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Fracture incidence in NCAA Women's Sports during 2009/10-2018/19

Avinash Chandran, PhD, MS, FACSM[1]

Adrian J. Boltz, MSH[1]

Neel Rao, MPH[1]

Kody R. Campbell, PhD[1]

Loretta DiPietro, PhD, MPH[2]

Stephanie Kliethermes, PhD[3]

[1] *Datalys Center for Sports Injury Research and Prevention, Indianapolis, IN*

[2] *Department of Exercise and Nutrition Sciences, Milken Institute School of Public Health, George Washington University, Washington DC*

[3] *Department of Orthopedics and Rehabilitation, University of Wisconsin- Madison, Madison, WI*

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Corresponding author:

Avinash Chandran, PhD, MS, FACSM
6151 Central Ave.

Indianapolis, IN 46220

avinashc@datalyscenter.org

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Abstract

Context: While bone health remains a critical concern for women of all ages, there exists limited research on the comprehensive incidence of fractures among female collegiate athletes.

Objective: To describe the epidemiology of sport-related fractures across women's National Collegiate Athletic Association (NCAA) sports.

Design: Descriptive epidemiology study

Setting: Injury surveillance in collegiate women's sports.

Patients or other participants: Women competing in NCAA sports during 2009/10-2018/19.

Main outcome measures: We examined fracture frequencies and distributions by sport, mechanism of injury, the injured body part, and injury history. We used a Bayesian framework to estimate fracture rates (per 10,000 AEs) by sport and event type.

Results: The NCAA ISP recorded 944 fractures across all women's sports during the study period, and fractures were most frequently reported among lower extremity body parts. Fractures were most commonly reported as non-contact/overuse injuries (39.0%), although equipment/apparatus contact mechanisms accounted for > 60% of fractures reported in field hockey and ice hockey. Fracture recurrence was most prevalently noted in track and field (17.8%) and gymnastics (17.6%). The posterior mean overall injury rate was 2.16 per 10,000 AEs (95% Credible Interval: [1.39, 3.44]), and the highest overall rate was estimated in gymnastics (Posterior mean= 6.29; 95% Credible Interval: [3.70, 10.31]).

Conclusions: Our findings indicate that fractures in women's gymnastics, lower leg fractures and fractures attributed to non-contact/overuse mechanisms, particularly among long-distance runners, warrant further attention in this population. Our results can inform targeted research efforts aimed at better understanding and improving bone health outcomes for female athletes.

Introduction

Bone health is a critical concern for women of all ages,[1] and bone injuries sustained during adolescence and early adulthood can not only be associated with short-term encumbrance but can also have lasting effects on functional capabilities and later life health outcomes.[2,3] Bone fractures during key developmental stages are of particular concern due to their potential for significant acute pain and prolonged recovery periods.[4,5] In addition, bone fractures during adolescence and early adulthood may also disrupt normal bone growth and remodeling,[5–7] increasing the risk of developing osteopenia or osteoporosis later in life.[8] Given the potential short-term severity and long-term implications of bone fractures, it is imperative to examine the features of these injuries in young women. Epidemiological data suggest that rates of bone fractures are highest among adolescent and young adult women,[9,10] and that fractures are primarily attributed to sport and recreational mechanisms in these age groups.

Collegiate competition represents the premier avenue for amateur sport participation in the US. Athletes competing at this level are considered elite and are performing at high standards that exert a significant physical burden on their bodies. During 2023/24, over 230,000 student-athletes competed in women's collegiate sports as part of the National Collegiate Athletic Association (NCAA), and participation in NCAA women's sports has followed an increasing trajectory over recent decades.[11] The large number of young adult women competing at this elite level, coupled with the fact that fractures are typically attributed to sport and recreation in this population, underscores the need to understand the burden of fractures on this group of athletes.

Public health and injury surveillance systems serve as invaluable epidemiological tools for assessing the extent and nature of injury issues across various populations.[12] The NCAA has maintained an injury surveillance system for more than four decades, and this system, known in its current form as the NCAA Injury Surveillance Program (ISP), is widely recognized as a preeminent surveillance method for examining the injury burden among NCAA athletes.[13,14] Since its inception, the system has recorded over 40,000 injuries in women's sports, thereby providing an ideal platform for investigating the extent of bone fractures in this demographic sub-group. Previous epidemiological research in this group has indicated a high incidence of bone stress fractures in NCAA women's sports, with an estimated incidence density of ~13 per 100,000 athlete-exposures.[15] In addition, previous research suggests that overuse bone fractures pose a particular problem in this population.[16] However, there is a lack of comprehensive data on the incidence and characteristics of bone fractures among women competing in NCAA sports. Accordingly, our objective was to characterize the epidemiology of such fractures among NCAA women's sports using injury surveillance data captured across a 10-year period.

Methods

We analyzed data captured within the NCAA ISP during the 2009/10-2018/19 academic years. The NCAA ISP, managed by the independent non-profit research organization, Datalys Center for Sports Injury Research and Prevention, is an essential tool for monitoring sports injuries in NCAA athletes. The methods employed by the surveillance program have been previously reviewed, deemed exempt, and thoroughly described in past studies;[13,14] we outline them briefly below.

Study data

During our study period, the NCAA ISP employed a convenience sampling scheme coupled with a rolling recruitment model to collect data. We focused on data captured within the following women's sports (as these represent sports in which data were consistently captured across the study period): basketball, cross country, field hockey, gymnastics, ice hockey, lacrosse, softball, soccer, swimming and diving, tennis, track and field, and volleyball. Athletic Trainers (ATs) at the participating institutions contributed to the data collection, providing exposure and injury data using their clinical Electronic Medical Record (EMR) systems. Data were extracted from EMR systems using a common data element export standard, and extracted data were de-identified and subjected to a series of automated verification procedures.[14] A reportable injury was defined as an injury that occurred due to participation in an organized intercollegiate practice or competition and necessitated medical attention by a team Certified Athletic Trainer or physician, regardless of the incurred time loss.[14] For each reportable injury, the ISP captured crucial details regarding the injury and the circumstances leading to the injury. An exposure was defined as any team-sanctioned athletic activity where student-athletes participated and were potentially "exposed" to the risk of injury.[14] Along with injury details, the ISP also captured specifics regarding these exposure events, including the number of participants in each event. We used these details to estimate the at-risk exposure time in terms of athlete-exposures (AEs), defined as a single athlete participating in one NCAA-sanctioned practice or competition event.[14,17,18]

Data analysis

We analyzed fracture frequencies and distributions by various characteristics such as sport, mechanism of injury (player contact, equipment/apparatus contact, non-contact/overuse, other/unknown), the injured body part, and injury history (new, recurrent, other/unknown). We utilized a Bayesian framework to estimate rates (per 10,000 AEs) of fractures reported by sport and event type. We briefly describe our conceptual approach for characterizing fracture incidence below; details regarding each step in our analytical process, along with accompanying Stan programs and posterior predictive checks, are included in Supplemental File 1.

Utilizing Bayesian inference in sports injury surveillance

The premise of our approach for estimating incidence density utilizing a Bayesian framework was the conceptualization of injury rates as underlying factors driving the observed injury counts. The goal of Bayesian analysis is to estimate distributions of parameters of interest by combining prior beliefs with observed data through a specified model, and subsequently describe the characteristics of these posterior distributions.[19,20] Although delving into the mathematical philosophies underpinning the frequentist (i.e. classical) and Bayesian methods is beyond the scope of this manuscript, one primary advantage of the Bayesian approach in this context is the ability to directly comment on the parameters of interest, and particularly their variability.[19,20] For instance, while classical methods allow for the calculation of observed injury rates and corresponding confidence intervals, the Bayesian credible interval provides a plausible range of values for the injury rate itself. In contrast, the classical confidence interval is a property of repeated sampling, indicating that if a sampling procedure was repeated *n* number of times, a certain fraction (i.e., commonly 90%, or 95%) of the resulting intervals would be expected to contain the true, yet unknown, injury rate. Furthermore, observational studies and injury surveillance often yield instances of sparse data across various variable contrasts or categories. In such cases, classical approaches may render parameters of interest inestimable. The Bayesian framework, however, offers a means to obtain realistic values for those parameters. Ultimately, our objective is not to advocate for the superiority of one approach over the other. Instead, we aim to present a different analytical perspective on injury surveillance data, offering more nuanced inferences than classical approaches.

We employed a negative binomial model for calculating injury rates, which accommodated for overdispersion in injury counts. In Bayesian inference, it is typical to assign prior distributions for each parameter included within a modeling framework.[19,20] For the analysis of injury rates using a negative binomial model, we used $Gamma\ (1, 500)$ as the prior for the rate parameter and $Beta\ (5, 100)$ as the prior for the overdispersion parameter. Our analytical models were customized and written in Stan.[21] We compiled and fit these models using the rstan package in R, running 2000 iterations across four chains to ensure convergence and sufficient posterior sampling.[19–21] Models were fit using No-U-Turn sampling, an advanced Markov Chain Monte Carlo algorithm and an extension of the Hamiltonian Monte Carlo method.[19–21] Posterior samples of the injury rates and probabilities were extracted for inference, and model diagnostics such as $\hat{R}$ and effective sample size (ESS), were computed to assess the convergence and efficiency of the sampling methods (details on model assessment criteria using these metrics are included in Supplemental File 1).[19–21]

Results

Fracture distributions by body part, injury mechanism, injury history

During the study period, the NCAA ISP recorded 944 fractures across all women's sports (Table 1). Fractures were most frequently reported among lower extremity body parts (Table 2). Over one-third of all fractures reported in cross country (39.3%), gymnastics (32.4%), and track and field (41.1%) were attributed to the foot. Similarly, a large proportion of fractures in cross country and track and field were attributed to the lower leg (Table 2). The hand and wrist were also commonly fractured body parts, accounting for 55.1% of all reported fractures in field hockey, and approximately 44% of all fractures in ice hockey and softball.

Fractures in NCAA women's sports were most commonly reported as non-contact/overuse injuries (Table 3). Most fractures reported in cross country (91.1%), swimming and diving (92.3%) and track and field (81.1%) were attributed to such mechanisms. Notably, equipment/apparatus contact accounted for > 60% of fractures reported in field hockey and ice hockey, and 57.9% of fractures reported in softball (Table 3). Most fractures in women's sports during the study period were also reported as new injuries (Table 3). The prevalence of recurrent fractures was highest in track and field (17.8%) and gymnastics (17.6%). Among all reported fractures, 17.1% (n = 161) were classified as chronic injuries (72.4% were classified as not chronic).

Fracture incidence rates

The 944 fractures captured were recorded over 4,804,395 athlete exposures (AEs) across the study period. Using our Bayesian approach, we obtained distributions of various injury rates, enabling us to understand their features comprehensively. For the overall fracture rate, the posterior mean rate (obtained using the posterior distribution of the overall rate calculated using both observed data and prior information) was 2.16 per 10,000 AEs (Table 1). The 95% Credible Interval (Cred. Int.) for this rate ranged from 1.39 to 3.44. This interval indicates that there is a 95% probability that the true fracture rate in NCAA women's sports lies between 1.39 and 3.44 per 10,000 AEs. When stratifying by event type, the posterior mean competition rate was 3.66 per 10,000 AEs, with a 95% Credible Interval from 2.32 to 5.83. For practices, the posterior mean rate was 1.71 per 10,000 AEs, with a 95% Credible Interval from 1.09 to 2.72 (Table 1). The posterior mean rate ratio between competition and practice rates was 2.26, with a 95% Credible Interval ranging from 1.09 to 4.24. This result suggests that we can be 95% confident that the fracture rate during competitions is truly higher than the fracture rate during practices in this population.

The posterior mean overall injury rate was highest in gymnastics (6.29 per 10,000 AEs; 95% Cred. Int.: [3.70, 10.31]), followed by cross country (4.04 per 10,000 AEs; [95% Cred. Int.: 2.42, 6.60]), and field hockey (3.38 per 10,000 AEs; 95% Cred. Int.: [1.96, 5.86]) (Table 1). The posterior mean practice rate was also highest in gymnastics, at 6.17 per 10,000 AEs (95% Cred. Int.: [3.70, 10.04]). Cross country (3.96 per 10,000 AEs; 95% Cred. Int.: [2.30, 6.74]) and basketball (2.60 per 10,000 AEs; 95% Cred. Int.: 1.59, 4.27) followed in terms of estimated practice incidence density. In contrast, the posterior mean competition rate was highest in field hockey (8.14 per 10,000 AEs; 95% Cred. Int.: [4.48, 14.03]), followed by gymnastics (7.42 per 10,000 AEs; 95% Cred. Int.: [2.86, 15.22]), and soccer (6.88 per 10,000 AEs; [95% Cred. Int.: 4.28, 11.20]).

Discussion

In this study, we examined the epidemiology of fractures reported in NCAA women's sports during a 10-year time span. While fractures are a concern in both men's and women's sports, we focused on NCAA women's sports given the growing body of literature emphasizing life course bone health in women, as well as the continued attention to factors such as energy availability, hormonal influences, and long-term musculoskeletal outcomes in female athletes. Our results indicate that fractures among NCAA women's sport athletes predominantly affect the lower leg and foot and are most commonly reported as non-contact/overuse injuries across several sports. The observed prevalence of recurrent fractures in gymnastics and track and field are also noteworthy, suggesting greater fracture recurrence in these groups. Our Bayesian models indicate that fracture incidence in this population is highest in gymnastics, cross country, and field hockey, respectively, with the highest competition-related injury rate in field hockey.

Fracture Distributions by Body Part

Our data indicate that fractures predominantly affect the lower extremities in NCAA women's sports, with a notable prevalence of foot and lower leg fractures across several sports. These findings align with existing literature and are biomechanically plausible given the movement dynamics inherent to the sports examined herein.[15,22] For instance, the high prevalence of foot and lower leg fractures in cross country is unsurprising, considering the significant stress placed on these areas during long-distance running.[23] We also observed similar results in soccer, which is intuitive given the nature of the sport. Previous studies have identified the lower extremities as the most frequently injured body regions in soccer;[18] however, further investigation is needed to better understand the athlete characteristics, injury inciting events, and contextual factors contributing to fracture occurrence in this population. With regards to upper extremity fractures, we observed a notable proportion of hand/wrist fractures in field hockey, ice hockey, and volleyball in our study. These body parts are frequently utilized during gameplay in these sports and may therefore be at risk of inadvertent contact with equipment or opponents.[24] Our findings are in alignment with the existing literature on fracture characteristics in these specific sports, and future efforts may be directed toward closely examining the circumstances under which hand/wrist fractures occur in these sports. These fractures may be viable targets for primary prevention strategies, such as the use of protective equipment or the implementation of improved training techniques that emphasize proper hand positioning and impact mitigation strategies.

Distribution of Fractures by Mechanism of Injury

Data examined in this study indicate that fractures in NCAA women's sports predominantly occur due to non-contact and overuse mechanisms, which aligns with the existing literature on bone injuries in female athletes.[25] Such fractures were prevalently reported among cross country and track and field athletes. Existing research suggests that female runners may be at increased risk of overuse and stress fractures due to low energy availability, defined as insufficient caloric intake relative to energy expenditure.[26] Low energy availability can lead to disruptions in menstrual cycles and subsequently decreased bone mineral density, thereby increasing fracture susceptibility.[27,28] Previous research also suggests that stress fractures from repetitive load-bearing, as in cross-country running, may predispose athletes to chronic bone density issues and heightened risk for future fractures.[29] The observed prevalence of non-contact and overuse fractures in our study underscores the potential role of diet and nutrition in injury risk assessment.[30,31] Future longitudinal studies on bone health markers are necessary among female runners in particular to identify potential relationships between dietary patterns and bone health, and to determine appropriate intervention points for improving bone health outcomes.

In contrast with the above-mentioned pattern in fracture mechanisms, fractures in soccer and basketball were most commonly attributed to player contact mechanisms. Indeed, we noted that ~41% of all fractures in soccer and basketball were attributed to player contact mechanisms. The prevalence of player contact-resultant fractures in soccer and basketball may be considered reflective of the high-contact nature of these sports, where players frequently engage in physical confrontations.[18,32–34] Previous research among soccer athletes in particular suggests that tackling and sudden directional changes may be notable contributors to contact injuries in this population.[35] While player contact is also a well-recognized aspect of basketball gameplay, further investigation is needed to identify the specific inciting events that contribute to contact-related injuries in this sport.[34,36,37] Understanding the interaction between frequently fractured body parts and fracture mechanisms is also essential in this regard, as the dynamics between anatomical site and injury mechanism can shape long-term bone health and recovery trajectories in female athletes. Prior studies indicate that fractures caused by high-impact mechanisms, such as player contact, may increase susceptibility to joint degeneration and early-onset osteoarthritis.[38] Therefore, future research should seek to clarify the mechanisms driving site-specific fractures in female athletes, with a particular emphasis on the potential interplay between injury location and mechanism on long-term bone health.

Equipment and apparatus contact emerged as a notable mechanism of fracture injury in field hockey, ice hockey, and softball. This may be unsurprising given the nature of these sports, where athletes are vulnerable to abrupt equipment contact during gameplay.[39–41] As noted above, these data suggest that the implementation of enhanced protective equipment and equipment-related safety measures may be effective in reducing the fracture burden in these sports. Future research should focus on elucidating the specific inciting mechanisms of injury involved in these fractures to inform advancements in protective equipment design and usage that may aid in prevention efforts.

Recurrent Fractures and Chronic Fractures

The prevalence of fracture recurrence varied by sport in our sample, with recurrent fractures most notably reported in gymnastics and track and field. We note that in the ISP, injury history is documented based on whether the athletic trainer classifies the injury as new or as a recurrence from the current or previous academic year. Fracture recurrence can have significant short-term and long-term implications. Recurrent fractures can lead to chronic pain, reduced mobility, and an increased risk of osteoporosis, all of which further elevates the likelihood of additional fractures and long-term disability.[3] Moreover, recurrent fractures may indicate underlying bone health issues with serious long-term implications, such as reduced bone mineral density.[3] We also noted that ~17% of all reported fractures in our study were reported as chronic injuries. This is noteworthy and further underscores the complexity of bone health in female athletes, as chronic fractures may develop gradually due to cumulative stress and inadequate bone remodeling. Existing evidence indicates that energy availability, hormonal imbalances, and low bone mineral density can impair bone remodeling and increase risk of chronic fractures over time.[42–45] While these physiological characteristics are challenging to elucidate using injury surveillance data, they should be specifically targeted in future, prospective studies. Such studies are necessary to determine how bone health indicators can serve as early markers for recurrent fracture risk and to understand how bone health progresses through the aging process in female athletes and active women.[46]

Fracture rates

Our findings indicate that fracture incidence in NCAA women's sports is nearly twice as high in competitions as compared with practices, aligning with other sports medicine research which indicates a higher injury incidence in competition settings.[22] This can be attributed to the inherently dynamic nature of competition gameplay and the relatively uncontrolled environments characteristic of competitive events compared to practices. Prior research has discussed how the unpredictability of competitive environments increases the likelihood of fractures due to sudden, high-impact events.[47] As such, it becomes vital to further examine the sports in which competition fracture incidence densities are highest. Our results suggest that competition fracture incidence is highest in field hockey, followed by gymnastics, and then soccer. Coupled with the fracture characteristics described herein, these findings offer important insights for targeted evaluation and intervention. Specifically, we observed higher prevalences of contact than non-contact fractures in field hockey and soccer. This suggests that in field hockey and soccer in particular, collision and impact events during play might be significant contributors to fracture risk.[48] Emphasizing the importance of proper technique, player/body awareness, and the use of adequate protective equipment could potentially reduce the incidence of contact-related fractures in these sports.[49] Furthermore, a closer examination of the injury-inciting events, particularly within the competition setting, could help identify if policy or gameplay considerations could reduce fracture incidence in these sports. There exist examples in youth sport settings where effective gameplay modifications have been shown to positively impact injury incidence.[50] Although not directly applicable to the present setting, this prior research may offer blueprints for similar evaluations in collegiate field hockey and women's soccer.

Our findings also indicate that overall fracture incidence among NCAA women’s sports is highest in gymnastics and cross country. The nature of gymnastics, involving high-impact landings and complex routines, may inherently contribute to fracture risk among these athletes.[51] Similarly, cross country athletes may be prone to overuse injuries and stress fractures due to repetitive high-mileage training on uneven terrain.[52] Previous studies have also noted a high fracture incidence in athletes of these sports, reinforcing the need for increased focus on these populations.[15,22] Considerable attention has been directed towards energy availability and nutrition in runners, particularly in conversations surround their risk of stress fractures. For instance, research has shown that inadequate calcium and vitamin D intake significantly increases the risk of stress fractures in runners.[53,54] Additionally, biomechanical factors such as running gait and footwear have been identified as contributing factors to fracture risk in runners.[55] Coupled with the existing literature, our findings support the need for developing sport-specific risk assessment and injury prevention programs that address the unique risks associated with gymnastics and cross country.

Limitations

Findings presented herein provide a critical overview of fracture epidemiology in NCAA women's sports; however, they are limited by a number of factors. The NCAA ISP employs a convenience sampling scheme with a rolling recruitment model. As a result, participation varies by sport and year, potentially limiting the external validity of these findings. That said, NCAA ISP recruitment strategies have evolved significantly over time, leading to a substantial improvement in participation throughout the study period (reflecting, for instance, support and communication from the NCAA Sport Science Institute). Regarding the estimates presented, we acknowledge the ongoing debate within sports injury surveillance surrounding the expression of at-risk exposure time in terms of AEs. While the use of AEs offers an efficient reporting solution, it may not represent the most precise measure of exposure time, potentially compromising the precision of injury incidence estimates. Additionally, we note that the ATs responsible for reporting data are not provided with study-specific diagnostic criteria or variable guidelines when documenting injuries. This is particularly relevant to the reporting of injury history and chronicity, as the ISP relies on AT clinical expertise and familiarity with an athletes' medical background to document these elements. As such, although NCAA ISP methods are designed to standardize reporting practices, there remains potential for between-AT variability in reporting, which could subsequently result in non-differential misclassification of the variables examined. Furthermore, as noted above, we employed a distinctive analytical approach in this study. It is recognized that Bayesian methods inherently involve subjective decision points, especially concerning prior specifications. Our decisions were made with plausible and conservative considerations in mind, and were supported by prior sensitivity checks. Nevertheless, we have transparently disclosed our decisions within the programs shared in the Supplemental file. We acknowledge that future investigators may adjust these parameterizations in different applications of these methods using surveillance data.

Conclusions

This study provides a comprehensive overview of fracture characteristics in collegiate women's sports over a 10-year period. Our findings provide valuable insights into fracture characteristics in this population, highlighting the need for greater attention to lower-leg and foot fractures, and to fractures among gymnastics athletes. As bone health remains a key focus in women's health across the life course, these results can inform targeted research efforts to better understand and improve bone health outcomes for female athletes during and beyond their athletic careers.

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Table 1. Fracture frequencies; Athlete Exposures (AEs); and mean posterior rates per 10,000 AEs (accompanied by 95% Credible Intervals) by sport

	Overall	Competitions	Practices
Basketball	165 619748 2.91 [1.82, 4.7]	55 150226 4.07 [2.42, 6.87]	110 469522 2.6 [1.59, 4.27]
Cross Country	56 152819 4.04 [2.42, 6.6]	6 12528 5.78 [2.12, 12.59]	50 140292 3.96 [2.3, 6.74]
Field Hockey	49 161922 3.38 [1.96, 5.86]	28 37803 8.14 [4.48, 14.03]	21 124119 1.97 [1.01, 3.57]
Gymnastics	68 118712 6.29 [3.7, 10.31]	7 11254 7.42 [2.86, 15.22]	61 107459 6.17 [3.7, 10.04]
Ice Hockey	56 269479 2.3 [1.36, 3.75]	31 74346 4.65 [2.51, 8.16]	25 195133 1.46 [0.76, 2.6]
Lacrosse	63 393103 1.79 [1.07, 3]	22 75551 3.32 [1.74, 5.83]	41 317552 1.45 [0.83, 2.47]
Softball	95 547374 1.92 [1.19, 3.1]	53 226500 2.63 [1.51, 4.39]	42 320874 1.47 [0.84, 2.47]
Soccer	174 669820 2.85 [1.79, 4.55]	103 164358 6.88 [4.28, 11.2]	71 505463 1.58 [0.94, 2.72]
Swimming & Diving	13 458570 0.34 [0.16, 0.63]	0 41107 0.27 [0.01, 1.04]	13 417462 0.37 [0.18, 0.68]
Tennis	12 104412 1.37 [0.63, 2.64]	6 25499 2.96 [1.06, 6.16]	6 78912 0.96 [0.36, 2.04]
Track and Field	90 802719 1.25 [0.76, 2.07]	12 102783 1.38 [0.64, 2.62]	78 699936 1.24 [0.75, 2.05]
Volleyball	103 505717 2.25 [1.39, 3.64]	37 152642 2.69 [1.51, 4.58]	66 353074 2.07 [1.23, 3.47]
Overall	944 4804395 2.16 [1.39, 3.44]	360 1074596 3.66 [2.32, 5.83]	584 3729799 1.71 [1.09, 2.72]

Note: Data presented in the order of reported number, followed by athlete exposures (AEs), estimated posterior mean injury rates, and associated 95% Credible Intervals for each sport. Rates presented are unweighted, and based on reported data. Data pooled association-wide are presented overall, and separately for practices and competitions. A reportable injury was one that occurred due to participation in an organized intercollegiate practice or competition, and required medical attention by a team Certified Athletic Trainer or physician (regardless of time loss). Only scheduled team practices and competitions were retained in this analysis.

Table 2. Fracture distributions by body part (data presented as observed frequencies and proportions)

	Ankle	Arm/ Elbow	Foot	Hand/ Wrist	Head/ Face	Hip/ Groin	Knee	Lower Leg	Shoulder	Thigh	Trunk
Basketball	6 (3.6)	5 (3)	46 (27.9)	39 (23.6)	32 (19.4)	0 (0)	6 (3.6)	26 (15.8)	0 (0)	1 (0.6)	4 (2.4)
Cross Country	0 (0)	1 (1.8)	22 (39.3)	0 (0)	0 (0)	0 (0)	0 (0)	19 (33.9)	0 (0)	12 (21.4)	2 (3.6)
Field Hockey	0 (0)	0 (0)	7 (14.3)	27 (55.1)	6 (12.2)	0 (0)	0 (0)	4 (8.2)	0 (0)	1 (2)	4 (8.2)
Gymnastics	4 (5.9)	1 (1.5)	22 (32.4)	7 (10.3)	1 (1.5)	0 (0)	3 (4.4)	16 (23.5)	0 (0)	0 (0)	14 (20.6)
Ice Hockey	1 (1.8)	4 (7.1)	4 (7.1)	25 (44.6)	0 (0)	0 (0)	1 (1.8)	7 (12.5)	10 (17.9)	0 (0)	4 (7.1)
Lacrosse	3 (4.8)	2 (3.2)	13 (20.6)	16 (25.4)	8 (12.7)	0 (0)	1 (1.6)	11 (17.5)	0 (0)	4 (6.3)	5 (7.9)
Softball	1 (1.1)	9 (9.5)	12 (12.6)	42 (44.2)	19 (20)	0 (0)	1 (1.1)	8 (8.4)	0 (0)	2 (2.1)	1 (1.1)
Soccer	7 (4.0)	13 (7.5)	32 (18.4)	31 (17.8)	30 (17.2)	1 (0.6)	7 (4.0)	30 (17.2)	8 (4.6)	6 (3.4)	9 (5.2)
Swimming & Diving	0 (0)	1 (7.7)	2 (15.4)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (7.7)	0 (0)	9 (69.2)
Tennis	0 (0)	1 (8.3)	3 (25)	0 (0)	1 (8.3)	0 (0)	0 (0)	3 (25)	1 (8.3)	0 (0)	3 (25)
Track and Field	2 (2.2)	1 (1.1)	37 (41.1)	1 (1.1)	0 (0)	0 (0)	1 (1.1)	34 (37.8)	0 (0)	9 (10)	5 (5.6)
Volleyball	4 (3.9)	5 (4.9)	27 (26.2)	38 (36.9)	4 (3.9)	0 (0)	0 (0)	15 (14.6)	1 (1)	0 (0)	9 (8.7)
Overall	28 (2.9)	43 (4.5)	227 (23.8)	226 (23.7)	101 (1.6)	1 (0.1)	20 (2.1)	173 (18.1)	21 (2.2)	35 (3.7)	69 (7.2)

Note: Data presented in the order of reported number, followed by the proportion of all injuries attributable to a given body part. Data represent the distribution of reported fractures by body part for each sport included in the analysis. Data presented are unweighted, and based on reported data. Data pooled across event types are presented overall. A reportable injury was one that occurred due to participation in an organized intercollegiate practice or competition, and required medical attention by a team Certified Athletic Trainer or physician (regardless of time loss). Only scheduled team practices and competitions were retained in this analysis.

Table 3. Fracture distributions by mechanism of injury and injury history (data presented as observed frequencies and proportions)

	Mechanism of Injury				Injury History		
	Player contact	Equipment/ Apparatus contact	Non-contact/ overuse	Other/ Unknown	New injury	Recurrent injury	Other/ Unknown
Basketball	67 (40.6)	15 (9.1)	58 (35.2)	25 (15.2)	143 (86.7)	13 (7.9)	9 (5.5)
Cross Country	0 (0)	0 (0)	51 (91.1)	5 (8.9)	47 (83.9)	4 (7.1)	5 (8.9)
Field Hockey	3 (6.1)	32 (65.3)	11 (22.4)	3 (6.1)	41 (83.7)	1 (2)	7 (14.3)
Gymnastics	0 (0)	13 (19.1)	33 (48.5)	22 (32.4)	55 (80.9)	12 (17.6)	1 (1.5)
Ice Hockey	5 (8.9)	34 (60.7)	4 (7.1)	13 (23.2)	52 (92.9)	3 (5.4)	1 (1.8)
Lacrosse	16 (25.4)	16 (25.4)	25 (39.7)	6 (9.5)	48 (76.2)	2 (3.2)	13 (20.6)
Softball	8 (8.4)	55 (57.9)	12 (12.6)	20 (21.1)	88 (92.6)	1 (1.1)	6 (6.3)
Soccer	72 (41.4)	21 (12.1)	44 (25.3)	37 (21.3)	145 (83.3)	18 (10.3)	11 (6.3)
Swimming & Diving	0 (0)	0 (0)	12 (92.3)	1 (7.7)	9 (69.2)	1 (7.7)	3 (23.1)
Tennis	0 (0)	2 (16.7)	9 (75)	1 (8.3)	8 (66.7)	2 (16.7)	2 (16.7)
Track and Field	0 (0)	0 (0)	73 (81.1)	17 (18.9)	63 (70)	16 (17.8)	11 (12.2)
Volleyball	16 (15.5)	22 (21.4)	40 (38.8)	25 (24.3)	81 (78.6)	8 (7.8)	14 (13.6)
Overall	187 (19.6)	210 (22.0)	372 (39.0)	175 (18.3)	780 (81.7)	81 (8.5)	83 (8.7)

Note: Data presented in the order of reported number, followed by the proportion of all injuries attributable to a given category. Data represent the distribution of reported fractures by mechanism and injury history for each sport included in the analysis. Data presented are unweighted, and based on reported data. Data pooled across event types are presented overall. A reportable injury was one that occurred due to participation in an organized intercollegiate practice or competition, and required medical attention by a team Certified Athletic Trainer or physician (regardless of time loss). Only scheduled team practices and competitions were retained in this analysis.

Fracture incidence in NCAA Women's Sports: 2009/10 - 2018/19

2024-10-31

Analytical approach & Model Assessment

Glossary of Sport Abbreviations

- **BB-W**: Women's Basketball
- **CC-W**: Women's Cross Country
- **FH-W**: Women's Field Hockey
- **GY-W**: Women's Gymnastics
- **IH-W**: Women's Ice Hockey
- **LA-W**: Women's Lacrosse
- **SB-W**: Women's Softball
- **SO-W**: Women's Soccer
- **SW-W**: Women's Swimming and Diving
- **TE-W**: Women's Tennis
- **TR-W**: Women's Track and Field
- **VB-W**: Women's Volleyball

Injury Rates

- The Bayesian framework allows for flexible estimation of injury rates by incorporating prior information and handling overdispersion in injury counts. This approach yields realistic results even in cases of sparse or variable data. Bayesian inference involves drawing samples, or simulations, from the posterior distribution to represent the range of plausible values for each parameter. By generating these simulated values, Bayesian models can capture complex patterns in the data, and the resulting credible intervals for the injury rate offer a direct interpretation of injury rate uncertainty, representing a plausible range of values based on observed data and prior beliefs.
- The approach is implemented in this specific analysis, using the Stan program noted below. The data block initializes inputs to the model, specifying total_injuries and total_exposures as non-negative values. Two key parameters of interest are defined within the parameters block. The injury_rate is defined as a non-negative parameter, and models the rate of injury per unit of exposure, following a broad, Gamma(1, 500) prior. The choice of the Gamma prior allows for substantial variability

and accommodates injury rate data with wide possible ranges. The overdispersion_factor, constrained between 0 and 1, handles potential overdispersion in the data by incorporating extra variability beyond what a standard Poisson model would assume. This parameter uses a Beta(5, 100) prior, suggesting realistic, and minor overdispersion. The prior specifications here are designed to be weakly informative, allowing the data to primarily drive the estimates. During analysis, these priors were adjusted (e.g., Cauchy(0, 10)) based on model flexibility and diagnostic performance.

```
data {
  int<lower=0> total_injuries; // Total number of injuries
  real<lower=0> total_exposures; // Total number of exposures
}

parameters {
  real<lower=0> injury_rate; // Injury rate parameter
  real<lower=0, upper=1> overdispersion_factor; // Constrained to be small
}

model {
  // Priors
  injury_rate ~ gamma(1, 500); // Weakly informative prior
  overdispersion_factor ~ beta(5, 100); // Weakly informative overdispersion prior

  // Negative Binomial likelihood
  total_injuries ~ neg_binomial_2(injury_rate * total_exposures, 1 / overdispersion_factor);
}

generated quantities {
  real std_injury_rate = injury_rate * 10000; // Standardized injury rate per 10,000 AEs
}
```

- The Stan model was fit using the RStan package, with data passed as a list containing total injuries and total exposures. No U-Turn Sampling was conducted with 2000 iterations across four chains. Posterior distributions were extracted from the model fit to further analyze injury counts, simulate future counts, and perform predictive checks for model validation.

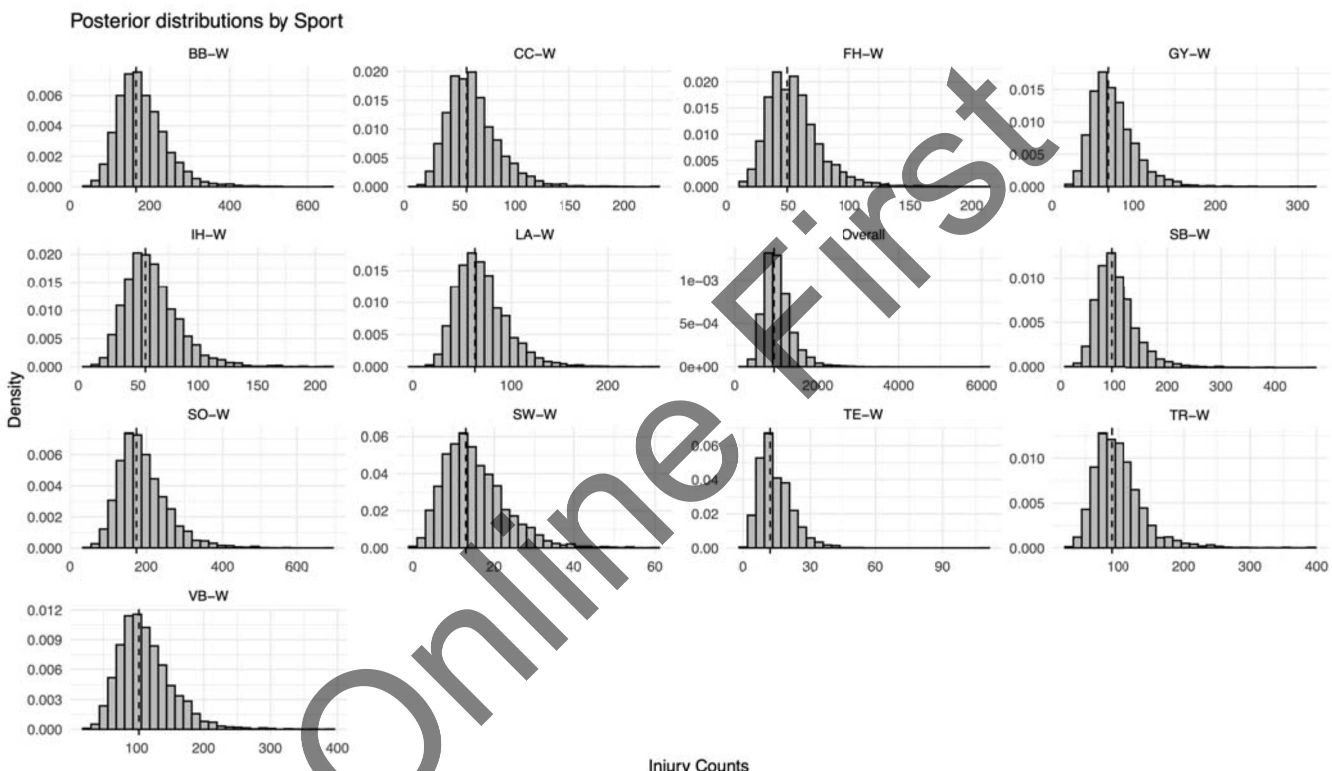
Overall rates: The table here includes observed injury counts and athlete exposures, alongside the estimated posterior mean injury rates and 95% credible intervals from the Stan model described above.

```
##    category                        Inj_rate
## 1   Overall 944; 4804395; 2.16 [1.39, 3.44]
## 2      BB-W   165; 619748; 2.91 [1.82, 4.7]
## 3      CC-W    56; 152819; 4.04 [2.42, 6.6]
## 4      FH-W   49; 161922; 3.38 [1.96, 5.86]
## 5      GY-W   68; 118712; 6.29 [3.7, 10.31]
## 6      IH-W    56; 269479; 2.3 [1.36, 3.75]
## 7      LA-W      63; 393103; 1.79 [1.07, 3]
## 8      SB-W    95; 547374; 1.92 [1.19, 3.1]
## 9      SO-W  174; 669820; 2.85 [1.79, 4.55]
## 10     SW-W   13; 458570; 0.34 [0.16, 0.63]
## 11     TE-W   12; 104412; 1.37 [0.63, 2.64]
## 12     TR-W   90; 802719; 1.25 [0.76, 2.07]
## 13     VB-W  103; 505717; 2.25 [1.39, 3.64]
```

- Below are metrics for model diagnostics- $\hat{R}$ and ESS corresponding to the primary parameters. $\hat{R}$, is referred to as the potential scale reduction factor, and assesses convergence across No U-Turn sampling process, with values less than or equal to 1.01 indicating a well-performing model. ESS stands or Effective Sample Size, and represents the amount of independent information in the posterior distribution, with values over 400 for all parameters generally required to diagnose convergence.

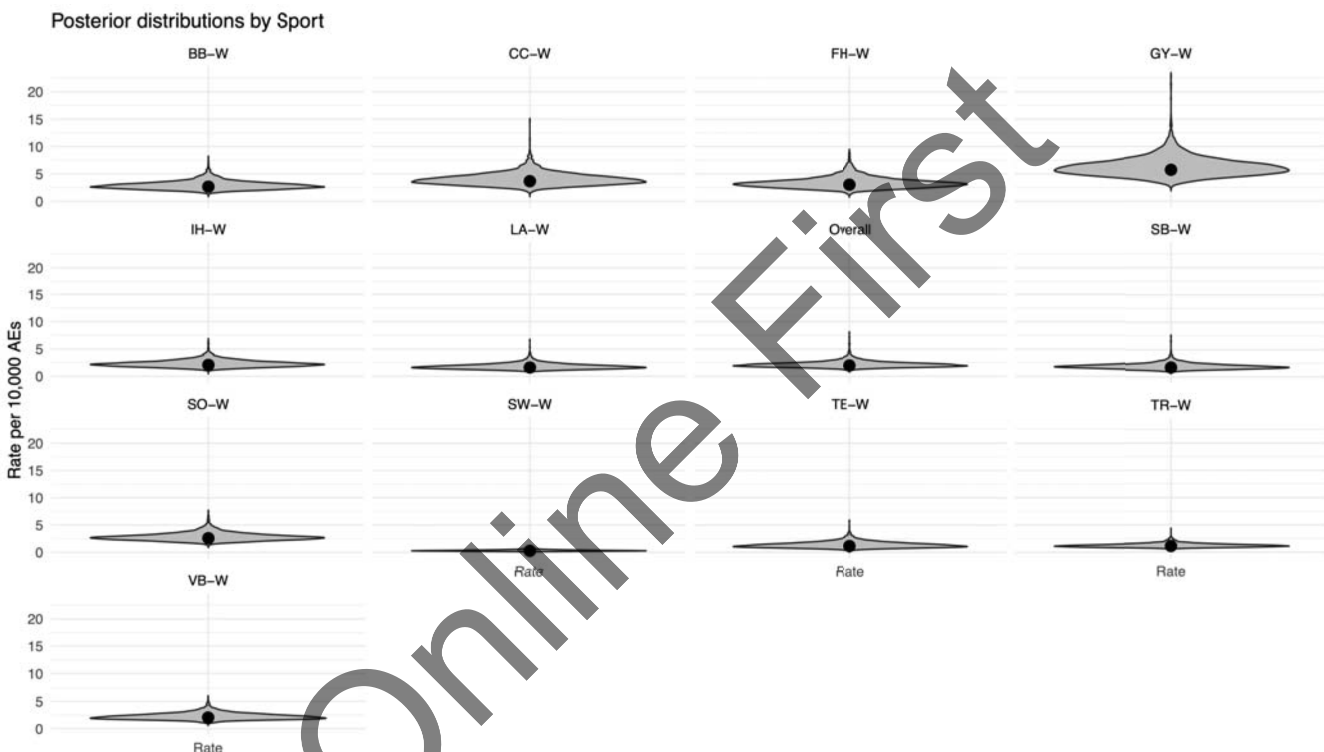
```
##    category std_rate_ESS std_rate_Rhat overdispersion_ESS overdispersion_Rhat
## 1   Overall         1617     1.0023649               2137           0.9995629
## 2      BB-W         1864     1.0031178               1948           1.0015614
## 3      CC-W         2177     1.0012764               2439           1.0014948
## 4      FH-W         2079     0.9998162               2706           1.0023285
## 5      GY-W         1902     1.0018379               2937           1.0005764
## 6      IH-W         2125     1.0008743               2639           0.9993706
## 7      LA-W         2069     1.0023525               2480           1.0001267
## 8      SB-W         2073     1.0007520               2401           0.9998725
## 9      SO-W         2110     1.0006712               2745           0.9996406
## 10     SW-W         2884     1.0015977               2533           0.9998886
## 11     TE-W         2801     0.9995384               2473           0.9996397
## 12     TR-W         1630     1.0014848               2443           1.0004125
## 13     VB-W         2278     1.0006988               2781           0.9998824
```

Posterior Distribution of Overall Injury Counts



Each histogram displays simulated injury counts from the posterior distribution, overlaid with the observed injury count for each sport. The dashed vertical line indicates the observed injury count, allowing for a visual assessment of how well the model predictions align with observed data. If the observed count falls within the range of simulated values, it suggests that the model is adequately capturing the variability in the data.

Posterior Distribution of Overall Injury Rates



Each violin plot shows the posterior distribution of injury rates for each sport, with the observed rate plotted as a solid point. Each plot represents the density of predicted injury rates, facilitating comparison between the observed rate and the distribution of predicted rates. If the observed rate falls within the high-density region of the plot, it indicates that the model predictions are consistent with the observed data.

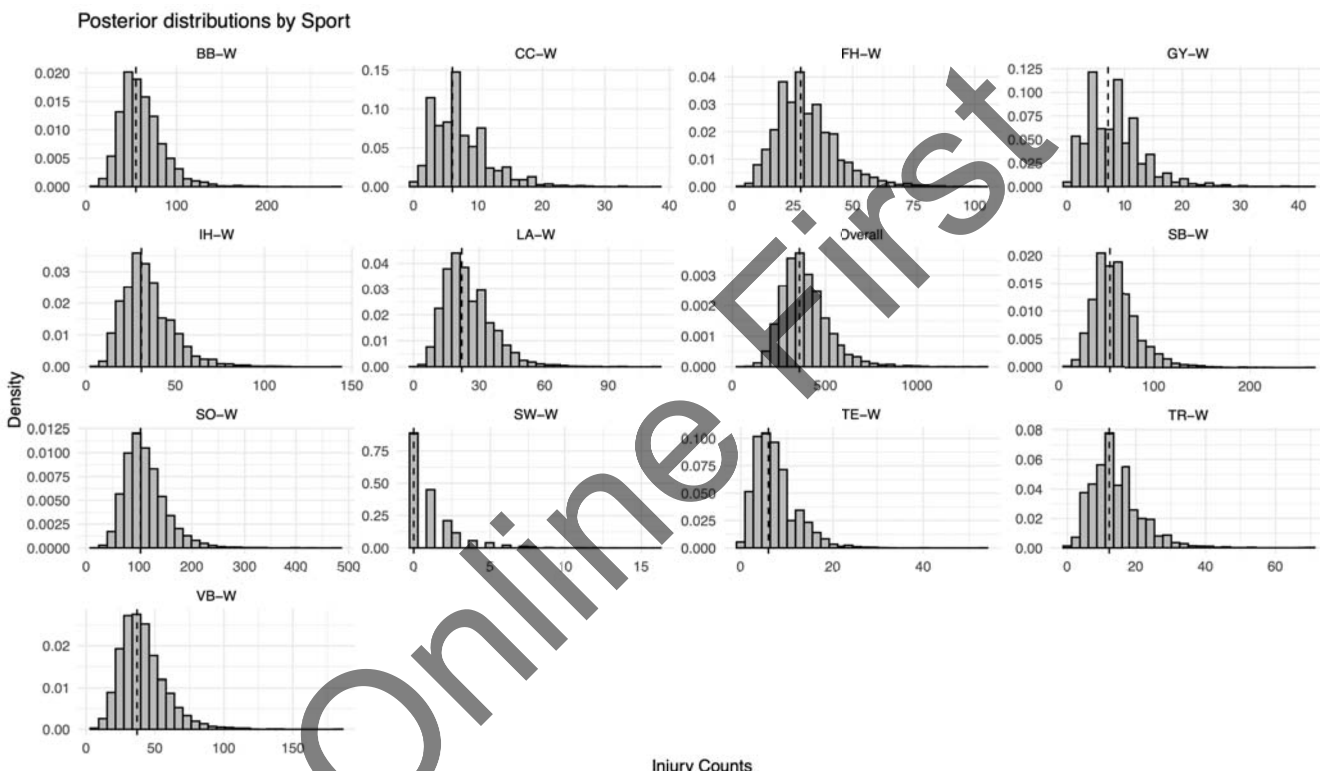
Competition rates: The table here includes observed competition injury counts and athlete exposures, along with estimated posterior mean injury rates and 95% credible intervals from the Stan model described above.

```
##    category                        Inj_rate
## 1   Overall 360; 1074596; 3.66 [2.32, 5.83]
## 2      BB-W   55; 150226; 4.07 [2.42, 6.87]
## 3      CC-W    6; 12528; 5.78 [2.12, 12.59]
## 4      FH-W   28; 37803; 8.14 [4.48, 14.03]
## 5      GY-W    7; 11254; 7.42 [2.86, 15.22]
## 6      IH-W    31; 74346; 4.65 [2.51, 8.16]
## 7      LA-W    22; 75551; 3.32 [1.74, 5.83]
## 8      SB-W   53; 226500; 2.63 [1.51, 4.39]
## 9      SO-W  103; 164358; 6.88 [4.28, 11.2]
## 10     SW-W     0; 41107; 0.27 [0.01, 1.04]
## 11     TE-W     6; 25499; 2.96 [1.06, 6.16]
## 12     TR-W   12; 102783; 1.38 [0.64, 2.62]
## 13     VB-W   37; 152642; 2.69 [1.51, 4.58]
```

- Below are metrics for model diagnostics- $\hat{R}$ and ESS corresponding to the primary parameters. These models are compiled similarly to the overall data analyses, and the diagnostic metrics can be interpreted following the guidelines provided above.

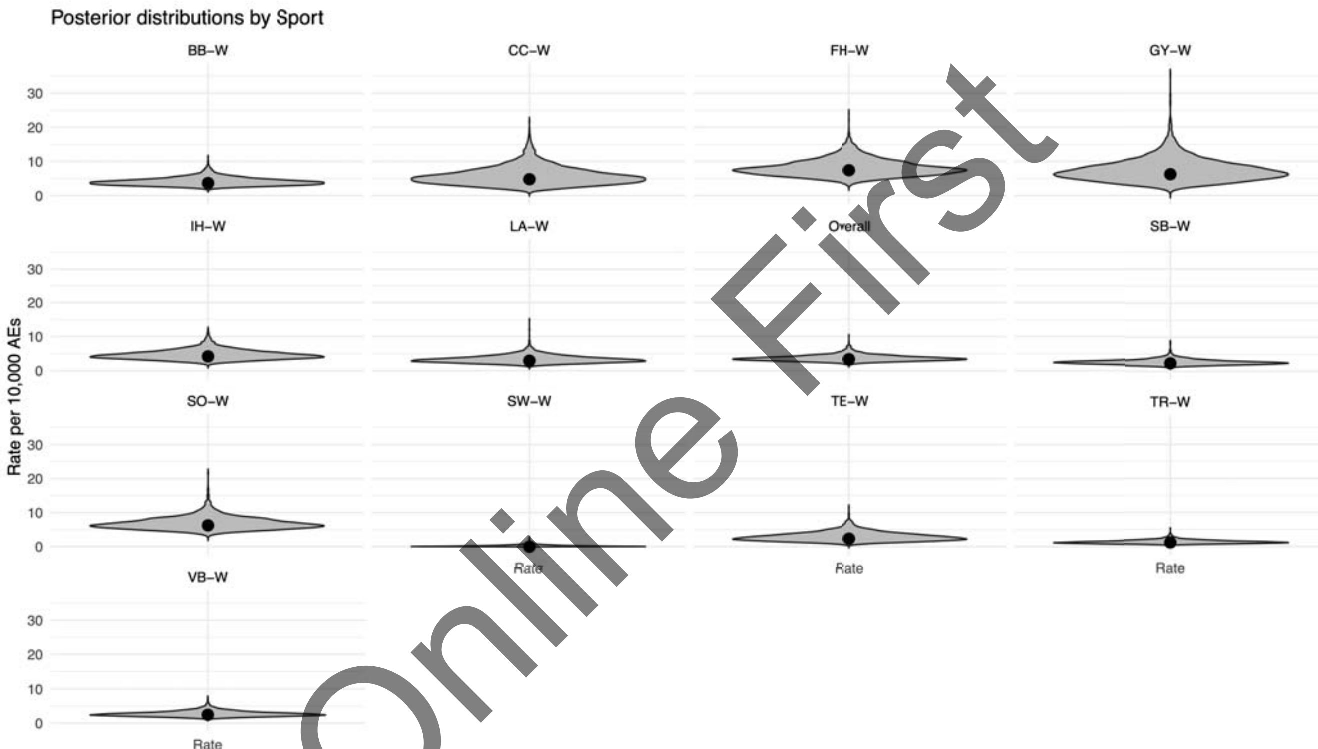
```
##    category std_rate_ESS std_rate_Rhat overdispersion_ESS overdispersion_Rhat
## 1   Overall         1960     0.9995904               2111           1.0012959
## 2      BB-W         1864     1.0034002               2413           1.0012689
## 3      CC-W         3088     0.9994132               2870           0.9995680
## 4      FH-W         2195     1.0001958               2133           1.0006041
## 5      GY-W         3278     0.9999852               2747           1.0007626
## 6      IH-W         2468     1.0005602               2828           1.0006946
## 7      LA-W         2656     1.0007285               2466           1.0010857
## 8      SB-W         2439     1.0013544               2660           1.0007329
## 9      SO-W         1290     1.0019721               2322           0.9998837
## 10     SW-W         3127     1.0008293               2224           1.0003864
## 11     TE-W         2763     1.0009967               2857           1.0001125
## 12     TR-W         2905     0.9998618               3536           1.0006252
## 13     VB-W         2023     1.0014592               2468           1.0022735
```

Posterior Distribution of Competition Injury Counts



Each histogram displays simulated injury counts from the posterior distribution, overlaid with the observed injury count for each sport (figures may be interpreted per the descriptions above regarding the overall rate models).

Posterior Distribution of Competition Injury Rates



Each violin plot shows the posterior distribution of injury rates for each sport, with the observed rate plotted as a solid point (figures may be interpreted per the descriptions above regarding the overall rate models).

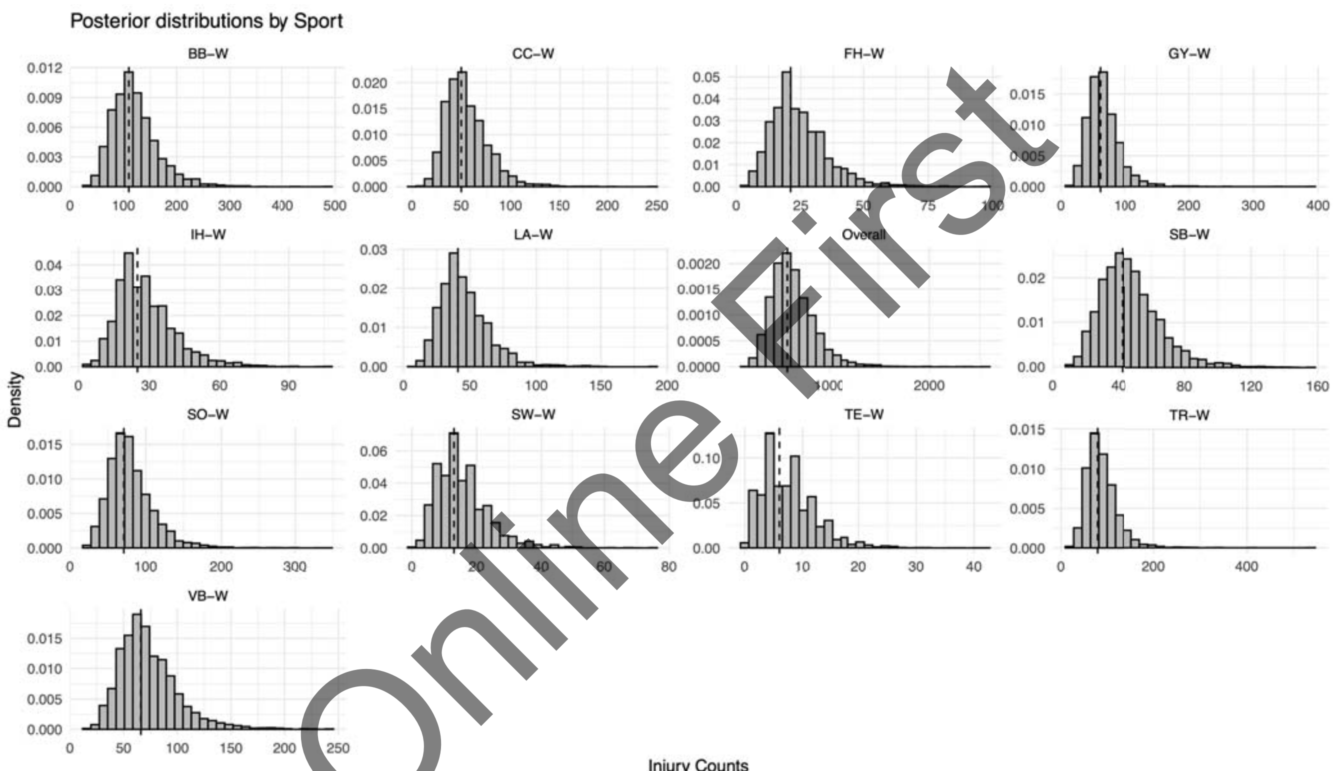
Practice rates: The table here includes observed practice injury counts and athlete exposures, along with estimated posterior mean injury rates and 95% credible intervals from the Stan model described above.

```
##    category                        Inj_rate
## 1   Overall 584; 3729799; 1.71 [1.09, 2.72]
## 2      BB-W   110; 469522; 2.6 [1.59, 4.27]
## 3      CC-W    50; 140292; 3.96 [2.3, 6.74]
## 4      FH-W   21; 124119; 1.97 [1.01, 3.57]
## 5      GY-W   61; 107459; 6.17 [3.7, 10.04]
## 6      IH-W    25; 195133; 1.46 [0.76, 2.6]
## 7      LA-W   41; 317552; 1.45 [0.83, 2.47]
## 8      SB-W   42; 320874; 1.47 [0.84, 2.47]
## 9      SO-W   71; 505463; 1.58 [0.94, 2.72]
## 10     SW-W   13; 417462; 0.37 [0.18, 0.68]
## 11     TE-W     6; 78912; 0.96 [0.36, 2.04]
## 12     TR-W   78; 699936; 1.24 [0.75, 2.05]
## 13     VB-W   66; 353074; 2.07 [1.23, 3.47]
```

- Below are metrics for model diagnostics- $\hat{R}$ and ESS corresponding to the primary parameters. These models are compiled similarly to the overall data analyses, and the diagnostic metrics can be interpreted following the guidelines provided above.

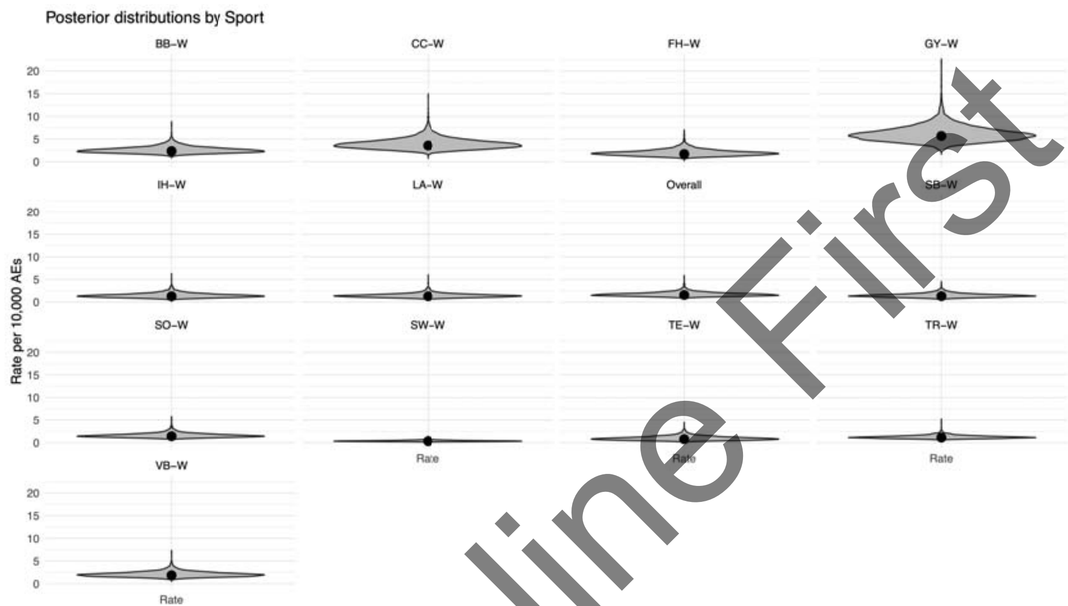
```
##    category std_rate_ESS std_rate_Rhat overdispersion_ESS overdispersion_Rhat
## 1   Overall         1707     1.0017781               2469           0.9995177
## 2      BB-W         1667     1.0017261               2202           0.9999842
## 3      CC-W         2548     1.0005204               2862           0.9997688
## 4      FH-W         2526     1.0006498               2355           1.0005671
## 5      GY-W         2201     1.0012983               2502           1.0009659
## 6      IH-W         2032     1.0000687               2512           0.9996769
## 7      LA-W         2160     1.0039235               2646           1.0013242
## 8      SB-W         2517     0.9999382               2393           1.0003991
## 9      SO-W         1675     1.0001781               2382           0.9999249
## 10     SW-W         2213     1.0044795               3048           0.9997454
## 11     TE-W         2385     1.0001090               2804           0.9996116
## 12     TR-W         1702     1.0000379               2160           0.9995498
## 13     VB-W         2317     1.0009341               2530           1.0002518
```

Posterior Distribution of Practice Injury Counts



Each histogram displays simulated injury counts from the posterior distribution, overlaid with the observed injury count for each sport (figures may be interpreted per the descriptions above regarding the overall rate models).

Posterior Distribution of Practice Injury Rates



Each violin plot shows the posterior distribution of injury rates for each sport, with the observed rate plotted as a solid point (figures may be interpreted per the descriptions above regarding the overall rate models).

Rate comparisons

- A similar approach to what is described above to obtain injury rates via a Bayesian framework can be implemented to compare rates between 2 groups. The underlying premise here would be to conceptualize the effect estimate used to compare the rates as parameter of interest.
- The approach is implemented in this specific analysis, using the Stan program noted below. The data block initializes inputs to the model, specifying injuries and exposures as non-negative values for two separate groups. Subsequently, four parameters of interest are defined within the parameters block to characterize group-specific injury rates. Lambda1 and Lambda2 represent the injury rates for each group as non-negative parameters, modeling the rate of injury per unit of exposure. These parameters follow a broad, Gamma(1, 500) prior (similar to the single-group injury rate model described above) to accommodate a wide range of possible rate values. Similarly, overdispersion parameters for each group are defined and constrained between 0 and 1, using a Beta(5, 100) prior to account for additional variability in the observed data beyond what is expected under a Poisson model. The priors are weakly informative, allowing the observed data to primarily drive the posterior estimates. As with the single-group model, prior specifications were adjusted (e.g., using Cauchy(0, 10)) to improve model performance based on diagnostic results. In the generated quantities block, the posterior distribution of the log rate ratio (logRR) is calculated as the difference in log injury rates between the two groups, providing a natural logarithmic scale for comparison. The corresponding rate ratio (RR) is obtained by exponentiating the log rate ratio, yielding a more interpretable comparison of injury rates between the two groups. This posterior distribution for the rate ratio allows for direct probabilistic statements about the relative injury rates, with credible intervals representing the uncertainty in this estimate driven by both observed data and prior beliefs.

```
data {
  int<lower=0> inj1;  // Injuries in group 1
  real<lower=0> AE1;  // Exposures in group 1
  int<lower=0> inj2;  // Injuries in group 2
  real<lower=0> AE2;  // Exposures in group 2
}

parameters {
  real<lower=0> lambda1; // Injury rate for group 1
  real<lower=0> lambda2; // Injury rate for group 2
  real<lower=0, upper=1> overdispersion1; // Overdispersion for group 1
  real<lower=0, upper=1> overdispersion2; // Overdispersion for group 2
}

model {
  // Priors
  lambda1 ~ gamma(1, 500);
  lambda2 ~ gamma(1, 500);
  overdispersion1 ~ beta(5, 100);
  overdispersion2 ~ beta(5, 100);

  // Negative binomial likelihood for each group
  inj1 ~ neg_binomial_2(lambda1 * AE1, 1 / overdispersion1);
  inj2 ~ neg_binomial_2(lambda2 * AE2, 1 / overdispersion2);
}

generated quantities {
  real logRR = log(lambda1 / lambda2);
  real RR = exp(logRR);
}
```

- The Stan model was fit using the RStan package, with data passed as a list containing total injuries and total exposures. No U-Turn Sampling was conducted with 2000 iterations across four chains to ensure adequate exploration of the parameter space. Posterior distributions were extracted from the model fit to perform predictive checks for model validation.

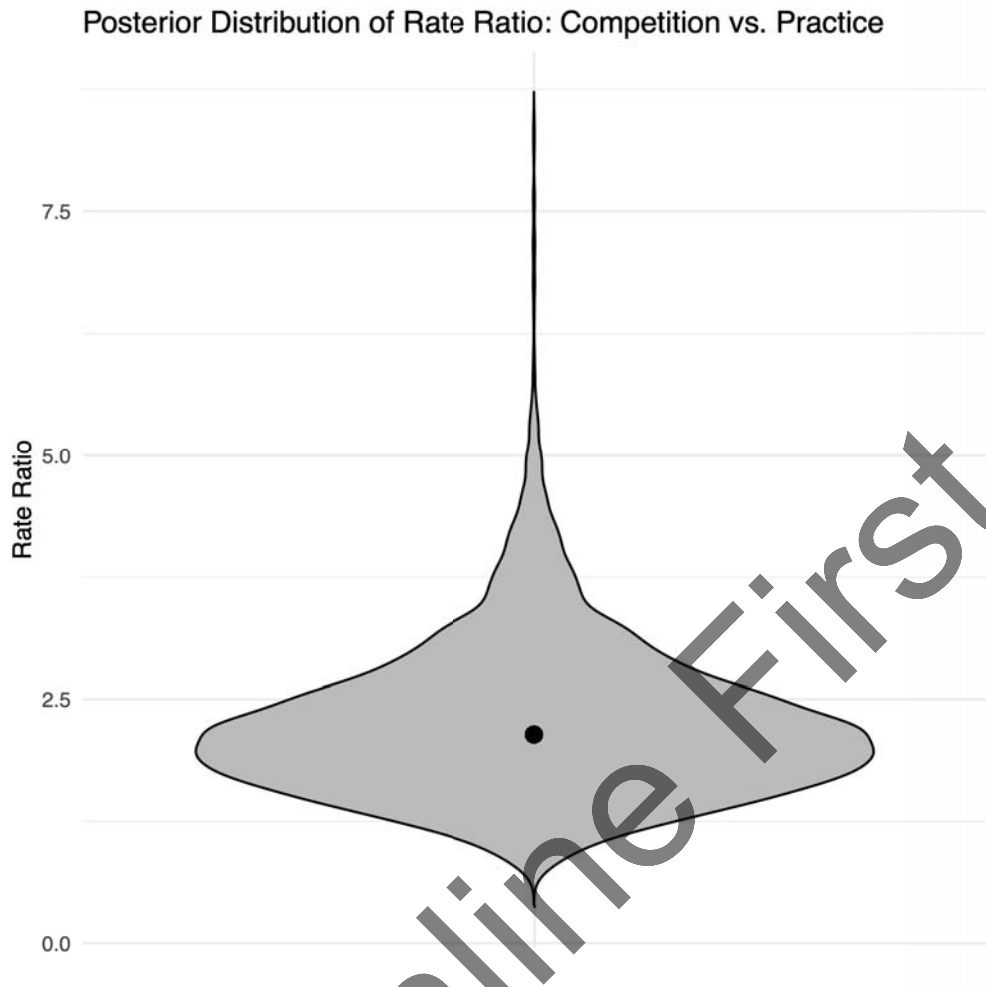
Injury rate ratio: Competition vs. Practice rates: The table here includes estimated posterior mean injury rate ratios and 95% credible intervals from the Stan model described above.

```
##                   IRR
## 1 2.26; [1.09, 4.24]
```

- Model diagnostics, $\hat{R}$ and ESS, for the primary parameters are included below. These models are compiled similarly to the stratified injury rate analyses described above, and the diagnostic metrics can be interpreted following the guidelines provided above as well.

```
##         Parameter     Rhat  ESS
## 1              RR 1.002020 2430
## 2         lambda1 1.002114 2226
## 3         lambda2 1.000289 2635
## 4 overdispersion1 1.000614 3364
## 5 overdispersion2 1.000890 3741
```

Posterior Distribution of Competition vs. Practice Injury Rate Ratio



The violin plot shows the posterior distribution of the injury rate ratio describing differential injury incidence between competitions and practices. The observed rate ratio is plotted as a solid point. It may be noted that individual group-specific injury counts and rates were also extracted for the purposes of model validation, although only the rate ratio plot is displayed here in the interest of presenting the most parsimonious description of the validation process.