the entirety of training camp – at risk for an injury.

Temporal Variation that Impacts Injury Rates and Risks

An evaluation of temporal changes in injury rates and risks may be complicated due to three sources of systematic error:

- Number and Types of AEs changing over time: The 2011 collective bargaining agreement (CBA) between the NFL and its players' union reduced the numbers of padded practices in training camp and the regular season (by as much as 50% in training camp and perhaps more in the regular season) (148-150).
    - Effect on Rates: This decreases the denominator for rates in recent years, which may inflate injury rates even if it reduces the number of injuries. More injuries tend to happen earlier in

training camp (79), meaning the numerator will decrease proportionally less than the denominator).

- Larger Rosters: The 2011 CBA also increased maximum roster sizes in training camp from 80 to 90 players, though the 53-man regular season roster size did not change (the game day roster size increased from 45 to 46, but this was effectively offset by the removal of the 3rd emergency QB designation) (148).
    - Effect on Rates and Risks: This is expected to be negligible because the target and study populations are limited to players who played at least one regular season game, and the majority of these additional training camp roster spots are occupied by players who never make a regular season or game-day roster.
- More Players Playing in the Regular Season: Data from pro-football-reference has shown an approximately 4% increase in the number of players playing in a regular season game from 2007 (1,903) to 2015 (1,979). The observed increase could be from more injury replacements or from increasing rotation of players within games.
    - Effect on Rates: If the observed increase is from increasing rotation of players, that could mean an "AE" today poses lower injury exposure risk than an "AE" in an earlier year, potentially biasing comparisons across years (with rates in more recent years being lower than they should be for a fair comparison).
    - Effect on Risks: This is expected to be negligible because of how we have chosen to define our risk denominator (players on the 53-man roster or on IR for 16 games). The majority of this increase is anticipated to be coming from players within the week 1 53-man roster (i.e. increasing rotation), rather than from totally new players being swapped in (e.g. injury replacements).

5. Methodologic Challenge: Multiple Injuries

It is possible for players to accrue multiple injuries on the injury report simultaneously, either in the same game or over multiple weeks. In those cases it is common to choose a primary injury (171), and we will do so with the following algorithm: 1. The earlier injury will take primacy until it is removed from the player's injury report entry, 2. Unless the later injury immediately sends the player to the IR list or is otherwise obviously more severe (e.g. if a player has a hamstring injury from week 2 onwards, but in week 5 tears his ACL in practice, the ACL becomes the primary injury for week 5).

6. Methodologic Challenge: Recurrent Injuries

The FO database tracks injuries by week. We defined an injury as a new, separate event if it meets 1 of 2 criteria: 1. It is of a different general type (e.g. foot, ankle) from any previous injury that season, or 2. It is of the same type as a previous injury that season, *but* the player has not been on the injury report with that injury for at least 2 weeks. For example, if Player X is listed with a hamstring injury in weeks 2-3, then suffers a shoulder injury for weeks 4-7, then re-injures his hamstring in week 10, these will be counted as 3 distinct injuries. If the second hamstring had occurred in week 5, however, we could consider it a continuation of the first hamstring injury and the player would be counted as having 2 injuries. This helps account for players who are brought back from an injury too soon and avoids any issues with injury reports not appearing during a team's bye week.

7. *Methodologic Challenge: Estimating Injury Severity and Return-to-Play*

Many studies have sought to measure injury severity, and – while some have access to detailed medical records that record, for example, the grade of a muscle strain – most of them have used the amount of time a player is away from practice and games as a proxy (3, 7, 34, 172-175). This typically works well for relatively short-term injuries that occur in the early or middle parts of the season, but for long-term injuries – such as ACL tears – or moderate injuries that occur late in the season, this estimate can fall short. In epidemiologic terms, we have censoring – a player can only miss days until the end of the season, then observation essentially stops and they're out until the next season (unless you're following them through the offseason and are able to estimate when they would have been able to return to practice, but that is rare). To address this issue, we'll use survival analysis methods to generate median return-to-play (RTP) estimates for each injury. Only injuries resulting in the player missing all 16 games or occurring during the regular season (i.e. not appearing on the week 1 injury report) will be used for this analysis. This will avoid downward bias from, for example, a 3-week hamstring injury occurring in preseason week 3 that then only appears to hamper a player for 1 week during the regular season.

One added consideration for the NFL in particular is the IR system (51). The incentives behind ending a player's season are complex, and a player being placed on IR doesn't always mean they have a season-ending injury. It may mean the team wants to keep them but free up a roster spot for another player. In addition, it becomes less costly for teams to put players on IR later in the season they get hurt, so a relatively minor injury is more likely to place a player on IR in week 15 than week 6. Once a player is on IR, he is out for the rest of the year (unless he is listed as IR-Designated for Return, an option that was introduced in 2012 and may be used by each team once per year). This issue is likely to bias the RTP estimates upwards. This bias may differ by position – for example, it may be less of a problem for QBs, who are less likely to be placed on the IR list in borderline cases. Unfortunately, any attempts at corrections would probably inject more uncertainty than they remove.

8. *Methodologic Challenge: Survivor Bias in Aging and Career Snapcount Analyses*

When investigating how injury risks and rates vary with chronological age or career snapcount, it is important to consider that their effects can be difficult to assess in an open cohort such as the NFL due to survivor bias. Survivor bias can impact the analyses via two mechanisms: 1.) only heartier players with a lower baseline injury risk continue to play into their later years or accumulate more snapcounts in the NFL, and 2.) positions that get hit and injured less, and thus have longer careers (e.g. QBs and kickers), are disproportionately represented in older age groups/higher snapcount categories. Either one causes older players to exhibit a substantially lower baseline injury risk, on average, than younger or less experienced players, which could make aging and experience appear to have no or a protective effect against injuries. One method to control for this and properly estimate the effect of aging and snapcount is to use closed cohorts of players who survive to a certain age or snapcount mark in the NFL (e.g. only those players who played to 30 years or 5,000 snaps or later) and then examine injury risks and rates in those cohorts up to the minimum level specified for the cohort (e.g. 30 years/5,000 snaps).

9. *Methodologic Challenge: Categorizing Special Teams Players*

Another issue when evaluating injury rates and risks by position is how to categorize special teams (ST) players. There are three specialized positions who play only on ST: placekickers, punters, and long snappers. Other players, however, especially lower-string backups, may be listed as one position (e.g. DB) but actually play primarily on special teams. As the data do not allow differentiating between ST players and those who play their listed position on offense or defense, the ST category will consist solely of placekickers, punters, and long snappers.

Chapter 3: Specific Aim 1. Descriptive Epidemiology of NFL Injuries, 2007-2015.

I. Abstract

Introduction: Football is a popular and violent sport with injury rates substantially above those of other professional sports in the U.S. Despite this, descriptive epidemiology of NFL injuries is surprisingly sparse.

Objective: We sought to calculate overall NFL injury rates and 1-season risks and investigate their associations with an array of player-, player-season-, and game-level variables.

Methods: A total of 19,389 player-seasons with 17,652 injuries from the 2007-2015 seasons were studied. Players without at least one career NFL game were excluded. Injuries were identified using a prospectively-collected database from the website Football Outsiders. The database was derived from NFL injury reports but supplemented with other sources. Injury rates per 1,000 regular season athlete-exposures (one athlete participating in one game or practice) and 1-season risks (regular season week 1 through regular season week 17 practices) were calculated. Rates and risks were compared across positions, turf type, game weather conditions, travel, rest days, week of season, year, player weight, age, career snapcounts, and two-year injury history. We calculated injury-specific rates and risks for ankle, back, concussion, groin, hamstring, knee ligament, shoulder, and upper extremity fractures.

Results: The overall injury rate was 15.1 per 1,000 AEs (SE 0.1). 68.1% of player-seasons involved at least one injury; 38.9% involved at least one missed game due to injury. Injury rates (per 1,000 AEs) were higher among running backs (20.7 per 1,000 AEs) and other mobile positions (range 16.9-17.4) than offensive (12.8) or defensive linemen (15.1). 2012-2015 visiting team injury rates were higher on artificial turf than grass (18.2 vs. 16.7); among specific turf types, A-Turf (21.1), Momentum Turf (19.3), and FieldTurf (19.2) all exhibited elevated injury rates. Injury rates were higher for heavier players except running backs. Hamstring and groin injuries were more common during warmer conditions and earlier in the year, while the corresponding results for concussions were in the opposite direction. Back, groin, hamstring, ankle, and knee ligament injury rates rose with increasing player age. Longer overall injury histories were associated with greater injury risk; this association was similar for specific injuries except for face and upper extremity bone and joint injuries. While reported injury rates did rise from 2007-2015, the largest increases occurred in minor injuries that caused no missed games.

Conclusions: NFL injuries are common. Rates varied by several known injury risk factors including position, weight, age, turf, weather, and injury history. While reported injury rates have also risen in recent years, this may be attributable to better reporting.

II. Introduction

American football is the most popular professional sport in the U.S (1). This popularity is reflected in the number of athletes playing it: in the 2013-14 school year there were 14,262 high schools with boys' 11-player football programs, comprising 1,093,234 athletes (8); the National Collegiate Athletic Association (NCAA) reported 70,147 men's college football players in 2013 (9); and in 2015, 1,979 players were listed on a National Football League (NFL) game-day roster for at least one regular season game, with a few hundred additional players on practice squads or in training camps (10). Football is also an inherently physical, chaotic, and violent game. Injuries occur with regularity in both practices and games in the NFL: previous studies have shown the injury rate is approximately 15-18 injuries per 1,000 athlete-exposures (3, 17). Athlete-exposure (AE) is a common measure in sports injury research, defined as a single athlete's participation in a game or practice (3). The rates in the NFL are approximately 5 times higher than those for high school football (7, 20, 176), approximately 1.5-2 times higher than those for college football (7, 33, 34, 176) or any college sport (21). NFL injury rates are also higher than the corresponding rates in Major League Baseball (MLB), the National Basketball Association (NBA), and the National Hockey League (NHL) (160, 161, 166, 176), as well as soccer and Australian Rules Football (162, 163, 176). Rugby appears to have injury rates comparable to those in the NFL, though there is some variation across studies (38, 164, 165, 176, 177). The number of studies evaluating NFL injuries increased over time: 78 studies appeared in press in the 3-year period from 2010-12 versus 28 studies published in the 5-year period 2000-04 (60). In the 2010-12 period the NFL also passed the MLB as the most studied U.S. professional league with regards to injuries (60).

Despite this increase in research interest, descriptive epidemiology data on NFL injuries are sparse. The most important data source is the NFL's Injury Surveillance System (NFL ISS), which has been in existence since 1980 (40, 41). However, most studies using the NFL ISS are focused on specific types of injuries such as ulnar collateral ligament (UCL) injuries or triceps tendon tears (42-48) rather than incidence estimates across a wide range of injuries. To our knowledge, only two previous studies exist that provide even reliable total counts of NFL injuries (41, 49). The reasons for that are unclear but may involve data access and research approval issues.

In the absence of access to NFL ISS data, an alternative source of data are the NFL's public injury reports, but research here is also limited. The existing injury report-based studies (17, 56) are limited because they used data from only two (2012 and 2013) seasons, were unable to consider several potentially important risk factors (e.g. precipitation, player weight and age), and did not calculate injury rates by AE (a common person-time unit in epidemiology sports injuries). Additionally, no study to date has rigorously calculated 1-season risks for NFL injuries.

We sought to fill these knowledge gaps by using a unique database of injuries created by football analytics researchers to supplement public injury reports with other information from media reports (167). The study's objectives were three-fold: 1. To calculate overall epidemiologic rates per 1,000 AEs and 1-season risks of NFL injuries **(Aim 1a)**; 2. To investigate the associations between injury rates and risks and a range of player-, player-season-, and game-level variables **(Aim 1b)**; 3. To investigate how these associations vary by injury type using injury rates **(Aim 1b)**.

III. Methods

A. Data Sources

Data on injuries comes from a database maintained by the football analytics website Football Outsiders (167). The data were collected prospectively from the 2007-2015 regular seasons. It is based on the official public injury reports released weekly by each NFL team, supplemented with additional details from media reports where available. Information for all injuries includes player name, team, position, week, season, injury type, final practice report status, and the player's anticipated availability and actual participation in that week's game. Due to possible temporal variations in injury reporting and data collection procedures, only injuries to players with at least one regular season game appearance were included. Thus, the study population includes all NFL players who appear in at least one regular season NFL game.

Other data on players (position, weight, height, and career snapcounts) and team-seasons (head coaches, schemes, and play types on offense and defense) were also provided by Football Outsiders. Regular season game-level data (date, time, home and away teams, temperature, stadium and turf type) were collected from Pro-Football-Reference.com (120). Turf type for each game was ascertained from publicly available online resources. Game-day precipitation data were extracted from Weather Underground using the weatherData package in R (178).

B. Injury Counts and Measures of Injury Frequency

Risk Period: Our primary risk period is the "regular season" from week 1 through week 17's practices. Injury information from week 17 games is only available for a subset of teams that make the playoffs.

Injury Counts: An "injury" was an event that appeared on the public injury reports NFL teams release before each regular season game or that placed a player on the "injured reserve" (IR) list – a designation given to players with long-term injuries. We included both time-loss and non-time-loss injuries. We defined an injury as a new, distinct event if it meets one of two criteria: 1. It is of a different general type (e.g. foot, ankle) from any previous injury that season, or 2. It is of the same type as a previous injury that season, but the player has not been on the injury report with that injury for at least 2 weeks excluding byes. Injuries were designated as occurring the week prior to their first appearance on a report, though we could not distinguish between injuries occurring in the previous week's game or the current week's practices. Our data contained

392 distinct injury definitions (e.g. anterior cruciate ligament (ACL) tear) over 41 anatomic locations (e.g. Knee).

Specific Injuries: We calculated risks and rates for all injuries together as well as eight specific types of injuries, chosen to represent common injuries across a wide range of body parts and mechanisms: soft tissue injuries (hamstring, groin, back Muscle); joint injuries (Ankle Sprains, Knee Ligament Injuries); contact-related joint injuries (Shoulder); and other contact-related injuries (Concussions, Upper Extremity (UE) Fractures). Further details and definitions are available in Table A1 of the Appendix.

Specific Injury Types for Prior Injury History Analyses: We grouped all 392 original injury definitions into 20 categories for analyzing the association between prior injury history and 1-season risk of missing 1+ games due to injury. All bruises and fractures except ankle and foot fractures were excluded. The categories were chosen a priori based on similar clinical expectations for future injury risk. The category definitions are given in detail in Table A1. Three categories ("Organ," "Other," and "Unknown") were excluded from all analyses due to small sample sizes (N < 20 injuries); this left 17 categories for all analyses of prior injury history.

Measures of Injury Frequency: Three different measures of injury frequency were calculated. Injury rates were calculated per 1,000 athlete-exposures (AEs), with one AE defined as one player participating in a game or practice. The formula for an injury rate is $\frac{\#\ of\ reported\ injuries}{Total\ athlete-exposures\ while\ at\ risk\ for\ the\ injuries\ in\ the\ numerator}$. The denominator used the 53-man active roster of each NFL team as a proxy for our target population of players appearing in at least one career game. We then calculated the AEs at risk as: (53 players per team x 32 teams x 4 practices per week x 17 weeks x 9 seasons) + (46 active game-day players x 480 team-games per season x 9 seasons) = 1,236,672 AEs. We then subtracted AEs for any player still on the 53-man roster who did not play in a game or did not participate in a practice[1](179). Because we did not have data on what play the injury occurred, we could not calculate injury rates on a per-play or per-snap basis. This also precluded us from calculating injury rates for rushing, passing, and special teams plays.

1-season injury risks were calculated using the formula $\frac{\#\ of\ athletes\ reported\ injured\ during\ season}{\#\ of\ athletes\ at\ risk\ for\ injury\ at\ start\ of\ season}$. To identify players at risk for a full season we restricted both numerator and denominator to player-seasons

[1] Our data set only had information from the last practice report issued by each team each week (for a Sunday game, Friday). This was then cross-referenced with full practice report data from CBS Sports in 2016 that showed that players with full/limited/no participation in their last practices missed on average 0.50/1.45/2.53 of 3 practices with reports that week, counting a limited practice as 0.5 practices missed. Extending this to 4 practices per week we subtracted 0.67/1.94/3.38 practices for players with a full/limited/no participation listing in our data. Those without a final practice status listing were counted as not missing any practices. For full season estimates, we applied an identical proportionate reduction to the 673,920 additional AEs we estimate were accrued during training camp and preseason.

where the player played at least one snap in week 1. This cutoff produced 12,687 player-seasons from 2007-2015, or 44.0 players per team-season over that timeframe. We also calculated the 1-season risk of missing 1 or more games due to injury, which may be a more relevant outcome for some stakeholders. This was calculated using the formula $\frac{\#\ of\ athletes\ missing\ 1{+}game\ due\ to\ injury\ during\ season}{\#\ of\ athletes\ at\ risk\ for\ injury\ at\ start\ of\ season}$.

Ancillary Injury Frequency Measures: Because the risks estimated above were conditional on a player making it to the first regular season game healthy (i.e. not out for the season), we sought to re-estimate these measures for a "full season" including training camp and preseason games but not the postseason. This may be a more relevant risk period for teams, training staffs, and other stakeholders. We modified injured player counts to include injuries occurring in training camp or preseason and impacting the player in the regular season (i.e. injuries appearing on the week 1 reports). We modified risk denominators to include players who missed all 16 regular season games. "Full-season" risks stratified by a subset of important variables are provided in an Appendix.

Lastly, a new measure – "end-season toll" – was calculated using as a risk numerator the number of athletes in the denominator who were on the injury report for regular season week 17. This captures the percent of players from the week 1 roster who were injured at the end of the regular season. Calculations of end-season toll stratified by a subset of variables is provided in the Appendix.

C. Injury Risk Factors

In addition to calculating overall injury rates and risks, we examined their association with various known or hypothesized risk factors at various levels. At the player level we investigated the time-independent variables position, weight, height, and body mass index (BMI) at the time the player entered the NFL. At the player-season level we considered age; total career snap count from all prior seasons; the percent of a player's team's plays that were rushes vs. passes; week of season; year; and the player's injury history over his previous two seasons. At the game level we considered the game's turf type, temperature, precipitation, rest since the previous game, and whether each player was at home or away. We limited analyses of turf type to the 2012-15 seasons to minimize the risk of turfs introduced in more recent years appearing to be worse because of a time trend of rising injuries; we also excluded home team injuries to remove the effects of the home team's roster, training staff, and other team-level factors that can impact injury rates. We defined all indoor stadium (domes and those with retractable roofs) games as dry and as their own temperature category. Because we lack data on injury timing more specific than week, for all game-level variables we made an assumption that all injuries occurred in the previous week's game rather than that week's practices. Studies have shown that >80% of NFL injuries occur in games rather than practices (17, 41, 47, 54, 55).

How we defined a player's injury history merits a brief discussion. Injury histories were defined as the number of discrete injuries of a given type over a player's previous two NFL seasons. Because we did not have reliable injury data from college or before 2007, we excluded seasons before 2009 as well as each player's first two seasons in the NFL. This left 7,525 player-seasons from 2009-2015 for the injury history analysis vs. 12,687 player-seasons in all other analyses.

When calculating injury rates and risks we distributed AE and player-seasons at risk proportionately to their distribution across risk factor categories. A detailed description of these allocations is provided in the Appendix.

D. Statistical Analysis

Using the definitions above we calculated injury rates per 1,000 AEs and 1-season risks for all injuries and eight specific injury types. As each team accrued 4,340 AEs each regular season, a 1-unit change in injury rate equates to 4.3 fewer injuries for a team over that time span. All frequency measures were calculated overall and stratified by the variables listed above except for game-level variables, for which we only calculated rates. Some data were restricted to an Appendix. Standard errors (SEs) were calculated using normal approximations to the Poisson distribution for counts/rates and binomial distributions for risk and prevalence. We present uncertainty in our rates and risks using one standard error (1-SE) bars rather than 95% confidence intervals to avoid conflation with null hypothesis significance testing. 95% confidence intervals can be generated from our data by adding or subtracting 1.96 times the standard error to our point estimates. Results for categorical variables variables are presented in tabular format. Other continuous variables are presented as line graphs or scatterplots.

For categorical variables we identified risk and rate differences meriting attention using a "minimally important difference" (MID) approach (180, 181). This approach is common in patient-reported outcomes in orthopedics and elsewhere, but it is applicable to population-level injury rates as well (182, 183). We defined a threshold above which an effect size would be considered meaningful to players, teams, or other stakeholders. The MID by its nature is subjective and depends on both the population under study and how big an effect a subject or other stakeholder considers worthwhile (181). We defined two MIDs. For specific injuries we chose an MID of one less injury of a given type per team per season – this translates to a rate difference of approximately 0.25 per 1,000 AEs. For overall injuries we chose an MID of 4 fewer injuries per team per season – this translates to a rate difference of approximately 1.0 per 1,000 AEs. This threshold was chosen because avoiding 4 injuries can materially impact an NFL team's season. The 17,652 injuries in our data caused 24,612 missed games for an average of 1.4 missed games per injury; 4 additional injuries translates to 5.6 missed player-games on average, which – especially if they occur to high-value players or are particularly severe injuries – could be the difference between teams winning or losing one or more of their 16 regular season games. Such a loss could also affect a team's bottom line. The average NFL salary is approximately $1.9 million, or approximately $120,000 for each of 16 regular season games (184). An average of 5.6 missed games translates to approximately $672,000 per team per season in lost player productivity due to injuries. For the 32 NFL teams as a whole, then, a rate difference of 1.0 injury per 1,000 AEs translates to $21 million more or less per year in lost productivity. All differences also had to be at least 1.5 SEs in magnitude to limit the identification of differences that are due to random error.

The MID is typically used to make comparisons between two groups, such as subjects before and after a treatment or running backs versus wide receivers. It is less clear how to apply this framework to variations in injury rates over a continuous variable such as temperature since the magnitudes of differences will be sensitive to the cutpoints of the variable used to make comparisons. Instead we present these data using line graphs of injury risks or rates across small buckets of each continuous variable (for example, 5-degree buckets for temperature). Bucket width was chosen to balance within-bucket homogeneity of rates with sample size concerns; all buckets had to contain a minimum of 20 player-seasons-at-risk over our study period. We then identified differences using two criteria: a consistent dose-response relationship (for example, did injuries increase or decrease in a consistent fashion over the entire range of temperatures we observed); and either physiologic plausibility or identification of the variable as a risk factor in prior literature. In the absence of a clear dose-response relationship, we considered any pairwise differences between buckets that exceeded the categorical MID to likely be chance findings resulting from multiple comparisons.

All analyses were performed in R version 3.3.2 and RStudio version 1.0.143. The Emory University IRB determined this project was not human subjects research as all data is publicly available.

IV. Results

There were 17,652 injuries in the 2007-2015 NFL regular seasons, corresponding to an injury rate of 15.1 per 1,000 AEs (SE 0.1) (Table 1). The 1-season risk of any injury for a player on the week 1 roster was 68.1% (SE 0.4%), while the 1-season risk of an injury costing a player at least 1 game was 38.9% (SE 0.4%) (Table 1). Among the specific injuries we studied, knee ligament injuries had by far the highest rate at 2.71 per 1,000 AEs; ankle sprains were second at 1.86 (Table 2).

Position:

Running backs (RBs) had the highest injury rate (20.7 per 1,000 AEs); followed by mobile positions such as linebackers (LBs), defensive backs (DBs), wide receivers (WRs), and tight ends (TEs) at around 17 per 1,000 AEs; then defensive linemen (DLs) at 15.1; offensive linemen (OLs) at 12.8, quarterbacks (QBs) at 8.6, and special teams players (STs) at 4.4 (Table 1).

With respect to specific injury types, RBs had above-average rates of ankle sprains, concussions, hamstring, knee ligament, and shoulder injuries (Table 2). DBs also had above-average concussion, groin, and hamstring injury rates (Table 2). LBs had elevated hamstring, knee, and shoulder rates (Table 2). Linemen (both OLs and DLs) had below-average rates of concussions and hamstring injuries but above-average rates of knee injuries (Table 2). OLs also had lower rates of groin but higher rates of ankle injuries (Table 2). TEs had the highest rate of concussions (1.72 (SE 0.16) per 1,000 AEs followed by DBs at 1.32 (SE 0.08)) (Table 2).

<u>Travel and Rest:</u>

Using our MID criterion there was no difference in injury rates for home and away games (Table 1). There was no clear trend in travel, though teams traveling 3+ time zones to the east (west coast to east coast, or any team to London) did have a lower rate than even home teams (13.7 vs. 14.9 per 1,000 AEs) (Table 1). Among the specific injury types we investigated, there were no differences between home and away games overall (Table 2).

Four-day (Sunday-Thursday) rest periods were associated with lower injury rates than typical 7-day (Sunday-Sunday) rests overall (14.4 vs. 16.0 per 1,000 AEs) (Table 1). When examined by injury type, the differences were only seen for knee and shoulder injuries (Table 2).

<u>Turf:</u>

Overall 2012-2015 visiting team injury rates were higher on artificial turf than grass (18.2 vs. 16.7) (Table 1). We also stratified by type of artificial turf; compared to natural grass over this period (16.7 per 1,000 AEs), A-Turf (21.1), Momentum Turf (19.3), and FieldTurf (19.2) all exhibited elevated injury rates. If we include home and visiting team injuries there is no longer an overall difference between grass and artificial turf (16.9 vs. 17.2 per 1,000 AEs), but FieldTurf (18.0) and A-Turf (18.8) remain elevated. There was no difference in grass and artificial turf visiting team injury rates from 2007-2011 (14.3 vs. 14.6 per 1,000 AEs).

<u>Precipitation:</u>

There were no overall differences between games that were dry (15.1 per 1,000 AEs), rainy (15.5), or snowy (14.5) (Table 1). When stratifying by injury type, snowy games were associated with lower rates of hamstring injuries and rainy games with lower rates of knee ligament injuries (Table 3). Data on precipitation stratified by turf type is available in the Appendix (Tables A2 and A3).

Table 3.1. Regular season injury counts, rates, and 1-season risk estimates for all NFL injuries, 2007-2015.

Variable	Injuries	AEs	Injury Rate per 1,000 AEs (SE)	Player-seasons with Injury	1-Season Injury Risk (SE)	Player-Seasons with 1+ Games Missed Due to Injury	1-Season Risk of Missing 1+ Games Due to Injury (SE)	Player-Seasons at Risk
Total	17,652	1,166,055	15.1 (0.1)	8,639	68.1% (0.4%)	4,930	38.9% (0.4%)	12,687
Position								
QB	585	67,834	8.6 (0.4)	237	68.1% (2.5%)	144	41.4% (2.6%)	348
RB	1,796	86,560	20.7 (0.5)	826	73.0% (1.3%)	530	46.8% (1.5%)	1,132
WR	2,241	130,677	17.1 (0.4)	988	74.2% (1.2%)	578	43.4% (1.4%)	1,331
TE	1,103	65,344	16.9 (0.5)	568	70.3% (1.6%)	348	43.1% (1.7%)	808
OL	2,553	199,662	12.8 (0.3)	1,302	66.3% (1.1%)	684	34.8% (1.1%)	1,963
DL	2,663	176,245	15.1 (0.3)	1,351	69.2% (1.0%)	721	36.9% (1.1%)	1,952
LB	2,607	152,532	17.1 (0.3)	1,316	70.7% (1.1%)	749	40.2% (1.1%)	1,862
DB	3,797	218,151	17.4 (0.3)	1,801	74.5% (0.9%)	1,098	45.4% (1.0%)	2,417
ST	307	69,050	4.4 (0.3)	250	28.6% (1.5%)	78	8.9% (1.0%)	874
Side								
Defense	9,067	546,928	16.6 (0.2)	4,468	71.7% (0.6%)	2,568	41.2% (0.6%)	6,231
Offense	8,278	550,077	15.0 (0.2)	3,921	70.2% (0.6%)	2,284	40.9% (0.7%)	5,582
Game Day Precipitation				-	-	-	-	-
Dry/Dome	14,322	946,198	15.1 (0.1)	-	-	-	-	-
Snow	689	47,499	14.5 (0.6)	-	-	-	-	-
Rain (> 0.05 in)	2,540	164,362	15.5 (0.3)	-	-	-	-	-
Turf Type[a]				-	-	-	-	-
Natural Grass	2,029	121,560	16.7 (0.4)	-	-	-	-	-
Any Artificial	2,319	127,170	18.2 (0.4)	-	-	-	-	-
Specific Turf Types[a]								
Natural Grass	2,029	121,560	16.7 (0.4)	-	-	-	-	-
A-Turf	145	6,883	21.1 (1.7)	-	-	-	-	-
Astroplay	142	8,581	16.5 (1.4)	-	-	-	-	-

Desso	328	18,586	17.6 (1.0)	-	-	-	-	-
FieldTurf	903	47,105	19.2 (0.6)	-	-	-	-	-
Matrix Turf	123	7,893	15.6 (1.4)	-	-	-	-	-
Momentum Turf	155	8,031	19.3 (1.6)	-	-	-	-	-
UBU	523	30,093	17.4 (0.8)	-	-	-	-	-
Rest								
4 days	754	52,381	14.4 (0.5)	-	-	-	-	-
5-6 days	1,307	79,271	16.5 (0.5)	-	-	-	-	-
7 days	11,379	711,674	16.0 (0.1)	-	-	-	-	-
8-11 days	1,818	110,641	16.4 (0.4)	-	-	-	-	-
12+ days	1,232	74,493	16.5 (0.5)	-	-	-	-	-
Travel Distance								
Home	8,601	578,567	14.9 (0.2)	-	-	-	-	-
Away	9,051	587,488	15.4 (0.2)	-	-	-	-	-
Within 2 Time Zones	8,086	520,191	15.5 (0.2)	-	-	-	-	-
3+ Time Zones West	468	31,054	15.1 (0.7)	-	-	-	-	-
3+ Time Zones East	497	36,243	13.7 (0.6)	-	-	-	-	-

[a]2012-2015, visiting teams only

Table 3.2. Regular season injury rates by injury type, 2007-2015. Red-shaded cells represent injury rates higher (using our MID framework) than those for the indicated referent group, while green-shaded cells represent the same but for lower injury rates.

Variable	Injury Rate per 1,000 AEs (SE)							
	Ankle	Back	Concussion	Groin	Hamstring	Knee (ligamentous)	Shoulder	UE Fracture
Total	1.86 (0.04)	0.71 (0.02)	0.92 (0.03)	0.67 (0.02)	1.27 (0.03)	2.71 (0.05)	1.27 (0.03)	0.14 (0.01)
Position (Ref. = Overall Average)								
QB	0.92 (0.12)	0.39 (0.08)	0.82 (0.11)	0.13 (0.04)	0.16 (0.05)	0.91 (0.12)	1.40 (0.15)	0.27 (0.06)
RB	2.99 (0.19)	0.65 (0.09)	1.21 (0.12)	0.71 (0.09)	2.03 (0.15)	3.80 (0.22)	1.52 (0.13)	0.22 (0.05)
WR	1.95 (0.12)	0.75 (0.08)	1.10 (0.09)	0.87 (0.08)	2.07 (0.13)	2.82 (0.15)	1.26 (0.10)	0.12 (0.03)
TE	2.04 (0.18)	0.83 (0.11)	1.72 (0.16)	0.52 (0.09)	1.22 (0.14)	3.11 (0.22)	1.20 (0.14)	0.11 (0.04)
OL	2.09 (0.10)	0.87 (0.07)	0.68 (0.06)	0.29 (0.04)	0.38 (0.04)	3.09 (0.13)	1.09 (0.07)	0.05 (0.02)
DL	1.83 (0.10)	0.89 (0.07)	0.56 (0.06)	0.68 (0.06)	0.74 (0.07)	3.06 (0.14)	1.36 (0.09)	0.09 (0.02)
LB	1.77 (0.11)	0.65 (0.07)	0.86 (0.08)	0.84 (0.07)	1.92 (0.11)	3.05 (0.15)	1.50 (0.10)	0.12 (0.03)
DB	1.99 (0.10)	0.64 (0.05)	1.32 (0.08)	1.01 (0.07)	1.95 (0.10)	2.52 (0.11)	1.47 (0.08)	0.25 (0.03)
ST	0.36 (0.07)	0.47 (0.08)	0.10 (0.04)	0.54 (0.09)	0.35 (0.07)	0.65 (0.10)	0.16 (0.05)	0.03 (0.02)
Side (Ref. = Offense)								
Defense	1.88 (0.06)	0.72 (0.04)	0.95 (0.04)	0.86 (0.04)	1.55 (0.05)	2.84 (0.07)	1.44 (0.05)	0.16 (0.02)
Offense	2.05 (0.06)	0.74 (0.04)	1.01 (0.04)	0.50 (0.03)	1.11 (0.05)	2.86 (0.07)	1.25 (0.05)	0.13 (0.02)
Game Day Precipitation (Ref. = Dry)								
Dry/Dome	1.84 (0.04)	0.71 (0.03)	0.89 (0.03)	0.68 (0.03)	1.26 (0.04)	2.75 (0.06)	1.29 (0.04)	0.14 (0.01)
Snow	1.92 (0.20)	0.91 (0.14)	0.96 (0.14)	0.51 (0.10)	0.84 (0.13)	2.89 (0.26)	1.35 (0.17)	0.25 (0.07)
Rain (> 0.05 in)	2.03 (0.11)	0.71 (0.07)	1.10 (0.08)	0.68 (0.06)	1.45 (0.09)	2.50 (0.13)	1.16 (0.08)	0.12 (0.03)
Turf Type[a] (Ref. = Natural Grass)								
Natural Grass	1.93 (0.13)	0.84 (0.08)	1.06 (0.09)	0.77 (0.08)	1.34 (0.11)	2.76 (0.15)	1.63 (0.12)	0.12 (0.03)
Any Artificial	2.11 (0.13)	0.71 (0.08)	1.42 (0.11)	0.66 (0.07)	1.36 (0.10)	3.34 (0.17)	1.46 (0.11)	0.12 (0.03)

A-Turf	2.06 (0.55)	0.44 (0.25)	2.05 (0.55)	0.29 (0.21)	1.92 (0.53)	3.65 (0.74)	2.37 (0.59)	0.29 (0.21)
Astroplay	1.66 (0.44)	0.23 (0.17)	1.17 (0.37)	0.59 (0.26)	1.88 (0.47)	2.80 (0.58)	1.89 (0.47)	0.23 (0.17)
Desso	2.01 (0.33)	0.87 (0.22)	1.52 (0.29)	0.86 (0.22)	1.19 (0.25)	3.32 (0.43)	1.58 (0.29)	0.05 (0.05)
FieldTurf	2.28 (0.22)	0.86 (0.14)	1.52 (0.18)	0.56 (0.11)	1.31 (0.17)	3.59 (0.28)	1.62 (0.19)	0.11 (0.05)
Matrix Turf	2.07 (0.52)	0.64 (0.28)	1.66 (0.46)	0.38 (0.22)	0.89 (0.34)	3.08 (0.64)	1.15 (0.38)	0.00 (0.00)
Momentum Turf	2.39 (0.55)	0.25 (0.18)	1.75 (0.47)	0.75 (0.31)	1.51 (0.44)	3.65 (0.69)	0.89 (0.34)	0.12 (0.12)
UBU	1.99 (0.26)	0.73 (0.16)	1.00 (0.18)	0.87 (0.17)	1.35 (0.21)	3.04 (0.33)	1.05 (0.19)	0.13 (0.07)
Rest (Ref. = 7 Days)								
4 days	1.70 (0.18)	0.52 (0.10)	0.88 (0.13)	0.54 (0.10)	1.20 (0.15)	2.36 (0.21)	0.95 (0.13)	0.14 (0.05)
5-6 days	1.82 (0.15)	0.86 (0.10)	1.01 (0.11)	0.79 (0.10)	1.21 (0.12)	2.85 (0.19)	1.29 (0.13)	0.10 (0.03)
7 days	1.88 (0.05)	0.74 (0.03)	0.94 (0.04)	0.69 (0.03)	1.25 (0.04)	2.66 (0.06)	1.30 (0.04)	0.13 (0.01)
8-11 days	1.99 (0.13)	0.68 (0.08)	0.99 (0.09)	0.52 (0.07)	1.15 (0.10)	3.02 (0.17)	1.25 (0.10)	0.14 (0.03)
12+ days	1.75 (0.15)	0.62 (0.09)	0.97 (0.11)	0.61 (0.09)	1.50 (0.14)	2.90 (0.20)	1.39 (0.13)	0.23 (0.05)
Travel Distance (Ref. = Home)								
Home	1.88 (0.06)	0.71 (0.04)	0.90 (0.04)	0.67 (0.03)	1.30 (0.05)	2.62 (0.07)	1.26 (0.05)	0.12 (0.01)
Away	1.85 (0.06)	0.72 (0.04)	0.95 (0.04)	0.67 (0.03)	1.24 (0.05)	2.81 (0.07)	1.29 (0.05)	0.15 (0.02)
Within 2 Time Zones	1.87 (0.06)	0.74 (0.04)	0.94 (0.04)	0.66 (0.04)	1.23 (0.05)	2.87 (0.08)	1.32 (0.05)	0.15 (0.02)
3+ Time Zones West	1.86 (0.25)	0.49 (0.13)	1.04 (0.18)	0.55 (0.13)	1.24 (0.20)	2.44 (0.29)	1.31 (0.21)	0.16 (0.07)
3+ Time Zones East	1.52 (0.21)	0.55 (0.12)	0.89 (0.16)	0.92 (0.16)	1.31 (0.19)	2.30 (0.26)	0.87 (0.16)	0.19 (0.07)

Green/Red Colors: Difference between rate and referent rate must be at least 0.25 per 1,000 AEs and 1.5 SEs.

[a]2012-2015, visiting teams only

<u>Temperature and Week of Season:</u>

Overall injury rates did not exhibit a clear dose-response relationship with temperature (Figure 1). Indoor games (stadiums with a dome or retractable roof) did not have different injury rates than outdoor games. When evaluating specific injuries, however, we observed varying trends. Leg muscle strains such as groin and hamstring injuries increased with rising temperatures, while concussion rates appeared to drop with higher temperatures (Figure 2). Indoor games did not have a higher rate for any of the specific injuries we investigated (Figure 2).

Figure 3.1. Regular season injury rates for all injuries by temperature, 2007-2015, with 1-standard error bars.

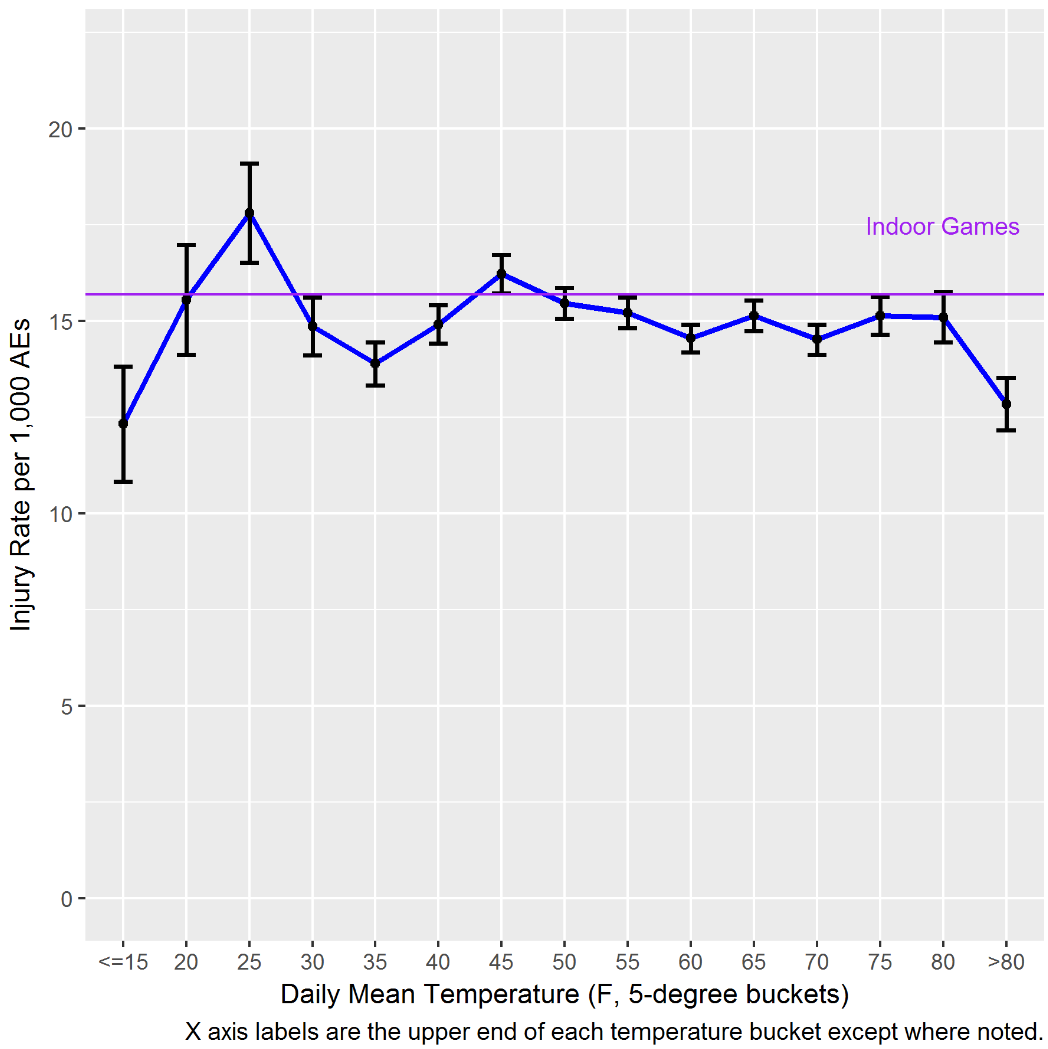
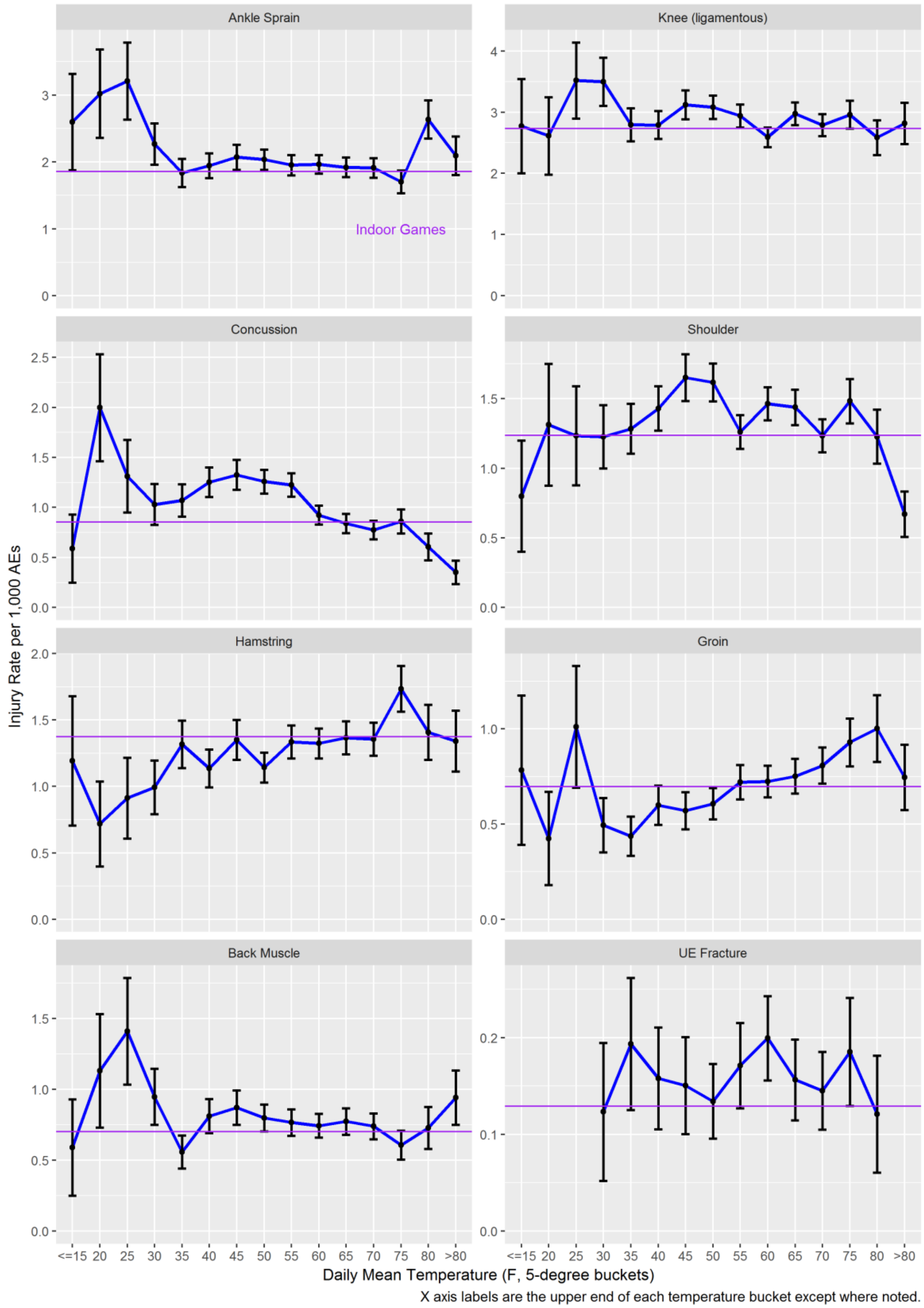


Figure 3.2. Regular season injury rates by temperature and injury type, 2007-2015, with 1-standard error bars.



When stratifying by week of season the analyses were restricted to indoor games to control for changes in temperature. Among indoor games injury rates did not vary over the season (Figure 3). After stratification by injury type, however, a more pronounced variation was observed. Hamstring and knee ligament injuries declined in the second half of the season (Figure 4), while concussions appear to increase over the course of a season (Figure 4).

Figure 3.3. Regular season injury rates by week of season, 2007-2015, with 1-standard error bars.

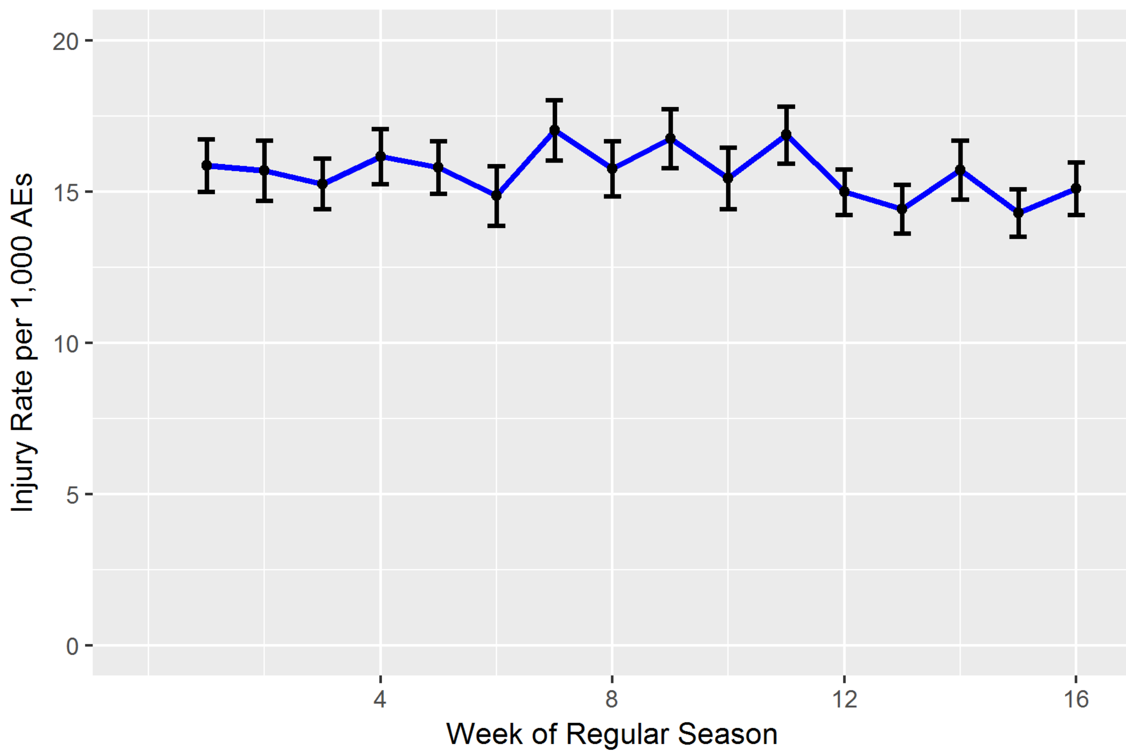
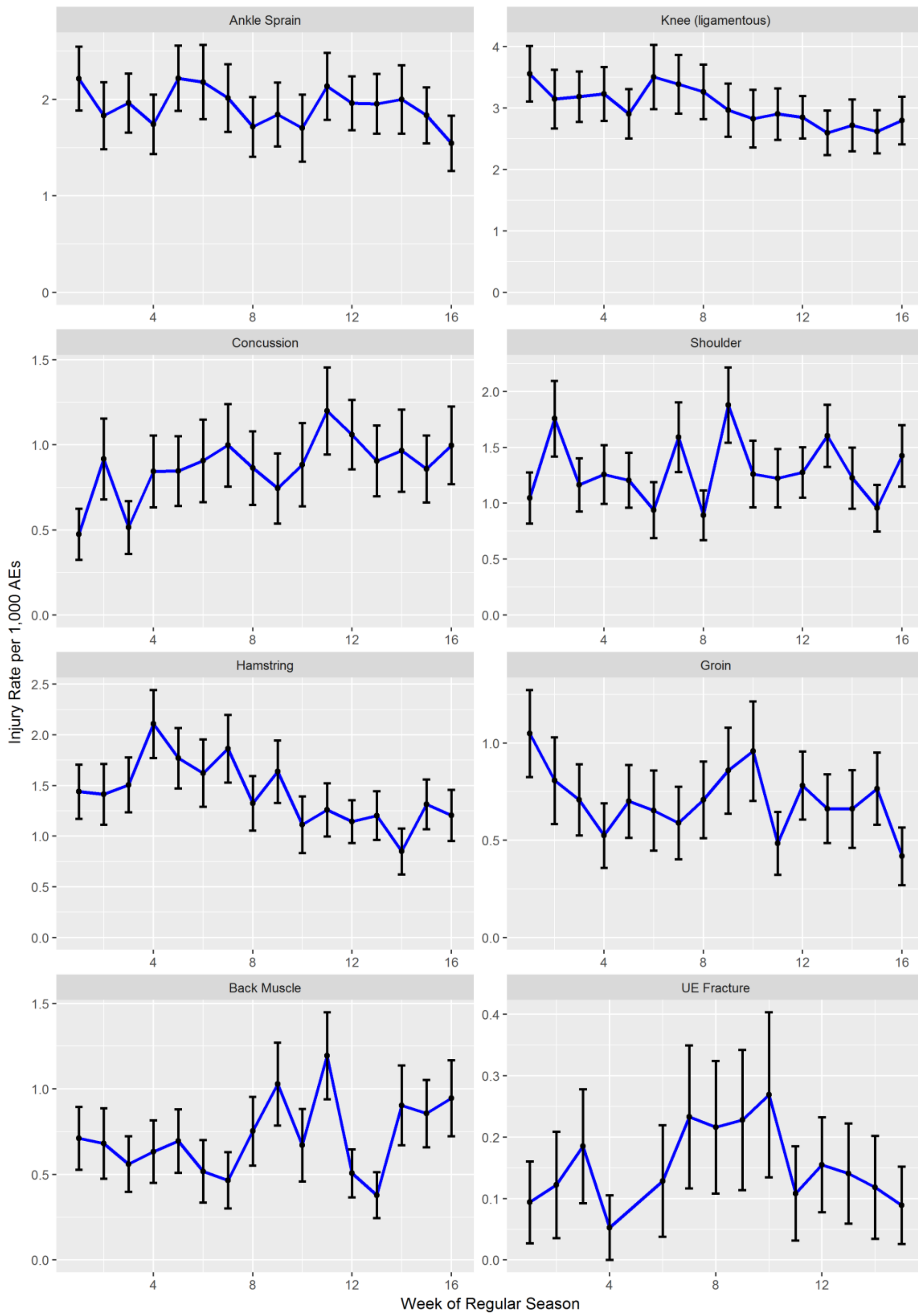


Figure 3.4. Regular season injury rates per 1,000 AEs by week of season and injury type, 2007-2015, with 1-standard error bars.



Player Size:

Data on injuries by 20-lb weight categories are presented by position. Increasing weight was associated with an increased injury rate for most positions (Figure 5a). Injury rates do not exhibit an association with weight for DLs. By contrast, among RBs and the heaviest TEs injury rates decrease with increasing weight (Figure 5a).

The association between weight and the 1-season risk of missing 1+ games due to injury were similar for most positions, with three notable differences. TEs experienced a more consistent decrease with increasing weight, LBs appeared to have a decreasing risk in contrast to their increasing rates, and WRs no longer exhibited an increase with rising weight (Figure 5b).

Although most position-specific analyses demonstrated no discernable association between player weight and injury type (Figure 6b), rates of hamstring injuries among LBs and DLs appeared to decrease with higher weights. The data for DLs exhibit the same trend with respect to groin injuries.

Figure 3.5a. Regular season injury rates by height, weight and position, 2007-2015, with 1-standard error bars.

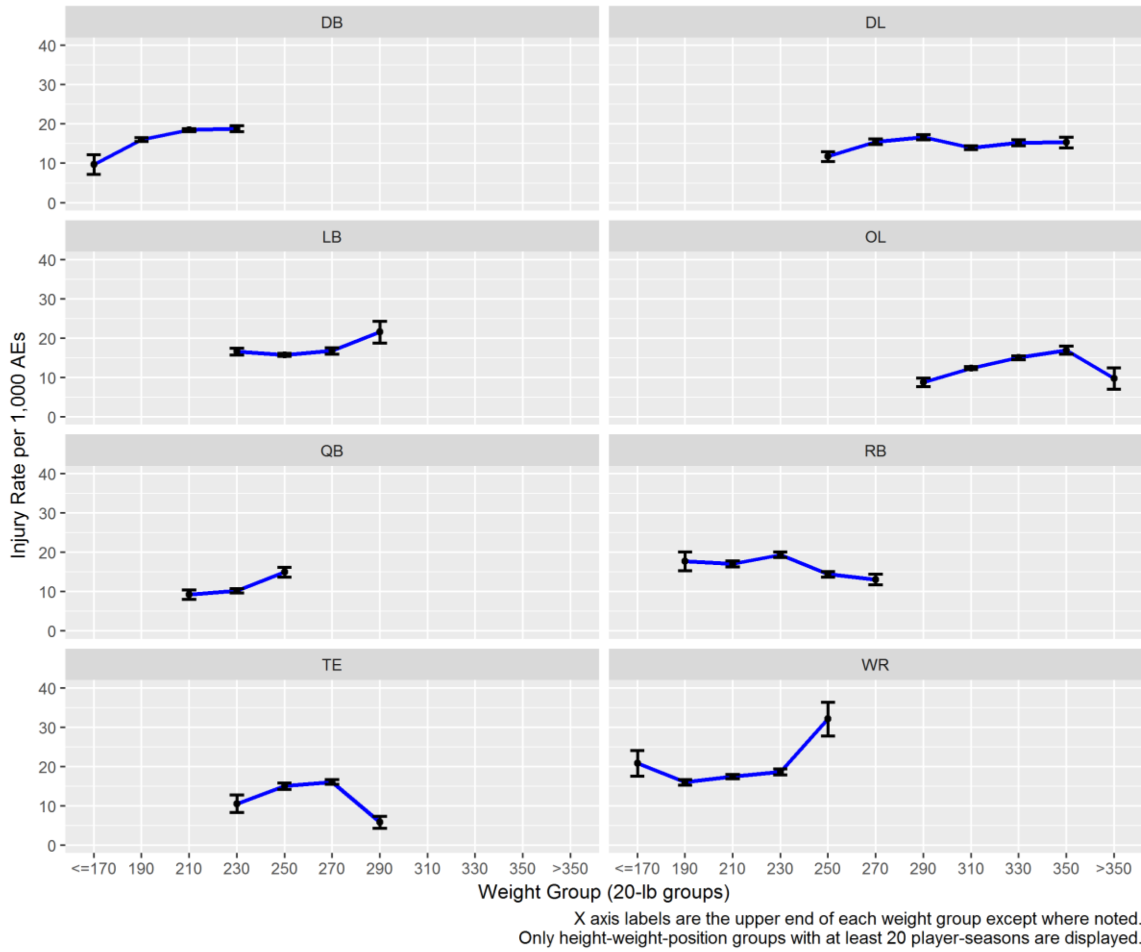


Figure 3.5b. 1-regular season risk of missing 1+ games due to injury, by weight and position, 2007-2015, with 1-standard error bars.

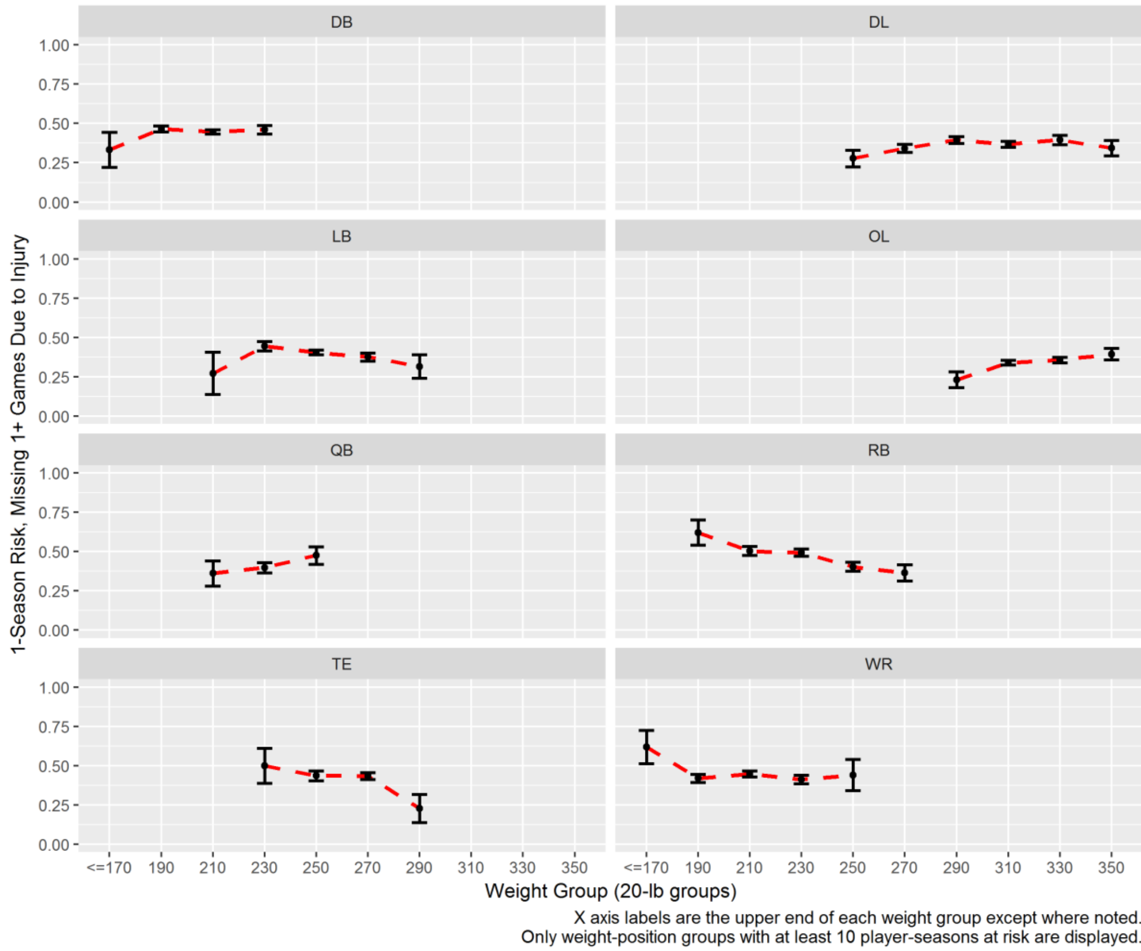
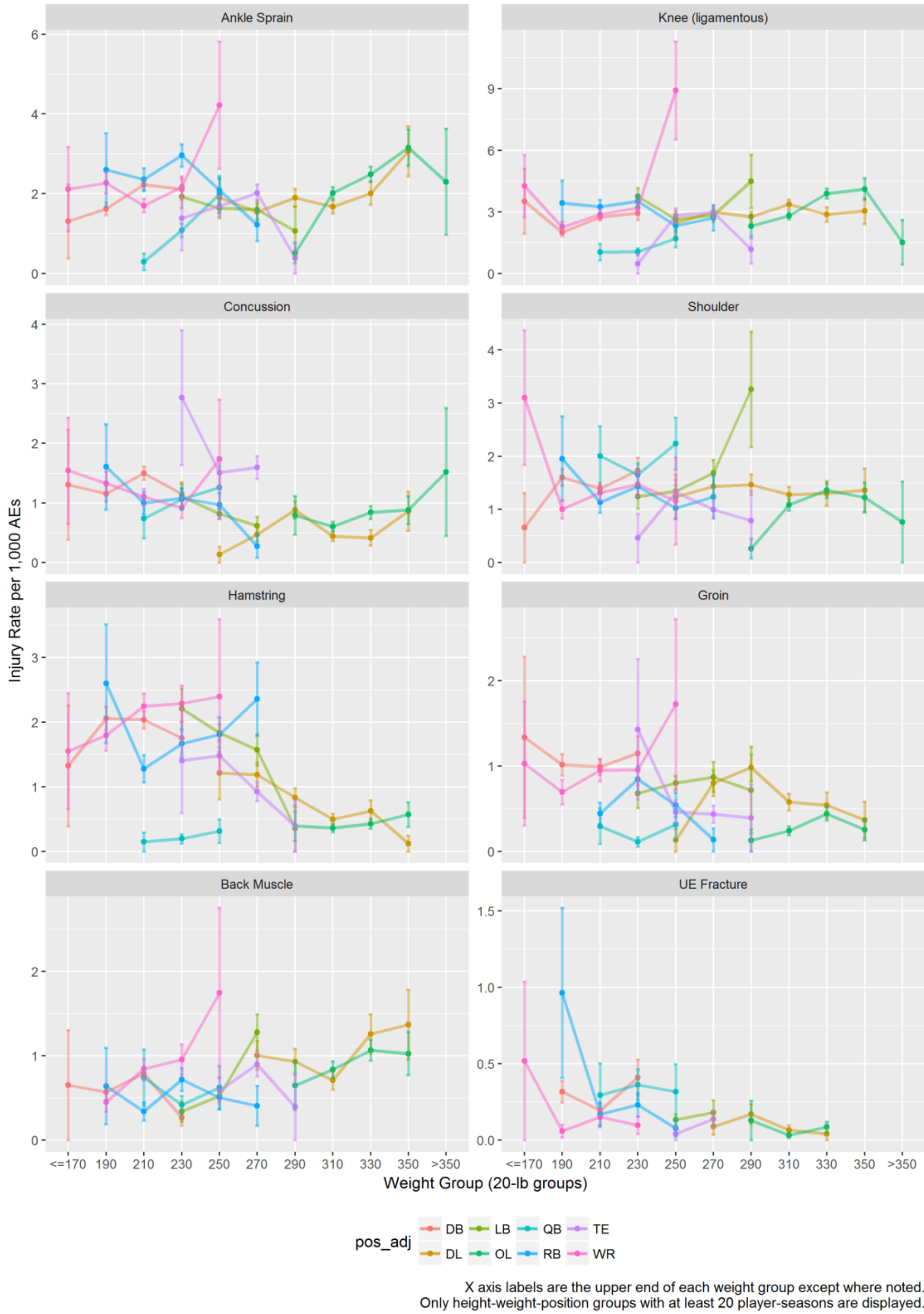


Figure 3.6. Regular season injury rates by height, weight and position, 2007-2015, with 1-standard error bars.

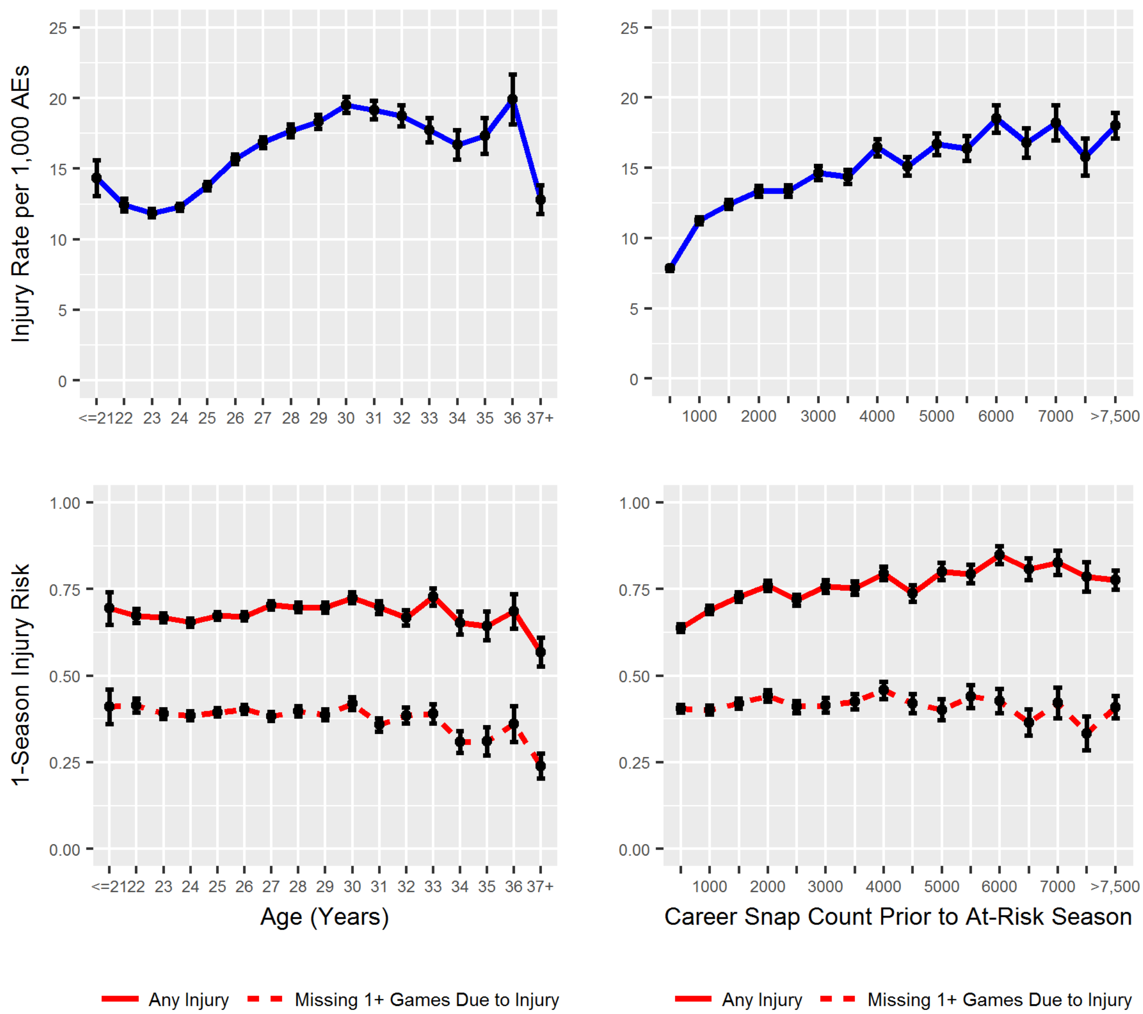


Player Age and Career Snapcounts:

Injury rates appeared to differ by age and by total number of plays or "snapcounts" (Figure 7). Among players in their early 20s the observed rates were 12-15 per 1,000 AEs; the corresponding rates for players in their early 30s were 18-20 per 1,000 AEs; and those in the late 30s experienced lower rates compared to their younger counterparts There was a sustained increase in injury rates with higher snapcounts. The risk of missing 1+ games due to injury, did not change with age until a player was around 30 years old. With snapcounts, the risk of missing 1+ game due to injury did not appear to vary in a notable pattern (Figure 7).

When examining specific injury types we observed the same general trend of an increasing injury rate with age in soft tissue and joint injuries (ankle sprains, knee ligaments, back muscles, hamstrings, and groins), but less so for contact-based injuries (concussions, shoulders, and UE fractures) (Figure 8). Career snapcount rate data by injury type is presented in the Appendix; patterns were generally similar to those for overall injuries (Figure A2).

Figure 3.7. Regular season injury rates and 1-season risks by player age and prior career snapcount (excluding ST players), 2007-2015, with 1-standard error bars.

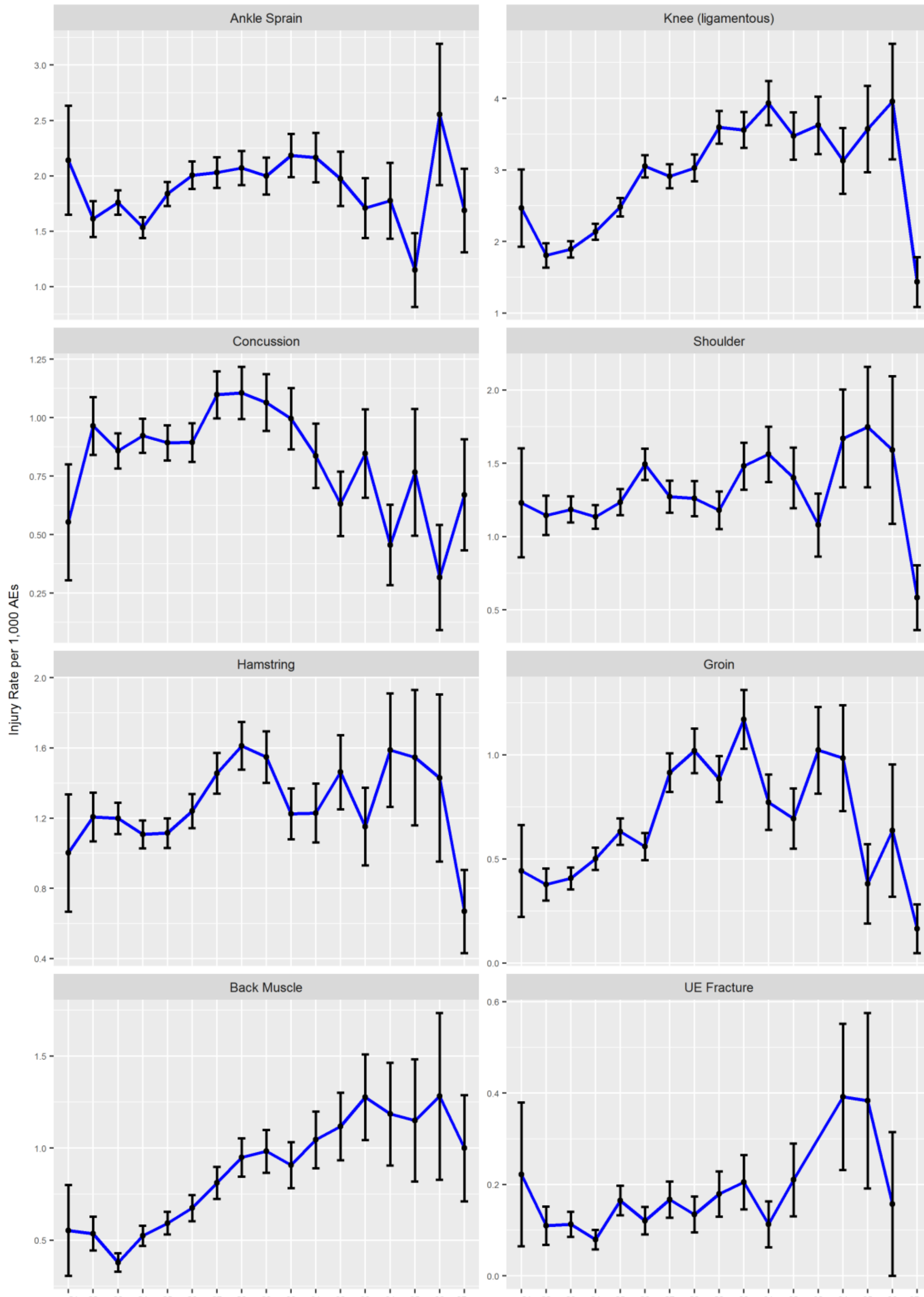


Snap count x axis labels are the upper end of each snap count group except where noted.

We hypothesized the decreases after 30 years of age could be for two reasons: 1. higher representation of QBs and STs – who have lower injury rates – in these groups, or 2. lower baseline injury risk among players managing to play for so long (survivor bias). After we excluded QBs and STs from the data, the previously observed decreases in the oldest ages were no longer evidence. In Figure 8 we further limited our data to stable cohorts of players playing until they were at least 28/30/32/35 years old. Here we also do not see decreases in the oldest ages. In addition we see that players who retire at older ages tend to have lower injury rates when they are younger.

Figure 3.8. Regular season injury rates and 1-season risks by player age for closed cohorts retiring at or after a certain age, 2007-2015, with 1-standard error bars.

Figure 3.9. Regular season injury rates by player age and injury type, 2007-2015, with 1-standard error bars.



<u>Season/Year:</u>

Injury rates and 1-season risks rose between 2007 and 2015 while the risk of missing 1+ game due to injury remained relatively unchanged over time (Figure 10). Rates rose steadily from approximately 12.5 to 17.5 per 1,000 AEs from 2007-2015. 1-season any-injury risks rose from around 62% to 75%, while the risk of missing 1+ game due to injury remained relatively flat around 38-40% (Figure 10). When stratifying by injury type we observed the same increase for all injury types except UE fractures. The increases were particularly pronounced for concussions – their rate more than doubled while those of other injuries increased about 20-50% (Figure 11).

Figure 12 presents the same analyses by injury severity (0, 1-2, or 3+ games missed) and head vs. other injuries in Figure 12. Figure 12 shows similar percentage increases in head injuries regardless of severity, but among non-head injuries much smaller increases were seen in the more severe categories than in those that did not cause any missed games.

Figure 3.10. Regular season injury rates and 1-season risks by season, 2007-2015, with 1-standard error bars.

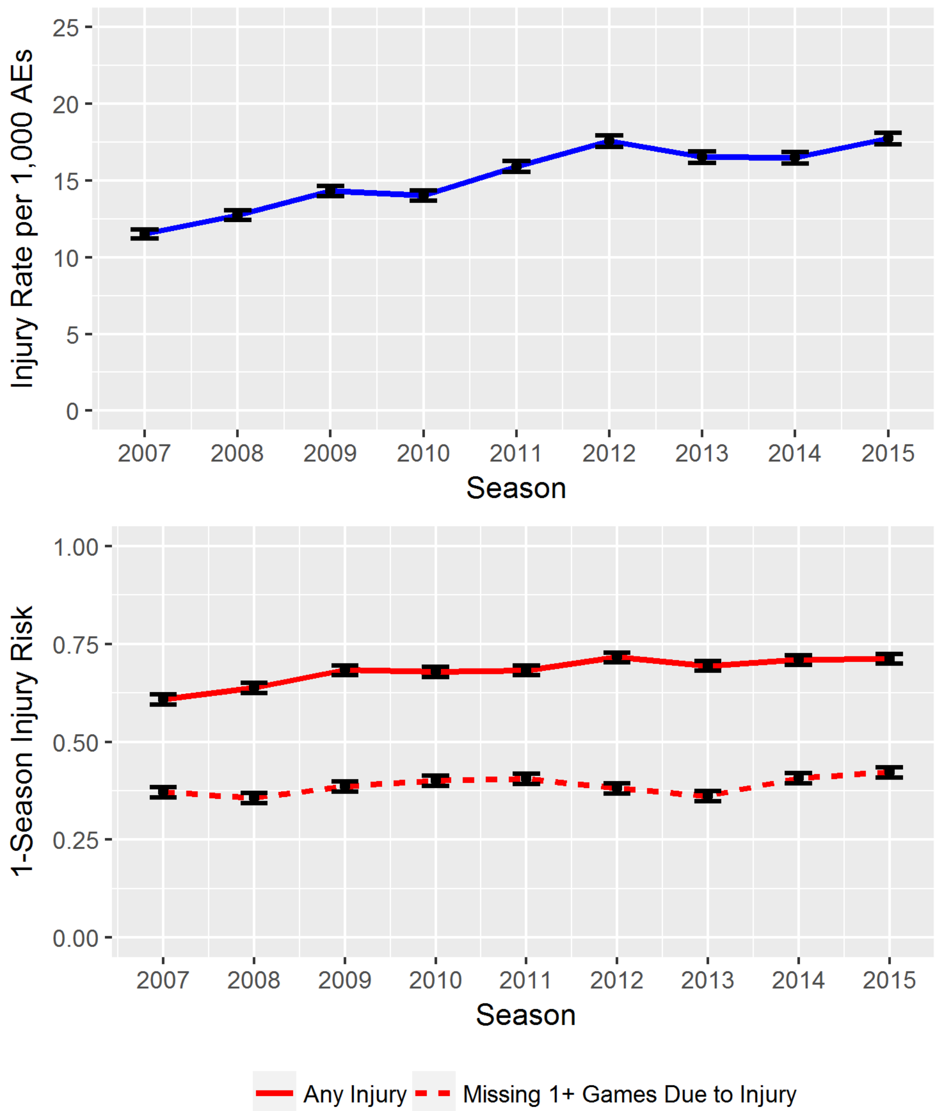


Figure 3.11. Regular season injury rates by season and injury type, 2007-2015, with 1-standard error bars.

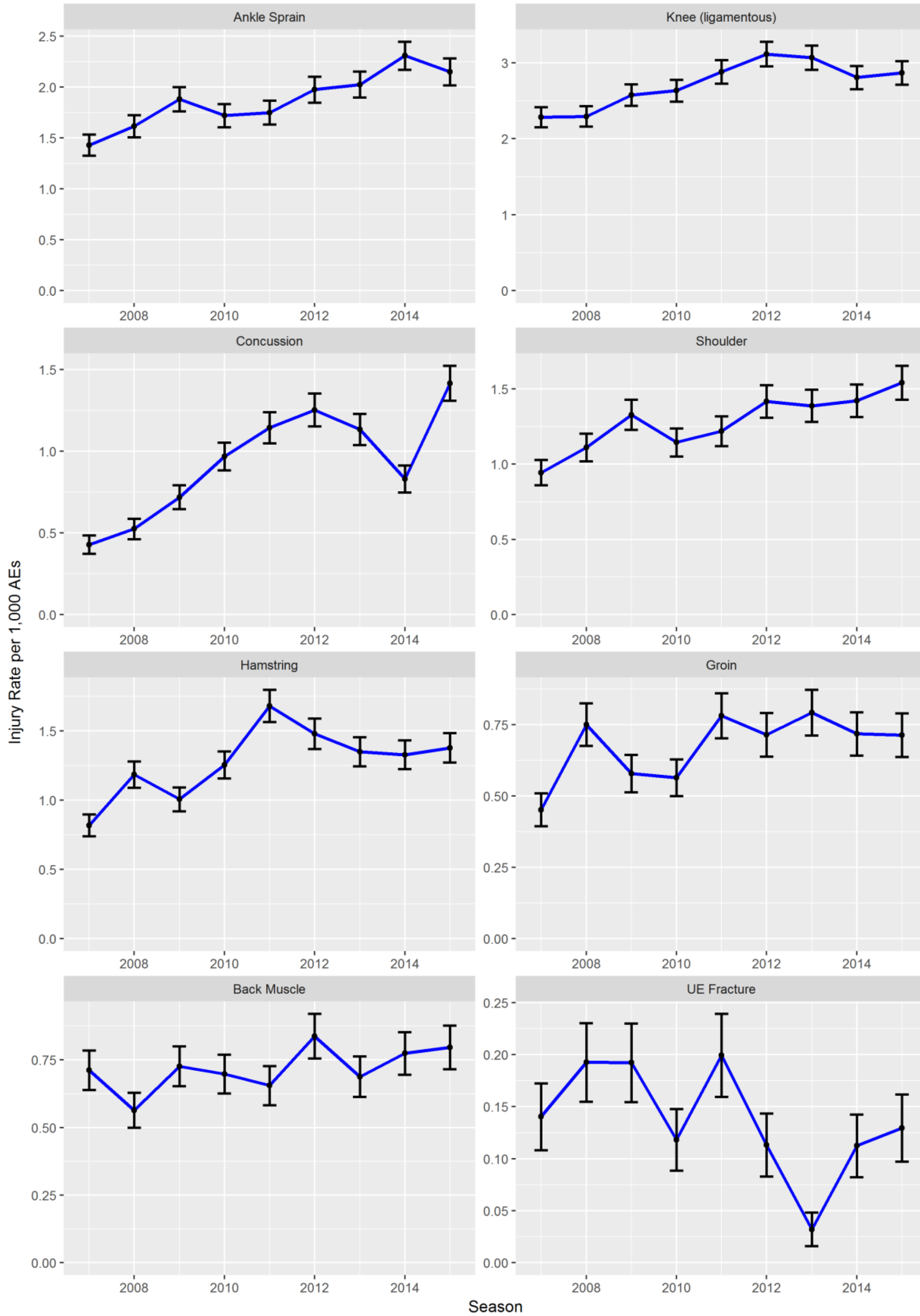
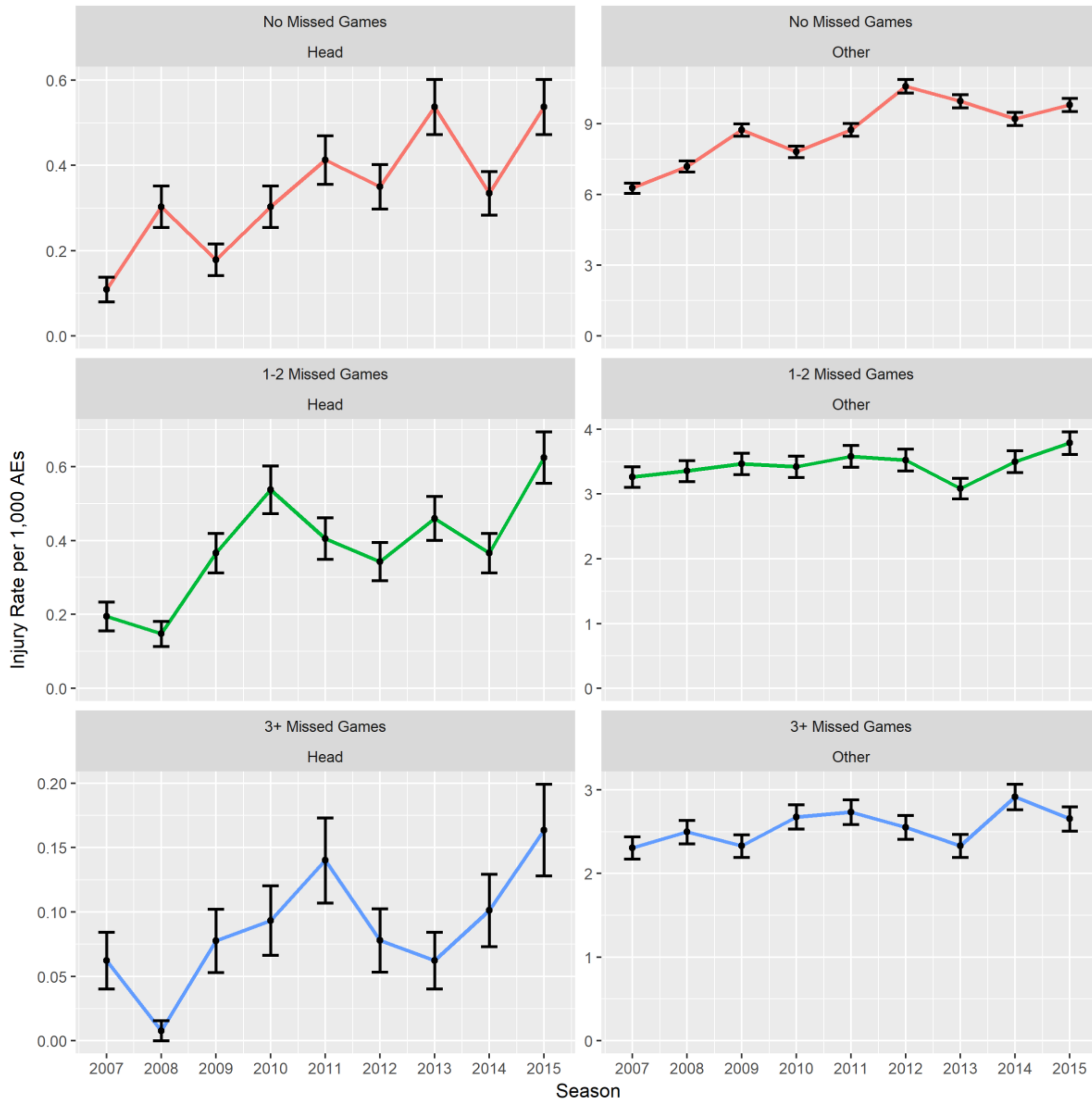


Figure 3.12. Regular season injury rates by season and injury severity, 2007-2015, with 1-standard error bars.



<u>Previous Injury History:</u>

The number injuries in the previous two NFL seasons was associated with the risk of missing 1+ games due to injury in the subsequent season (Figure 13a). There was an exponential pattern in injury risk with an increasing number of prior injuries; the increases are steepest when comparing o injury history to a modest history of three injuries over the previous two years (Figure 13a). In the injury type-specific analyses there were consistent linear increases of injury risk as the number of previous injuries of a given type rises; the only exceptions are Face/Eye and Upper Extremity (UE) Bone and Joint injuries (Figure 13b).

Figure 3.13a. 1-season risk of missing 1+ games due to injury by number of prior injuries in the previous two seasons, 2007-2015, with 1-standard error bars.

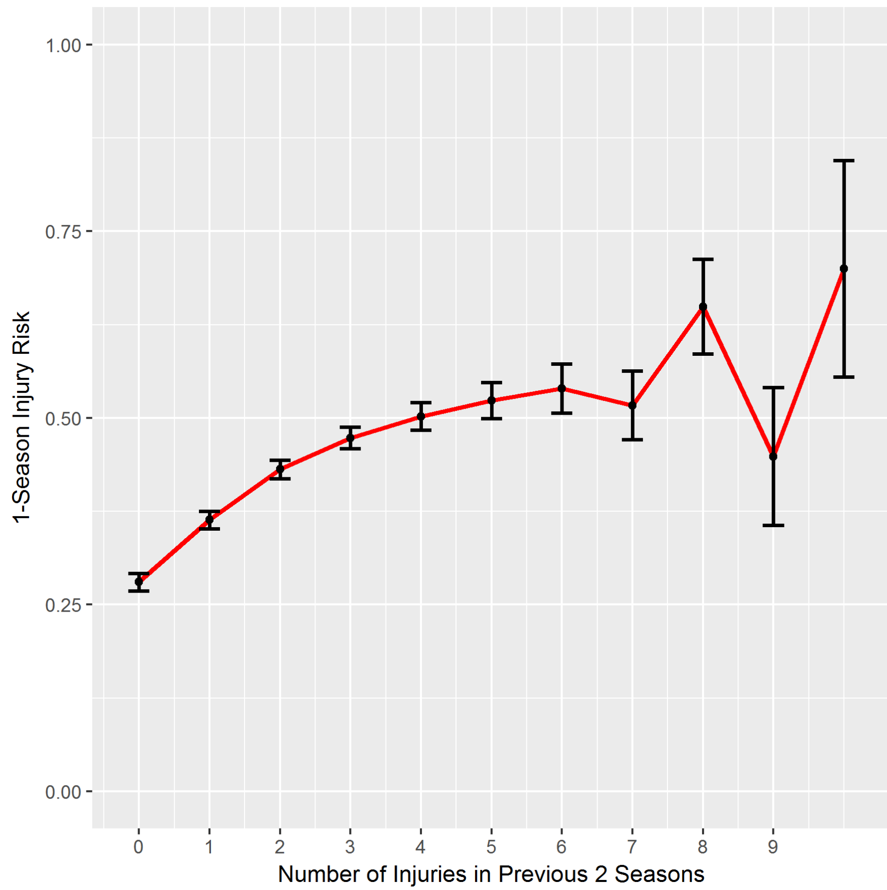
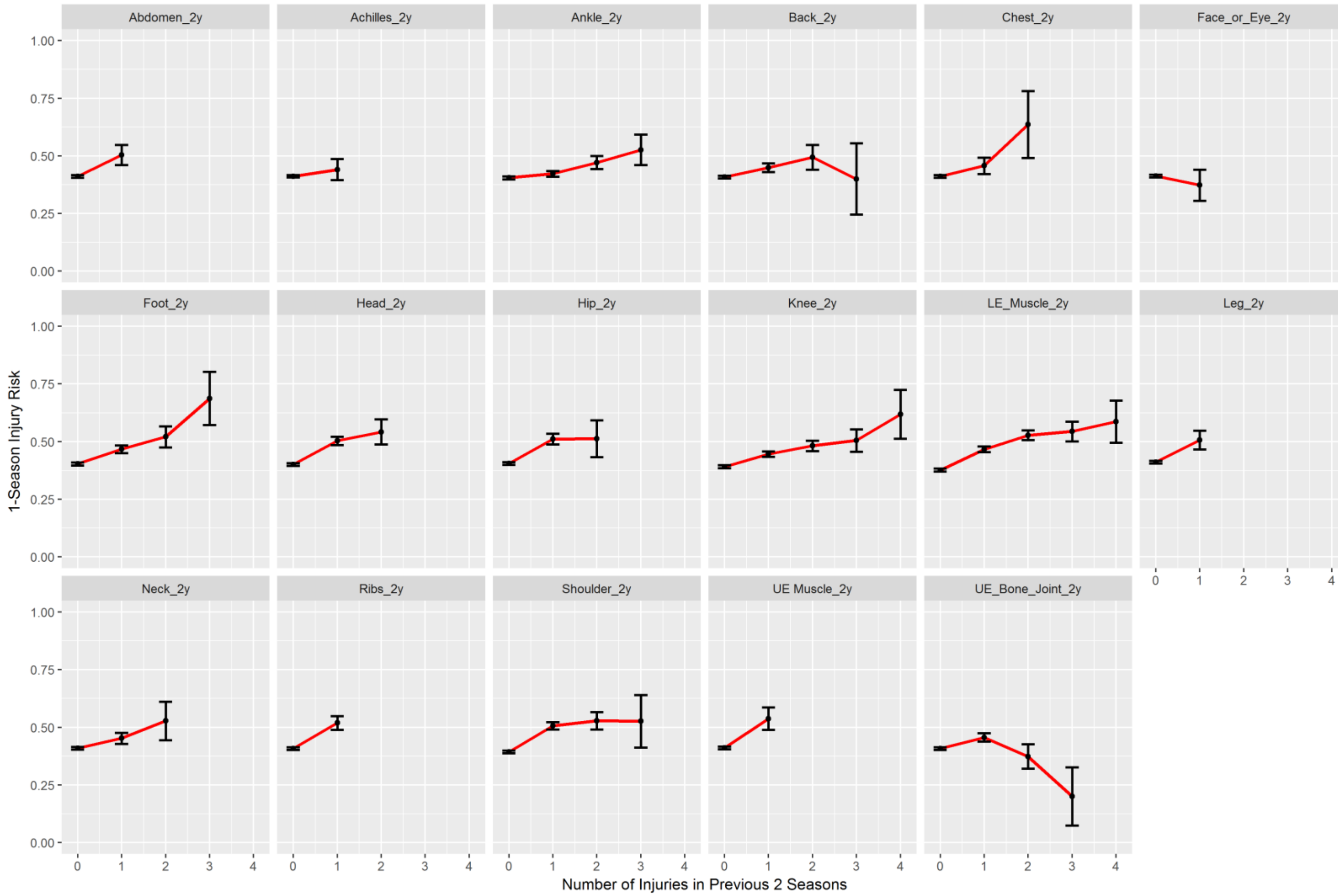


Figure 3.13b. 1-season risk of missing 1+ games by prior injuries of specific types in the previous two seasons, 2007-2015, with 1-standard error bars.



V. Discussion

This study identified 17,652 injuries in 9 regular NFL seasons, for a rate of 15.1 per 1,000 AEs. The 1-season risk of any injury was 68%, and 39% of player-seasons resulted in at least 1 game missed due to injury. There were several interesting associations between various intrinsic and extrinsic risk factors and injury rates. Running backs and mobile positions suffered more injuries than linemen. Among visiting team injuries from 2012-2015 artificial turf exhibited worse injury rates than natural grass, with certain brands of artificial turf exhibiting particularly high rates. Injury rates were generally higher for heavier players, but this depended greatly on the roles players of varying weights play on their teams. Soft tissue injuries were more common in warmer games and earlier in the year, while concussions exhibited the opposite trends. Individual players suffer higher soft tissue and joint injury rates as they age, but a survivor effect that leaves only the hardiest players at older ages mean on average the risk for a 30+ player missing a game is not higher than that for younger players. While reported injury rates have risen in recent years it appears this is mostly due to reporting and diagnostic bias rather than true changes in the underlying rate. Finally, a player's injury history appears to be a strong predictor of future injury risk regardless of the types of injuries they have suffered. These findings suggest important avenues for future research to better understand and mitigate injuries in a high-risk sport like football.

This study has several important limitations. Public injury reports do not use a strong case definition of "injury" – the official NFL guidance is that "significant and noteworthy injuries," as well as anything causing a player to miss any part of a game, must be reported (53). That definition is fungible. Public injury reports are also subject to differences in team injury reporting behaviors; teams are known to exhibit variable reporting behaviors and possibly manipulate the injury report for competitive advantage (3, 52, 61, 179). Both of these limitations could lead to unpredictable over- or under-counting of injuries. We also lacked data on various elements of injury timing: we did not know when an injury occurred in the preseason period, nor did we know if it occurred in a practice versus a game during the regular season. This likely led us to inappropriately attribute some injuries that occurred in practices rather than games to a particular stadium's turf or game day temperature, which in turn may have led to overestimates in our rates for game-level variables across the board. Whether these rates were differentially over- or underestimated in different categories of these variables is unclear. For example, while the rates of injuries for games in rainy and dry conditions are likely higher than they should be, whether rainy rates are any more upwardly biased than dry game rates is unknown. We also lacked data on when (i.e. on which play or snap) an injury occurred. This forced us to calculate injury rates on a per-practice or per-game level rather than a per-snap level and left us unable to, for example, compare ST player injury risk to others on a per-snap basis. As a result ST players – who participate in only a few snaps per game – in our study appear to have especially low injury rates on a per-AE (game or practice) basis when prior studies have shown injury rates on ST plays are higher than other plays (118). Additionally, we lacked data on the mechanism of injury (e.g. contact vs. non-contact), which limits our ability to draw conclusions about the effects of playing more contact-prone positions. We also did not have access to player medical records to determine when injuries were new vs. re-aggravations or recurrences. We chose to define a new injury as any injury that hadn't appeared on that player's injury report for at least two weeks, byes excluded. Based on comparisons with the NFL ISS over our study time period (41) this may have led us to overestimate the true number of unique injuries in our cohort, inflating rates. Finally, our data were not able to account for multiple injuries at once, though only 0.7% of our injuries had a secondary issue associated with them. In those cases whichever injury took place first took precedence until it disappeared from the report unless the second injury was known to be more severe (e.g. an ACL tear versus an AC sprain). This likely caused slight underestimates in our injury rates. Any bias induced by these limitations was likely less for risks than it was for rates, as risks only allow for any injury to have happened or not happened in a given season, while rates require us to accurately count each injury that occurred. Despite these limitations, this study offers several important insights into the epidemiology of NFL injuries.

Although we identified many associations in our results, we focus our discussion on the four most interesting below. First, while many players have complained about injury risk in games on short rest (185, 186) 4-day rest periods were associated with lower injury rates (14.4 per 1,000 AEs vs. 16.0 for a typical 7-day rest) (Table 1). These results are consistent with the NFL's own analyses of its ISS that shows lower injury rates for games on short rest in three out of the last four years (187). However, the overall injury rate differences between short and normal rest games are most likely quirk of NFL injury reporting: the first injury reports are issued 5 days after a Thursday (short rest) game, but 2 days after the more common Sunday games. Thus any injury that resolves in the 2-5 day timeframe will be counted for a Sunday game but not for a Thursday game, driving the Thursday rates down. Another possible explanation is that players have less time to recover from old injuries and re-join the injury risk pool on a short week, pushing new injury rates downward. Regardless, injury reports do not offer strong evidence for an elevated injury rate in games on short rest as some have contended.

Second, injury rates exhibited an increase with weight in most positions. This is likely due to the greater forces and strain being placed on joints and ligaments by heavier players. There are two exceptions to this trend: RBs exhibited lower injury rates at higher weights, and the heaviest TEs (270-290 lbs) exhibited a drop in rates (Figure 5a). It is possible these are due to the ways in which heavier TEs and RBs are used –as blockers or short-yardage runners who may cover less ground and are involved in fewer violent collisions. Interestingly, hamstring injuries among LBs and DLs and groin injuries among DLs exhibited clear decreases with higher weights; DLs exhibit the same trend for groin injuries (Figure 6). It is possible these are due to lower running and sprinting demands placed upon these players relative to lighter defensive linemen and linebackers (188). Previous youth and high school football studies have shown a mixed association between player size (BMI) and injury risk: four found substantial crude associations between higher BMI and overall injury risk (22, 23, 101, 102) while three others found no crude association (24, 28, 103). Only one of these adjusted for position (by looking solely at linemen) (101). Prior investigations of this topic in the NFL do not exist, to our knowledge. Our study thus adds to the knowledge base on BMI and injuries in football by suggesting that, within positions, greater weight is generally associated with higher injury rates except when the changing duties of higher-weight players offsets it.

Third, while there is broad consensus both in the NFL and other sports that older athletes are at higher risk for various injuries, we could not identify any prior studies that have investigated this in the NFL specifically (89-93). Age was associated with overall injury rates and a range of soft tissue and joint injuries (ankle sprains, knee ligaments, back muscles, hamstrings, and groins), but it did not exhibit an association with several contact-based injuries (concussions, shoulders, and UE fractures) (Figure 8). This suggests that the underlying trauma of the game, rather than age-related biological processes, is likely the biggest determinant of contact-based injury rates. In our study injury rates rose with age before dropping for those over 30 (Figure 7). We hypothesized that our observed decreases in risk after 30 years of age could be for two reasons: 1. higher representation of QBs and STs – who have lower injury rates – in these groups (confounding by position), or 2. lower baseline injury risk among players managing to play for so long (survivor bias) (189). To investigate this, we first eliminated QBs and STs from our data, which eliminated the decreases seen in the oldest ages. We then further limited our data to stable cohorts of players playing until they were at least 28/30/32/35 years old. Here we noted that players who retire at older ages tend to have lower injury rates when they are younger (Figure 8) – for example, those retiring at 28 or later had an injury rate of about 4 per 1,000 AEs when they were 23 vs. 1 per 1,000 AEs at the same age for players who retired at 32 or later. This suggests players who play later into their careers may be "heartier" in some way than others, indicating a survivor effect may be present when looking at crude injury rates by age. Whether this survivor effect is a bias depends on one's specific research question, however. If we want to know the causal effect of age, closed cohorts adjusting for survivor bias (Figure 8) are better. But if we are an NFL team curious about a player's injury risk before signing him to a contract, the crude results (excluding QBs and STs) are more pertinent as they account for the "current wisdom" of the NFL with regards to signing older players and their injury risk.

Finally, prior injury history is a heavily-studied predictor of subsequent injuries (93, 94, 97, 98). Studies from college football for concussions and all injuries combined show higher injury risk for those with a history of prior injuries (97, 98). At the NFL level, this relationship has not been explicitly studied for all injuries. Although there is some evidence from single-team records that players with substantial college injury histories are less likely to play in the NFL and, if they do make it, have shorter careers (57, 58, 96, 99), the association with injury risk itself was never assessed. Our analysis found a strong association between a player's past injury history and current injury risk (Figure 13a). The increase was exponential and steepest when comparing someone with no injuries in the previous two years to someone with a modest injury history (e.g. 2-3 injuries). As injury histories continued to worsen the risk increases weakened but did not disappear, suggesting a "diminishing returns" effect of total injury history. However, this type of association could also be driven by particularly long injury histories forcing many players out of the NFL, leaving hardier or higher-skilled players who suffered bad injury luck over a short period. This selection would artificially deflate injury rates among players with the longest histories. When looking at specific injury types longer injury histories corresponded to a linearly increasing risk of future injuries (Figure 13b). Two categories did not exhibit an increasing linear trend (Face/Eye and Upper Extremity (UE) Bone and Joint injuries), but both of these tend to be traumatic injuries that are not prone to recurrence and so were unlikely to be associated with future injury risk.

VI. Conclusions

Football is a violent sport with injury rates substantially above those of other professional sports in the U.S. Running backs and mobile positions suffer more injuries than linemen. There were fewer injuries on grass versus artificial turf. Injury rates were generally higher for heavier players, but this depended greatly on the roles players of varying weights play on their teams. Soft tissue injuries were more common in warmer games and earlier in the year, while concussions exhibited the opposite trends. Individual players suffer higher soft tissue and joint injury rates as they age, but a survivor effect that leaves only the hardiest players at older ages mean on average the risk for a 30+ player missing a game is not higher than that for younger players. While reported injury rates have risen in recent years it appears this is mostly due to reporting and diagnostic bias rather than true changes in the underlying rate. Finally, a player's injury history appears to be a strong predictor of future injury risk regardless of the types of injuries they have suffered. Despite its limitations, this study represents a large, recent, thorough, and publicly available analysis of NFL injury data, and as such it makes an important contribution to public health.

VII. Appendix

Table 3.A1. Specific injury type definitions.

Injury Description	Specific Injury Type Definitions	
	Main Analyses	Prior Injury History
Abdomen		Abdomen
Abdomen - bleeding		Abdomen
Abdomen - bruise		Abdomen
Abdomen - hernia		Abdomen
Abdomen - oblique		Abdomen
Abdomen - oblique strain		Abdomen
Abdomen - oblique tear		Abdomen
Abdomen - strain		Abdomen
Abdomen - tear		Abdomen
Achilles		Achilles
Achilles - partial tear		Achilles
Achilles - strain		Achilles
Achilles - tear		Achilles
Ankle	Ankle Sprain	Ankle
Ankle - bone bruise	Ankle Sprain	Ankle
Ankle - bone chips	Ankle Sprain	Ankle
Ankle - broken		Ankle
Ankle - bruise	Ankle Sprain	Ankle
Ankle - dislocation		Ankle
Ankle - high ankle sprain		Ankle
Ankle - ligament	Ankle Sprain	Ankle
Ankle - ligament strain	Ankle Sprain	Ankle
Ankle - ligament tear	Ankle Sprain	Ankle
Ankle - sprain	Ankle Sprain	Ankle
Ankle - stress fracture		Ankle
Ankle - tendon tear		Ankle
Appendix		Organ
Arm		UE Bone or Joint
Arm - bone bruise		
Arm - broken	UE Fracture	
Arm - broken forearm	UE Fracture	
Arm - bruise		
Arm - forearm	UE Fracture	UE Bone or Joint
Arm - forearm strain		UE Muscle
Arm - infection		UE Bone or Joint

Arm - upper arm		UE Bone or Joint
Back	Back Muscle	Back
Back - broken		Back
Back - bruise	Back Muscle	Back
Back - disc		Back
Back - nerves	Back Muscle	Back
Back - spasms	Back Muscle	Back
Back - sprain	Back Muscle	Back
Back - strain	Back Muscle	Back
Back - tailbone		Back
Back - tailbone bruise		Back
Biceps		UE Muscle
Biceps - bruise		
Biceps - strain		UE Muscle
Biceps - tear		UE Muscle
Biceps - tendon tear		UE Muscle
Blood clot - heart		Organ
Blood clot - leg		Leg
Blood clot - lung		Organ
Buttocks		LE Muscle
Buttocks - bruise		LE Muscle
Buttocks - strain		LE Muscle
Calf		LE Muscle
Calf - bruise		
Calf - partial tear		LE Muscle
Calf - strain		LE Muscle
Calf - tear		LE Muscle
Chest		Chest
Chest - bruise		Chest
Chest - internal bleeding		Chest
Chest - strain		Chest
Clavicle	Shoulder	Shoulder
Clavicle - broken	Shoulder	
Clavicle - bruise	Shoulder	
Clavicle - dislocation	Shoulder	Shoulder
Concussion	Concussion	Head
Concussion - spinal	Concussion	Spine
Cramps		Other
Dehydration		Other
Depression		Illness
Elbow		UE Bone or Joint

Elbow - bone chips		UE Bone or Joint
Elbow - broken	UE Fracture	
Elbow - bruise		
Elbow - dislocation		UE Bone or Joint
Elbow - hyperextension		UE Bone or Joint
Elbow - infection		UE Bone or Joint
Elbow - laceration		UE Bone or Joint
Elbow - ligament		UE Bone or Joint
Elbow - ligament sprain		UE Bone or Joint
Elbow - ligament tear		UE Bone or Joint
Elbow - sprain		UE Bone or Joint
Elbow - strain		UE Bone or Joint
Elbow - tendon		UE Bone or Joint
Elbow - tendon tear		UE Bone or Joint
Elbow - UCL		UE Bone or Joint
Elbow - UCL sprain		UE Bone or Joint
Eye		Face or Eye
Eye - myasthenia gravis		Face or Eye
Eye - pink eye		Face or Eye
Face		Face or Eye
Face - broken		Face or Eye
Face - broken jaw		Face or Eye
Face - broken nose		Face or Eye
Face - cheek		Face or Eye
Face - chin		Face or Eye
Face - ear		Face or Eye
Face - jaw		Face or Eye
Face - nose		Face or Eye
Face - teeth		Face or Eye
Face - teeth infection		Face or Eye
Face - throat		Face or Eye
Face - throat, broken cartilage		Face or Eye
Finger		UE Bone or Joint
Finger - broken	UE Fracture	
Finger - dislocation		UE Bone or Joint
Finger - laceration		UE Bone or Joint
Finger - ligament tear		UE Bone or Joint
Finger - sprain		UE Bone or Joint
Finger - tendon tear		UE Bone or Joint
Foot		Foot
Foot - arch/plantar fascia		Foot

Foot - arch/plantar fascia partial tear		Foot
Foot - arch/plantar fascia sprain		Foot
Foot - arch/plantar fascia strain		Foot
Foot - arch/plantar fascia tear		Foot
Foot - broken		
Foot - bruise		
Foot - heel		Foot
Foot - Jones Fracture		Foot
Foot - ligament		Foot
Foot - ligament sprain		Foot
Foot - ligament tear		Foot
Foot - Lisfranc		Foot
Foot - Lisfranc fracture		Foot
Foot - Lisfranc sprain		Foot
Foot - Lisfranc tear		Foot
Foot - midfoot sprain		Foot
Foot - midfoot strain		Foot
Foot - sprain		Foot
Foot - strain		Foot
Foot - stress fracture		Foot
Foot - tendon		Foot
Foot - tendon tear		Foot
Groin	Groin	LE Muscle
Groin - hernia	Groin	LE Muscle
Groin - partial tear	Groin	LE Muscle
Groin - sports hernia	Groin	LE Muscle
Groin - strain	Groin	LE Muscle
Groin - tear	Groin	LE Muscle
Groin - tendon tear	Groin	LE Muscle
Gunshot		NFI
Hamstring	Hamstring	LE Muscle
Hamstring - bruise	Hamstring	LE Muscle
Hamstring - partial tear	Hamstring	LE Muscle
Hamstring - strain	Hamstring	LE Muscle
Hamstring - tear	Hamstring	LE Muscle
Hand		UE Bone or Joint
Hand - broken	UE Fracture	
Hand - bruise		
Hand - flexor tendon tear		UE Bone or Joint
Hand - laceration		UE Bone or Joint
Hand - ligament		UE Bone or Joint

Hand - tendon tear		UE Bone or Joint
Head	Concussion	Head
Head - cluster headaches		Head
Heart		Organ
Heart - abnormal rhythm		Organ
Heel - bruise		
Hip		Hip
Hip - abscess		Hip
Hip - bone bruise		
Hip - broken		
Hip - bruise		
Hip - cartilage		Hip
Hip - cartilage tear		Hip
Hip - dislocation		Hip
Hip - flexor		Hip
Hip - flexor strain		Hip
Hip - flexor tear		Hip
Hip - labrum tear		Hip
Hip - ligament tear		Hip
Hip - strain		Hip
Hip - tendon tear		Hip
Illness		
Illness - acute leukemia		
Illness - asthma		
Illness - Crohn's		
Illness - epilepsy		
Illness - flu		
Illness - gastroenteritis		
Illness - gout		
Illness - infection		
Illness - intestine blockage		
Illness - lung cancer		
Illness - lymphoma		
Illness - pneumonia		
Illness - respiratory		
Illness - seizures		
Illness - staph		
Illness - stomach		
Illness - strep		
Illness - stroke		
Illness - tonsils		

Illness - virus		
Kidney		Organ
Kidney - bruise		Organ
Kidney - laceration		Organ
Knee	Knee (ligamentous)	Knee
Knee - ACL	Knee (ligamentous)	Knee
Knee - ACL partial tear	Knee (ligamentous)	Knee
Knee - ACL partial tear/MCL	Knee (ligamentous)	Knee
Knee - ACL tear	Knee (ligamentous)	Knee
Knee - ACL tear/MCL sprain	Knee (ligamentous)	Knee
Knee - ACL/LCL/iliotibital band tear	Knee (ligamentous)	Knee
Knee - ACL/LCL/meniscus tear	Knee (ligamentous)	Knee
Knee - ACL/MCL tear	Knee (ligamentous)	Knee
Knee - ACL/MCL/meniscus tear	Knee (ligamentous)	Knee
Knee - ACL/MCL/PCL tear	Knee (ligamentous)	Knee
Knee - ACL/meniscus tear	Knee (ligamentous)	Knee
Knee - ACL/patellar tendon tear	Knee (ligamentous)	Knee
Knee - ACL/PCL tear	Knee (ligamentous)	Knee
Knee - bone bruise		Knee
Knee - bone chips		Knee
Knee - broken		Knee
Knee - broken kneecap		Knee
Knee - bruise		Knee
Knee - bursa		Knee
Knee - cartilage		Knee
Knee - cartilage tear		Knee
Knee - dislocated kneecap	Knee (ligamentous)	Knee
Knee - dislocation	Knee (ligamentous)	Knee
Knee - hyperextension	Knee (ligamentous)	Knee
Knee - infection		Knee
Knee - kneecap		Knee
Knee - kneecap subluxation	Knee (ligamentous)	Knee
Knee - laceration		Knee
Knee - lateral meniscus tear		Knee
Knee - LCL sprain	Knee (ligamentous)	Knee
Knee - LCL tear	Knee (ligamentous)	Knee
Knee - LCL/PCL tear	Knee (ligamentous)	Knee
Knee - ligament	Knee (ligamentous)	Knee
Knee - ligament sprain	Knee (ligamentous)	Knee
Knee - ligament tear	Knee (ligamentous)	Knee
Knee - MCL	Knee (ligamentous)	Knee

Knee - MCL partial tear	Knee (ligamentous)	Knee
Knee - MCL sprain	Knee (ligamentous)	Knee
Knee - MCL tear	Knee (ligamentous)	Knee
Knee - MCL/LCL sprain	Knee (ligamentous)	Knee
Knee - MCL/PCL partial tear	Knee (ligamentous)	Knee
Knee - MCL/PCL sprain	Knee (ligamentous)	Knee
Knee - MCL/PCL tear	Knee (ligamentous)	Knee
Knee - meniscus		Knee
Knee - meniscus partial tear		Knee
Knee - meniscus tear		Knee
Knee - meniscus/MCL tear		Knee
Knee - nerve		Knee
Knee - patella tendon	Knee (ligamentous)	Knee
Knee - patella tendon tear	Knee (ligamentous)	Knee
Knee - PCL	Knee (ligamentous)	Knee
Knee - PCL partial tear	Knee (ligamentous)	Knee
Knee - PCL sprain	Knee (ligamentous)	Knee
Knee - PCL tear	Knee (ligamentous)	Knee
Knee - popliteus tear	Knee (ligamentous)	Knee
Knee - scope		Knee
Knee - sprain	Knee (ligamentous)	Knee
Knee - strain		Knee
Knee - tendon	Knee (ligamentous)	Knee
Leg		Leg
Leg - bone bruise		
Leg - broken		Leg
Leg - bruise		
Leg - infection		Leg
Leg - shin		Leg
Leg - stress fracture		Leg
Liver		Organ
Lung		Organ
Lung - bruise		Organ
Lung - collapse		Organ
Lung - puncture		Organ
Migraine		Head
Neck		Neck
Neck - broken		Neck
Neck - disc		Neck
Neck - ligament tear		Neck
Neck - nerves		Neck

Neck - sprain		Neck
Neck - stinger		Neck
Neck - strain		Neck
NFI		NFI
Non-injury		NFI
Pectoral		Chest
Pectoral - partial tear		Chest
Pectoral - strain		Chest
Pectoral - tear		Chest
Pelvis		Other
Pelvis - bone bruise		Other
Pelvis - broken		
Pelvis - tear		Other
Personal		NFI
Player decision		NFI
Quadriceps		LE Muscle
Quadriceps - bruise		LE Muscle
Quadriceps - strain		LE Muscle
Quadriceps - tear		LE Muscle
Quadriceps - tendon strain		LE Muscle
Quadriceps - tendon tear		LE Muscle
Rest		NFI
Ribs		Ribs
Ribs - broken		Ribs
Ribs - bruise		Ribs
Ribs - cartilage		Ribs
Ribs - cartilage tear		Ribs
Ribs - dislocation		Ribs
Ribs - sternum		Ribs
Ribs - sternum separation		Ribs
Ribs - strain		Ribs
Shoulder	Shoulder	Shoulder
Shoulder - AC sprain	Shoulder	Shoulder
Shoulder - broken	Shoulder	
Shoulder - broken scapula	Shoulder	
Shoulder - bruise	Shoulder	
Shoulder - capsule tear	Shoulder	Shoulder
Shoulder - cartilage tear	Shoulder	Shoulder
Shoulder - dislocation	Shoulder	Shoulder
Shoulder - labrum partial tear	Shoulder	Shoulder
Shoulder - labrum tear	Shoulder	Shoulder

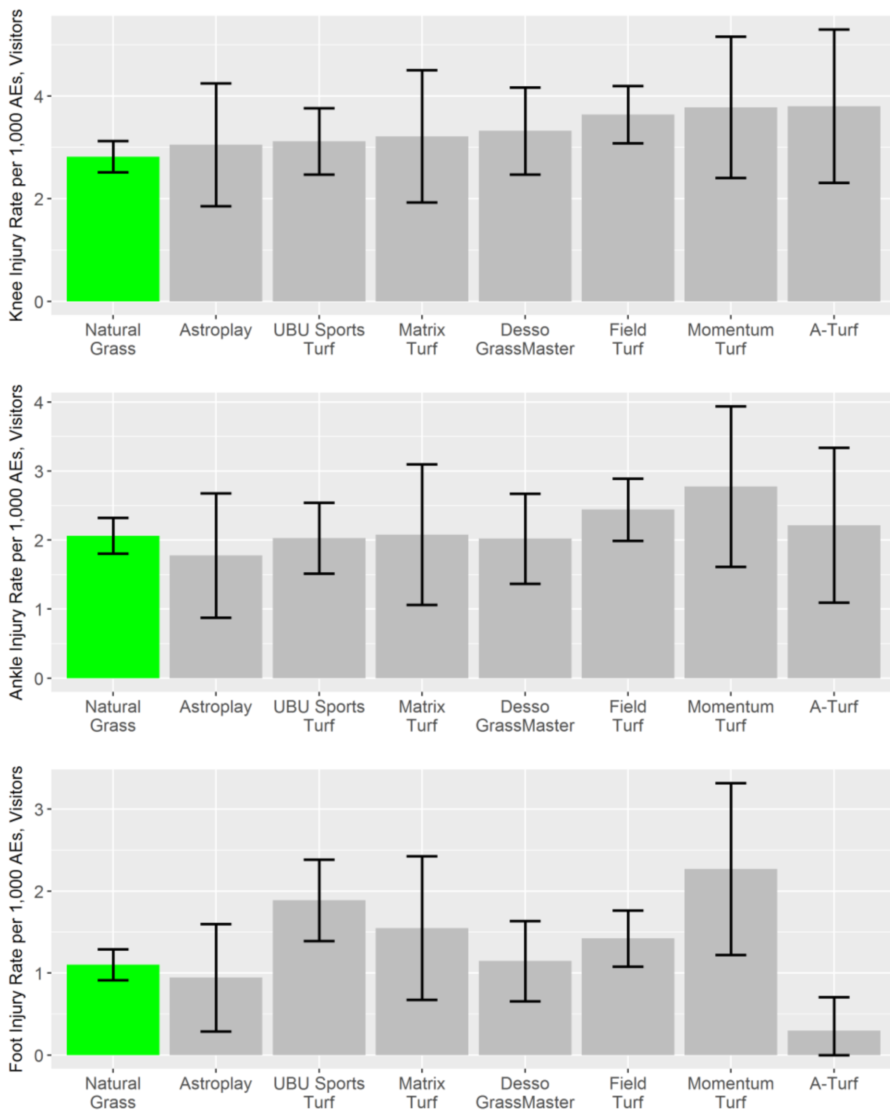
Shoulder - ligament tear	Shoulder	Shoulder
Shoulder - nerve	Shoulder	Shoulder
Shoulder - rotator cuff	Shoulder	Shoulder
Shoulder - rotator cuff partial tear	Shoulder	Shoulder
Shoulder - rotator cuff strain	Shoulder	Shoulder
Shoulder - rotator cuff tear	Shoulder	Shoulder
Shoulder - SC joint	Shoulder	Shoulder
Shoulder - SC joint sprain	Shoulder	Shoulder
Shoulder - scope	Shoulder	Shoulder
Shoulder - separation	Shoulder	Shoulder
Shoulder - sprain	Shoulder	Shoulder
Shoulder - strain	Shoulder	Shoulder
Shoulder - subluxation	Shoulder	Shoulder
Skin - infection		Other
Skull - broken		Head
Spine		Neck
Spine - broken		Neck
Spine - bruise		Neck
Spine - cervical		Neck
Spine - stenosis, cervical		Neck
Spleen		Organ
Spleen - bruise		Organ
Spleen - laceration		Organ
Spleen - rupture		Organ
Stomach		Organ
Team decision		NFI
Testicles - infection		Other
Thigh		LE Muscle
Thigh - broken		LE Muscle
Thigh - bruise		LE Muscle
Thigh - strain		LE Muscle
Thigh - tear		LE Muscle
Thumb		UE Bone or Joint
Thumb - bone bruise		
Thumb - broken	UE Fracture	
Thumb - dislocation		UE Bone or Joint
Thumb - laceration		UE Bone or Joint
Thumb - ligament		UE Bone or Joint
Thumb - ligament partial tear		UE Bone or Joint
Thumb - ligament tear		UE Bone or Joint
Thumb - sprain		UE Bone or Joint

Thumb - surgery		UE Bone or Joint
Toe		Foot
Toe - broken		
Toe - bruise		
Toe - dislocation		Foot
Toe - infection		Foot
Toe - ligament tear		Foot
Toe - sprain		Foot
Toe - tendon tear		Foot
Trapezius		Back
Trapezius - strain		Back
Triceps		UE Muscle
Triceps - partial tear		UE Muscle
Triceps - strain		UE Muscle
Triceps - tear		UE Muscle
Triceps - tendon tear		UE Muscle
Turf toe		Foot
Turf toe - tear		Foot
Undisclosed		Unknown
Unknown		Unknown
Upper Body		Unknown
Wrist		UE Bone or Joint
Wrist - broken	UE Fracture	
Wrist - bruise		
Wrist - dislocation		UE Bone or Joint
Wrist - ligament		UE Bone or Joint
Wrist - ligament tear		UE Bone or Joint
Wrist - sprain		UE Bone or Joint
Wrist - surgery		UE Bone or Joint

Artificial Turf Type for Knee, Ankle, and Foot Injuries:

We stratified by type of artificial turf, limiting to the years 2012-15 to ensure that turfs introduced in more recent years do not appear worse because of the time trend of rising injuries. We also limited ourselves to visiting teams only to remove the effects of the home team's roster, training staff, and so on, which can have a major impact on injuries. When we restrict ourselves to knee, ankle, and foot injuries natural grass looks superior to the worst artificial turfs for these lower limb issues, which are the most likely injuries to be impacted by poor turf (Figure A1).

Figure 3.A1. Knee, Ankle, and Foot injury rates per 1,000 AEs by type of artificial turf in the NFL regular season, 2012-2015, with 95% confidence intervals.



Precipitation Injury Rates, Stratified by Turf:

There is some indication that wet games on grass have a more positive effect relative to dry games on grass than the same comparison for artificial turf.

Table 3.A2. Injury rates by turf type and precipitation, 2007-2015.

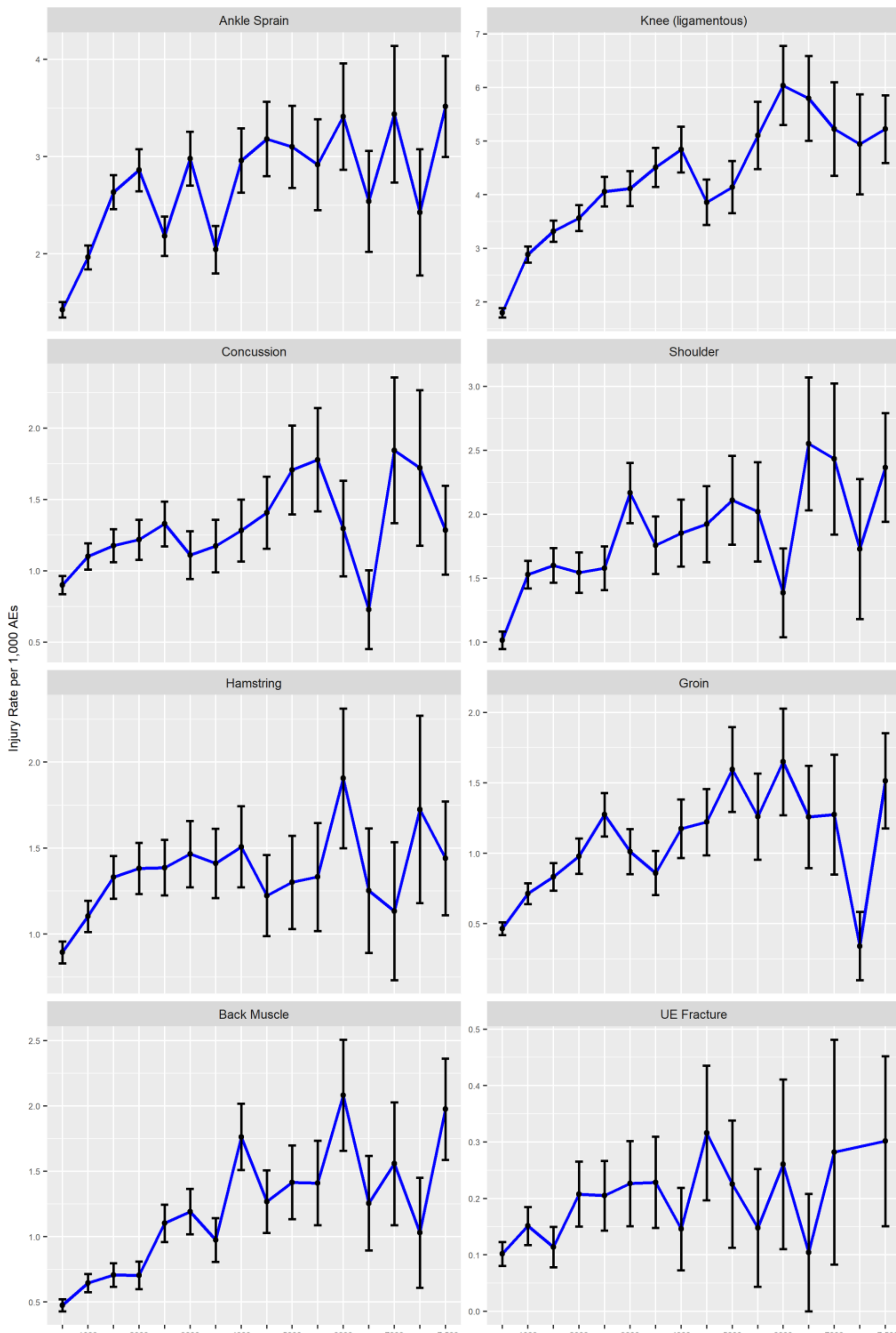
Variable	Injuries	AEs	Injury Rate per 1,000 AEs (95% CI)
Precipitation x Turf			
Dry, Artificial	7,337	480,550	15.3 (14.9, 15.6)
Dry, Grass	6,985	465,648	15.0 (14.6, 15.4)
Snow, Artificial	397	26,731	14.9 (13.4, 16.3)
Snow, Grass	292	20,768	14.1 (12.4, 15.7)
Wet, Artificial	1,331	81,539	16.3 (15.4, 17.2)
Wet, Grass	1,209	82,824	14.6 (13.8, 15.4)

Table 3.A3. Injury rates by injury type, turf type and precipitation, 2007-2015.

Variable	Injury Rate per 1,000 AEs (SE)							
	Ankle	Back	Concussion	Groin	Hamstring	Knee (ligamentous)	Shoulder	UE Fracture
Precipitation x Turf (Ref. = Dry of Given Turf)								
Dry, Artificial	1.88 (0.06)	0.76 (0.04)	0.96 (0.04)	0.61 (0.04)	1.18 (0.05)	2.85 (0.08)	1.20 (0.05)	0.15 (0.02)
Dry, Grass	1.80 (0.06)	0.66 (0.04)	0.82 (0.04)	0.75 (0.04)	1.34 (0.05)	2.66 (0.08)	1.39 (0.06)	0.12 (0.02)
Snow, Artificial	1.88 (0.27)	0.98 (0.19)	0.98 (0.19)	0.57 (0.15)	0.84 (0.18)	2.91 (0.34)	1.27 (0.22)	0.38 (0.12)
Snow, Grass	1.97 (0.31)	0.83 (0.20)	0.93 (0.21)	0.44 (0.15)	0.83 (0.20)	2.86 (0.39)	1.44 (0.27)	0.10 (0.07)
Wet, Artificial	2.08 (0.16)	0.74 (0.10)	1.26 (0.12)	0.72 (0.09)	1.52 (0.14)	2.71 (0.19)	1.15 (0.12)	0.14 (0.04)
Wet, Grass	1.97 (0.16)	0.68 (0.09)	0.95 (0.11)	0.64 (0.09)	1.38 (0.13)	2.29 (0.17)	1.17 (0.12)	0.10 (0.03)

Prior Career Snap Count by Injury Type:

Figure 3.A2. Regular season injury rates by injury type and prior career snap count, 2007-2015, with 1-standard error bars.



<u>End-Season Toll:</u>

27.9% (95% CI 27.1-28.7%) of players beginning their season on the week 1 roster were injured as of the final week of the regular season (Table A5). WRs had the second greatest end-season toll, with 32.6% (95% CI 30.1-35.1%) of receivers ending the regular season on the injury report (Table A5).

Table 3.A4. Regular season injury end-season toll estimates for all NFL injuries, 2007-2015.

Variable	**End-Season Toll**	**Player-Seasons with Injury at End of Regular Season**
Total	27.7% (27.0%, 28.5%)	3,518
Position		
QB	32.5% (27.6%, 37.4%)	113
RB	32.2% (29.4%, 34.9%)	364
WR	32.1% (29.6%, 34.6%)	427
TE	26.2% (23.2%, 29.3%)	212
OL	26.4% (24.5%, 28.4%)	519
DL	26.7% (24.7%, 28.7%)	521
LB	29.1% (27.0%, 31.1%)	541
DB	30.7% (28.8%, 32.5%)	741
ST	9.2% (7.2%, 11.1%)	80
Side		
Defense	28.9% (27.8%, 30.1%)	1803
Offense	29.3% (28.1%, 30.5%)	1635

Full-Season Injury Measures:

Full-season injury frequency measures all follow similar patterns to, but are modestly higher than, their regular season counterparts (Table A6, Figures A7-A8). Overall 1-season risk was estimated as 71.1% vs. 68.5% for the regular season only (Tables 1 and A6), while the risk of missing 1+ regular season game was 41.7% vs. 39.0% in just the regular season. End-season toll was 33.3% and 27.9%, respectively (Tables A5 and A6).

Table 3.A5. Full-season injury counts, 1-season risks, and end-season toll estimates for all NFL injuries, 2007-2015.

Variable	**Player-seasons with Injury**	**1-Season Injury Risk**	**Player-Seasons with 1+ Games Missed Due to Injury**	**1-Season Risk of Missing 1+ Games Due to Injury (95% CI)**	**End-Season Toll**
Total	9,394	71.1% (70.4%, 71.9%)	5,502	41.7% (40.8%, 42.5%)	33.3% (32.5%, 34.1%)
Position					
QB	264	72.1% (67.5%, 76.7%)	162	44.3% (39.2%, 49.4%)	36.6% (31.7%, 41.5%)
RB	881	75.4% (73.0%, 77.9%)	568	48.6% (45.8%, 51.5%)	38.1% (35.3%, 40.9%)
WR	1,080	77.5% (75.3%, 79.7%)	656	47.1% (44.4%, 49.7%)	38.7% (36.2%, 41.3%)
TE	623	73.5% (70.5%, 76.4%)	389	45.9% (42.5%, 49.2%)	31.5% (28.4%, 34.6%)
OL	1,436	69.6% (67.6%, 71.6%)	793	38.4% (36.3%, 40.5%)	32.1% (30.1%, 34.1%)
DL	1,473	72.5% (70.5%, 74.4%)	815	40.1% (38.0%, 42.2%)	32.3% (30.2%, 34.3%)
LB	1,440	74.1% (72.1%, 76.0%)	843	43.4% (41.2%, 45.6%)	35.2% (33.1%, 37.3%)
DB	1,922	76.8% (75.1%, 78.4%)	1,188	47.4% (45.5%, 49.4%)	36.5% (34.6%, 38.3%)
ST	275	31.1% (28.1%, 34.2%)	88	10.0% (8.0%, 11.9%)	10.8% (8.7%, 12.8%)

Figure 3.A3. Full season injury measures: 1-season risks by weight and position, 2007-2015, with 1-standard error bars.

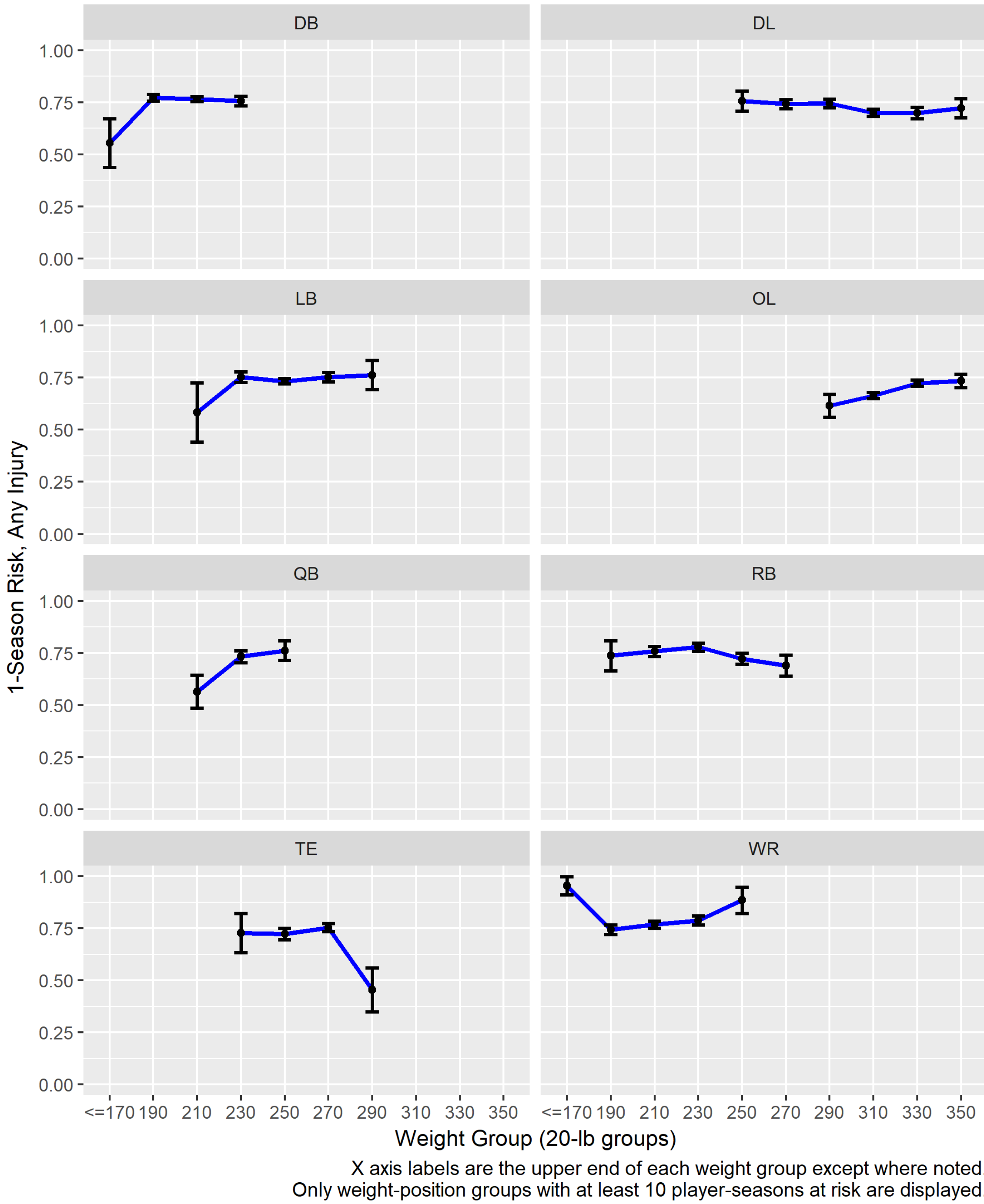
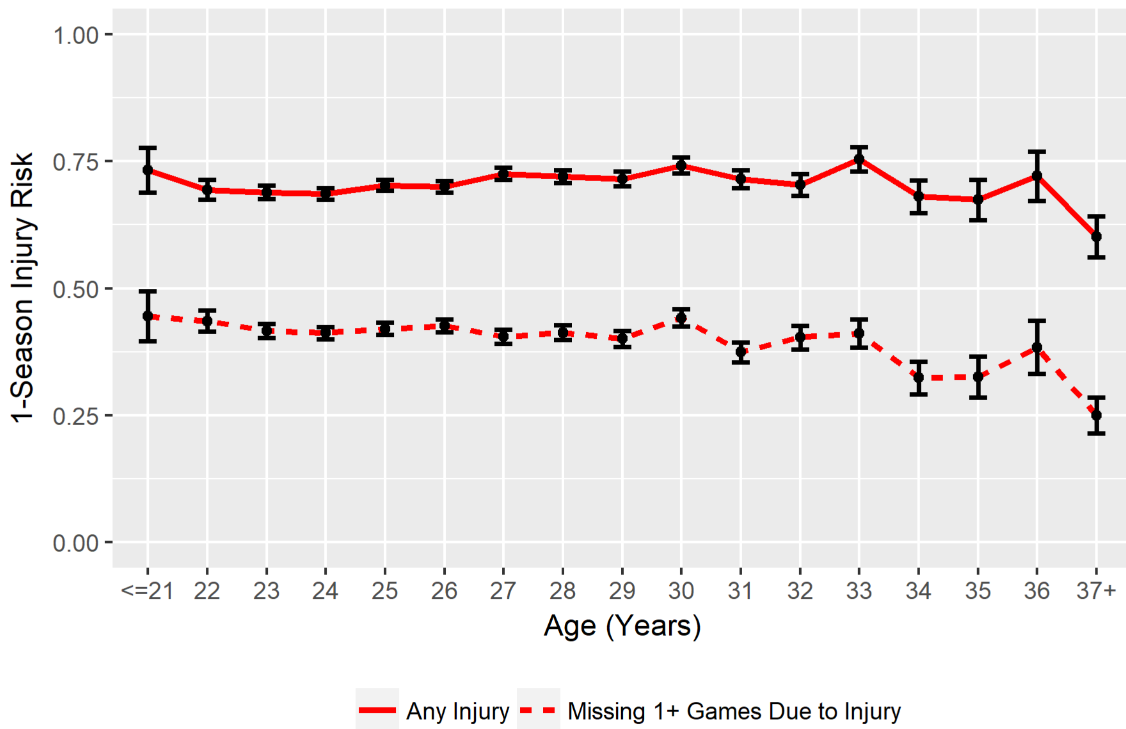


Figure 3.A4. Full-season injury measures: 1-season risks by age, 2007-2015, with 1-standard error bars.



<u>Allocation of AEs and Player-Seasons At-Risk Across Injury Risk Factor Categories:</u>

Position: AEs for each position were calculated proportionally according to one typical composition of a 53-man NFL roster – 3 quarterbacks (QB), 4 running backs (RB), 6 wide receivers (WR), 3 tight ends (TE), 9 offensive linemen (OL), 8 defensive linemen (DL), 7 linebackers (LB), 10 defensive backs (DB), and 3 special teams (ST) (190). In below calculations this makes for 25 offensive, 25 defensive, and 3 ST players. We do not have injury data at the play-level, so we do not make comparisons between ST players, who tend to play fewer snaps, and other players on a per-snap level.

Weight: Weight is the player's weight when they were drafted (or, if undrafted, when they debuted in the NFL). We split players into 20-lb weight buckets. We repeated this analysis with 2-unit buckets of body mass index (BMI), but the results were nearly identical and so are not presented here. Because weight is tightly correlated with position we present only stratified estimates; collapsing obscures any association between weight and injury frequency. AEs were distributed proportional to the player-seasons observed in each position-weight stratum.

Game-Level Variables (Turf, Weather, Rest, Home vs. Away): Because we lack data on injury timing more specific than week, for all game-level variables we made an assumption that all injuries occurred in the previous week's game rather than that week's practices. Other studies have shown that >80% of NFL injuries occur in games rather than practices (17, 41, 47, 54, 55). We also only calculate injury rates as 1-season risks do not make sense at this level. AEs were distributed proportional to the number of regular-season games in each stratum of the variables. To maintain party with other rates, practice AEs were included despite our assumption of all injuries happening in-game. Rates including only game AEs would be higher across the board, but the comparisons across strata should be similar.

Turf: Turf data were extracted from PFR and then cross-referenced for accuracy with stadium data from Wikipedia and sports news sources. Artificial turfs were categorized by manufacturer as the specific product installed was not always available. We limited turf analyses to the 2012-15 seasons to ensure that turfs introduced in more recent years do not appear worse because of the time trend of rising injuries. We also limited these analyses to visiting team injuries to remove the effects of the home team's roster, training staff, and other team-level factors, which can impact injury rates.

Precipitation: Precipitation was measured for the full day of the game and was classified as follows. First, all games in domes and stadiums with retractable roofs were considered dry. Second, if any snow was noted the game was marked as such. Third, if there was 0.05 inches or more of non-snow precipitation the game was considered wet. All other games were dry. Preliminary analyses showed injury rates did not differ appreciably between indoor venues and outdoor dry games.

Temperature: Temperature was measured as the mean temperature of the home team's city on the game day per Weather Underground and was classified as follows. We plotted injury rates for all outdoor games by 5-degree Fahrenheit buckets. All games in domes or stadiums with retractable roofs were considered indoor games and plotted separately.

Rest: The most frequent time between games is 7 days (Sunday-Sunday). We categorized rest into 4 days (short week, Thursday Night Football after a Sunday game), 5-6 days, 7 days, 8-11 days (extended rest, non-bye week) and 12+ days (bye week). Week 1 games were excluded.

Home vs. Away: We split away games by the travel burden in time zones: 0-2 time zones in either direction, 3+ east (local time later than body clock), or 3+ west (local time earlier than body clock). Neutral site games, including London, were counted as away for both teams.

Age: Age was bucketed at either extreme to ensure >= 100 injuries in each category. We looked at measuring age as years of NFL experience, but because this and chronological age were so tightly correlated we present only the results for age below. Because the distribution of position differs at older ages, we conducted a sensitivity analysis excluding QBs and STs. We also conducted a second sensitivity analysis to account for survivor bias – the idea that players playing at older ages are systematically different ("heartier") than the players who do not make it that long. To conduct this analysis we extended our injury data back from 2007 to 2000 and only included a stable, closed cohort of players whose entire careers were observed and who retired at 28, 30, 32, and 35 years of age and older.

Career Snapcount: This is used as a secondary measure of age that accounts for the wear-and-tear a player has experienced as the number of plays he has participated in in live regular and postseason games. Only snaps occurring prior to the current player-season are counted (e.g. an injury occurring in Kelechi Osemele's 2015 season would be associated with a career snap count of 2,539 snaps played by Osemele from 2012-2014). This analysis was restricted to players who made their NFL debut in 2002 or later because we needed full career snap count data. Special teams players were also excluded, as they reflect a special population of players with very low snap counts and injury rates. We tried numerous categorization schemes (100-, 500-, and 1,000-snap buckets) and found 500-snap buckets did the best at capturing injury trends while maintaining an interpretable graph. We bucketed every player-season with a career snapcount above 7,500 (the maximum snap count was 12,637) to ensure there were sufficient player-seasons in each bucket.

Rushing Percent: This was used as a proxy measure for team-level playing style: does a team like to run or pass the ball more relative to other teams? It was defined at the team-season level as the number of rushes divided by rushes + passing plays (attempts + sacks) over the course of a season. It was calculated separately for the two sides of the ball: offense (the team's own plays) and defense (the plays each team faced). AEs were allocated to buckets proportionately by the number of team-side-seasons in each bucket; injury counts and at-risk players were assigned to buckets based on the team and side of the ball on which they played (players playing on multiple teams in a single season were excluded). These data are provided in the Appendix, Figure A1.

<u>Additional Discussion of Interesting Results:</u>

The overall injury rate in our study (15.1 per 1,000 AEs) was somewhat higher than those calculated from other NFL studies. Deubert et al's study using the NFL's ISS yielded a rate of approximately 13.7 per 1,000 AEs based off 12,476 injuries reported from 2009-2015 and the calculations for AEs outlined in our Methods (41). Our data yielded 14,352 regular season injuries over this same time, a difference of 1,876 injuries. This may understate the true difference, however, as our data did not include injuries from week 17 and the NFL ISS data did. Two main methodological differences may explain our variation from the NFL ISS data in Deubert: different data sources, and differences in how a new injury was defined. We defined a new injury as any broad class of injury (e.g. hamstring) that was not listed for at least the two previous weeks, byes excluded; Deubert simply states that all injuries reported to the NFL ISS were counted. If their definition of a new injury was moderately stricter, this could explain the differences in rates. Our rate was nearly identical to another study using public injury report data – 15.0 per 1,000 AEs using the AE counting process outlined in our Methods (17), which further suggests the differences between our study and the Deubert study derive from their use of the NFL ISS versus our use of public injury report data.

Looking by position RBs had the highest injury rate (20.7 per 1,000 AEs) and 1-season risk of missing at least 1 game due to injury (Table 1). Several other positions (WRs, TEs, LBs, and DBs) were clumped together with injury rates around 17 per 1,000 AEs (Table 1). These are the more mobile positions who are more likely to engage in sprinting, sharp directional changes, and high-velocity impacts. Linemen, especially offensive linemen, are less mobile and had lower injury rates; their reported injury rates may also be lower if they are more often able to play through minor injuries than other positions. The injury profiles of different positions also were consistent with their in-game duties, with linemen having fewer concussions, groin and hamstring injuries, while DBs, WRs, and RBs had the highest rates of hamstring injuries. Linemen did have above-average rates of knee and, on the offensive line, ankle injuries, possibly due to their high weights and associated joint stresses. TEs had the highest rate of concussions by a wide margin (Table 2), suggesting they suffer more hits to the head than other positions. These positional results are consistent with previous studies of football injuries in high school, college, and the NFL that found particularly high injury rates for running backs and higher rates for mobile positions than linemen (7, 17, 34).

While there was a higher injury rate for home teams versus those who travel at least 3 time zones east (west coast to east coast, or any team to London) (13.7 vs. 14.9 per 1,000 AEs) (Table 1), the lack of a difference among other travel categories leads us to interpret this as a spurious finding. It is possible that an east-only difference could be due to differential difficulty in correcting one's circadian rhythms, leading to injury. However, this runs counter to what we would expect given the well-known handicap in winning percentage and some performance metrics west coast teams traveling to the east coast face as well as the previous literature on jet lag (147, 191). The previous literature on NFL injury rates for home and away teams is limited, but one other study found statistically significantly lower rates of knee, ankle, and shoulder injuries for teams traveling at least 3 time zones, though it did not differentiate between directions (56). With all this in mind, we treat our finding of safer eastward travel as likely spurious.

We found higher injury rates on artificial turf versus natural grass among visiting team injuries from 2012-2015. We limited our analysis to this period to ensure that turfs introduced in more recent years do not appear worse because of the time trend of rising injuries, and we limited our analysis to visiting team injuries to remove the effects of the home team's roster, training staff, and other team-level factors that can impact injury rates. However, for full disclosure we did not observe a difference between grass and artificial turf in 2007-2011 or when including home team injuries from 2012-2015. Previous NFL studies have found statistically significantly elevated injury rates for artificial turf, particularly for knee and ankle injuries; this is hypothesized to be due to greater stiffness of and shoe-surface friction on artificial turf (45, 48, 56, 93). Two other studies found no statistically significant difference in ACL tears and Achilles tears between turf and grass (73, 136), but no NFL study to our knowledge has found significantly *lower* injury rates on turf. Among specific brands of artificial turf Matrix Turf had the lowest injury rate, but the fact that it is only installed in one stadium (Dallas) makes drawing firm conclusions difficult; its large standard error prevented it from meeting our MID definition versus natural grass (Table 1). A-turf had the worst injury rate, and even though it was also installed at only one stadium (Buffalo) the difference between it and grass was large enough (4.4 per 1,000 AEs) to meet our MID definition (Table 1). Momentum Turf and FieldTurf – the latter of which is the most common artificial turf used in the NFL – exhibited elevated injury rates relative to natural grass (Table 1). All other artificial turfs were similar to natural grass with regards to injury rate (Table 1). Similar patterns were apparent for knee, ankle, and foot injuries specifically in the Appendix (Figure A1). To our knowledge there are no prior studies that compare NFL injury rates on artificial turf from different manufacturers. Overall our findings are consistent with those of previous studies that found artificial turf may exhibit moderately higher injury rates, and natural grass may be the safer choice in climates and stadiums where it is feasible.

Precipitation – categorized as dry, wet, or snowy – exhibited no relationship with overall injury rates. Snowy games were associated with lower rates of hamstring injuries, possibly due to less high-speed sprinting in these games. Rainy games exhibited lower rates of knee ligament injuries (Table 3). This may be because wet fields have less traction than dry fields, leading to more slipping but fewer hard cuts putting extreme torsion on leg joints (128). One previous NFL study found significantly fewer ankle sprains, but not knee sprains, on wet football fields (48); we found no difference in ankle sprains on wet vs. dry fields. While it may have an association with specific injuries, precipitation does not seem to be a reliable indicator of overall injury rates in the NFL.

We investigated temperature and week of season together because the two are closely correlated in the approximately 75% of NFL games that occur outdoors, with warmer temperatures early in the season (the NFL regular season runs from September to December). Overall injury rates did not vary with temperature (Figure 1) or week of the season when we controlled for temperature by looking at indoor games only (Figure 3). When stratifying by injury type we saw leg muscle strains such as groin and hamstring injuries were higher at higher temperatures; hamstring injuries were also higher earlier in the season in indoor games. We would expect more leg muscle injuries in colder temperatures due to tighter muscle fibers and early in the season due to lower muscle fiber tolerance, which improves with training (3, 130). Combining our results with our expectations it is likely the increase in hamstring injuries with temperature is at least partially confounded by week of the season, but further studies are needed to tease out these dueling associations. We also observed a drop in knee injuries in indoor games in later weeks of the season, but the reason for this is unclear (Figure 4). It is possible this is a survivor effect where those at risk for knee injuries tend to suffer those early in the season and leave the risk pool for as long as those injuries continue to hamper them. However, no other injuries exhibited a change over the season, and it is unclear why only knee injuries would be subject to a survivor effect. Although there is substantial noise, Figure 4 also suggested an increase in concussion rates as the season drags on, which is consistent with the higher rates at lower temperatures we also observed (Figure 2). This may indicate a build-up of sub-concussive head traumas over the early part of the season that leaves players more susceptible to them later on (97), but more studies would be needed to fully investigate this possibility. Previous NFL studies have found more knee and hamstring injuries in warmer temperatures and concussions in colder temperatures, which is consistent with our crude temperature findings (48, 56); these analyses did not adjust for week of season, however. NFL studies on week of season have exhibited mixed results by the type of injury: overall injuries, hamstrings, ACLs, and Achilles tears down, concussions up, and no effect on total knee and ankle injuries later versus earlier in the season (56, 73, 143); these results all align with our own. In summary, while our study found no overall association between injury rates and temperature or week of season, leg muscle injuries appear to the decline over the course of the season while concussions rise; corresponding trends were seen for the temperatures that correlate with week of the season.

Injury rates rose steadily over time from approximately 12.5 to 17.5 per 1,000 AEs from 2007-2015 (Figure 10). When stratifying by injury type we see the same increase for all injury types except UE fractures, though reported concussions experienced a particularly rapid increase (Figure 11). Prior studies have also shown an increase in injuries over time, including for concussions (41, 143). Because these changes may be driven by increased reporting and diagnosis of injuries – especially head injuries – rather than a change in the underlying rate, we stratified by injury severity (0, 1-2, or 3+ games missed) and head vs. other injuries in Figure 12. Increased reporting might be expected to have a differentially stronger effect in less severe injuries. The additional attention paid to concussions might be expected to increase reported head injuries overall and more circumspect approaches to treatment might be expected to cause more players suffering concussions to miss games. Figure 12 demonstrates this: there are smaller rises in non-head injuries causing players to miss games versus all other groups. This suggests that a large proportion of the increase over time may be due to reporting and diagnostic bias rather than a true change in the underlying injury rate.

Chapter 4: Specific Aim 2. 2011 CBA's Effects on Injuries.

I. Abstract

Introduction: The National Football League's (NFL) 2011 collective bargaining agreement (CBA) with its players placed a number of contact and quantity limitations on offseason, training camp, and regular season practices and workouts. Some coaches and others have expressed a concern that this has led to poor conditioning and a subsequent increase in injuries. Rigorous studies on the effects of the NFL's new practice restrictions have not been performed, however.

Objective: We sought to assess whether the 2011 CBA's practice restrictions affected the number of overall, conditioning-dependent, and/or non-conditioning-dependent injuries in the NFL or the number of games missed due to those injuries.

Methods: The study population was player-seasons from 2007-2016 for any player who had participated in at least one career regular season game. We included only regular season, non-illness, non-head, game-loss injuries. Injuries were identified using a database from the website Football Outsiders based on public NFL injury reports and the injured reserve list. The primary outcomes were overall, conditioning-dependent and non-conditioning-dependent injury counts by season. We also investigated games missed due to these injuries as a secondary outcome. We calculated injury counts and games missed per season and compared the results before (2007-2010) and after (2011-2016) the CBA. We also used a Poisson interrupted time series model to assess whether there was an immediate change after the CBA or if a pre-CBA increase in injuries accelerated post-CBA.

Results: The number of game-loss regular season, non-head, non-illness injuries grew from 701 in 2007 to 804 in 2016 (15% increase). The number of regular season weeks missed exhibited a similar increase. Conditioning-dependent injuries increased from 197 in 2007 to 271 in 2011 (38% rise), but were lower and remained relatively unchanged at 220-240 injuries per season thereafter. Non-conditioning injuries decreased by 37% in the first three years of the new CBA before returning to historic levels in 2014-2016. Poisson models for all, conditioning-dependent, and non-conditioning-dependent game-loss injury counts did not show statistically significant detrimental changes associated with the CBA.

Conclusions: We did not observe a sustained increase in conditioning- or non-conditioning-dependent injuries following the 2011 CBA. Other concurrent injury-related rule and regulation changes limit specific causal inferences about the practice restrictions, however, and further studies are warranted.

II. Introduction

Periodically the National Football League (NFL) and the NFL Players' Association (NFLPA) negotiate a new collective bargaining agreement (CBA) that governs labor associations between the NFL and its players.

The most recent CBA was negotiated after a 4.5-month offseason "lockout" period prior to the 2011 season. During the lockout players and teams were prohibited from any contact including practices and medical examinations. The new CBA placed a number of limitations on offseason, training camp, and regular season practices and workouts (148). These new limitations reduced the physical burdens put on players outside of games: organized team activities (OTAs) each spring were reduced from 14 days to 10, the voluntary offseason workout program reduced from 14 to 9 weeks, twice-daily padded practices were eliminated during the 6-week training camp prior to each season, and regular season padded practices were restricted from no limit to 14 during the 17-week season (149, 150). These regulations were implemented to improve player safety and reduce injuries by avoiding overtraining and increasing rest (148-150). Some, however, have argued that they have had the opposite effect, leading to undertraining that worsens player conditioning and leaves them more susceptible to injuries (151-154).

There is evidence for both undertraining and overtraining increasing injury risk. A substantial body of sports research in track and field, baseball, cricket, rugby, and Australian Rules Football suggests that high intensity training and high activity loads may lead to injuries, particularly soft tissue injuries (156, 157, 192-200). On the other hand, the extant literature suggests that too little training – particularly a low long-term "chronic" workload – is also a predictor of increased injury risk in sports such as cricket and rugby (156, 193, 201). The goal is to find a balance between undertraining and overtraining that leaves athletes equipped to perform at a high level and renders them less susceptible to injuries. More recent research has demonstrated the importance of a balanced "acute:chronic workload ratio," wherein a high long-term chronic workload is necessary to achieve fitness and maximize competitive performance but excessive short-term acute workloads can lead to fatigue overwhelming fitness and an increase in injury risk (156). Associations between rapid changes in workload and increased injury risk have been reported in in cricket, rugby, soccer, and Australian Rules Football (193, 202-205).

Studies of practice or training load and injury risk in American football, however, are relatively limited. One study from the Big 10 Conference in college football found that 1998 rules to limit scrimmages and full-contact practices in the spring did not decrease the number of spring injuries per year, though injuries in the fall did decline by one third (4). Two studies of middle school and high school football players in Oklahoma City found that the extent of participation in preseason conditioning activities did not differ among players who sustained an injury and those who remained injury-free (23, 24). To our knowledge no similar studies of preseason practice load and injury risk been performed for the NFL, however.

It is unknown whether the NFL's practice regimens resulted in overtraining in the pre-CBA era, undertraining in the post-CBA era, both, or neither. One research group identified a sudden increase of Achilles tendon injuries immediately after the 2011 NFL lockout ended and training camp began, noting 12

Achilles tendon ruptures the first 29 days after the lockout versus 6 and 10 total Achilles tendon ruptures the last two full seasons, respectively (155). The evidence we can take from such a short period is limited, however.

We hypothesized that the effects of undertraining and overtraining would be most apparent in overuse injuries such as muscle strains, which we refer to as "conditioning-dependent" injuries. However, fewer practices – and especially fewer padded practices – also result in fewer chances for suffering an injury in the post-CBA era. This effect may be more evident in contact-based injuries such as fractures and trauma of internal organs, which we refer to as "non-conditioning-dependent" injuries.

In an effort to tease out the varying effects of the 2011 CBA's practice restrictions, we sought to investigate whether the restrictions were followed by changes in the number of overall, conditioning-dependent, and non-conditioning-dependent injuries in the NFL. A secondary objective was to investigate whether the 2011 CBA's practice restrictions were associated with changes in the number of games missed due to these injuries.

III. Methods

Study Population: Any player who had participated in at least one regular season NFL game in their career through the 2016 season was eligible for this study. The study population included 19,803 player-seasons and 22,331 injuries from 2007-2016. We excluded 2,643 preseason injuries (11.8%) to ensure comparable populations in the pre- and post-CBA eras since the CBA increased preseason roster sizes. We excluded 11,399 non-game-loss injuries (51.0%) to account for the more complete reporting of minor injuries in recent years seen in Specific Aim 1 (143, 206). We excluded 685 head injuries (4.1%) to minimize the impact of improved reporting and diagnosis of concussions on our results (207, 208). Finally, we excluded 179 illnesses (0.8%) because they are unlikely to be related to any practice rule changes but tend to spike and drop quickly, introducing noise into the data. This left a total of N=7,425 injuries over ten seasons. We conducted sensitivity analyses removing the preseason, minor injury, and head injury exclusions.

Outcome: The primary outcomes of interest in these analyses were conditioning-dependent and non-conditioning-dependent injury counts at the season and player-season levels. We used counts rather than rates because the new CBA reduced practices and thus decreased the total number of athlete-exposures (AEs), a common denominator unit in calculating rates of sports injuries. This reduction could increase injury rates even if it decreased the number of injuries overall. To examine injury severity we investigated the number of regular season games missed due to conditioning-dependent, non-conditioning-dependent, and all injuries as a secondary outcome.

We defined an injury as any relevant event that appeared on the public injury reports NFL teams release before each regular season game or that placed a player on the long-term "injured reserve" list. A new injury had to meet one of two criteria: 1. It was to a different location (e.g. foot, ankle) from any previous injury that season, or 2. It was to the same location as a previous injury that season, but the player had not been on the injury report with that injury for at least two weeks, excluding weeks without a game.

Conditioning-Dependent Injuries: The definitions of conditioning and non-conditioning injuries are given in Table A1 in the Appendix. Conditioning injuries involved soft tissues such as the Achilles tendon, calf, groin, hamstring, biceps, triceps, pectoral, quadriceps, and anterior cruciate ligament (ACL). Non-conditioning injuries included contact injuries such as fractures, high ankle sprains, and various types of trauma to the face and eye, Lisfranc joint, internal organs, neck, ribs, or toes. Some injuries – such as non-ACL knee and ankle injuries – could not be reliably categorized as conditioning-dependent or non-conditioning-dependent and were kept as a separate category or only included in the all-injury analysis. We conducted a sensitivity analysis re-classifying all non-ACL knee and ankle injuries as non-conditioning. We also conducted a sensitivity analysis using only hamstring injuries, which are some of the most likely injuries to be impacted by poor conditioning.

<u>Exposure:</u> The main independent variable of interest was the time interval, which was dichotomized as post-CBA (2011-2016) vs. pre-CBA (2007-2010)

<u>Statistical Analysis:</u>

The primary hypothesis for the NFL's practice restrictions worsening injury risks is that with less training players are more poorly conditioned, leading to more injuries. We thus sought to evaluate the CBA's effects within a subset of injuries most likely to be impacted by this mechanism of poor conditioning and in those that weren't. In the absence of any bias, the CBA training restrictions could plausibly affect injury risk via three possible mechanisms:

1. Fewer practices → more rest → fewer injuries

2. Fewer practices → poorer conditioning → more injuries

3. Fewer practices → fewer chances for injury → fewer injuries

Each of the three proposed mechanisms is expected to differentially affect counts of conditioning and non-conditioning injuries (Table 1).

Table 4.1. Possible Effects of CBA on Conditioning and Non-Conditioning Injuries.

CBA's Effect on Conditioning Injuries	CBA's Effect on Non-Conditioning Injuries	Mechanisms Responsible
Fewer Injuries	Fewer Injuries	1, 3
Fewer Injuries	No Change/More Injuries	1
No Change	Fewer Injuries	3
No Change	No Change/More Injuries	None, or 1 & 2 offsetting
More Injuries	Decline	2, 3
More Injuries	No Change/More Injuries	2

To examine the hypothesis that CBA practice restrictions may affect risk of injury we first calculated counts of injuries and games missed by year. We then stratified these counts by whether the injuries were conditioning-dependent. We inspected these curves for evidence of immediate and delayed effects of the CBA on injury counts. A rise or fall was defined as a sustained change of at least 1 injury per 1,000 AEs, which is equivalent to a 6.7% change in injury counts, for three or more seasons from the pre-CBA to post-CBA period.

In order to account for a secular trend in increasing injuries before the 2011 CBA we used a mixed Poisson interrupted time series model at the player-season level to separate out the effects of the CBA from broader time trends:

$$\ln(Y_{ij}) = \ln(G_{ij}) + \beta_0 + \beta_1 * t_{ij} + \beta_2 * CBA_{ij} + \beta_3 * PostCBA_{ij} + \beta_4 * Age_{ij} + b_{0i} + e_{ij}$$

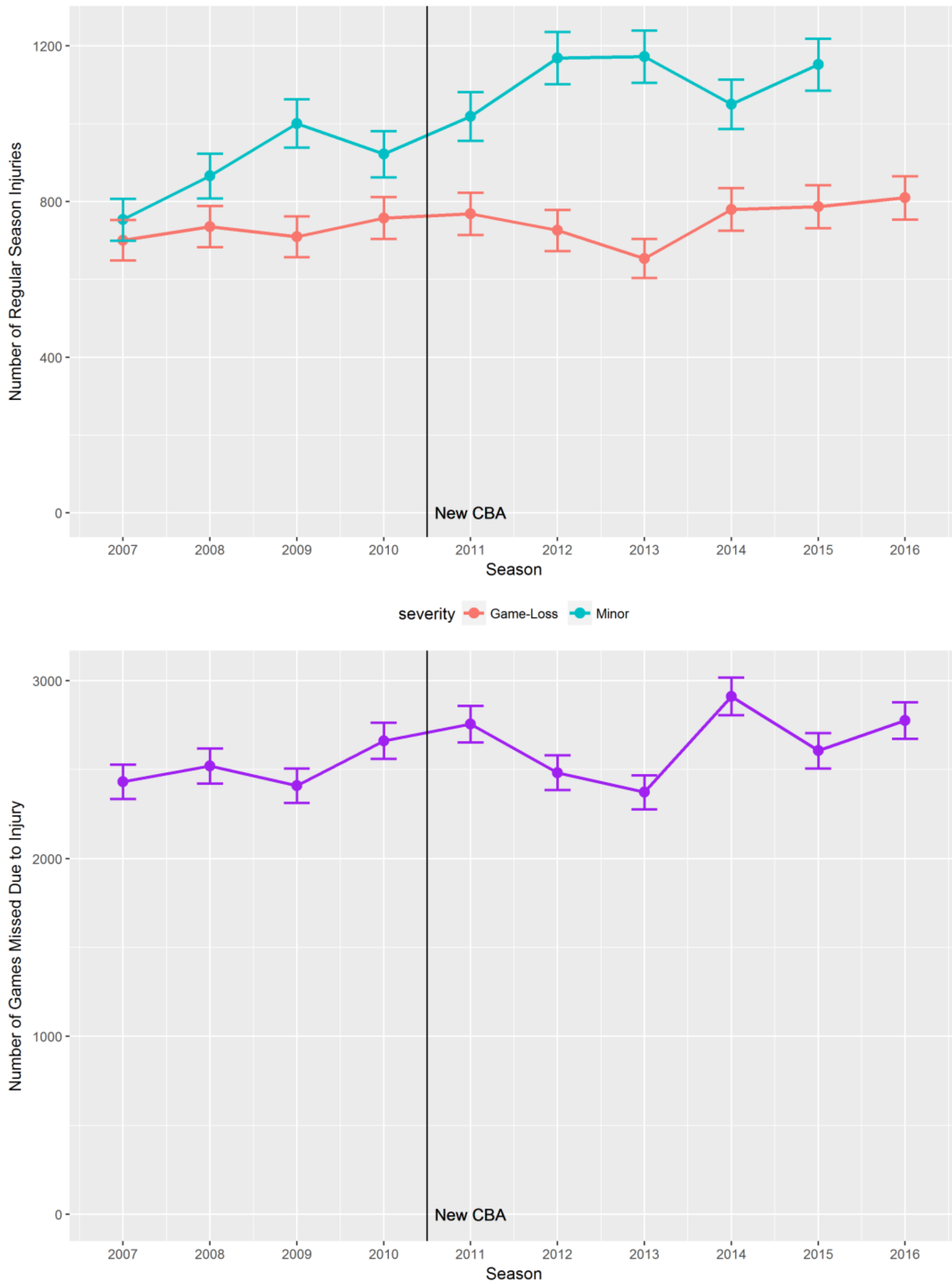
where Y_{ij} = count of injuries or games missed due to injury for the i'th player in the j'th season; t_{ij} = Year – 2007; CBA_{ij} = 1 if 2011 or later, 0 if 2010 or earlier; $PostCBA_{ij}$ = 0 for 2007-11, otherwise Year – 2011; Age_{ij} = age of the i'th player in the j'th season; and b_{0i} is a random intercept to account for correlated risks of injury within the same player. $\ln(G_{ij})$ is an offset accounting for the number of games player i was at risk of injury in season j. When exponentiated, β_2 represents the effect of the CBA on injuries (i.e. the percent change in injury rates from the pre-CBA to post-CBA eras). When exponentiated, β_1 represents the percent change in injury rates from one year to another in the pre-CBA era. When exponentiated, $\beta_1 + \beta_3$ represents the percent change in injury rates from one year to another in the post-CBA era. To assess model fit we summed each player-season's predicted count of injuries or games missed due to injury for each year and plotted these predicted counts against the actual injury counts for each year.

All analyses were performed in R version 3.3.2 and RStudio version 1.0.143 with the exception of the Poisson models, which were run in SAS v. 9.4 (SAS Institute, Cary, NC). The Emory University IRB determined this project was not human subjects research as all data is publicly available.

IV. Results

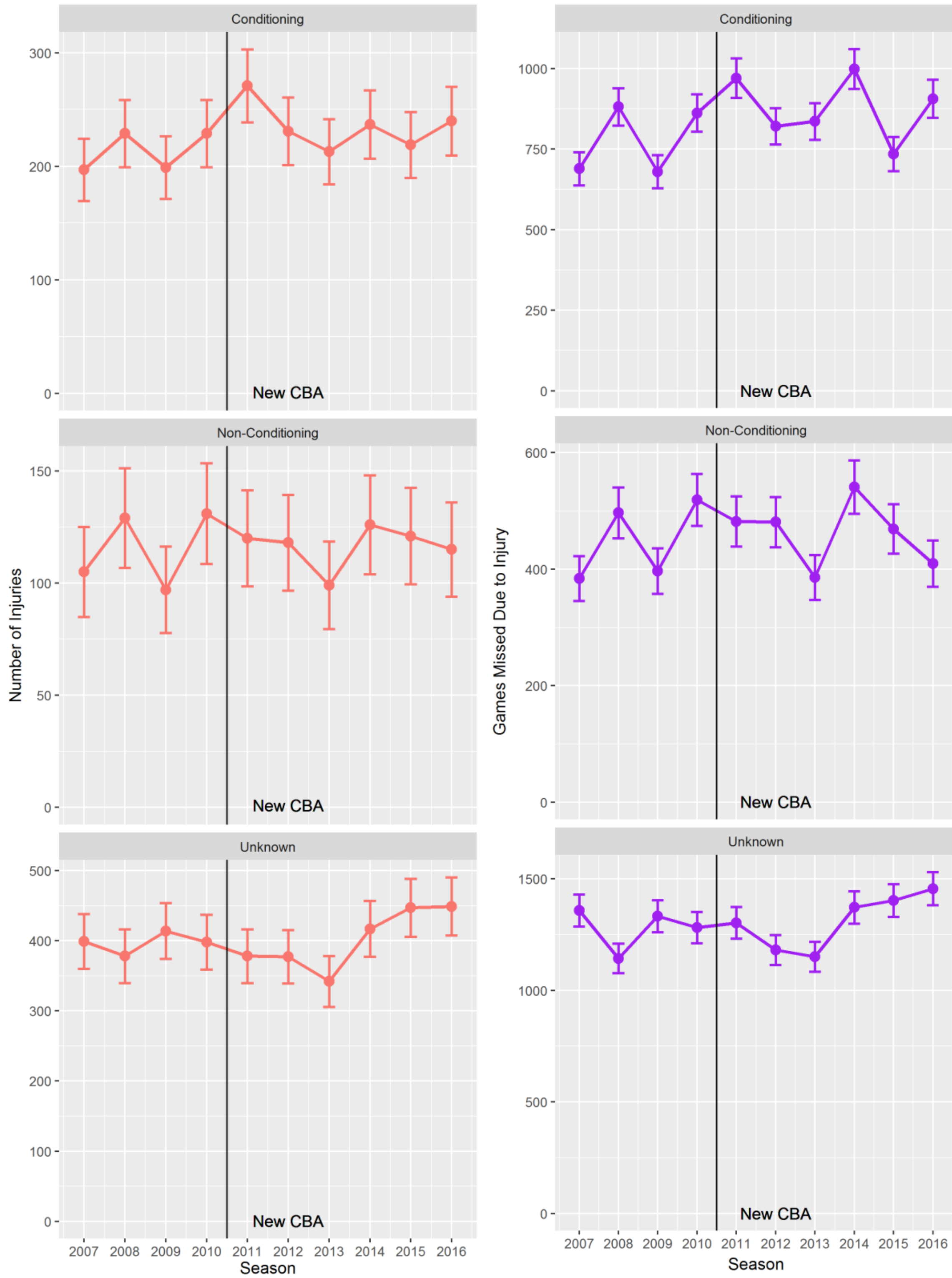
Overview of Time Trends: The number of minor regular season, non-head, non-illness injuries increased substantially from 754 in 2007 to 1,169 in 2012 (55% rise) from 2007-2012 before stabilizing through 2016 (Figure 1, blue line). The number of game-loss injuries exhibited a smaller increase of approximately 15% (804 in 2016 vs. 701 in 2007). The number of regular season weeks missed (Figure 1, purple line) – which accounts for injury severity – largely corresponds to the number of game-loss injuries (red line).

Figure 4.1. Number of Regular Season Non-Head, Non-Illness Injuries and Weeks Missed, 2007-2016, with 95% CIs.



Time Trends Stratified by Conditioning Status : The overall number of regular season, non-head, non-illness conditioning-dependent injuries increased from 197 in 2007 to 271 in 2011 (38% rise) from before reaching a plateau at 220-240 injuries per season between 2012 and 2016 (Figure 2, top left). Regular season non-conditioning injuries remained at historical levels in post-CBA (Figure 2, middle left). Other regular season injuries remained stable before rising 19% between 2012 and 2015 (Figure 2, lower left). The time trends in the number of regular season weeks missed resemble those of the injury counts (Figure 2, right).

Figure 4.2. Number of Regular Season Game-Loss, Non-Head, Non-Illness Injuries and Games Missed, Stratified by Conditioning Status, 2007-2016, with 95% Poisson CIs.



Poisson Interrupted Time Series Models:

Among all regular season non-head, non-illness injuries there was little evidence of a detrimental effect of the 2011 CBA (Figure 1, top row, red line). A Poisson model estimated that injury rates were 7% lower in the post-CBA era than they would have been had the CBA never been implemented (95% CI -17% to +3%) (Table 2, "CBA" coefficient). The model also estimated an annual 3% increase in injury rates in both the pre- (95% CI 0% to +7%) and post-CBA (95% CI +1% to +4%) eras (Table 2). For total games missed, the model estimated a pre-CBA annual increase in the rate of games missed of 13% (95% CI +11% to +16%), while in the post-CBA period this decreased to a 4% annual rise (95% CI +3% to +5%) (Table 2).

Among conditioning-dependent injuries there appeared to be an immediate one-year increase post-CBA (Figure 2, top row); the model estimated that injury rates were 5% higher overall in the post-CBA era than the pre-CBA era (95% CI -13% to +27%) (Table 2). These injuries appeared to be increasing prior to the CBA before stabilizing in the post-CBA era (Figure 2, top row). This result was consistent with the Poisson model, which estimated a pre-CBA annual change in injury rates of 4% (95% CI -2% to +10%) but no time trend in the post-CBA era (-1% annual change, 95% CI -4% to +2%) (Table 2). The results were similar when considering the number of games missed due to injury (Table 2).

Non-conditioning injuries remained at historical levels (Figure 2, middle row). The model estimated that non-conditioning injury rates were 10% lower in the post-CBA era than they would have been had the CBA never been implemented (95% CI -31% to +16%). It also estimated an annual increase in the injury rate of 5% CBA (95% CI -4% to +14%) and no time trend in the post-CBA era (0% annual change, 95% CI -4% to +5%) (Table 2). The results were similar when considering the number of games missed due to injury (Table 2).

Table 4.2. Poisson Models for Regular Season Game-Loss, Non-Head, Non-Illness Injuries and Games Missed, Stratified by Conditioning Status, 2007-2016.

Model	Rate Ratio	95% CI	p-value[a]
Number of Injuries			
All Injuries			
Pre-CBA Time Trend (1-year increase)	1.03	1.00, 1.07	0.07
CBA (Post-CBA vs. Pre-CBA)	0.93	0.83, 1.03	0.16
Post-CBA Time Trend (1-Year increase)	1.03	1.01, 1.04	0.74
Age (1-year increase)	1.01	1.00, 1.01	0.16
Conditioning Injuries			
Pre-CBA Time Trend (1-year increase)	1.04	0.98, 1.10	0.25
CBA (Post-CBA vs. Pre-CBA)	1.05	0.87, 1.27	0.62
Post-CBA Time Trend (1-Year increase)	0.99	0.96, 1.02	0.19
Age (1-year increase)	1.02	1.00, 1.03	0.01
Non-Conditioning Injuries			
Pre-CBA Time Trend (1-year increase)	1.05	0.96, 1.14	0.27
CBA (Post-CBA vs. Pre-CBA)	0.90	0.69, 1.16	0.42
Post-CBA Time Trend (1-Year increase)	1.00	0.96, 1.05	0.37
Age (1-year increase)	1.02	1.00, 1.03	0.07
Games Missed Due to Injury			
All Injuries			
Pre-CBA Time Trend (1-year increase)	1.13	1.11, 1.16	0.00
CBA (Post-CBA vs. Pre-CBA)	0.90	0.85, 0.96	<.0001
Post-CBA Time Trend (1-Year increase)	1.04	1.03, 1.05	<.0001
Age (1-year increase)	1.07	1.06, 1.08	0.00
Conditioning Injuries			
Pre-CBA Time Trend (1-year increase)	1.13	1.09, 1.18	<.0001
CBA (Post-CBA vs. Pre-CBA)	0.97	0.88, 1.08	0.64
Post-CBA Time Trend (1-Year increase)	1.04	1.02, 1.07	0.00
Age (1-year increase)	1.10	1.08, 1.11	<.0001
Non-Conditioning Injuries			
Pre-CBA Time Trend (1-year increase)	1.19	1.13, 1.25	<.0001
CBA (Post-CBA vs. Pre-CBA)	0.90	0.78, 1.03	0.13
Post-CBA Time Trend (1-Year increase)	0.98	0.95, 1.01	<.0001
Age (1-year increase)	1.06	1.04, 1.08	<.0001

[a]p-values for post-CBA time trends are for a difference between the pre- and post-CBA time trends.

Sensitivity Analyses: We conducted several sensitivity analyses. Including minor injuries in did not substantially alter the model's coefficients, nor did including preseason injuries or re-classifying knee and ankle injuries from unknown to non-conditioning. When examining hamstring injuries specifically, we observed an increase of these injuries over time pre-CBA followed by a reversing of that trend in the post-CBA era (Figure 3). The Poisson models also indicated stronger beneficial effects of the CBA. The models estimated a pre-CBA annual increase in hamstring injury rates of 12% (95% CI +2% to +23%) but a 4% annual decrease in the post-CBA era (95% CI -8% to +1%) (Table 3). The results were similar when considering the number of games missed due to injury (Table 3).

Figure 4.3. Number of Regular Season Game-Loss Hamstring Injuries, 2007-2016, with 95% Confidence Interval.

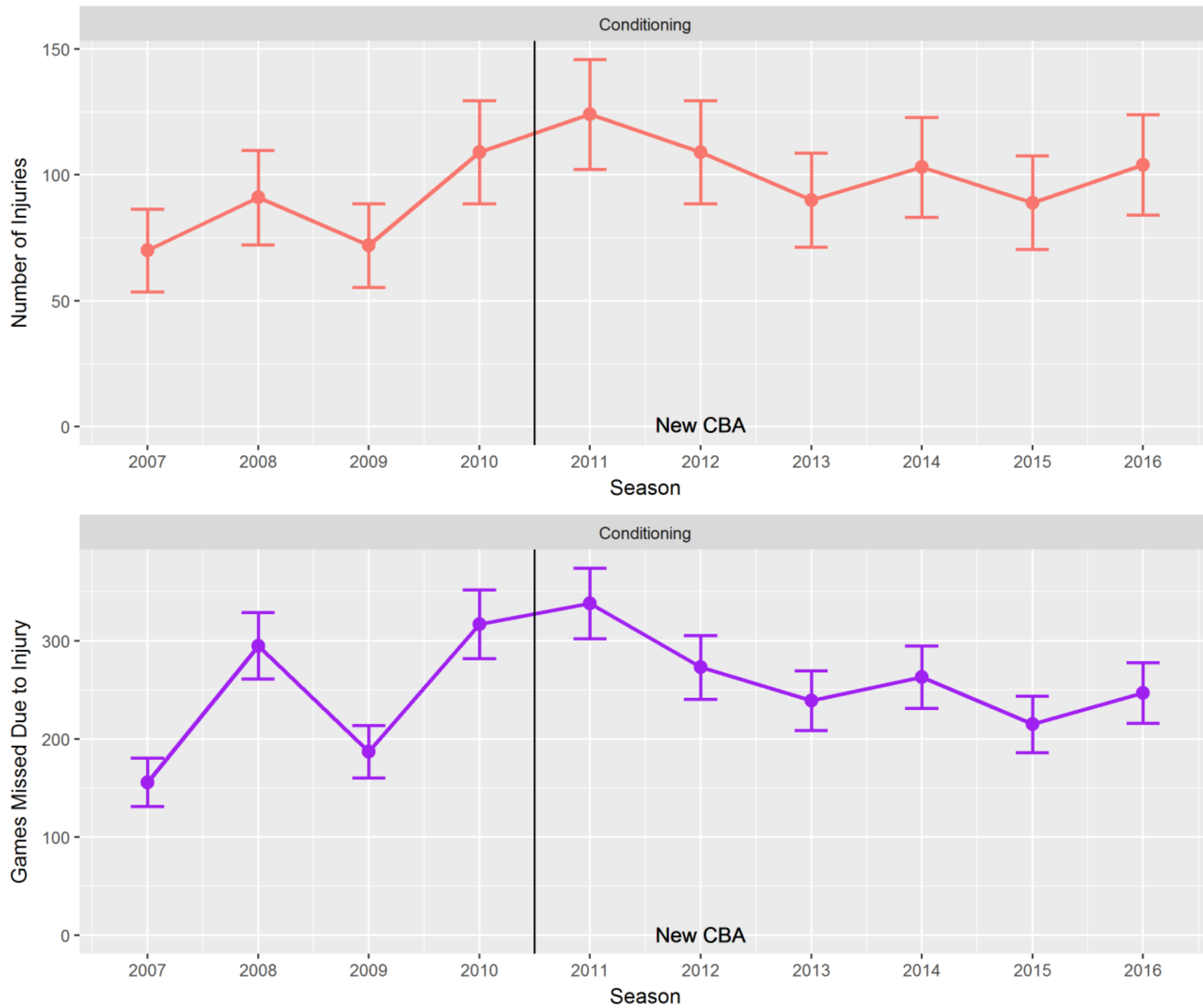


Table 4.3. Poisson Models for Regular Season Game-Loss Hamstring Injuries and Games Missed, 2007-2016.

Model	Rate Ratio	95% CI	p-value[a]
Number of Injuries			
Hamstring Injury Counts			
Pre-CBA Time Trend (1-year increase)	1.12	1.02, 1.23	0.02
CBA (Post-CBA vs. Pre-CBA)	0.98	0.74, 1.31	0.92
Post-CBA Time Trend (1-Year increase)	0.96	0.92, 1.01	0.01
Age (1-year increase)	0.97	0.95, 0.99	0.00
Hamstring Games Missed			
Pre-CBA Time Trend (1-year increase)	1.29	1.21, 1.38	<.0001
CBA (Post-CBA vs. Pre-CBA)	0.73	0.61, 0.88	0.00
Post-CBA Time Trend (1-Year increase)	0.99	0.95, 1.02	<.0001
Age (1-year increase)	1.01	0.99, 1.03	0.53

[a]p-values for post-CBA time trends are for a difference between the pre- and post-CBA time trends.

V. Discussion

Overall regular season game-loss, non-head, non-illness injuries did not rise or fall from the pre- to post-CBA practice restriction period. Our conclusions are primarily based on the descriptive data in Figures 2 and 3 and the definitions of rise and fall presented in the Methods, but they are consistent with the interrupted time series models presented in Figure 3 and Table 2, which show no evidence for an increase in conditioning-dependent injuries or injuries overall in the post-CBA era. In the context of the three injury-affecting mechanisms we outlined in the Methods, the results suggest we have seen either none of these mechanisms operating or nearly-offsetting effects from additional rest/fewer chances for injury and poorer conditioning.

The limitations of the Poisson interrupted time series models underlying Figure 3 and Table 2 merit additional discussion. As with any interrupted time series analysis our conclusions are reliant on assumed counterfactuals for the post-CBA period. If we assume that injury counts would have continued rising unabated the CBA's practice restrictions may appear beneficial. If we instead assume that injury rates would have plateaued even in the absence of the CBA then the effects could better be described as non-detrimental. In models that included no pre- or post-CBA time trends, the CBA appeared detrimental (results not presented). The choice of counterfactual assumption exerts a strong effect on the interpretations of our models.

With that said, the models are a useful supplement to visual graph inspection and descriptive analyses. Among all regular season non-head, non-illness injuries visual inspection and comparison to the rise/fall criteria outlined in the Methods suggested no detrimental effect of the practice restrictions (Figure 1, top row, red line). Consistent with our interpretation, the model estimated injury rates were 7% lower in the post-CBA era than they would have been absent the CBA and no change in time trends pre- and post-CBA (Table 2). Visual analysis suggested a similar lack of detrimental effects for conditioning-dependent injuries (Figure 2, top row). The Poisson model did not identify a substantial difference in injury rates or time trends in the pre- vs. post-CBA eras (Table 2). Visual inspection of non-conditioning injuries suggested they remained largely at historical levels (Figure 2, middle row). This interpretation is consistent with the results of the Poisson models, though the large year-to-year variance in these injuries (Figure 2) suggests the model's coefficients may not be reliable.

In 2014 there was a substantial jump in injuries of unknown conditioning status that lasted through the 2016 season (Figure 2). The increase was across a range of injury locations – knee, ankle, foot, back, and shoulder, primarily. This is unlikely to be an effect of the CBA's practice restrictions due to its delayed timing and sudden onset. However, we were unable to identify a single event or set of events between the 2013 and 2014 seasons to account for this change.

To our knowledge this is the first study to investigate the injury effects of the 2011 CBA's practice restrictions over a substantial time period. One research group identified a sudden increase in Achilles injuries immediately after the 2011 NFL lockout ended and training camp began (12 Achilles tendon ruptures the first 29 days after the lockout versus 6 and 10 total Achilles tendon ruptures the last two full seasons, respectively) (155). Our findings are consistent with theirs, however: we classified Achilles injuries as conditioning-dependent, and such injuries did exhibit a temporary bump in 2011 before returning closer to historical levels (Figure 2).

This study has several strengths. We analyzed 10 full years of data – 4 years pre- and 6-years post-intervention – which allows us to place the effects of the practice restrictions in context of broader injury trends and mitigates the risks of drawing conclusions from natural season-to-season variations. We also attempted to account for time trends that might distort a simple pre-/post-CBA comparison using interrupted time series models.

There are also several important limitations in this study. First, there were several other changes designed to enhance player safety and reduce injuries concomitant with the 2011 CBA and throughout the study period. Changes concomitant with the CBA included moving the kickoff up to encourage more touchbacks and the expansion of the "defenseless players" list to include, among others, receivers who have not re-established themselves as runners. It is difficult to disentangle the effects of all these various changes in our data, but it is most likely these effects would have biased injuries in later years downward from what they would have been absent these changes. This would in turn have made the CBA look more beneficial than it truly was.

Second, we interpreted our models assuming as a counterfactual that the pre-CBA rise in injuries would have continued unabated during our study period absent the CBA. If instead injuries would have plateaued absent the CBA our estimated effects would be biased in favor of the CBA.

Third, our data often only gives us the body part injured rather than the specific injury, which along with the unknown impact of conditioning on many injuries inserts the possibility for misclassification of conditioning/non-conditioning injuries. Additional information such as whether the injury was contact or non-contact would help with making these designations in future studies. The direction of this bias can be inferred by comparing the fitted lines for all conditioning injuries (Figure 3, middle row) to those for only hamstring injuries (Figure 4), which are known to be affected by over- and undertraining (209). The trend in hamstring injuries switches from an increase pre-CBA to a decrease post-CBA (Figure 4 and Table 3); if this represents the true effect of practice restrictions on conditioning-dependent injuries, then our full conditioning-dependent results (which do not show decreasing injury counts post-CBA) may suffer from misclassification that biases it against a beneficial effect of the CBA.

VI. Conclusions

Among regular season game-loss, non-head, non-illness injuries, descriptive analyses and interrupted time series models did not indicate the CBA's practice restrictions had a net harmful effect on injury burden in the NFL. It does not appear that the practice restrictions pushed the NFL, on average, from a state of optimal training to one of undertraining, but whether there was previous overtraining – or whether there is still undertraining – remains unclear. However, other concurrent injury-related rule and regulation changes are potential confounding factors that limit specific causal inferences about the practice restrictions, and further studies are warranted.

VII. Appendix

Table A1 lists 51 injury types from our injury database and how they were classified with respect to the impact of conditioning on the incidence of those injuries. As described below, we also conducted a sensitivity analysis where ankle sprains, general ankle injuries, knee sprains, and general knee injuries were classified as not conditioning-dependent rather than unknown. These categories were chosen because they were the largest components of the unknown group, which was substantially larger than either the conditioning or non-conditioning groups in the main analysis.

Table 4.A1. Condensed Injury Types and Conditioning Status.

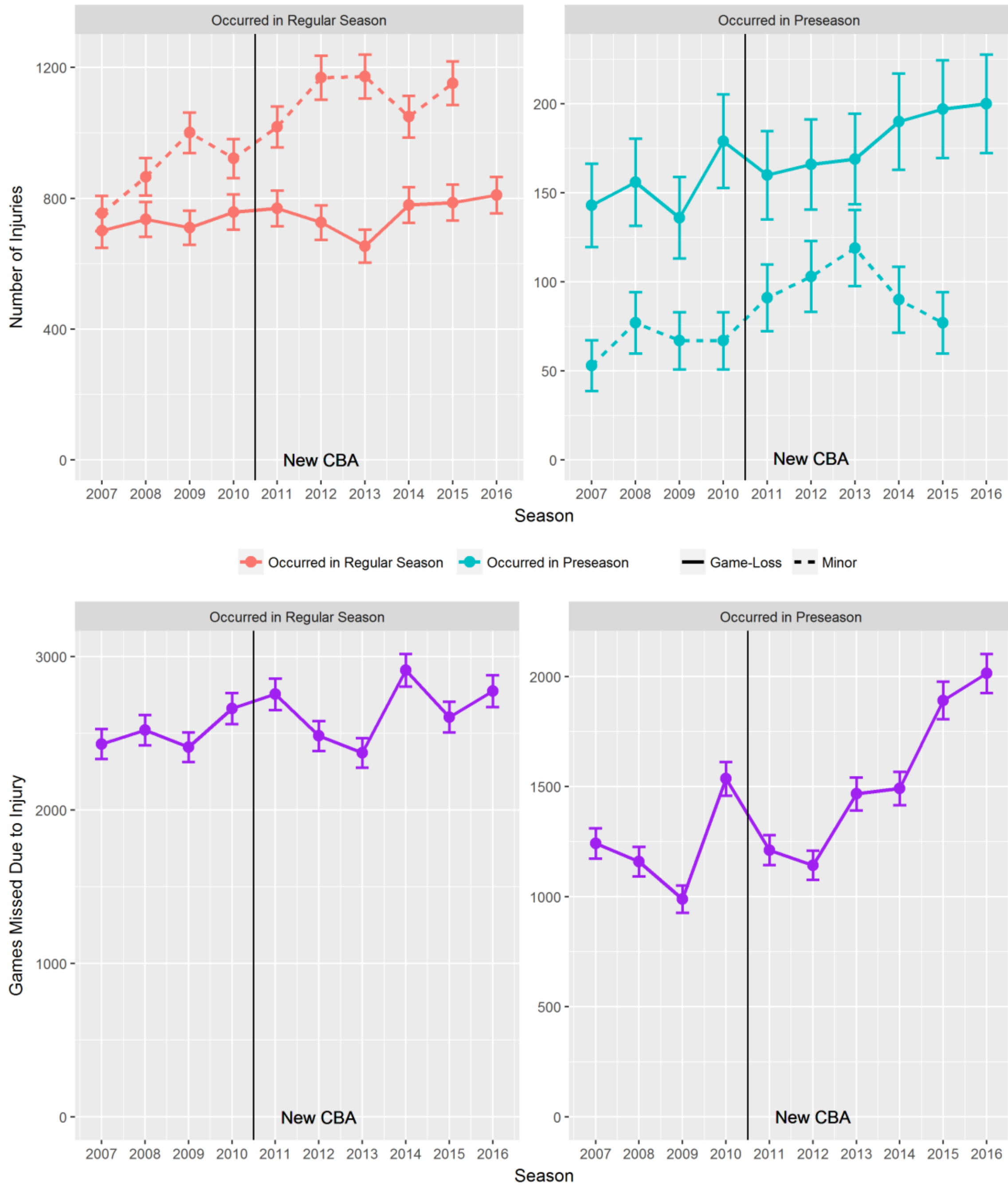
Condensed Injury Type	Conditioning-Dependent?	Alternative Conditioning Designation
Abdomen	No	
Achilles	Yes	
Ankle - High Ankle Sprain	Unknown	
Ankle - Other	Unknown	No
Ankle - Sprain	Unknown	No
Arm - Broken	No	
Arm - Other	No	
Back	Unknown	
Biceps	Yes	
Buttocks	Yes	
Calf	Yes	
Chest	Yes	
Elbow	No	
Eye	No	
Face	No	
Finger	No	
Foot - Broken	No	
Foot - Lisfranc	No	
Foot - Other	Unknown	
Groin	Yes	
Hamstring	Yes	
Hand	No	
Head - Concussion	EXCLUDED	
Head - Other	EXCLUDED	
Heart	No	
Hip	Unknown	
Illness	EXCLUDED	
Knee - ACL	Yes	
Knee - Other	Unknown	No

Knee - Sprain	Unknown	No
Knee - Tear, non-ACL	Unknown	
Leg - Broken	No	
Leg - Other	No	
Lung	No	
Neck	No	
Non-Injury	No	
Other	No	
Pectoral	Yes	
Pelvis	Unknown	
Quadriceps	Yes	
Ribs	No	
Shoulder - Other	Unknown	
Shoulder - Tear	Unknown	
Spine	Unknown	
Thigh	Unknown	
Thumb	No	
Toe - Other	No	
Toe - Turf Toe	No	
Triceps	Yes	
Unknown	Unknown	
Wrist	No	

Stratified Time Trends: Among regular season injuries, there has been a large increase in minor injuries while game-loss injuries have remained relatively flat over our study period (Figure A2, upper left). Among preseason injuries, both minor and game-loss injuries exhibited steady increases over our study period (Figure A2, upper right).

When looking at games missed due to injury, those due to injuries in the regular season exhibited a modest but inconsistent increase over our study period (Figure A2, lower left). Games lost due to preseason injuries, however, exhibited a rapid increase from 2012-2016 (Figure A2, lower right). The spike from 2014 to 2015-16 was almost entirely driven by an increase in “Undisclosed” injuries that landed players on injured reserve, the majority of which occurred to career backups who were likely at the end of their careers. These may not reflect a true increase so much as more thorough reporting and capturing of these sorts of injuries.

Figure 4.A1. Number of Non-Head, Non-Illness Injuries and Games Missed, Stratified by Severity and Timing, 2007-2016, with 95% CIs.



Sensitivity Analysis – Include Preseason Injuries: As seen in Figure A1, preseason game-loss injuries and the games missed due to them increased steadily from 2007-2015 while game-loss injuries occurring in the regular season remained relatively flat. When we include preseason injuries in our analysis our injury count results do not differ substantially from the main analysis (Figure A2, Table A2, Figure 3, Table 2).

While it would be ideal to include preseason injuries in our analysis as this may be where the CBA's practice restrictions had their strongest effect, it is difficult to define a player population that is exchangeable with the pre-CBA period due to another concomitant rule instituted by the CBA. Specifically, the maximum training camp roster increased from 80 players to 90; the cut-down periods during training camp have also been progressively pushed back in recent years. All this means more players are collecting more exposures to injury in the preseason, driving counts up. We attempted to account for this by limiting our target population to players with at least one career NFL game, but there are still a substantial number of veterans with game experience who make these expanded training camp rosters but would not have made a training camp in the pre-CBA period (210). We attempted but could not find a satisfactory way to define a consistent population of preseason players that is exchangeable between the pre- and post-CBA periods. Thus we have limited our main analysis to the regular season, which has maintained a consistent 53-man roster throughout the entire study period. "Practice squad" rosters – which contains players who usually do not play except as injury replacements – did expand from 8 to 10 under the new CBA, as well, but the bias from this is likely minor and would be in the direction of a detrimental effect of the new CBA.

Figure 4.A2. Number of Game-Loss, Non-Head, Non-Illness Injuries Stratified by Conditioning Status, 2007-2016, with Poisson Additive Model Regression Line and 95% Confidence Interval.

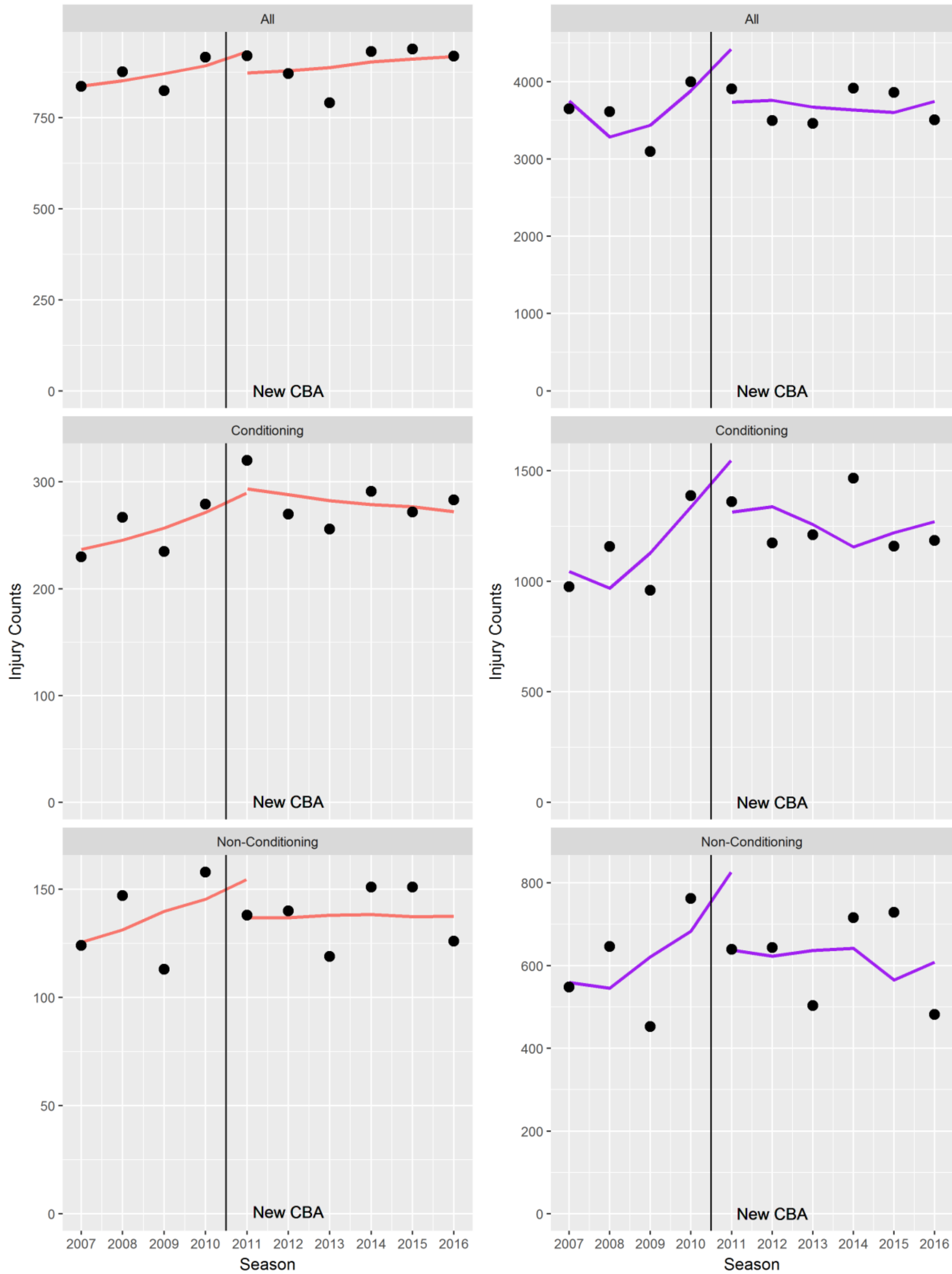


Table 4.A2. Poisson Additive Models for Game-Loss, Non-Head, Non-Illness Injuries and Games Missed, Stratified by Conditioning Status, 2007-2016.

Model	Rate Ratio	95% CI	p-value[a]
Number of Injuries			
All Injuries			
Pre-CBA Time Trend (1-year increase)	1.04	1.01, 1.07	0.02
CBA (Post-CBA vs. Pre-CBA)	0.94	0.85, 1.03	0.19
Post-CBA Time Trend (1-Year increase)	1.02	1.00, 1.03	0.22
Age (1-year increase)	1.00	0.99, 1.01	0.66
Conditioning Injuries			
Pre-CBA Time Trend (1-year increase)	1.05	1.00, 1.12	0.06
CBA (Post-CBA vs. Pre-CBA)	1.01	0.85, 1.20	0.87
Post-CBA Time Trend (1-Year increase)	0.99	0.96, 1.02	0.06
Age (1-year increase)	1.01	1.00, 1.02	0.11
Non-Conditioning Injuries			
Pre-CBA Time Trend (1-year increase)	1.05	0.98, 1.14	0.19
CBA (Post-CBA vs. Pre-CBA)	0.89	0.70, 1.12	0.32
Post-CBA Time Trend (1-Year increase)	1.00	0.96, 1.05	0.28
Age (1-year increase)	1.00	0.99, 1.02	0.60
Games Missed Due to Injury			
All Injuries			
Pre-CBA Time Trend (1-year increase)	1.21	1.19, 1.24	0.00
CBA (Post-CBA vs. Pre-CBA)	0.85	0.80, 0.89	<.0001
Post-CBA Time Trend (1-Year increase)	0.98	0.97, 0.99	<.0001
Age (1-year increase)	1.10	1.09, 1.11	<.0001
Conditioning Injuries			
Pre-CBA Time Trend (1-year increase)	1.28	1.23, 1.32	<.0001
CBA (Post-CBA vs. Pre-CBA)	0.85	0.78, 0.93	0.00
Post-CBA Time Trend (1-Year increase)	1.00	0.98, 1.02	<.0001
Age (1-year increase)	1.11	1.09, 1.12	<.0001
Non-Conditioning Injuries			
Pre-CBA Time Trend (1-year increase)	1.26	1.21, 1.32	<.0001
CBA (Post-CBA vs. Pre-CBA)	0.77	0.68, 0.87	<.0001
Post-CBA Time Trend (1-Year increase)	0.96	0.94, 0.99	<.0001
Age (1-year increase)	1.05	1.03, 1.07	<.0001

[a]p-values for post-CBA time trends are for a difference between the pre- and post-CBA time trends.

Chapter 5: Specific Aim 3. Predicting 1-Year Injury Risk in the NFL.

I. Abstract

Introduction: Effective and accurate injury prediction models is an important topic sports medicine. However, this is a difficult task particularly in contact sports, and published injury prediction models have produced mixed results.

Objective: We sought to use publicly-available data on established NFL injury risk factors to develop a preseason injury prediction model for the 1-seaon risk of a player missing one or more games due to injury.

Methods: The data included N=7,669 player-seasons from 2009-2016 for non-quarterback, non-special teams NSL players who participated in their team's week 1 game or missed all 16 due to injury. Injuries were identified using a database from the website Football Outsiders based on public NFL injury reports and the injured reserve list. The outcome of interest was 1-season risk of missing 1 or more games due to injury. Separate models examined the risk of any injury and lower extremity (LE) muscle injuries. We used logistic regression with generalized estimating equations to predict the injury risk using player age, position, height, weight, injury history, turf, and expected rest in the upcoming season. The data were divided into a training (2009-2014) and a validation (testing) set (2015-2016). Discrimination and calibration in each model were examined separately by position.

Results: The overall risks of missing 1+ games due to any injury were 41% and 46% in the training and testing datasets, respectively. LE muscle injury risk was 13% in both sets. For all injuries, training area under the curve (AUCs) estimates ranged from 0.57 to 0.64 for different positions; testing AUCs were similar and ranged from 0.53 to 0.61. For LE muscle injuries, the corresponding training and testing ranges were 0.55 to 0.62 and 0.53 to 0.71. Calibration was acceptable in the training data but poor in the testing data for all models.

Conclusions: The models were unable to effectively predict NFL injuries. Discrimination and calibration were both poor in the testing data. This may have been due to lacking the right predictors or insufficiently-sophisticated models. Future studies should consider the use of more detailed player data available from individual teams or from the NFL's Injury Surveillance System.

II. Introduction

Effective and accurate injury prediction models have been called the "Holy Grail" of sports medicine (211). However, predicting sports injuries is a notoriously difficult task (212) especially in violent contact sports such as American football (7, 23, 34, 55, 213).

The precise form of a predictive model – including the predictors it uses – depends on its audience, prediction timeframe, and intended use. For example, if we are trying to make a prediction before a sports season begins we are limited to predictors known at that time such as player age or their score on a pre-season screening test. If, on the other hand, the objective is to develop a model to make dynamic risk predictions for each player during a season there may be an opportunity to incorporate repeated time-dependent measurements such as weekly training load. Key choices for developing a predictive model also vary by sport. For example, models in basketball have tried to predict any in-game injury (214) while those for more violent contact sports have focused on non-contact injuries, which are assumed to be more predictable (209, 213).

Published injury prediction models in sports medicine have relied on a variety of methods and produced mixed results. One basketball study reported remarkable success (area under the curve [AUC] 0.92) predicting any in-game injury in the next 7 days using information from the previous 14 days including distance run and average speed. It is important to note, however, that the authors of that study may have used variables that reveal underlying injuries rather than predict new issues (214). Among contact sports, one rugby model using weekly differences between planned and actual training loads found success predicting injuries on the player-week level (sensitivity 87.1%, specificity 98.8%) (213). By contrast, another study from Australian Rules Football that used training load over various time windows to predict non-contact injuries using various machine learning methods showed "limited ability to predict future injury" with most AUCs in the 0.5-0.65 range (209).

To our knowledge there are no injury prediction models for American football published in the peer-reviewed academic literature. There is an extensive literature on individual injury risk factor identification (3, 17, 56, 93, 215), but multivariable prediction models are lacking. Some private organizations have claimed remarkable success predicting NFL injuries with AUCs as high as 0.81 (216), while others present their work as unspecified "algorithms" that deliver results with no validation or uncertainty quantification (217). Even when validation data are presented, however, the model specifications are typically undisclosed for competitive reasons, preventing scientific scrutiny. What information is available sometimes suggests methodological flaws such as assessing predictive ability across all positions rather than within positions and using future player usage to predict injury risk (which itself impacts future player usage) (216). There is a need for more transparent and verifiable models that can be revised and deployed across the football landscape.

With these considerations in mind, our goal was to develop a transparent model to predict the risk of a National Football League (NFL) player missing 1 or more games due to injury in the upcoming season. The model is designed to be used in the preseason period, and for this reason it is limited to predictors that are known at that time such as player age, position, weight, height, and prior injury history. We chose candidate predictors based off those shown to exhibit a bivariate association with injury risk in Specific Aim 1 and prior publications to ensure our model had a strong theoretical framework. To achieve greater applicability of the model the independent variables of interest were based on the information about players that is publicly available. This precluded us from using physical screening tools such as the Functional Movement Screen, but these tools have shown limited predictive ability in American football (218). A transparent preseason injury prediction model based off public data, if effective, would be of immense value and interest to players, the NFL, agents, teams, and other parties.

III. Methods

Data and Study Population

Data on injuries were obtained from a database maintained by the football analytics website Football Outsiders (167). The data covering NFL regular seasons were collected prospectively from 2007-2016. The database is based on the official public injury reports released weekly by each NFL team, supplemented with additional details from media reports. Information for all injuries includes player name, team, position, week, season, injury type, age, height, weight, final practice report status, and the player's anticipated availability and actual participation in that week's game. Only injuries to players who have participated in at least one regular season game in their career were included.

Outcome

The outcome of interest was 1-season risk of missing 1 or more games due to injury, defined as $\frac{\#\ of\ player-seasons\ missing\ 1+game\ due\ to\ injury\ during\ season}{\#\ of\ player-seasons\ at\ risk\ for\ injury\ at\ start\ of\ season}$. Separate analyses focused on all-injury risk and the risk of lower extremity (LE) muscle injuries (i.e. hamstring, groin, calf, and quadriceps). We hypothesized that LE muscle injuries would be easier to predict because they are usually not related to violent in-game contact.

The data were restricted to players who played at least one snap in week 1 of the regular season or were on the long-term "injured reserve" list for the entire season. This ensured all players were at risk for the full season. The risk period began in the preseason and ended in week 17, excluding the last regular season game because injury reports from the week 17 game are only available for teams that appear in the playoffs. As predictions were based on the history of injuries in the previous two years the analyses also excluded each player's first two seasons. Quarterbacks and special teams players were also excluded due to the low injury risks for these positions. Following these exclusions, the analyses were based on a total of 7,669 player-seasons from 2009-2016, or 30.0 players per team-season.

Training and Validation Datasets

To ensure the model will be useful for making future predictions rather than assessing past injuries, we employed a prospective validation approach (219). We trained our model on 2009-2014 data (N = 5,764) and tested it on 2015-2016 data (N = 1,905). For the final all-injury model, 43 and 16 player-seasons were excluded from the training and the testing data, respectively, due to missing data. This gave final sample sizes for the final models of N = 5,721 for training and N = 1,889 for testing.

Modeling Strategy

We used a multivariable logistic regression model to predict the risk of a player missing at least one game due to injury during the upcoming season. Within-player correlations were taken into account using Generalized Estimating Equations (GEE) (220) with an exchangeable correlation structure.

The full model was based on bivariate analyses of the association between each candidate predictor and the outcome of interest. Variables were used as linear terms except where indicated below. The candidate predictors were selected on the basis of an association with injury risks in Specific Aim 1, the bivariate analyses described above, or in prior scientific studies. The candidate predictors included:

- Player age
- Height and weight at the time the player was drafted
- The number of injuries during the previous two years in the NFL, coded as 0/1/2/3/4/5+
- The number of games missed due to injury over the previous two seasons
- The number of specific injuries over the past two seasons in up to 17 site categories: Abdomen, Achilles tendon, Ankle, Back, Chest/Pectoral, Face/Eye, Foot, Head, Hip, Knee, LE Muscle, Leg, Neck, Ribs, Shoulder, Upper Extremity (UE) muscle, and UE Bone/Joint. These 17 categories represented 392 discrete injury types in our raw data.
    - Not all 17 categories were used in each model. Only those exhibiting the strongest bivariate associations with the outcome of interest were included.
- Two composite injury history measures (216):
    - Durability, defined as a ratio of games missed due to injury and games played, coded such that the maximum value was 0.4
    - Susceptibility, defined as the total number of injuries per season played, coded such that the maximum value was 1.0
- Position: defensive back (DB), defensive line (DL), linebacker (LB), offensive line (OL), running back (RB), tight end (TE), and wide receiver (WR)
- Two-way interaction terms between position and age and position and weight

- An indicator for whether the player is scheduled to play more than 8 games on artificial turf in the upcoming season
- Number of games to be played on short (<7 days) or long (>7 days) rest in upcoming season

Other variables considered but not included were head coach experience, career snapcounts (a measure of player "mileage" beyond chronological age), the number of games played 3 time zones east or west of a team's home city, calendar year, and the number of games played in the "morning" or "evening" of a player's body clock. These were excluded because they did not meet one of our inclusion criteria as outlined above.

As separate models for each player position did not converge, we used a single model for all positions (running back (RB), offensive line (OL), wide receivers (WR), tight ends (TE), defensive line (DL), linebackers (LB),)). However, because injury risks vary widely by position and a team must be made up of players from all positions all predictions and model performance assessments were stratified by position. This ensures we are predicting injuries *within* as well as across positions.

A modified stepwise backwards elimination procedure was used to develop a "final" reduced model based on lower Quasilikelihood under the Independence model Criterion (QIC) to indicate better models (221, 222). First we dropped interaction terms (weight and age with position). If this yielded a worse QIC we kept both interaction terms and the main effects of age, weight, and position in the model. If not, we dropped the interaction terms and all other terms were subject for elimination. We then sought to drop combinations of variables with missing data: durability, susceptibility, and games on turf. After considering these missing variables we proceeded to eliminate other variables one by one choosing the highest p-value for elimination each time. We continued until the QIC rose, indicating worse model fit.

We then compared discrimination and calibration measures between the full and final reduced models. If there was evidence that the full model performed better than the reduced model, we added variables back in until there were no substantial performance degradations between the two models. We only present our final models in the Results; the full models can be found in the Appendix.

Model Performance Evaluation

We calculated three model performance metrics for all models.

- Maximum Accuracy: The maximum percent of player-seasons correctly classified as having the outcome of interest at whatever the optimal cutpoint is for this number. It is a top-line number that is easy for laymen to interpret. We compared this number to a "no player gets injured" model that assumes no player suffers the type of injury that the model attempts to predict.

- Calibration: A comparison of observed and model-predicted risks. It is commonly measured using the Hosmer-Lemeshow Goodness-of-Fit statistic (223) or by plotting the observed and predicted risks by quantile of predicted risk.
- Discrimination: The ability of the model to differentiate between events and non-events. It is typically measured by the area under the curve (AUC) of the receiver-operator characteristic (ROC) curve (223, 224).

IV. Results

Descriptive Statistics of Training and Testing Cohorts:

As shown in Table 1, the distributions of predictors were similar in the training and testing data. The largest discrepancies were with prior injury history – player-seasons in the testing data tended to have greater injury histories (Table 1).

Table 5.1. Descriptive statistics for training and testing data.

	Mean (SD), Median [IQR], or Percent	
	Training (N = 5,764 player-seasons)	**Testing (N = 1,905 player-seasons)**
Age, years	27.8 (2.8)	27.6 (2.7)
Position, %		
DB	20.3%	21.3%
DL	17.5%	16.6%
LB	16.1%	16.4%
OL	18.6%	18.0%
RB	9.5%	8.5%
TE	6.9%	7.8%
WR	11.2%	11.4%
Height, in	74.0 (2.7)	74.1 (2.7)
Weight, lbs	244.0 (46.7)	249.0 (46.5)
Number of Injuries in Previous 2 Seasons	2 [1-3]	2 [1-4]
Number of Games Missed Due to Injury in Previous 2 Seasons	1 [0-3]	1 [0-5]
Durability	0.00 [0.00-0.10]	0.08 [0.02-0.20]
Susceptibility	0.8 [0.4-1.0]	1.0 [0.7-1.0]
Number of Games Played on Artificial Turf	10 [4-12]	9 [4-12]
Number of Games Played on Short (<7 Days) Rest	2.0 (0.9)	2.4 (0.7)
Number of Games Played on Long (>7 Days) Rest	2.8 (0.9)	3.3 (0.9)

Injury History, % With Any History of Each Injury in Previous 2 Seasons		
Abdomen	1.7%	2.6%
Achilles	2.0%	2.4%
Ankle	32.7%	38.2%
Back	12.0%	13.0%
Chest/Pectoral	3.0%	4.5%
Face/Eye	0.7%	0.9%
Foot	15.8%	19.3%
Head	13.0%	16.0%
Hip	7.1%	10.1%
Knee	45.7%	46.7%
LE Muscle	47.9%	52.0%
Leg	2.4%	2.8%
Neck	7.5%	6.9%
Ribs	4.1%	4.2%
Shoulder	19.9%	22.7%
UE Muscle	12.6%	16.0%
UE Bone/Joint	1.7%	1.7%

The overall risk of missing 1+ games due to any injury was somewhat higher in the testing versus training data: 46% vs. 41%, with the most pronounced position-specific differences observed among DBs, OLs, and TEs (Table 2). The differences for LE muscle injuries were much smaller.

Table 5.2. Number of Player-Seasons and Injury Risk in Training and Testing Cohorts.

	Number of Player-Seasons		**Risk of Player Missing 1+ Games Due to Injury**			
			LE Muscle Injury		**Any Injury**	
Position	**Train**	**Test**	**Train**	**Test**	**Train**	**Test**
DB	1171	406	14%	17%	43%	50%
DL	1006	317	9%	11%	39%	43%
LB	930	312	14%	13%	43%	42%
OL	1074	343	5%	5%	36%	45%
RB	545	162	12%	13%	45%	49%
TE	395	148	7%	7%	42%	51%
WR	643	217	13%	13%	44%	41%
Total	5764	1905	11%	11%	41%	46%

Final Model Results – LE Muscle Injuries:

Discrimination was poor across all LE muscle injury models. AUCs in the training data ranged from 0.55 for DLs to 0.62 for DBs (Figure 1). The corresponding estimates in the testing data were generally similar and ranged from 0.53 for RBs to 0.71 for LBs; confidence intervals in the testing data were wide (Figure 2). Calibration was acceptable in the training data but poor in the testing data, particularly for RBs and TEs (Figure 2). Final model coefficients are given in Table 3; 10 of 16 full-model variables remained in the final model.

The predicted risk cutoff for maximum accuracy varied greatly by position (15-45% in the testing data using the final model) but never performed substantially better than a simpler "no player gets injured" model in the training data (Tables 2 and Appendix A1a).

Figure 5.1. Discrimination, Final Model, LE Muscle Injuries.

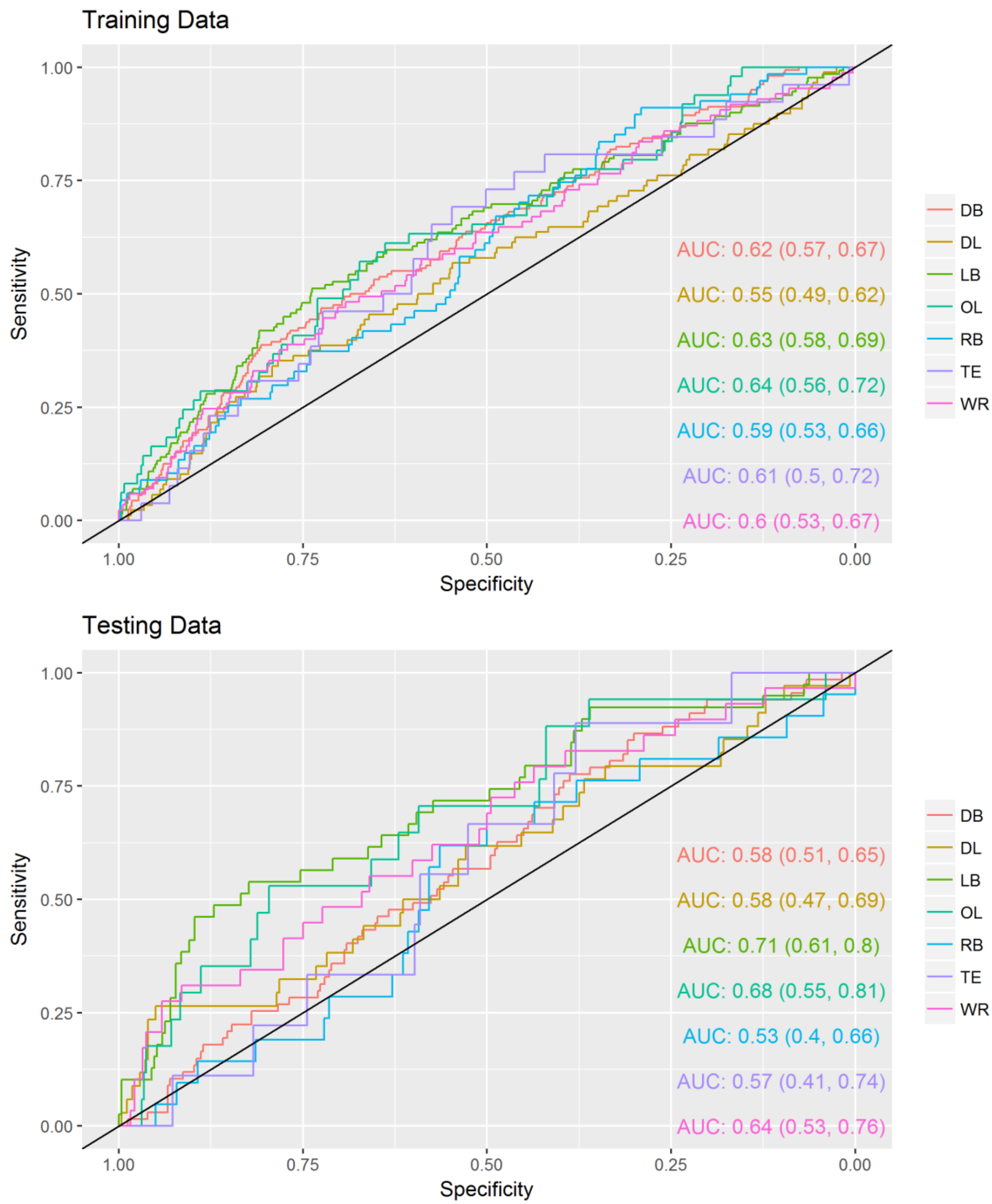


Figure 5.2. Calibration, Final Model, LE Muscle Injuries.

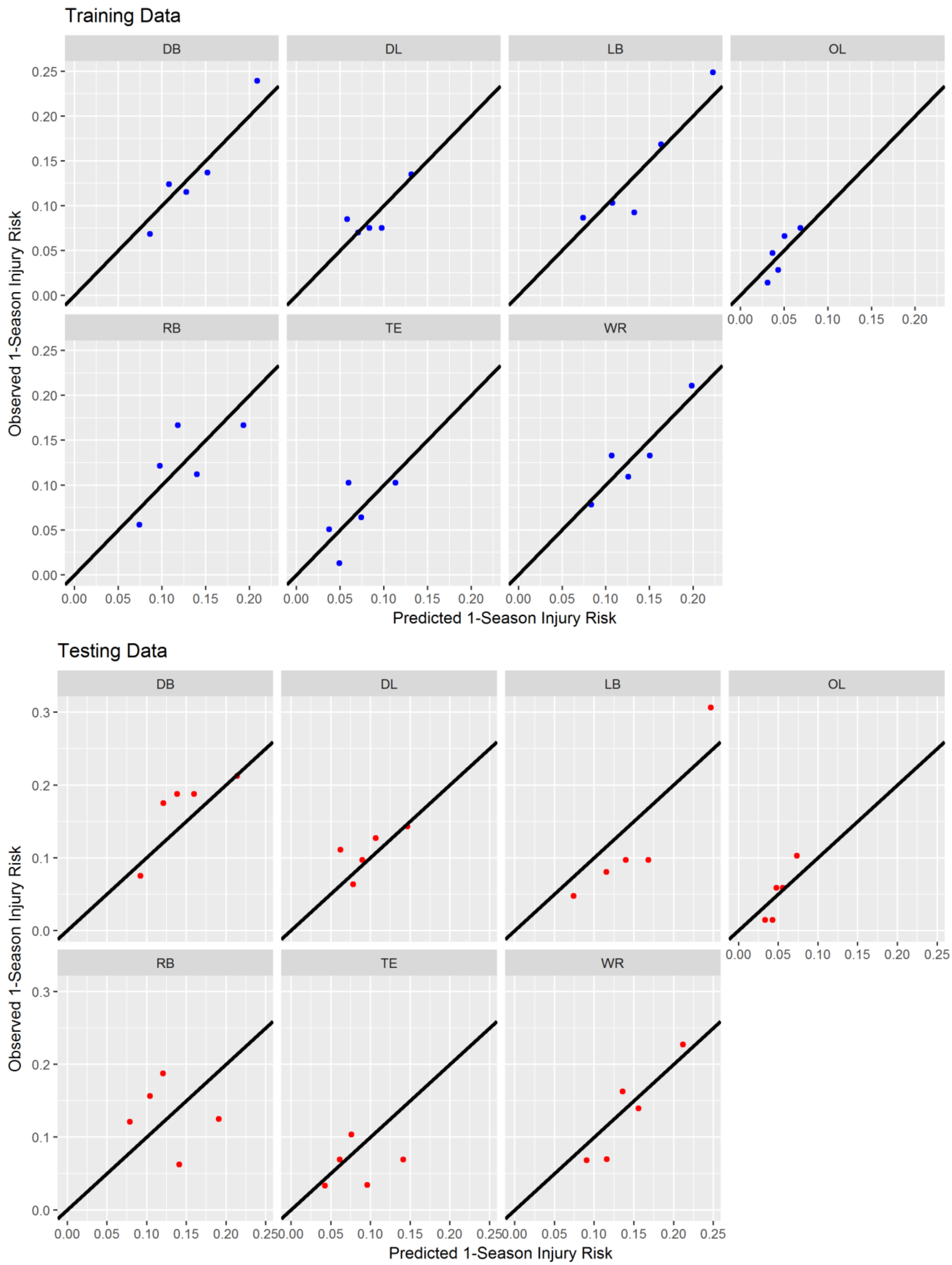


Table 5.3. Final Model Coefficients.

Variable	Model Coefficients, Beta (SE)			
	LE Muscle		All	
	Beta (SE)	**p-value**	**Beta (SE)**	**p-value**
Intercept	-1.85 (1.46)	0.206	-0.07 (1.05)	0.950
Age	0.02 (0.02)	0.136	0.01 (0.01)	0.368
Position (Ref. = DB)				
DL	-1.75 (1.84)	0.342	-2.90 (1.30)	0.025
LB	5.29 (2.41)	0.028	4.13 (1.64)	0.012
OL	-3.81 (3.26)	0.242	-4.14 (1.90)	0.030
RB	-3.76 (1.95)	0.053	0.72 (1.41)	0.611
TE	5.42 (5.17)	0.294	5.01 (3.26)	0.125
WR	-1.57 (1.99)	0.429	-0.71 (1.47)	0.628
Height, in	-	-	-	-
Weight, lbs	-0.01 (0.01)	0.355	-0.01 (0.01)	0.330
Durability	-	-	0.90 (0.32)	0.006
Susceptibility	0.69 (0.18)	0.000	0.34 (0.10)	0.000
Total Injuries in Previous 2 Seasons	-0.09 (0.04)	0.020	-	-
Total Games Missed in Previous Two Seasons	0.01 (0.01)	0.158	0.01 (0.01)	0.334
Expected Games on Artificial Turf	-	-	-	-
Count of Injuries in Previous 2 Seasons				
LE_Muscle_2y	0.30 (0.06)	0.000	0.15 (0.04)	0.000
Foot_2y	0.18 (0.10)	0.078	-	-
Shoulder_2y	-	-	0.16 (0.06)	0.006
UE_Muscle_2y	0.56 (0.30)	0.059		
Knee	-	-	-	-
Hip	-	-		
UE Bone or Joint				
Achilles			-	-
Head			0.11 (0.08)	0.137
Ankle				
2+ vs. 0-1	-	-		
3+ vs. 0-2	-	-		
Age x Position Interaction (Ref. = DB)				
Age x DL	-	-	-	-
Age x LB	-	-	-	-
Age x OL	-	-	-	-
Age x RB	-	-	-	-
Age x TE	-	-	-	-
Age x WR	-	-	-	-
Weight x Position Interaction (Ref. = DB)				

Weight x DL	0.01 (0.01)	0.409	0.01 (0.01)	0.052
Weight x LB	-0.02 (0.01)	0.058	-0.02 (0.01)	0.031
Weight x OL	0.01 (0.01)	0.332	0.01 (0.01)	0.043
Weight x RB	0.02 (0.01)	0.060	0.00 (0.01)	0.763
Weight x TE	-0.02 (0.02)	0.279	-0.02 (0.01)	0.162
Weight x WR	0.01 (0.01)	0.443	0.00 (0.01)	0.621

Final Model Results – All Injuries:

Discrimination was also poor in the all-injury models. AUCs in the training data ranged from 0.57 for DLs to 0.64 for TEs (Figure 3). The corresponding estimates in the testing data were similar and ranged from 0.55 for TEs to 0.61 for OLs; confidence intervals in the testing data were generally quite wide (Figure 3). Calibration was acceptable in the training data but poor in the testing cohort for all positions (Figure 4). Final model coefficients are given in Table 3; 10 of 17 full-model variables remained in the final model.

The model's best accuracy was observed around a predicted risk cutoff of 40-50% and resulted in 5-10% more correct predictions than a simpler "no player gets injured" model in the training data (Tables 2 and Appendix A1c). For example, a predicted risk cutoff of 46% for RBs led to 60% of RB player-seasons being correctly classified as injured or non-injured in the testing data; a "no player gets injured" model would only correctly classify 51% of RB player-seasons.

Figure 5.3. Discrimination, Final Model, All Injuries.

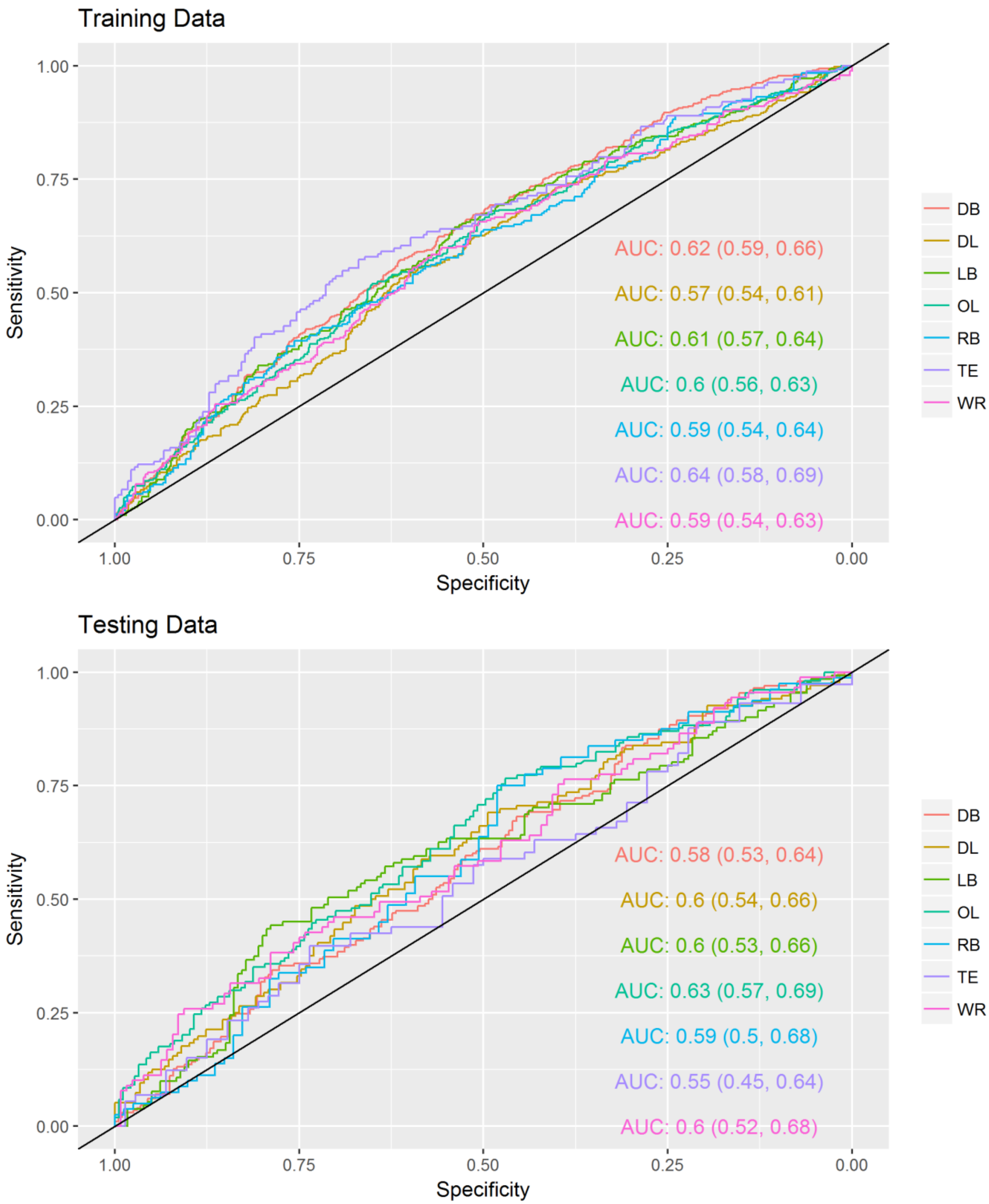
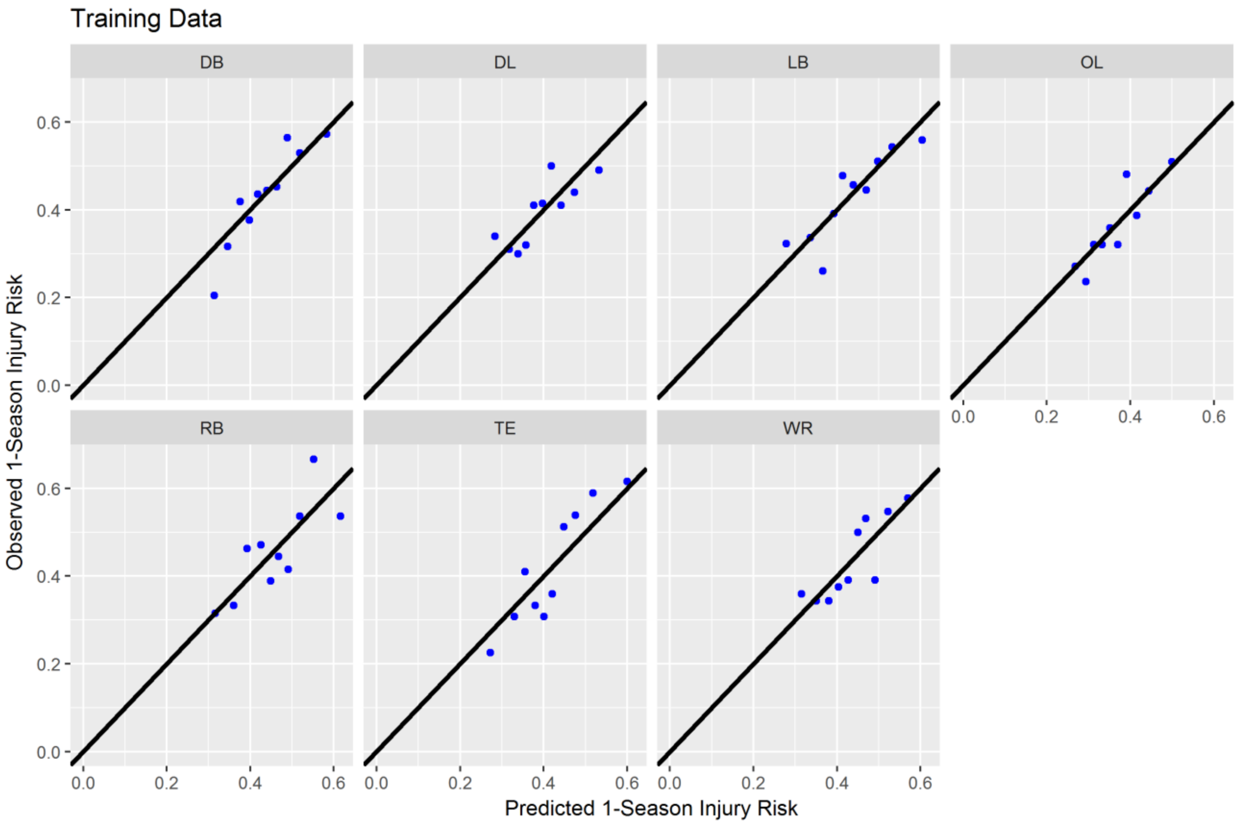
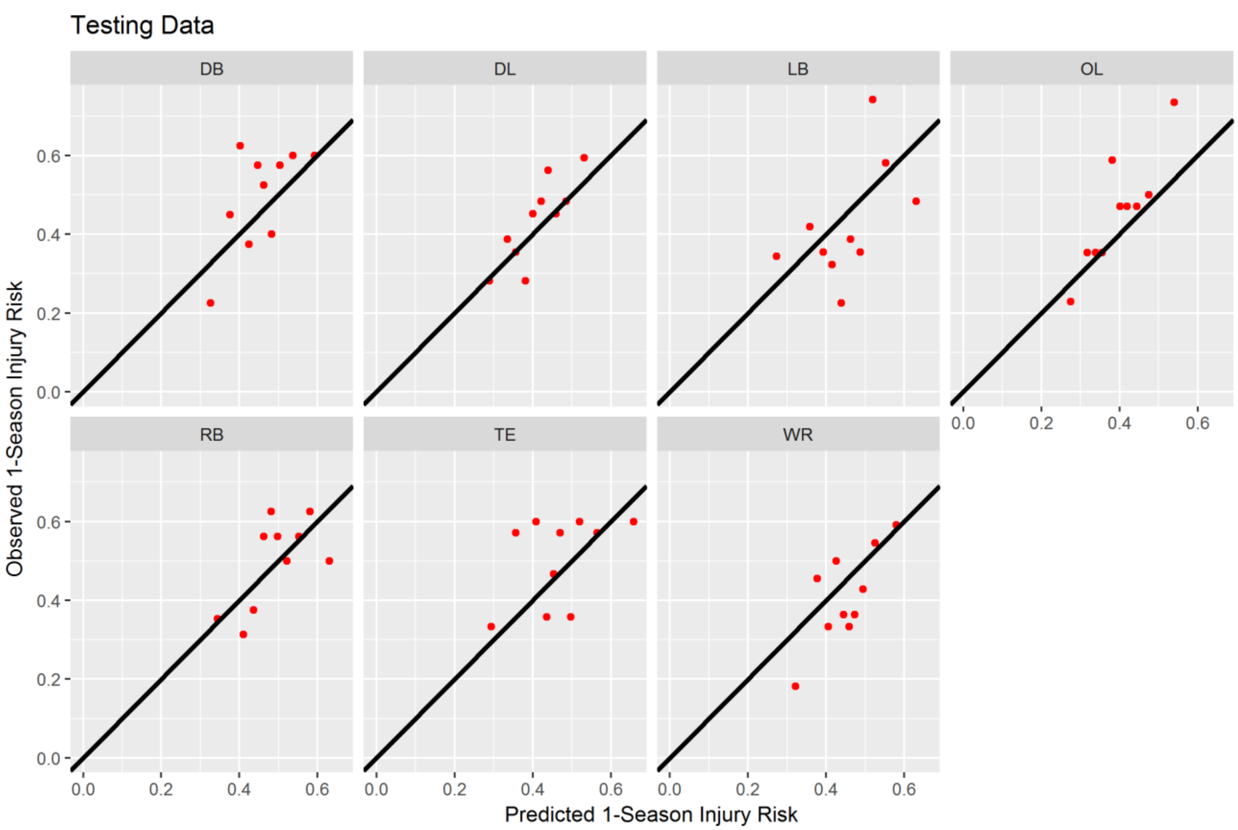


Figure 5.4. Calibration, Final Model, All Injuries.





V. Discussion

Overall we did not find that publicly-available established risk factors allowed effective preseason injury predictions for the 1-seaon risk of missing one or more games due to any or LE muscle injuries. It is instructive to compare our results to those from similar models in violent contact sports. Our LE muscle injury results exhibited worse AUCs than those from a similar study in an Australian Rules Football study and a rugby study, but these groups used daily player training loads while we used higher-level publicly-available predictors (209, 213). Our results were also worse than another NFL model that used publicly-available risk predictors (AUC 0.81 in 2016 testing data) (216). However, this model was created for a private company (SportsInjuryPredictor.com (SIP)) and its exact methods and predictors have not been publicly disclosed. One explanation for this model's better performance is it made its predictions across all positions together while we evaluated our predictions separately for each position. To maximize their utility NFL injury prediction models should be able to identify the high-risk players within each position group since all these groups are needed to form a team; models should thus be evaluated on a position-specific basis. Moreover, by combining all positions together the large differences in risk between positions inflates discrimination relative to a model that considers predictions within each position. This inflation is exacerbated in the case of the SIP model by the fact that it also includes 58 QB seasons (9.5% of its dataset) – QBs are a particularly low-risk position that are easy to discriminate from other positions in terms of injury risk. These easily discriminated QBs were excluded from our study. However, when re-assessing AUC for all positions together our models achieved an AUC of only 0.65, so it is unlikely that this difference in assessment fully explains the AUC differences between our models. A second explanation for the SIP model's superior performance is it uses an unspecified projection of future player usage as a predictor in its model. Teams most commonly will wish to make a decision on player usage based off injury risk rather than vice versa. A third explanation is that the SIP model considers injuries that occur in the preseason or training camp as risk factors for injuries during the upcoming regular season. Because we sought to make predictions about the upcoming season prior to the beginning of the regular season, we did not include such a predictor in our model. Unfortunately, the private nature of this model makes it difficult to identify what other factors might be responsible for the observed performance differences. To summarize, our models exhibited worse prediction than other injury prediction models for contact sports, but direct comparisons are difficult due to differences in predictor and performance assessment choices.

Discrimination was similarly poor in the training and testing data for all models, while calibration was generally acceptable in the training but not the testing data. The consistency in our discrimination across our training and testing data suggests we may have identified risk factors that operate similarly in both groups. However, the poor AUCs suggest they were too weak to separate injured and non-injured players effectively. The drop in calibration from training to testing data suggests the potential for overfitting. Simpler models yielded worse discrimination in the training and testing data, however, so while further model reduction may have closed the calibration gap between training and testing data it would have been unlikely to result in major model improvements.

Our discrimination was poor when calibration was acceptable because there was not a steep separation of predicted risks (Figures 2 and 4). For example, the mean predicted LE muscle injury risks in the middle 3 quintiles for DBs are all between 11 and 15% (Figure 2). This narrow range of predictions makes separating the injured and non-injured difficult.

Whether a model's AUC is "good" or "bad" depends on its intended application. Our models' discrimination was between 0.5 and 0.7, generally considered poor. More importantly, it would not be effective if applied to screen players for an NFL team. As an example we consider our best model performance by AUC in the testing data – 0.71 from the LE muscle injury model for LBs. Identifying 55% of all LE muscle injuries to LBs (55% sensitivity) results in a 25% false positive rate (75% specificity) (Figure 1). With a 1-season risk of missing 1+ games due to an LE muscle injury of 13% among LBs, in a group of 100 player-seasons we would expect 13 to be injured. To correctly identify 0.55 x 13 ≈ 7 of these 13 player-seasons as "high-risk" we would also have to tag approximately 0.25 x (100-13) ≈ 22 uninjured player-seasons as "high-risk." Thus among 29 "high-risk" player-seasons, 7/29 would be expected to truly result in injury (positive predictive value of 24%). Furthermore, in this scenario we would still not identify almost half of the player-seasons with an actual injury. It is likely teams would be willing to allocate additional injury prevention efforts to 29% of LBs in order to stop 7% or less from developing a LE muscle injury. However, our predictions would not be useful for teams deciding whether to sign a player based on his injury risk: teams would be unlikely to accept shying away from 29% of LBs in order to avoid 7% who will get injured. Our predictions would also not likely be useful for teams seeking to quantify and manage their exposure to injury risks via disability insurance policies to pay some or all of a high-risk player's salary if they are injured for similar reasons. In short, it would be difficult to make the case to use these models to decide which players to sign or not sign, though it may be possible to make the case for using them to identify already-signed players for additional training, therapy, or treatment designed to reduce injury risk.

Our models performed poorly despite using commonly-accepted risk factors for NFL injuries. Our poor model performance could be due to three reasons: our data did not include sufficiently strong predictors of NFL injuries, our methods did not allow us to properly model injury risk, and/or NFL injuries are simply not predictable on a population level. To the first reason, we chose our predictors a priori based on previously demonstrated associations in the literature and/or theory-based associations with injury risk. However, we were restricted to predictors that were both publicly available and known during the preseason timeframe. We did not have information on the severity of injuries (e.g. a grade 1 vs. grade 3 hamstring strain), the circumstances surrounding them (e.g. contact vs. non-contact, game vs. practice), or the players' performance on injury screening tools. Our goal of 1-season risk prediction also precluded the use of dynamic training load data, which is commonly used for shorter-term injury predictions (156, 196, 225). All of these predictor exclusions may have limited our ability to predict injuries.

To the second reason, some researchers have suggested the processes underlying injury occurrence function as a complex system or web of determinants that may require sophisticated machine learning methods such as random forests or neural networks to identify (212). This analysis used logistic regression – which, in the absence of interaction terms, assumes an additive linear relationship between the predictors and the log-odds of injury risk. A preliminary replication of our full logistic regression model using random forests – which allow for non-linear relationships and interactions among all predictors – did not improve the model's AUC, however. This lack of improvement when using a model that allows for more complex associations between our available predictors and injury risk suggests the problem may be with our data rather than our use of a model that does not account for sufficiently complex relationships among predictors.

The third – and perhaps most likely – reason for poor model performance is that NFL injuries are simply not predictable, at least on the level we investigated. A large proportion of NFL injuries are due to contact and violent collisions. This makes injury prediction in contact sports particularly difficult (213). It is unlikely we would be able to predict a broken bone or an ankle sprain due to contact with another player, but our models were not better when limiting to LE muscle injuries, which are often non-contact. It may be that even non-contact injuries are difficult to predict due to the complex web of interacting factors that can impact their occurrence (212).

This study has several limitations. Our definition of prior injury history forces us to exclude players in their first two years from the model, but the added ability to account for injury-proneness outweighs that concern. Another limitation may be that player-seasons at truly high risk are already being filtered out by teams, complicating our prediction efforts and weakening model discrimination. Our data only includes player-seasons where the player at least attempted to play and does not include instances where, for example, a severe injury history prevented them from ever being signed to a team. This survivor effect is likely to be most severe among lower-skilled players, though running the models on a subset of higher-skilled players – defined as those playing 25 or more snaps per active game – did not improve performance. Finally, as discussed above our model does not include a variety of risk factors such as training load data that may aid in injury prediction.

VI. Conclusions

Overall we did not find that publicly-available established risk factors allowed effective preseason predictions for the 1-seaon risk of missing one or more games due to any injury or LE muscle injuries.

Discrimination (AUC 0.5-0.7) and calibration were both poor when we fit the model to testing data from the 2015-16 NFL seasons. It is possible our models did not include sufficiently strong or frequent risk factors to make effective population-level predictions or that NFL injuries are simply not predictable. Any future efforts to predict NFL injuries should consider the use of more granular player data available from individual teams or the NFL's Injury Surveillance System.

VII. Appendix

Full Model Results – LE Muscle Injuries:

Discrimination, calibration, and maximum accuracy were generally similar to the final model in both the training and testing data. The largest differences were in calibration for DBs and DLs in the testing data – the full model appeared to perform slightly better in this group, though calibration was still poor.

Figure 5.A1. Discrimination, Full Model, LE Muscle Injuries.

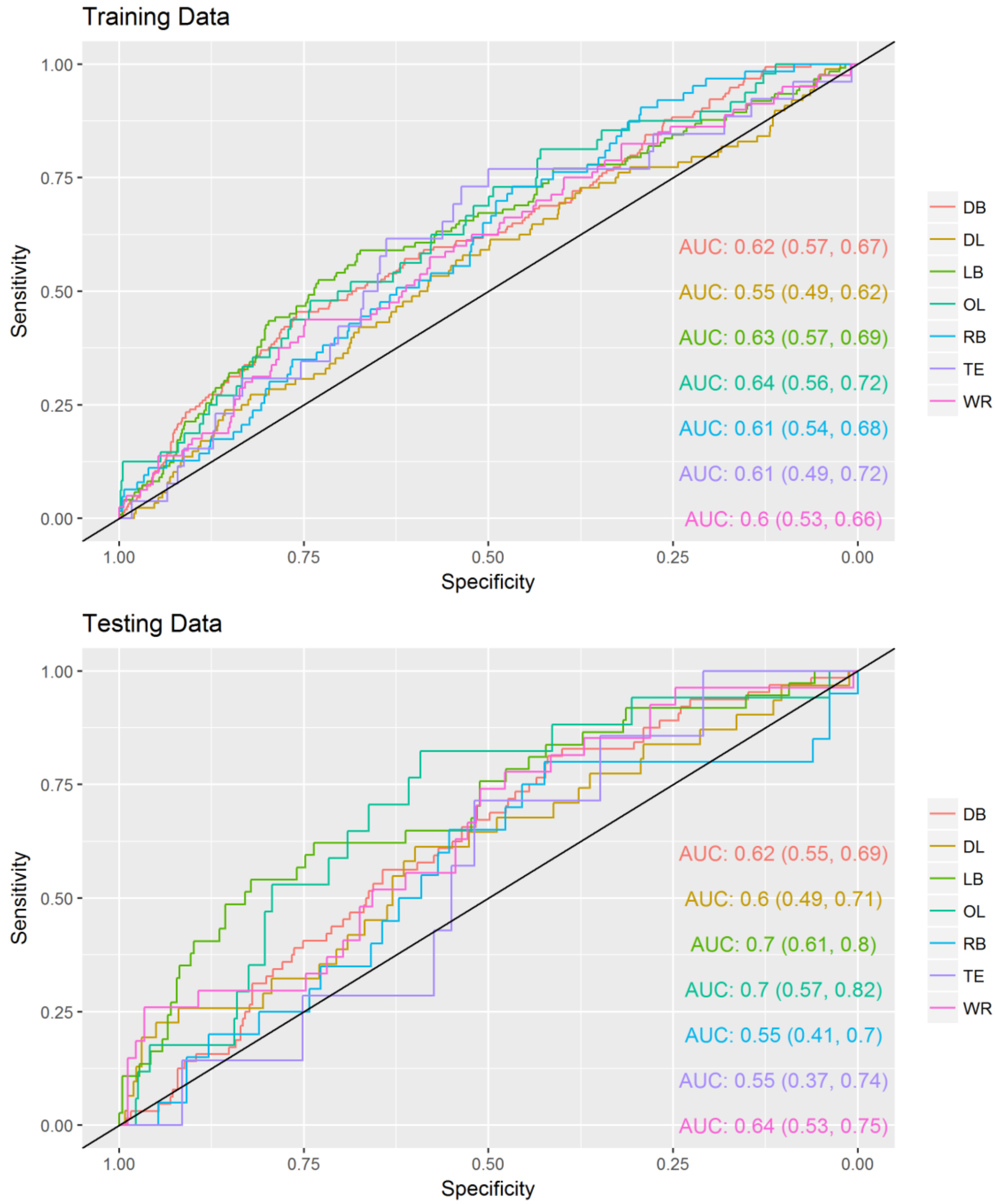
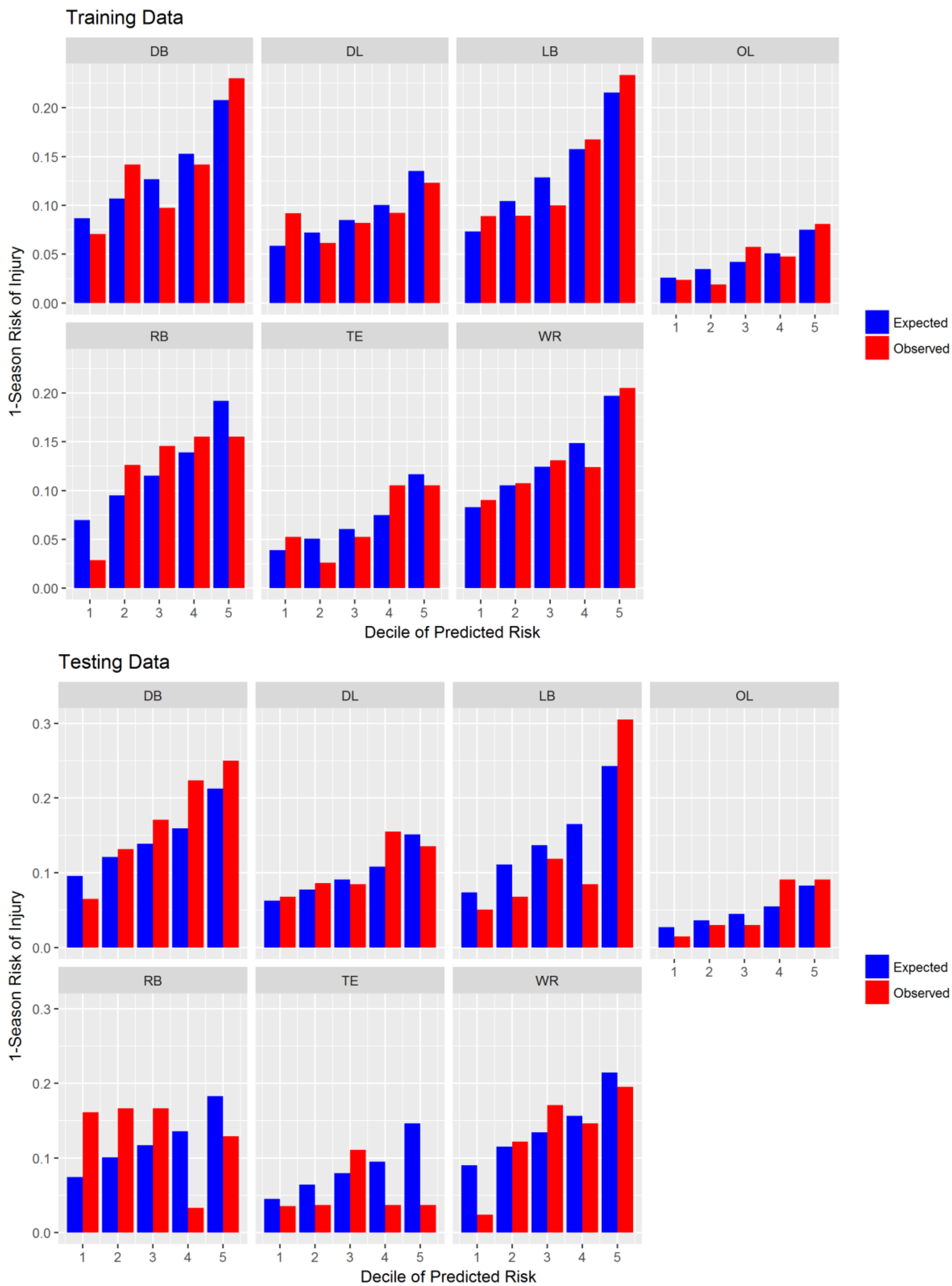


Figure 5.A2. Calibration, Full Model, LE Muscle Injuries.



Full Model Results – Ankle Injuries:

Discrimination, calibration, and maximum accuracy were generally similar to the final model in both the training and testing data. The largest differences were in calibration for DBs in the testing data and OLs in the training data – the full model appeared to perform slightly better in these groups.

Figure 5.A3. Discrimination, Full Model, Ankle Injuries.

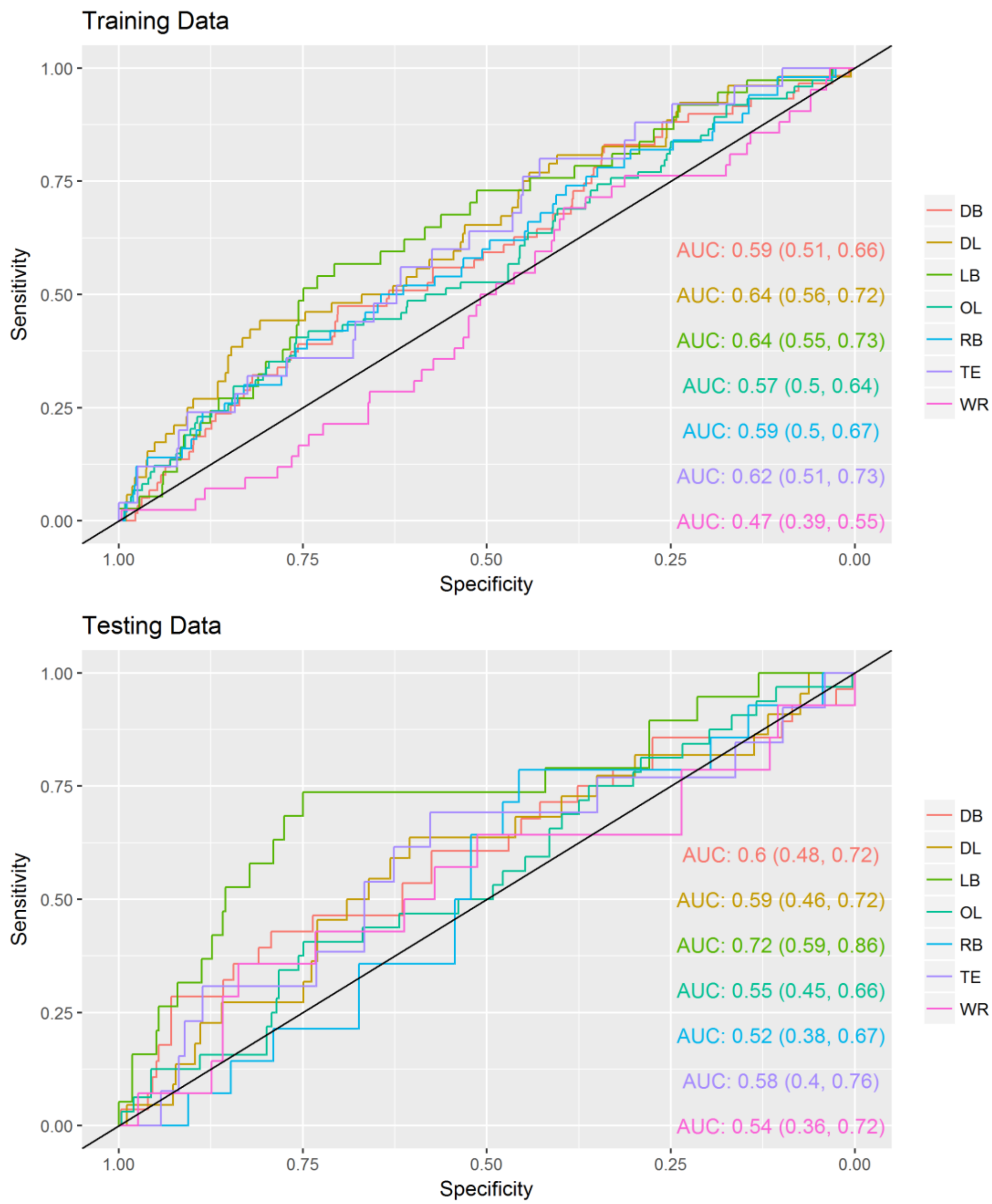
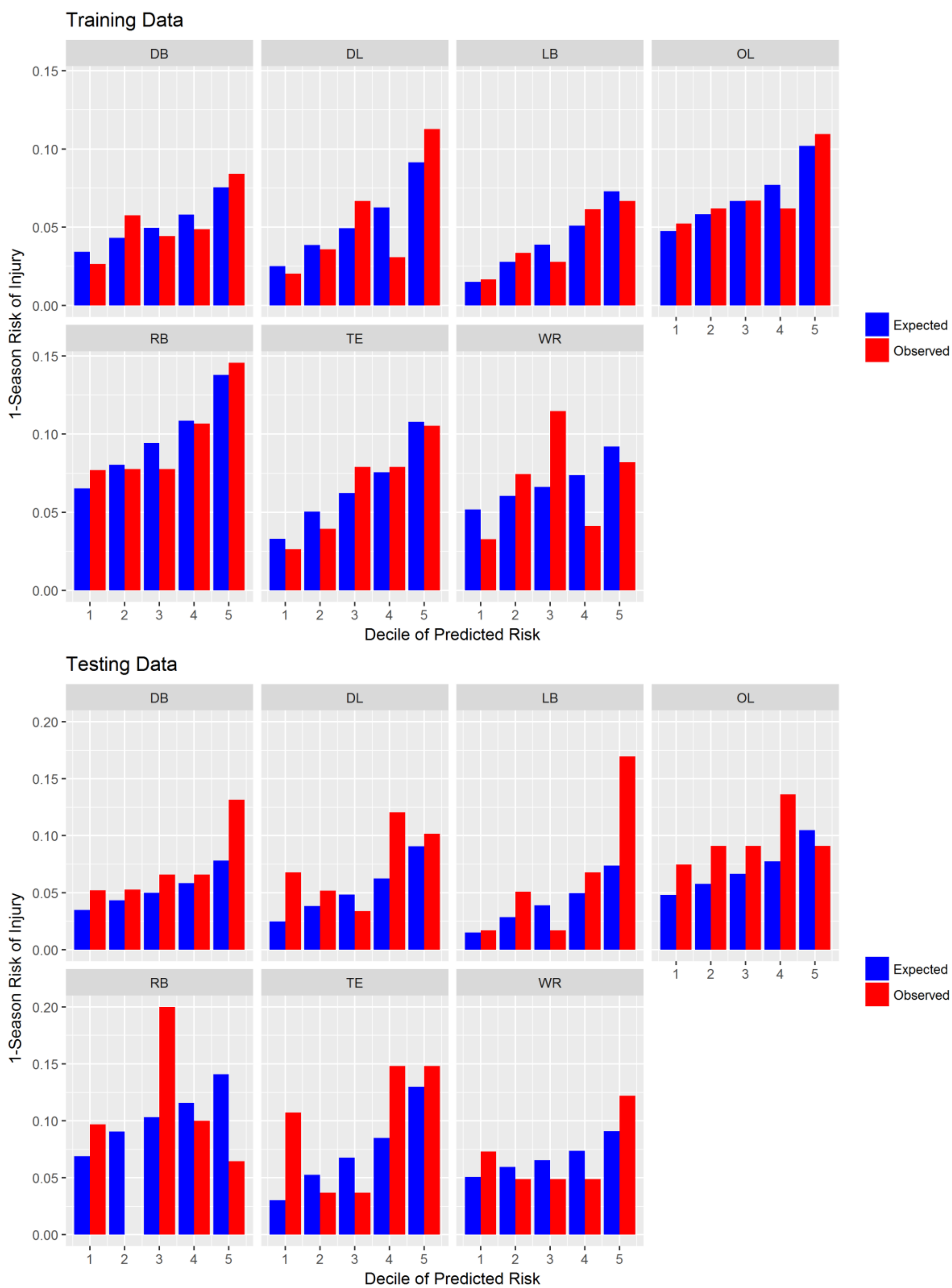


Figure 5.A4. Calibration, Full Model, LE Muscle Injuries.



Maximum Accuracy for All Models:

Table 5.A1a. Maximum Accuracy for Full and Final Models, LE Muscle Injuries.

	Full Model				Final Model			
	Training Data		Testing Data		Training Data		Testing Data	
Position	**Threshold**	**% Correctly Classified**	**Threshold**	**% Correctly Classified**	**Threshold**	**% Correctly Classified**	**Threshold**	**% Correctly Classified**
DB	0.51	86%	0.35	83%	0.49	86%	0.43	83%
DL	0.32	91%	0.25	89%	0.31	91%	0.22	89%
LB	0.35	87%	0.35	89%	0.37	86%	0.36	88%
OL	0.14	96%	0.19	95%	0.19	96%	0.15	95%
RB	0.27	88%	0.23	87%	0.28	88%	0.25	88%
TE	0.26	93%	0.24	95%	0.26	93%	0.23	94%
WR	0.29	87%	0.26	87%	0.3	87%	0.45	87%

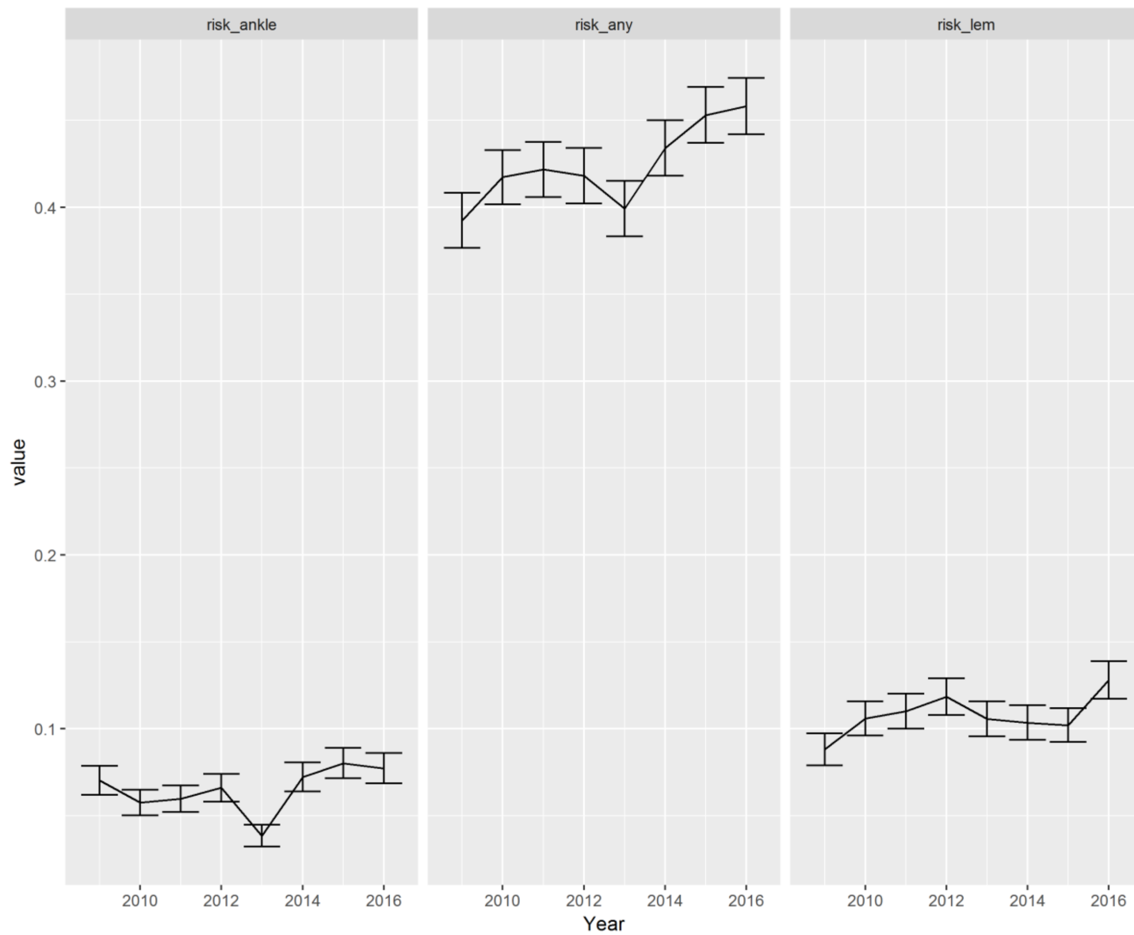
Table 5.A1b. Maximum Accuracy for Full and Final Models, All Injuries.

	Full Model				Final Model			
	Training Data		Testing Data		Training Data		Testing Data	
Position	**Threshold**	**% Correctly Classified**	**Threshold**	**% Correctly Classified**	**Threshold**	**% Correctly Classified**	**Threshold**	**% Correctly Classified**
DB	0.47	61%	0.42	57%	0.47	60%	0.4	57%
DL	0.49	62%	0.49	61%	0.51	61%	0.43	59%
LB	0.52	60%	0.47	62%	0.5	60%	0.5	64%
OL	0.52	65%	0.42	60%	0.5	65%	0.44	60%
RB	0.51	59%	0.44	64%	0.5	59%	0.46	60%
TE	0.5	63%	0.49	64%	0.43	63%	0.5	57%
WR	0.5	59%	0.56	63%	0.51	60%	0.52	64%

Bivariate Association Between Injury Risk and Time for Each Outcome:

In addition to the bivariate investigations we added a centered year term (Year – 2012) to each final model to see if it improved calibration (it had trivial if any effects on discrimination). It had no beneficial effect on calibration for any of our injury models.

Figure 5.A5. Association Between Ankle, All, and LE Muscle Injury Risk and Time.



Chapter 6: Public Health Impact/Significant Contribution to the Field

American football is the most popular professional sport in the U.S.: in a recent Harris Poll asking 1,510 people who reported following at least one sport to pick their favorite from 21 options, the professional-level National Football League (NFL) held the top spot and college football ranked third (1). The popularity of the sport is reflected in the number of athletes playing football: in the 2013-14 school year there were 14,262 high schools with boys' 11-player football programs, comprising 1,093,234 athletes (8). The National Collegiate Athletic Association (NCAA) reported an additional 70,147 men's college football players in 2013 (9). Football is also an inherently physical, high-speed game. Injuries occur with regularity in both practices and games in the NFL: the injury rate is approximately 15-18 injuries per 1,000 athlete-exposures (3, 17) (AE, a single athlete's participation in a game or practice) overall, with much higher rates in games (64.7 per 1,000 AEs) (3). These rates are approximately 5 times higher than those for high school football (7, 20), approximately 1.5-2 times higher than those for college football (7, 33, 34); higher than those for any college sport (21); and higher than Major League Baseball (MLB), the National Basketball Association (NBA), and the National Hockey League (NHL) (160, 161, 166); and higher than soccer and Australian Rules Football (162, 163), though some rugby studies have found higher injury rates than the NFL (177). These data – particularly the fact that over a million high school students play football each year – demonstrate that football injuries exert a major toll on public health. NFL players, as a very high-risk population with particularly rich data available, represent a fertile target for public health and epidemiologic studies.

In addition to their high injury risk, football players, and NFL players in particular, are subject to lifelong health sequelae from various types of trauma sustained during their playing careers. The physical toll of the sport carries over long into retirement. Studies have shown that 7% of NFL retirees use opioids – triple the general population prevalence (226). 40.6% of NFL retirees under 60 reported having arthritis, versus just 11.7% of U.S. males under 60 (227). 14.7% of retirees overall suffer from moderate to severe depression and 47.6% report difficult with pain as quite or very common, with both of these correlated with trouble sleeping, financial difficulties, marital or relationship problems, and problems with fitness, exercise, and aging (228). 24% of NFL retirees reported 3 or more concussions during their playing career, which was associated with a 5x and 3x increases in the prevalence of mild cognitive impairment (MCI) and significant memory problems, respectively, versus retirees reporting no concussions (229). Finally, retirees reporting more concussions reported higher incidence of depression (9-year risk 3.0% in those reporting no concussions versus 26.8% in those with 10 or more) (230). These studies demonstrate that injuries are a major lifelong health issue for thousands of retired NFL players. Anything that can be done to reduce injury rates now will pay large public health dividends as thousands of ex-players – including college and high school players, as well – age.

These data, along with the sport's intense public interest and the amount of attention and money the NFL is directing towards injury prevention and medical research (231), underscore the importance of studying the occurrence and determinants of injuries among football players. The pace of research on football injuries has rapidly risen in recent years, with the NFL generating twice as many studies from 2010-2012 than the previous leader, Major League Baseball (60). Despite this increase in research output, many questions about NFL injuries remain unanswered. This dissertation has contributed to answering some of those questions.

Aim 1 confirmed that NFL injury rates and risks were high. We also found rates varied by several known and hypothesized injury risk factors including position, weight, age, turf, weather, and injury history. We did not previously have rigorous epidemiologic estimates of injury rates and risks that could be compared with other sports. There were also previously no academic studies investigating how injury rates varied with weight, age, or artificial turf type, all three of which our analysis quantified. Injury rates were generally higher for heavier players, but this trend was reversed for running backs, possibly because of lower workloads for heavier RBs. Visiting team injury rates were higher on artificial turf than grass (18.2 vs. 16.7); among specific turf types, A-Turf (21.1), Momentum Turf (19.3), and FieldTurf (19.2) all exhibited elevated injury rates. Back, groin, hamstring, ankle, knee ligament, and overall injury rates rose as players aged, but a strong survivor effect leaving lower-risk players at older ages caused the risk curve to flatten after about 30 years of age. In addition, no previous NFL study had explicitly calculated the injury risk for players with varying injury histories. We found longer overall injury histories were associated with greater injury risk, and this association held for a range of specific non-traumatic injuries. While reported injury rates did rise from 2007-2015, the largest increases occurred in minor injuries that caused no missed games. In addition to these novel findings, this analysis gives us a better idea of the strongest risk factors to focus on – and where we may not want to waste our time. Some of the findings – especially those for turf and age – could have real world impacts on stadium construction and roster risk management. Other results – such as those for rest and changes over time – indicate that common explanations for injuries in the football world are not borne out in the data.

Aim 2 also makes a contribution to the NFL injury literature. Some coaches and other NFL stakeholders have blamed the CBA for increasing injury rates, but there had been no previous academic investigation of this allegation. Aim 2 identified little evidence for an increase in conditioning-dependent injuries or injuries overall following the 2011 CBA and its practice restrictions. The practice restrictions did not appear to move the NFL from a state of optimal to undertraining with regards to injury risk; elite NFL athletes appear to be as well-conditioned for injury avoidance under the new regimen as the old one. This suggests that mitigating practice loads further is an injury management tool worth pursuing.

Aim 3's predictive models were unable to effectively predict NFL injuries using publicly-available, accepted risk factors including age, weight, and injury history. Our predictors were too weak to effectively separate high- and low-risk players. The results were a clear illustration of how difficult it is to predict injuries in violent contact sports, and injury prediction models claiming excellent performance should be investigated carefully. That said, we were restricted to predictors that were both publicly available and known during the preseason timeframe. We did not have information on the severity of injuries (e.g. a grade 1 vs. grade 3 hamstring strain), the circumstances surrounding them (e.g. contact vs. non-contact, game vs. practice), the players' performance on injury screening tools, or ongoing training load and physical performance measurements. It is possible that such data may allow for better prediction of NFL injuries in the future. For now our results suggest that any future efforts at NFL injury prediction need to be undertaken with care and will require spending time to collect data that are not publicly available.

All of these aims fill major gaps in the NFL injury literature. For example, Aim 1 identified what appear to be particularly dangerous brands of artificial turf, which teams re-surfacing their fields may wish to avoid in the future. Aim 2 suggests that the CBA's practice time reductions did not result in an increase in injuries; this has real-world implications for how teams at the NFL level and below design training schedules. Aim 3 found that publicly-available risk factors could not be used to effectively predict NFL injuries; this should encourage skepticism of models that claim otherwise and encourage anyone wishing to attempt such predictions to collect more granular data on such things as player training load and the mechanisms of injuries.

This work also suggests a number of ideas for future studies. Further research into the injury rates on the most dangerous artificial turfs identified in Specific Aim 1 is merited. It is possible there is something in the design of those specific turfs that leads to higher rates of certain kinds of injuries. More robust studies of the health effects of short between-game rests are also needed. For example, as injury reports do not describe the full health burden placed upon NFL players, players should be surveyed regularly during the season to determine in more detail their health status before and after games on short, normal, and long rest. Lastly, Aim 2 suggests there is room to further reduce practice and training loads to minimize injury risks. A thorough survey of practice schedules for multiple NFL teams with varying injury rates could help identify more accurately the optimal balance between over- and under-training.

This dissertation investigated sports injuries in a small very-high-risk occupational group (NFL players), but the results on risk factors, training practices, and injury prediction are applicable to reducing injuries and their lifelong effects among the million-plus high school players who engage in the sport every year. As such, this paper makes a substantial contribution to public health knowledge.

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