Title: What factors influence concussion risk in American football? Bayesian analysis of 8 seasons of National Football League data.

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**Data Sharing Statement:**
The full dataset used for this study will be made available as an online supplement upon acceptance of this paper for publication.
Abstract

Importance: Professional American football players are concerned that artificial turf playing surfaces and extended seasons increase health risks, but existing research is limited by weak methodology and limited sample size.

Objective: To examine how playing surface, time of season, and game temperature relate to concussion risk in the National Football League (NFL).

Design: Retrospective cohort study of 8 years of NFL regular season games.

Setting: Database of NFL game data and weekly injury reports.

Participants: All NFL players who participated in a regular season game from the 2012-2019.

Exposures: NFL game participation.

Main Outcomes and Measures: The primary outcome was the number of concussions within a game. Bayesian negative binomial regression models were fit to relate how playing surface (artificial turf vs. natural grass), game temperature, and week of the season independently related to concussion risk, and any interactions between these factors.

Results: 1096 concussions were identified in the 1830 games were included in this study. There was a 98% probability that concussion risk was reduced on grass surface (median Incidence rate ratio (IRR) = 0.534), 99% probability that concussion risk was lower at higher temperatures (IRR=0.979 for each 1°C), and 91% probability that concussion risk increased with each week of the season (IRR=1.019). There was an 84% probability for a surface x temperature interaction (IRR=1.013) and 74% probability for a surface x week interaction (IRR=1.018). If the model was fitted without interaction terms, the probability of each main effect was >99%.

Conclusions and Relevance: Concussion risk is increased on artificial turf compared to natural grass, and this is exacerbated in cold weather. Concussion risk is also increased later in the season (regardless
of temperature) on both surfaces, but the apparent protective effect of natural grass is diminished in later weeks. The complex interplay between these factors may explain seemingly contradictory findings in the literature and must be accounted for in sports injury epidemiology. These findings suggest that player safety concerns regarding artificial turf and extended playing seasons are warranted and should be considered by the NFL. The risk factors should be explored at non-professional levels, and in other sports.
Introduction

Concerns regarding neurodegenerative diseases have prompted sports organizations to consider implementing policies and interventions aimed at reducing sport-related concussions.\(^1\) Identifying modifiable risk factors for concussions in American football is particularly important,\(^2\) due to the potential risk of chronic traumatic encephalopathy.\(^3,4\) There has been considerable interest in examining the role of playing surfaces on brain injuries, and artificial turf fields are commonly marketed with claims of reducing the risk of concussions.\(^5-8\) Conversely, the National Football League’s (NFL) Players Association (NFLPA) claims that artificial turf is detrimental to player safety and long-term health,\(^9\) but there is currently limited evidence to support this claim specific to brain injuries.

Analysis of the 2012-2013 seasons of National Football League (NFL) data found no association between playing surface and concussion risk.\(^2\) A 2019 systematic review and meta-analysis concluded that concussion risk was slightly, but significantly, decreased when contact sports were played on an artificial surface compared to natural grass.\(^10\) This includes studies which found no differences in concussion risk between one specific brand of artificial turf product and natural grass in American college football over three years,\(^11\) and a greater risk of concussion on natural grass over five seasons of high school football.\(^12\) However, existing research does not consider other factors that may influence this relationship, such as temperature and week of season.

There are within-season trends in injury rates in football and similar sports. Examination of four years of NFL data revealed a significant increase in concussion risk during the second half of the season, compared to the first half,\(^13\) and for games played in colder weather.\(^14\) Biological factors, such as a reduced concussion threshold,\(^15-18\) could explain within-season changes in injury risk. It is also possible that within-season changes in the material properties of the playing surface (e.g., friction and shock absorption) could influence concussion risk.\(^19\) These may be due to wear/damage to the field\(^20-22\) or temperature-dependent effects,\(^23,24\) both of which may differ between playing surfaces.
Playing surface, time of season, and game temperature all potentially influence concussion risk in football, but these factors are inter-related and existing analyses do not disentangle their potential confounding effects upon one another. Additionally, many analyses of these factors have divided temperature and week of season into categories, and it is possible that arbitrary categorization could lead to spurious associations for concussion risk. Thus, the objective of this study was to holistically examine how playing surface, game temperature, and week of season influenced concussion risk in NFL games.

**Methods:**

**Study Design and Data Collection**

We performed a retrospective cohort analysis of eight NFL seasons (2012-13 through 2019-20) of concussion data from the PBS Frontline Concussion Watch and Football Outsiders injury databases. The Football Outsiders database includes data from all weekly NFL injury reports during this time period, including concussion and non-concussion injuries from weeks 1-16 of the regular season. This concussion dataset was combined with data from the Frontline database, which provided an independently collected list of concussions incurred by an NFL player from 2012-2015. Previously identified erroneous data points within the Frontline data set were excluded. Injury report data from Week 17 are not available for teams that did not qualify for the playoffs, and therefore only the first 16 weeks of data (15 games per team) were analyzed, as is consistent with previous studies. We assumed that all concussions occurred in a game setting, unless 1) previous data from the Frontline database specified it occurred during a practice (in which case, it was excluded from analysis) or 2) if a concussion was listed for a player in the absence of him taking any snaps in games that week. Multiple analyses suggest that approximately 95% of concussions in the NFL occur during games.
Stadium and Playing Surface

Aberrations from a team’s normal home stadium were accounted for in the dataset, including games played in international locations and games which were moved to a different stadium due to extenuating circumstances. Likewise, within-season and between-season changes in playing surface type within a stadium were accounted for (e.g., the Houston Texans played one game on natural grass before switching to artificial turf for the remainder of the 2015 season).

Playing surface was categorized into natural grass, artificial turf, and hybrid (a surface which includes an artificial turf foundation, combined with natural grass, potential resulting in unique profile of material properties). Preliminary analysis revealed hybrid surfaces may be associated with a distinct difference in concussion risk compared to natural grass and artificial turf (eTable 1, eFigure 1), but represented <5% of total games (Table 1). Thus, games played on hybrid surfaces (n=82) were excluded from analysis.

Game Temperature

The Pro-Football-Reference database provides official weather details for most games. For games which any of this data was missing, temperature was retrieved from official NFL game reports and annual team media guides. If temperature was not provided in these sources, data were retrieved from WeatherUnderground from the zip code of the stadium at the nearest time point prior to kickoff (generally within one hour). The official NFL summary occasionally provided the temperature for indoor games (generally 20-22°C), and when this was not provided, it was assumed to be 20°C.

To determine game temperature in stadia with a retractable roof, the respective team’s media guide was examined to determine if the game was played under indoor conditions (i.e., roof closed, doors/windows closed) or outdoor conditions (i.e., roof open). If this information was not available in the media guide, Wikipedia game summaries, the official NFL summary, news records, and game video were used to
determine whether the roof was open or closed. Games in which the doors/windows were open, but the roof was closed (n=8) were excluded from analyses, since game temperature was not certain.

**Data Analysis**

Data analysis was performed in R Studio v1.4.1106.\(^3\)

**Primary Model**

Preliminary analysis of the complete dataset revealed the number of concussions within a game followed a negative binomial distribution (eFigure 2). Thus, negative binomial regression models were developed to determine the relationship between risk factors and the number of concussions within a game. The number of concussions in a game served as the dependent variable. Week of season (heretofore referred to as “week”), playing surface (artificial turf vs. natural grass, hybrid surfaces excluded as noted above), and game temperature served as independent predictor variables.

As noted previously, surface wear occurs over the course of a season and this may differ between surface types. The material properties of playing surface also seem to be temperature dependent, and this may also vary by surface type. Thus, the two-way interactions of surface × week and surface × temperature were included in the model. We did not have any *a priori* justification to include the two-way interaction of week × temperature or the three-way interaction between all independent predictor in the model, so these were not included in our primary model. However, we did run these models, which confirmed these additional interactions added little to the model (eTable 2A-B).

The *rstanarm* package was used to compute posterior distributions and credible intervals for each model parameter.\(^3\) Weakly informative prior distributions were used. The prior intercept parameter was set a normal distribution centered around -0.92 based on previous research indicating an average of 0.40
concu...span (ln 0.40 = -0.92). A scale factor of 0.3 was used for the normal distribution, to constrain the prior intercept to realistic values (i.e., there cannot be a negative concussion rate). Previous research using Poisson regression models did not find any relationship between time of season (four categories of four weeks) or playing surface (natural grass versus artificial turf) across two NFL seasons. Thus, the priors for “week” and “playing surface” were set to 0 with a normal distribution (scale=2.5). Previous research suggested an increased risk of concussion at colder (≤9.7°C) temperatures compared to reference (≥21.0°C) temperature, thus a prior with a negative value (-0.01) with a normal distribution (scale=2.5) was utilized for game temperature. The Bayesian model was performed using eight chains of 20,000 iterations (5000 warm-up and 15,000 samples, each). This allowed for models to reach an appropriate effective sample size (>10,000) for stable 95% high density intervals (credible intervals) to be computed.

Leave one out cross validation was then performed using the LOO package, and models with a shape parameter k < 0.5 of the fitted Pareto distribution were considered indicative of an appropriate model fit (i.e., no individual game had undue influence on the model). Sampling quality and model fit were then assessed using visual examination of MCMC trace plots (i.e., convergence and consistency between chains). The coefficients for each model parameter were then exponentiated to compute the incidence rate ratio (IRR).

Graphical posterior predictive checks were performed to determine if the model was a good fit. Observed versus model-predicted number of concussions from 1000 simulations using the posterior predictive distributions were plotted and visually assessed.

The median value and 89% and 97% credible intervals (high density intervals) were computed for the IRR of each parameter. While 95% intervals are typically used in frequentist statistics for null hypothesis significance testing, these values have been recommend for Bayesian statistics in an effort to help readers consider the arbitrary nature of specific credible intervals when interpreting model results.
Additionally, the probability of a true effect was computed as the percentage of the IRR distribution which did not cross 1.0.

**Results**

**Games Included**

There were 1920 games played during the first 16 weeks of the 2012-2019 seasons (Table 1). Of these, a total of 1830 games met the inclusion criteria described in the methods and were included in the primary model. Temperature distribution varied by playing surface and week of season (eFigure 3A-C).

**Model Results**

**Model diagnostics and fit**

Evaluation of the Bayesian posterior distribution diagnostic data and leave one out validation parameters revealed no abnormalities. Effective sample size was >10,000 for each model parameter, and R-hat was ~1.000 for each parameter. Post-warmup trace plots demonstrated convergence to a common distribution for all chains, with all chains achieving stationarity (eFigure 4). Evaluation of the Pareto smoothed importance sampling revealed all k values < 0.5, suggesting there were no games points which had undue influence on the posterior distribution. A power density overlay plot revealed the model was an excellent fit (eFigure 5A-B).

**Model parameters**

A summary of model parameters are presented in Table 2 and probability density plots for the posterior distribution with credible intervals for concussion rate and IRRs for each parameter are provided in Figure 1. Grass playing surface (98% probability), early season games (91% probability), and higher
temperature (99% probability) games are all independently associated with a decreased risk of concussion.

The two-way interactions of surface × week (74% probability) and surface × temperature (84% probability) also appeared likely to influence concussion risk (Figure 1C), such that the protective effect of grass surface compared to artificial turf was somewhat attenuated in warmer conditions and late-season games (Figures 2A-B and 3). While the risk of concussion increases over the course of the season regardless of surface, this weekly increase in risk seems to be greater on natural grass than it does on artificial turf when temperature is held constant (Figure 2A-B). The risk of concussion seems to increase substantially on artificial turf in colder temperatures, whereas cold temperatures do not seem to exacerbate the risk of concussion on natural grass as much when week of season is held constant (Figure 3).

Though the two-way interactions appeared to be associated with concussion risk, we also ran the models without these interactions. When this main effects model is used, all three independent predictors have a >99% probability (credible interval does not cross 1.0, eTable 3, eFigures 6A-C). Since week and temperature are inter-related with one another, we also ran separate models attempting to control for each of these, which confirmed both as independent predictors (eTables 4A-C and 5A-B).

**Discussion**

To our knowledge, this is the first study to comprehensively examine how the interaction of surface, temperature, and time in season factors interact to influence concussion risk and the first to use a Bayesian approach to evaluating concussion risk. We found that the risk of concussion is reduced on natural grass playing surfaces, increased later in the season, and increased in colder temperatures. While all of these factors independently modify concussion risk, week and temperature both modify the effect of playing surface. These findings provide compelling evidence that artificial turf is associated with greater
concussion risk in the NFL, and support the NFL Player’s Association’s advocacy for transitioning to natural grass fields to improve player safety. Additionally, these results suggest that extending the NFL season will likely increase concussion risk.

The large sample size combined with the Bayesian negative binomial regression model provide us with a high-level of confidence in our results, which conflict with some existing literature with smaller sample sizes. In an industry-funded study, Meyers found a slightly greater risk of concussion on natural grass compared to one specific manufacturer’s (FieldTurf) artificial turf over three seasons of college football. We ran a separate analysis comparing natural grass surfaces to FieldTurf surfaces, and found natural grass was still associated with lower concussion risk (eTables 6A-B). Discrepancies may be attributable to greater sample size in our study, differences between college versus professional football, or differences in time period studied. The evidence that week and temperature interact with surface effects may also explain conflicting findings within the literature regarding the role of playing surface in athletic injuries.

**Explanatory Mechanisms**

The most likely explanation for lower concussion risk between on natural grass compared to artificial turf is rooted in the biomechanics of helmet-to-ground impacts. Video review of injuries across five NFL seasons (1996-2001), suggests helmet-to-ground impacts account for 16% to 22% of concussions. A more recent study across two seasons (2015-2016) found 18% of concussion with a clear source of impact were due to this mechanism. The biomechanics of helmet-to-ground impacts are substantially different than player-to-player impacts, and football helmets are not tested (or designed) for these types of impacts. These impacts are potentially more severe, due to unusually high angular velocities and accelerations, and the potential for rebounds (both of the head within the helmet, and with the helmet and head combined).
Grass tears in relation to translational force, whereas artificial turf does not – which allows the latter to
have greater force transmission between the player and the surface.\textsuperscript{45,46} Increased friction between the
helmet and surface could lead to greater torque placed about the head upon a helmet-ground interaction.\textsuperscript{43}
Indeed, laboratory reconstruction of helmet-to-ground impacts has revealed the severity of impact is
highly sensitive to the compliance and frictional properties of the surface.\textsuperscript{42} Reconstruction of 10
representative impacts causing concussion from NFL games demonstrated greater severity index and head
injury criterion for all helmet-to-ground impacts on artificial turf (n=2) compared to helmet-to-helmet
impacts (n=8).\textsuperscript{47} If our results are indeed driven by surface materials, this has implications for other
athletes, since head-to-ground impacts account for 5-20\% of concussions across various sports.\textsuperscript{48-53}

Week of season and game temperature were independently found to influence concussion risk, which are
also likely rooted in helmet impact biomechanics. Both surfaces degrade over the course of the season,\textsuperscript{20,21}
which can influence friction and energy absorption.\textsuperscript{22,54} Likewise, surface temperature influences
shock absorption properties of artificial turf,\textsuperscript{23,24} and soil hardness and grass quality of soccer fields
(moisture dependent, with the greatest effect in winter months).\textsuperscript{54} Artificial surface temperature is also
highly influenced by solar radiation,\textsuperscript{55} which varies with season. As demonstrated by the interaction
effects (Figures 1C, 2A-B), there is a reasonably high probability that natural grass fields may also be
prone to greater degradation within a season compared to artificial turf (e.g., soil compaction, significant
decrease in grass density, etc.),\textsuperscript{54,56} and lose some of its apparent protective effect later in the season.

Various biological factors could independently account for increased concussion risk later in the season.
It has been theorized that prior history of repeated sub-concussive head impacts could change one’s
biological threshold for a concussion,\textsuperscript{57} and there is mixed evidence to support this.\textsuperscript{15-18,58-61} Additionally,
cross-sectional data suggests that brain volume changes seasonally in the general population,\textsuperscript{62} and this
could theoretically influence concussion risk over the course of a season, regardless of game conditions or
cumulative impact exposure.
Limitations

This study also has a number of limitations. There is considerable heterogeneity within the broad categories of artificial turf and natural grass, and we did not attempt to differentiate between different them (with the exception of Field Turf, eTable 6A-B). In other sports, certain species/cultivars may be associated with differing risks of musculoskeletal injuries independent of ground hardness (attributable to differences in thatch), though not concussions. Surface moisture can also influence surface material properties. One could attempt to account for this by including weather in analysis, however, pre-existing precipitation influence the surface even if game-time weather as dry and weather can vary considerably within a game. We were also unable to quantify field “wear” given different environmental conditions (e.g., sunlight) and non-game activity (e.g., concerts, setup and maintenance), and these may vary between stadia.

Given the increased risk of concussion later in the season and at colder temperatures, we suspect that concussion risk would be greatest during the playoff season. However, accurate injury reports are not available for teams which fail to advance to the next round of playoffs (or after the championship game), which precludes the possibility of a valid analysis of concussion risk during this time.

Conclusions

Eight years of data demonstrated that concussion risk is substantially increased in NFL games played on artificial turf. While concussion risk also increases with cold weather regardless of playing surface, the risk is particularly amplified on artificial turf. There is also an increased risk of concussion later in the season, even when temperature is controlled for, but it remains uncertain if is this is due to biological factors, field degradation, or a combination. These data suggest that extending the NFL season may provide greater health risk to players, and that player concerns over the use of artificial turf are warranted.
Further research is necessary to determine if these findings extend to non-professional levels of American football, and other team sports.

**What is already known about this topic**

- There is great interest in making contact sports safer for athletes of all levels, but there is conflicting information regarding the risk factors for sports-related concussions and the effectiveness of interventions to reduce concussion incidence.
- The sports environment (i.e., playing surface and game temperature) and time of season may influence concussion risk, but the inter-relationships of these factors make it difficult to determine their individual and interactive roles in concussion risk.

**What this study adds**

- There is a heretofore undescribed complex interplay between playing surface, game temperature, and time of season which influences concussion risk in American football.
- Artificial turf playing surfaces increase the risk of concussion, despite manufacturer claims to the contrary.

**How this study might affect research, practice, or policy**

- Sports organizations and policymakers must consider the potential increased risk of brain injury attributable to artificial turf and extended playing seasons (especially into winter months).
- Governing bodies and consumer advocacy groups should investigate artificial turf manufacturer’s marketing claims regarding safety.
- Future sports injury epidemiology research studies must consider the interaction between playing surface, temperature, and time of season.
Footnotes

JMS and ZOB both contributed to the development of this manuscript and had full access to all the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. JMS and ZOB compiled all data. JMS performed all statistical analyses. No other individuals were involved in data analysis or writing this manuscript. The authors would like to thank PBS Frontline and Football Outsiders for providing the publicly accessible datasets that were used for this study.

JMS and ZOB and have no conflicts-of-interest to declare. This study was performed without any funding.

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### TABLE 1. Summary of NFL games included in the primary model.  
Note, games which were played in stadia with a retractable roof closed, but doors and windows open (n=8) are excluded from the table.

|                | Indoor Games (Concussions) | Outdoor Games (Concussions) | Combined Games (Concussions) |
|----------------|-----------------------------|-----------------------------|-----------------------------|
| Artificial Turf| 359 (218)                   | 441 (334)                   | 800 (552)                   |
| Natural Grass  | 63 (25)                     | 967 (519)                   | 1030 (544)                  |
| Hybrid Surface | 0 (N/A)                     | 82 (52)                     | 82 (52)                     |
| Combined (Including Hybrid) | 422 (243)       | 1490 (905)                  | 1912 (1148)                 |
| Combined (Excluding Hybrid) | 422 (243)       | 1408 (853)                  | 1830 (1096)                 |
Table 2. Summary of parameters from the primary negative binomial regression model, including relevant two-way interaction terms (n=1830 games). Grass surface was associated with a reduced risk of concussion compared to artificial surface (98% probability). Concussion risk was also reduced with greater temperatures (99% probability) and increased with each week of the season (91% probability). There is reasonable probability (74-84%) that the two-way interaction terms affect concussion risk. If the two-way interaction terms are interpreted as “no effect” and removed from the model, all three main effects have a >99% probability of influencing concussion risk (eTable 3, eFigures 6A-B and 7A-B).

| Parameter      | β       | Incidence Rate Ratio (IRR) | 89% Credible Interval for IRR | 97% Credible Interval for IRR | Markov chain Monte Carlo Diagnostics |
|----------------|---------|---------------------------|-------------------------------|-------------------------------|-------------------------------------|
|                | Median  | SD                        | Median Lower (5.5%)           | Upper (94.5%)                 | R-hat     | Effective Sample Size (ESS) | Monte Carlo Standard Error (MCSE) |
| Intercept      | -0.218  | 0.185                     | 0.804                         | 0.599                         | 1.081     | 0.538                       | 1.200                            | 1.000                             | 54041                             | <0.001                           |
| Grass Surface  | -0.629  | 0.262                     | 0.534                         | 0.351                         | 0.810     | 0.302                       | 0.944                            | 1.000                             | 45517                             | 0.001                            |
| Week           | 0.019   | 0.011                     | 1.019                         | 1.001                         | 1.037     | 0.995                       | 1.044                            | 1.000                             | 60680                             | <0.001                           |
|                  |        |        |        |        |        |        |        |        |        |
|------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Temperature      | -0.021 | 0.007  | 0.979  | 0.968  | 0.991  | 0.964  | 0.995  | 1.000  | 62214  | <0.001 |
| Grass × Week     | 0.018  | 0.016  | 1.018  | 0.992  | 1.045  | 0.983  | 1.054  | 1.000  | 51589  | <0.001 |
| Grass × Temperature | 0.013  | 0.009  | 1.013  | 0.998  | 1.028  | 0.993  | 1.034  | 1.000  | 52790  | <0.001 |
Figure Legends

**Figure 1. Probability distributions for all parameters primary model.** All coefficients were exponentiated to compute Incidence Rate Ratio. For all figures, the vertical bar within each curve represents the median value for prior distribution, gray shading represents the 89% credible interval and the tails represent the 97% credible interval for each parameter coefficient. The intercept represents the concussion rate (number of concussions per game). The posterior distribution for the IRR of natural grass surface is below 1.0 (dotted red line, for frame of reference), representing a decreased risk for concussion.

**Figure 1A. Concussion Rate.** The median intercept in the model was 0.804. While this single value is greater than expected for a concussion rate, the model indicates that the actual concussion rate may be higher or lower, depending on the inter-related effects of playing surface, temperature, and week of the season (Figures 1B and 1C).

**Figure 1B. Probability distribution for natural grass playing surface.** The overall probability that concussion risk was reduced on natural grass compared to artificial turf was 98%, with a median incident rate ratio of 0.534 (~46% reduced risk). However, positive values for two-way interactions (Figure 1C) suggest that the protective effect of natural grass may diminished with greater temperatures and later in the season.

**Figure 1C. Probability distribution for game temperature, week of season, and the two-way interactions included in the model.** There was a high probability (99%) that concussion risk was reduced at greater temperatures, and increased later in the season (91%). Much of the density of the posterior distributions for week and the two-way interactions were >1.0, suggesting that these values may influence concussion risk, however cautious interpretation of these parameters may be warranted as their probabilities are a bit lower (Grass × Week: 75%; Grass × Temperature: 84%). If the two-way interactions are interpreted as “non-significant” and removed from the model, all main effect parameters increase to 99% probability of association with concussion risk (eTable 3).
**Figure 2A. Marginal effects of concussion rate by week of season, at a fixed temperature of 20°C.**

The black spline represents predicted concussion rate and grey shading represents the 89% credible intervals. 20°C is utilized as it represents the temperature for indoor games, and a realistic temperature for outdoor games in temperate climates over the entire season (see eFigure 3A-C).

**Figure 2B. Marginal effects of concussion rate by week of season, at fixed temperatures of 15°C and 25°C.** These temperatures are reasonably possible for outdoor games throughout the entire football season (see eFigure 3). At any given week of the season, the risk of concussion on artificial turf is magnified during colder temperatures.

**Figure 3. Marginal effects of concussion rate by temperature, fixed to Week 8 of the NFL season.**

The black spline represents predicted concussion rate and grey shading represents the 89% credible interval. Week 8 is utilized for visualization because it represents a time of the season with a wide range of game temperatures.
Probability Density for Other Model Parameters

Grass x Temperature

Grass x Week

Game Temperature (C)

Week of Season

Probability Density for Incidence Rate Ratios
Predicted concussion rate at 15C and 25C

Game_Temperature_C = 15

Game_Temperature_C = 25

Concussion Rate (Number per Game)

Week

Surface_Category
- Artificial
- Grass
