



Rethinking sex differences in adolescent sports injuries: Distinguishing injury distribution from per-participant risk

Kong E

Submitted: September 4, 2025, Revised: version 1, December 19, 2025, version 2, February 26, 2026, version 3, March 28, 2026
 Accepted: March 31, 2026

Abstract

Sports-related ankle injuries are often reported to occur more frequently in female adolescents than males, but it remains unclear whether this reflects higher per-participant risk or differences in injury distribution within injured populations. Using 2024 National Electronic Injury Surveillance System data, we analyzed 33,977 sports-related injuries among individuals aged 10–24 years to examine sex differences across developmental stages and to distinguish within-sample injury distribution from participation-adjusted risk. Among adolescents (10–17 years), females had higher adjusted odds that an injury involved the ankle/foot rather than another body region (OR 1.70, 95% CI: 1.58–1.83), whereas this difference was attenuated and non-significant among young adults (18–24 years; OR 1.08, 95% CI: 0.92–1.27). Ankle/foot injuries accounted for a greater proportion of injuries among females in early adolescence (16.4% vs. 8.0%), with convergence by ages 22–24 (12.9% vs. 13.0%). However, participation-normalized analyses indicated comparable ankle injury risk between sexes in early adolescence and lower per-participant risk among females from mid-adolescence onward. These findings demonstrate that widely reported sex differences in ankle injury patterns during adolescence primarily reflect differences in injury distribution within injured samples rather than elevated absolute risk among female athletes. The observed convergence across developmental stages further suggests that these disparities are transient rather than persistent. Distinguishing injury distribution from denominator-based risk is essential for accurate interpretation of sex differences and for designing appropriately targeted prevention strategies.

Keywords

Sports injury epidemiology, Ankle sprain, Sex differences, Adolescent athletes, Injury risk, Injury distribution, Participation normalization, Developmental stages, Musculoskeletal injuries, Youth sports

Ellie Kong, American Heritage Schools, Broward Campus, 12200 W Broward Blvd, Plantation, FL 33325, USA.
elliekgkong@gmail.com

1. Introduction

Sports participation offers numerous physical, mental, and social benefits for youth, such as promoting cardiovascular health, bone density development, psychological resilience, and social connections. However, with these benefits, participation in sports also comes with a heightened risk of injury, particularly during adolescence, a period marked by rapid physical and hormonal changes. Adolescence is a vulnerable period, as young athletes go through major changes in body composition, coordination, and strength, all while participating in intense training and competition.

Among sports-related injuries, those involving the lower extremities are especially common, with the ankle representing one of the most frequently injured anatomical sites across court and field sports (1). National surveillance data indicate that ankle injuries accounted for 17.6% of all sports-related injuries among high school athletes, marking them as the second most common injury site (2), while U.S. epidemiological analyses further demonstrate their substantial incidence and healthcare burden across age groups (3). Injuries to this site can range from minor sprains to severe ligament tears and fractures, with lateral ankle sprains being the most frequent type of ankle injury (1,3). Consensus guidelines emphasize that acute lateral ankle sprains require structured clinical assessment due to their high recurrence risk and potential for chronic sequelae (4). Consensus reviews from the International Ankle Consortium have further highlighted the high prevalence and long-term impact of lateral ankle sprains across athletic populations (5). Beyond

immediate time loss and performance limitations, recurrent sprains may progress to chronic ankle instability, premature joint degeneration, and elevated re-injury risk, with recurrence rates reaching up to 70% in some populations (6-8). The contemporary conceptual model of chronic ankle instability incorporates mechanical insufficiency, sensorimotor deficits, and recurrent injury cycles (9), highlighting multiple pathways through which risk factors may shape injury patterns over time.

While injury prevention efforts have traditionally focused on training load, biomechanics, and conditioning, increasing evidence suggests that biological sex may play an important role in shaping injury patterns, especially during adolescence (10,11). Sex-related physiological differences have been documented in large-scale epidemiological and sport-specific studies over the past two decades, prompting greater attention to how these factors influence injury risk during pubertal development.

Sex-based differences in sports injury patterns were well-established in the literature. Multiple large-scale studies have documented that female athletes, particularly during adolescence, show a higher proportion of ankle and foot injuries compared with males across various sports and competition levels (10-16). Higher proportions or reported incidence have also been reported at the professional and semiprofessional levels (12). The prevalence of chronic ankle instability was similarly higher among females, with rates as high as 23.4% among high school and collegiate athletes (17). Risk factor profiles differed markedly by sex: males showed

increased vulnerability related to prior injuries, higher body mass index, and reduced hip strength or balance, whereas females demonstrated risk primarily linked to lower concentric dorsiflexion strength (15).

Among youth soccer players specifically, female athletes sustained ankle injuries at nearly twice the rate of males, with non-contact ankle injuries occurring at particularly elevated rates (16). These patterns persisted across multiple sports, including basketball, track and field, and volleyball, with injury rates consistently highest during competition rather than practice (18,19). Despite the extensive body of literature documenting sex differences in sports injuries, far less is known about how these disparities change across developmental stages. Prior studies rarely compare early adolescence, mid-adolescence, late adolescence, and young adulthood within the same large-scale surveillance dataset. This developmental perspective represents a critical gap addressed by the present study.

Biological and physiological factors have been proposed as potential contributors to observed sex differences in injury patterns, although causal mechanisms remain uncertain. Sex hormone fluctuations—particularly estrogen, progesterone, and testosterone—affected musculoskeletal development, neuromuscular control, and soft tissue composition. Estrogen had been linked to altered collagen synthesis and increased ligament laxity, potentially elevating joint vulnerability during periods of hormonal flux (7,20,21). Progesterone fluctuated across the menstrual cycle, influencing mood, energy levels, and muscle recovery (6,22). Anatomical

differences, including greater joint laxity, wider pelvic angles, and variations in hip-knee-ankle alignment (Q-angle), may have further modulated the risk of injury (23,24).

Although sex-based disparities in youth and adolescent sports injuries are well established, important questions remain regarding how these patterns evolve across developmental stages. Most existing research examined single sports or individual institutions, potentially limiting generalizability across broader athletic populations. While associations between injury risk and specific physiological factors (Q-angle variations, hormonal fluctuations) have been identified, the extent to which these variables quantitatively explain observed sex differences when examined across developmental stages remains unclear. Furthermore, comprehensive analyses spanning the extended adolescent and young adult years (ages 10–24) using large-scale emergency department surveillance data were limited.

The present study aimed to build upon prior work by delineating how sex disparities in ankle and foot injury risk vary across four developmental stages (10–13, 14–17, 18–21, and 22–24 years) using NEISS 2024 data from a national sample of hospital emergency departments. A secondary objective was to integrate these epidemiological findings with an exploratory ecological analysis of age-related physiological factors, specifically Q-angle and estrogen levels—to examine whether broad developmental physiology may help contextualize the observed injury patterns. This framing represents the primary contribution of the study, distinguishing it from prior work that

focuses on single age groups or single-sport cohorts.

2. Materials and Methods

2.1 Data source

This study used unweighted case-level data from the 2024 National Electronic Injury Surveillance System (NEISS), a surveillance system operated by the U.S. Consumer Product Safety Commission that collects injury data from a stratified probability sample of approximately 100 U.S. hospital emergency departments. Because sample weights were not applied, results reflect injury patterns observed in NEISS-participating hospitals rather than nationally representative estimates. The analysis examined cases involving adolescents and young adults aged 10–24 who sustained product-related injuries in sport or recreational settings. This age range was selected to capture the developmental period spanning pre-adolescence through young adulthood, when participation in competitive sports peaked and sex-based physiological differences were most pronounced.

2.2 Study population

The study population consisted of individuals aged 10–24 years with sports-related injury records identified from the 2024 NEISS dataset. A total of 88,156 unweighted records were initially identified. Records were then restricted to injuries occurring in relevant sports-related settings (recreation/sports facilities, schools, or public property) and to cases with complete data on sex, age, diagnosis, and injury location. Cases with missing sex data, non-sports-related settings, or incomplete injury details were

excluded. After applying these inclusion and exclusion criteria, the final analytic sample comprised 33,977 sports-related injuries.

2.3 Age group classification

Age groups were derived directly from the individual-level patient age variable recorded in the NEISS dataset. Each case was classified into one of four developmental categories based on age at the time of the emergency department visit: 10–13 years ($n = 31,611$), 14–17 years ($n = 31,099$), 18–21 years ($n = 15,858$), and 22–24 years ($n = 9,588$). Age group counts for the initial unfiltered dataset are reported in Table 1. These age categories were selected to align with key developmental transitions in pubertal maturation, competitive sports participation, and physiological development.

2.4 Outcome variables

The primary outcome was ankle and foot injuries, identified using NEISS body part codes. NEISS body part codes were recoded into clinically meaningful categories as follows: internal organs (code 0), head/face/neck (codes 75–94), shoulder/upper trunk (codes 30–31), arm/elbow (codes 32–33), wrist/hand (code 34), knee (code 35), lower leg (code 36), ankle/foot (code 37), and pubic region (code 38). Injury severity was classified using NEISS diagnosis codes: severe injuries (codes 50, 52, 57, 59, 62, 64–70), moderate injuries (codes 53–56, 58, 60–61, 63), burns/thermal injuries (codes 46–49, 51), and ingestion/aspiration (codes 41–42). Injury location was categorized from NEISS location codes: recreation/sports facility (code 9), school/daycare (code 8), public property (codes 4–5), home (code 1),

industrial/workplace (code 7), and farm/mobile home (codes 2, 6).

The primary exposure variable was biological sex, recorded as male or female. Location of injury was categorized as: recreation/sports facility, school/daycare, public property, home, industrial/workplace, farm/mobile home, or other. In the NEISS coding system, a “product” refers to any consumer item or piece of equipment associated with the injury, such as sports gear, athletic footwear, gym flooring, playground equipment, or protective equipment. Product involvement was categorized as single product (only one item associated with injury) or multiple products (two or more items involved in the injury event). Sports-related injuries were defined as cases occurring at recreation/sports facilities, schools/daycare centers, or public property, based on the NEISS location variable. Cases with NEISS body part or diagnosis codes that did not map to the predefined categories were excluded.

2.5 Statistical analysis

Descriptive statistics were used to calculate all the study variables. Categorical variables were presented as frequencies and percentages. Chi-square tests were used to assess differences in the distribution of categorical variables between sexes. To examine sex differences in injury patterns while accounting for potential confounders, three multivariable regression models were constructed: Model 1 (Injury Location): Multinomial logistic regression assessed the association between sex and body part injured (ankle/foot, knee, head/face/neck, shoulder/upper trunk, arm/elbow, wrist/hand, lower leg, internal organs, pubic region),

adjusting for age group and injury location. The reference category for the outcome was ankle/foot injuries. Model 2 (Injury Severity): Multinomial logistic regression was used to examine the association between sex and injury severity (severe, moderate, burns/thermal, and ingestion/aspiration), adjusting for age group and injury location. The reference category for the outcome was severe injuries. Model 3 (Multiple Products): Binary logistic regression was used to evaluate the association between sex and involvement in multiple products, adjusting for age group and injury location.

All models included the following predictor variables: sex (female vs. male, reference), age group (14–17, 18–21, 22–24 vs. 10–13 years, reference), and injury location (school/daycare, public property vs. recreation/sports facility, reference). Results were reported as odds ratios (OR) with 95% confidence intervals (CI) and p-values calculated using likelihood ratio tests. To assess how sex-based injury disparities evolved across developmental stages, all multivariable regression models were repeated separately for two age strata: 10–17 years (adolescents, $n = 27,659$) and 18–24 years (young adults, $n = 6,318$). This stratification allowed direct comparison of sex differences during peak adolescent development versus young adulthood.

All regression models were assessed for multicollinearity using variance inflation factors (VIF). VIF values less than 5.0 were considered acceptable, with values less than 2.0 indicating minimal collinearity. Correlation matrices were generated to visualize pairwise correlations among predictor variables. Model fit was

evaluated using multiple metrics: *Nagelkerke pseudo R²*, *McFadden pseudo R²*, *Akaike Information Criterion (AIC)*, and *Bayesian Information Criterion (BIC)*. Residual diagnostics were performed to identify influential observations and assess model assumptions. All analyses were performed using R version 4.4.1 (R Foundation for Statistical Computing, Vienna, Austria).

2.6 Participation rate normalization

To address potential confounding by age-related differences in sports participation rates, injury counts were also scaled relative to estimated sports participation levels to facilitate comparison across age and sex groups. Population denominators were obtained from U.S. Census Bureau Vintage 2024 population estimates by single year of age and sex (NC-EST2024-AGESEX-RES). Sports participation rates by age group and sex were estimated from published sources: CDC National Health Interview Survey (2020), Sports & Fitness Industry Association participation reports (2024), and National Federation of State High School Associations surveys (2024–25). Estimated participation rates were: males 55% (ages 10–13), 60% (14–17), 35% (18–21), 30% (22–24); females 50% (10–13), 55% (14–17), 25% (18–21), 20% (22–24). Sensitivity analyses were conducted using alternative participation rate assumptions, including those suggested by the reviewer. The estimated number of sports participants in each age-sex stratum was calculated as population $\times$ participation rate, and scaled injury counts relative to estimated participation were computed for total injuries and ankle/foot injuries separately. Participation-normalized analyses were

conducted using a broader sports-location-filtered dataset (N=44,232), prior to exclusion of cases with incomplete covariate or injury classification data used in regression analyses (analytic sample N=33,977).

2.7 Ecological analysis of physiological factors

An exploratory ecological-level analysis was conducted to examine relationships between population-level physiological factors and observed sex differences in ankle injury rates across age groups. Age-stratified ankle injury proportions (injuries per 100 cases) were calculated separately for males and females across four age categories (10–13, 14–17, 18–21, and 22–24 years), yielding eight age-sex strata. Normative reference values for two physiological variables were extracted from published literature: (1) Q-angle measurements by age and sex from Sharma et al. (23), a systematic review of adolescents; and (2) estrogen levels (estradiol, pg/mL) by age and sex from the West Virginia University Health Database reference ranges. These population-level values were correlated with the corresponding age-stratified injury rates using Pearson correlation coefficients. To assess whether the original correlations were confounded by declining participation rates at older ages, the ecological analysis was repeated using participation-scaled injury counts in place of raw injury proportions.

Linear regression models were constructed to quantify the relationship between physiological factors and ankle injury rates in females: Model A: Ankle injury rate $\sim$ Q-angle (female mean), Model B: Ankle injury rate $\sim$ log(estrogen level), and Model C: Ankle injury rate $\sim$ Q-angle

+ log(estrogen level). Standardized regression coefficients were calculated to assess the relative importance of each physiological variable. An attempt was made to “normalize” female injury rates by adjusting for estimated effects of Q-angle and estrogen differences, using the regression coefficients to calculate adjusted rates. However, this ecological-level analysis had inherent limitations, as correlating population averages with aggregate injury rates across only 8 age-sex strata could not establish individual-level causal mechanisms and was subject to ecological fallacy and unmeasured confounding.

3. Results

3.1 Descriptive characteristics

The initial dataset consisted of 88,156 unweighted cases (Table 1). After applying inclusion criteria, the final analytic sample included 33,977 cases used for regression analyses. The initial dataset consisting of 88,156 unweighted cases, was grouped by sex: male and female (Table 1). Age distributions were similar between groups, though younger age brackets were slightly more represented. Among males, 36.3% were aged 10–13 and 36.3% were 14–17, compared to 35.0% and 33.6% of females, respectively. However, females had a higher proportion of older individuals; 19.3% were aged 18–21 and 12.1% were 22–24,

compared to 17.2% and 10.2% of males. Injury location patterns showed clear differences by sex. Ankle and foot injuries made up a larger share of female injuries (11.9%) than male injuries (8.5%). In contrast, males had higher proportions of upper-body injuries, including shoulder and upper trunk (9.7% vs. 6.8%) and arm/elbow injuries (6.9% vs. 5.7%). Head, face, and neck injuries were the most common across both groups, accounting for 56.8% of male and 59.4% of female injuries. Regarding injury severity, severe injuries, such as fractures, dislocations, and internal trauma, were more common among males (60.2%) than females (54.4%). Moderate injuries, including sprains and contusions, showed a similar distribution across sexes (17.1% in males, 17.7% in females). However, burns and thermal injuries were more than 1.5 times as frequent among females (1.6%) compared to males (0.9%). Differences were also observed in the location of injuries. Males were more likely to be injured in recreation or sports facilities (37.3%) than females (27.8%), while females had a higher proportion of injuries at home (19.7% vs. 12.2%). School or daycare injuries were similarly distributed (about 9% in both groups)—product involvement varied by sex. Females were more likely to have injuries involving multiple products (10.5%) compared to males (8.5%). The vast majority of cases across both groups involved a single product (over 89%).

Table 1. Characteristics of sports-related injuries categorized by age group, Sex, injury location, type, severity, incident location, and product involvement

Characteristic, n (%)	Total, N = 88156 ¹	Male, N = 55520 ¹	Female, N = 32636 ¹
Age group, years			
10-13 years	31,611 (35.9%)	20,178 (36.3%)	11,433 (35.0%)
14-17 years	31,099 (35.3%)	20,141 (36.3%)	10,958 (33.6%)

18-21 years	15,858 (18.0%)	9,565 (17.2%)	6,293 (19.3%)
22-24 years	9,588 (10.9%)	5,636 (10.2%)	3,952 (12.1%)
Primary injury location			
Head, face, and neck	50,960 (57.8%)	31,561 (56.8%)	19,399 (59.4%)
Shoulder and upper trunk	7,604 (8.6%)	5,392 (9.7%)	2,212 (6.8%)
Arm and elbow	5,706 (6.5%)	3,846 (6.9%)	1,860 (5.7%)
Wrist and hand	4,529 (5.1%)	3,072 (5.5%)	1,457 (4.5%)
Knee	6,603 (7.5%)	4,074 (7.3%)	2,529 (7.7%)
Lower leg	2,922 (3.3%)	1,994 (3.6%)	928 (2.8%)
Ankle and foot	8,632 (9.8%)	4,744 (8.5%)	3,888 (11.9%)
Internal organs	533 (0.6%)	315 (0.6%)	218 (0.7%)
Pubic region	667 (0.8%)	522 (0.9%)	145 (0.4%)
Other	0 (0.0%)	0 (0.0%)	0 (0.0%)
Injury type and severity			
Severe injuries	51,167 (58.0%)	33,421 (60.2%)	17,746 (54.4%)
Moderate injuries	15,298 (17.4%)	9,513 (17.1%)	5,785 (17.7%)
Burns and thermal injuries	1,032 (1.2%)	522 (0.9%)	510 (1.6%)
Ingestion/Aspiration	511 (0.6%)	301 (0.5%)	210 (0.6%)
Other	20,148 (22.9%)	11,763 (21.2%)	8,385 (25.7%)
Incident location			
Home	13,209 (15.0%)	6,765 (12.2%)	6,444 (19.7%)
Recreation/Sports facility	29,797 (33.8%)	20,719 (37.3%)	9,078 (27.8%)
School/Daycare	8,167 (9.3%)	5,149 (9.3%)	3,018 (9.2%)
Public property	6,268 (7.1%)	4,233 (7.6%)	2,035 (6.2%)
Industrial/Workplace	9 (0.0%)	6 (0.0%)	3 (0.0%)
Farm/Mobile home	63 (0.1%)	30 (0.1%)	33 (0.1%)
Other	30,643 (34.8%)	18,618 (33.5%)	12,025 (36.8%)
Product involvement			
Multiple products involved	8,135 (9.2%)	4,718 (8.5%)	3,417 (10.5%)
Single product involved	80,021 (90.8%)	50,802 (91.5%)	29,219 (89.5%)

¹Values are presented as n(%) unless otherwise specified. Table 1 presents characteristics of the initial unfiltered dataset (N=88,156) prior to application of inclusion criteria

3.2 Age-stratified multivariable regression analyses

Age-stratified analyses revealed important developmental patterns in sex-based injury disparities (Tables 2A and 2B). Among adolescents aged 10–17 years (n=27,659), females had higher adjusted odds that an injury involved the ankle and foot rather than other body regions (OR 1.70, 95% CI: 1.58–1.83, p<0.001; Table 2A). This substantial sex difference was observed alongside elevated odds of knee injuries among females (OR 1.30,

95% CI: 1.18–1.44, p<0.001). Conversely, adolescent females had significantly lower odds of upper-body injuries, including shoulder and upper trunk (OR 0.64, 95% CI: 0.57–0.71, p<0.001), arm and elbow (OR 0.84, 95% CI: 0.76–0.93, p<0.001), and wrist and hand injuries (OR 0.89, 95% CI: 0.80–0.99, p=0.029). Multiple product involvement was less common among adolescent females (OR 0.84, 95% CI: 0.75–0.93, p=0.001). Among young adults aged 18–24 years (n=6,318), the sex-based disparity in ankle and foot injuries was substantially

attenuated and no longer statistically significant (OR 1.08, 95% CI: 0.92–1.27, $p=0.341$; Table 2B). Similarly, the sex difference in knee injuries observed during adolescence was absent in young adults (OR 1.00, 95% CI 0.82–1.22, $p = 0.994$). The pattern of lower odds of upper-body injuries among females persisted into young adulthood, with continued reduced odds for shoulder and upper trunk injuries (OR 0.54, 95% CI 0.44–0.67, $p < 0.001$). Multiple product involvement remained less common among young adult females (OR 0.63, 95% CI: 0.50–0.79, $p<0.001$). These age-stratified findings demonstrated a clear developmental pattern: sex-based disparities in lower extremity injuries, particularly ankle and foot injuries, were most pronounced during early-to-mid adolescence and diminished substantially by young adulthood.

Table 2A. Multivariable Logistic Regression: Sports Injuries (Ages 10-17)

Covariates: Sex, Location Category - NEISS 2024			
Outcome - Injury Location	Covariate	Odds Ratio (95% CI)	P-value
Shoulder and upper trunk	Sex: Female vs Male	0.64 (0.57, 0.71)	<0.001
Shoulder and upper trunk	Location: School/Daycare	0.49 (0.43, 0.56)	<0.001
Shoulder and upper trunk	Location: Public property	0.73 (0.62, 0.86)	<0.001
Arm and elbow	Sex: Female vs Male	0.84 (0.76, 0.93)	<0.001
Arm and elbow	Location: School/Daycare	0.69 (0.62, 0.77)	<0.001
Arm and elbow	Location: Public property	0.98 (0.85, 1.13)	0.749
Wrist and hand	Sex: Female vs Male	0.89 (0.80, 0.99)	0.029
Wrist and hand	Location: School/Daycare	0.65 (0.58, 0.73)	<0.001
Wrist and hand	Location: Public property	0.62 (0.52, 0.74)	<0.001
Knee	Sex: Female vs Male	1.30 (1.18, 1.44)	<0.001
Knee	Location: School/Daycare	0.58 (0.51, 0.65)	<0.001
Knee	Location: Public property	0.74 (0.63, 0.88)	<0.001
Lower leg	Sex: Female vs Male	0.87 (0.76, 1.00)	0.051
Lower leg	Location: School/Daycare	0.49 (0.41, 0.58)	<0.001
Lower leg	Location: Public property	1.05 (0.88, 1.27)	0.575
Ankle and foot	Sex: Female vs Male	1.70 (1.58, 1.83)	<0.001
Ankle and foot	Location: School/Daycare	0.69 (0.63, 0.75)	<0.001
Ankle and foot	Location: Public property	0.37 (0.31, 0.44)	<0.001
Internal organs	Sex: Female vs Male	1.49 (0.91, 2.45)	0.114
Internal organs	Location: School/Daycare	13.19 (6.19, 28.08)	<0.001
Internal organs	Location: Public property	10.48 (4.39, 25.02)	<0.001
Pubic region	Sex: Female vs Male	1.09 (0.63, 1.88)	0.751
Pubic region	Location: School/Daycare	0.24 (0.09, 0.68)	0.007
Pubic region	Location: Public property	2.34 (1.31, 4.18)	0.004
Injury Severity			
Moderate injuries	Sex: Female vs Male	1.01 (0.95, 1.08)	0.747
Moderate injuries	Location: School/Daycare	1.11 (1.03, 1.19)	0.008
Moderate injuries	Location: Public property	1.89 (1.73, 2.07)	<0.001
Burns and thermal injuries	Sex: Female vs Male	0.96 (0.53, 1.74)	0.904
Burns and thermal injuries	Location: School/Daycare	4.18 (2.18, 8.02)	<0.001
Burns and thermal injuries	Location: Public property	7.76 (3.83, 15.72)	<0.001
Ingestion/Aspiration	Sex: Female vs Male	1.52 (0.92, 2.51)	0.101

Ingestion/Aspiration	Location: School/Daycare	22.25 (9.46, 52.32)	<0.001
Ingestion/Aspiration	Location: Public property	19.41 (7.45, 50.56)	<0.001
Product Involvement			
Multiple products involved	Sex: Female vs Male	0.84 (0.75, 0.93)	0.001

Note: OR>1.0; higher odds compared to reference; <1.0: lower odds compared to reference. Reference groups: Male, Recreation/Sports facility. N=27659

Table 2B. Multivariable Logistic Regression: Sports Injuries (Ages 18-24)

Covariates: Sex, Location Category - NEISS 2024			
Outcome - Injury Location	Covariate	Odds Ratio (95% CI)	P-value
Shoulder and upper trunk	Sex: Female vs Male	0.54 (0.44, 0.67)	<0.001
Shoulder and upper trunk	Location: School/Daycare	0.45 (0.29, 0.69)	<0.001
Shoulder and upper trunk	Location: Public property	0.52 (0.43, 0.63)	<0.001
Arm and elbow	Sex: Female vs Male	0.82 (0.62, 1.08)	0.162
Arm and elbow	Location: School/Daycare	0.87 (0.48, 1.57)	0.647
Arm and elbow	Location: Public property	1.44 (1.11, 1.86)	0.005
Wrist and hand	Sex: Female vs Male	0.86 (0.64, 1.15)	0.313
Wrist and hand	Location: School/Daycare	0.53 (0.28, 1.03)	0.061
Wrist and hand	Location: Public property	0.75 (0.57, 0.98)	0.037
Knee	Sex: Female vs Male	1.00 (0.82, 1.22)	0.994
Knee	Location: School/Daycare	0.48 (0.30, 0.76)	0.002
Knee	Location: Public property	0.67 (0.55, 0.82)	<0.001
Lower leg	Sex: Female vs Male	0.97 (0.72, 1.30)	0.836
Lower leg	Location: School/Daycare	0.64 (0.33, 1.24)	0.19
Lower leg	Location: Public property	0.96 (0.73, 1.27)	0.78
Ankle and foot	Sex: Female vs Male	1.08 (0.92, 1.27)	0.341
Ankle and foot	Location: School/Daycare	0.68 (0.50, 0.92)	0.013
Ankle and foot	Location: Public property	0.31 (0.26, 0.38)	<0.001
Internal organs	Sex: Female vs Male	1.01 (0.40, 2.51)	0.989
Internal organs	Location: Public property	26.96 (3.61, 201.53)	0.001
Pubic region	Sex: Female vs Male	0.58 (0.19, 1.76)	0.338
Pubic region	Location: School/Daycare	1.73 (0.37, 7.98)	0.485
Pubic region	Location: Public property	0.97 (0.37, 2.56)	0.95
Injury Severity			
Moderate injuries	Sex: Female vs Male	0.89 (0.78, 1.01)	0.07
Moderate injuries	Location: School/Daycare	0.92 (0.70, 1.21)	0.547
Moderate injuries	Location: Public property	1.56 (1.38, 1.76)	<0.001
Burns and thermal injuries	Sex: Female vs Male	1.54 (0.83, 2.83)	0.168
Burns and thermal injuries	Location: School/Daycare	13.08 (5.19, 32.97)	<0.001
Burns and thermal injuries	Location: Public property	5.61 (2.51, 12.53)	<0.001
Ingestion/Aspiration	Sex: Female vs Male	0.88 (0.33, 2.29)	0.786
Ingestion/Aspiration	Location: School/Daycare	0.00 (0.00, 0.00)	<0.001
Product Involvement			
Multiple products involved	Sex: Female vs Male	0.63 (0.50, 0.79)	<0.001
Multiple products involved	Location: School/Daycare	0.30 (0.21, 0.42)	<0.001
Multiple products involved	Location: Public property	0.72 (0.57, 0.92)	0.009

Note: OR>1.0: higher odds compared to reference; <1.0: lower odds compared to reference. Reference groups: Male, Recreation/Sports facility, N=6318. Both tables (2A and 2B) present results from multivariable logistic regression models examining sports-related injuries categorized by age group. Models include sex and location categories as covariates. Reference groups are Male and Recreation/Sports facilities.

It is important to note that these odds ratios reflect within-sample comparisons—that is, among individuals who presented to the emergency department, the relative odds of having an ankle injury versus other injury types. They do not directly estimate per-participant injury risk, which requires external denominator data (see Participation-Normalized Analysis below).

3.3 Injury patterns categorized by age and sex
Visual analysis of injury location patterns by age group and sex (Figure 1) confirmed these

developmental trends. Among the most common injury locations in sports, ankle and foot injuries were significantly more common among females, especially during early adolescence. However, the sex gap in this category narrowed gradually with age, consistent with the regression analyses, which showed convergence during late adolescence and early adulthood. For shoulder and upper trunk injuries, males consistently showed higher percentages across all age groups, with the gap widening steadily as age increased.

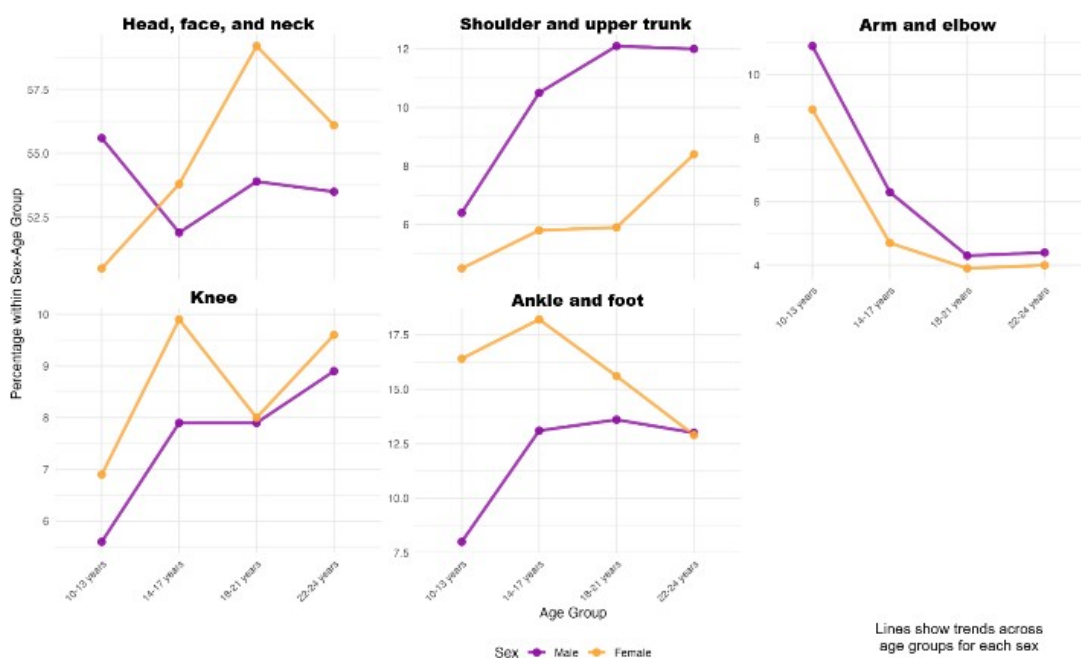


Figure 1. Injury location patterns by age group and sex. Top five most common injury locations in sports.

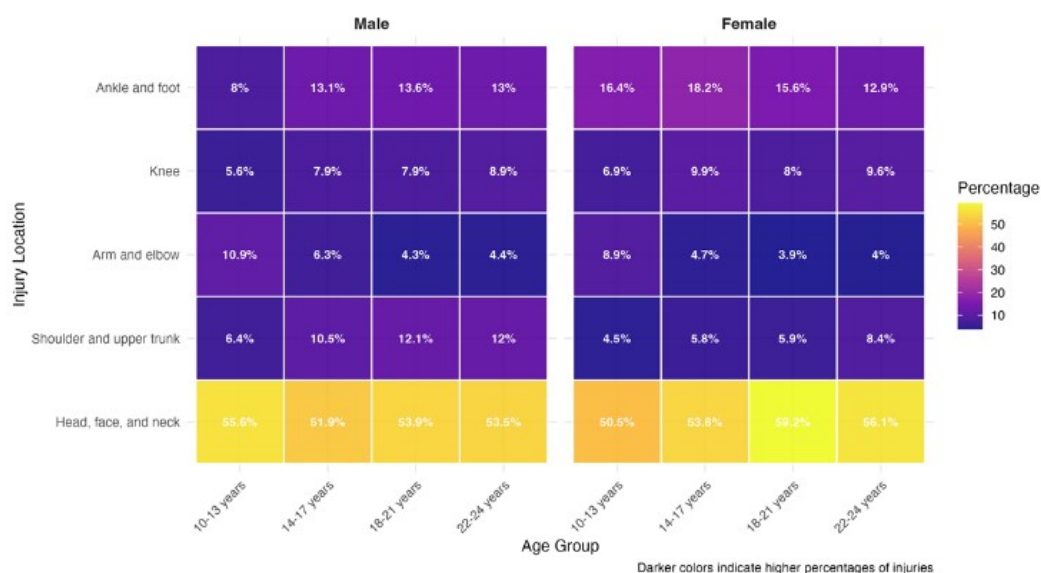


Figure 2. Injury location heatmap categorized by age group and sex. Percentage of injuries categorized by body part within each age-sex group.

Heat map visualization (Figure 2) further highlighted these patterns. Among 10–13-year-olds, 16.4% of female injuries involved the ankle and foot, compared with 8.0% of male injuries. This pattern persisted but attenuated in older groups: 18.2% vs. 13.1% (ages 14–17), 15.6% vs. 13.6% (ages 18–21), and 12.9% vs. 13.0% (ages 22–24), where the sex difference essentially disappeared. These findings indicate that ankle and foot injuries accounted for a larger proportion of female injuries during early and mid-adolescence, with convergence by young adulthood.

3.4 Participation-normalized injury analysis

To address the possibility that raw injury count declines with age reflected declining sports

participation rates rather than reduced per-athlete risk, ankle injury rates were normalized per 100 estimated sports participants (Figure 3, Table 3, Supplementary Figure S1). Among females, the participation-normalized ankle injury rate (scaled relative to estimated participation) was 0.020 at ages 10–13, 0.019 at ages 14–17, 0.011 at ages 18–21, and 0.008 at ages 22–24, representing a 62% decline from youngest to oldest age group. This decline was consistent across all sensitivity analyses using alternative participation rate assumptions (range: 54–66% decline). Among males, the normalized ankle rate was 0.019 at ages 10–13, 0.027 at ages 14–17, 0.016 at ages 18–21, and 0.011 at ages 22–24.

Table 3. Participation-normalized ankle injury rates categorized by age group and sex

Age Group	10-13	10-13	14-17	14-17	18-21	18-21	22-24	22-24
Sex	<i>F</i>	<i>M</i>	<i>F</i>	<i>M</i>	<i>F</i>	<i>M</i>	<i>F</i>	<i>M</i>
Total Injuries	5,609	11,571	5,796	12,404	1,846	4,089	880	2,037
Ankle Injuries	804	902	922	1,472	237	499	100	222
Ankle % of Injuries	14.3	7.8	15.9	11.9	12.8	12.2	11.4	10.9
Population	8,115,509	8,513,211	8,635,655	9,071,359	8,728,593	9,147,391	6,604,426	6,882,771
Participation Rate, Primary assumptions	0.5	0.55	0.55	0.6	0.25	0.35	0.2	0.3
Participation Rate, Reviewer assumptions	0.61	0.61	0.56	0.56	0.25	0.25	0.25	0.25
Est. Participants, Primary assumptions	4,057,754	4,682,266	4,749,610	5,442,815	2,182,148	3,201,587	1,320,885	2,064,831
Est. Participants, Reviewer assumptions	4,950,460	5,193,059	4,835,967	5,079,961	2,182,148	2,286,848	1,651,106	1,720,693
Total Rate per 100	0.14	0.25	0.12	0.23	0.08	0.13	0.07	0.1
Ankle Rate per 100	0.02	0.02	0.02	0.03	0.01	0.02	0.01	0.01
Total Rate per 100 (R)	0.11	0.22	0.12	0.24	0.08	0.18	0.05	0.12
Ankle Rate per 100 (R)	0.02	0.02	0.02	0.03	0.01	0.02	0.01	0.01

Note: This table presents ankle injury counts and scaled injury counts relative to estimated sports participation levels for females and males across four age groups (10–13, 14–17, 18–21, 22–24 years). Columns include total sports-related injuries (sports-location-filtered NEISS cases), ankle injury counts, ankle injuries as a percentage of all injuries, U.S. Census 2024 population estimates, estimated sports participation rates (proportion of population), estimated number of sports participants, and the resulting total and ankle scaled injury rates per 100 participants. Counts are based on sports-location-filtered cases prior to application of full analytic inclusion criteria. Rates are reported under both primary participation rate assumptions and reviewer-suggested assumptions (rows marked 'R'). Population data are from U.S. Census Bureau Vintage 2024 estimates (NC-EST2024-AGESEX-RES). Participation rates are estimated from CDC NHIS 2020, SFIA 2024, and NFHS 2024–25 surveys.

The female-to-male ratio of participation-normalized ankle injury rates was ~ 1.03 at ages 10–13, indicating near parity, and declined below 1.0 from mid-adolescence onward (0.72 at ages 14–17; ~ 0.70 at ages 18–24). Thus, on a per-participant basis, females had comparable ankle injury risk to males in early adolescence, whereas males had higher per-participant ankle injury rates from mid-adolescence onward. In contrast, ankle injuries accounted for a greater proportion of injuries among females across most age groups, indicating that the regression and descriptive findings reflect differences in injury distribution within the injured sample rather than elevated absolute ankle injury risk among females. These participation-normalized findings underscore the importance of distinguishing injury distribution from per-participant risk when interpreting sex differences across developmental stages.

Figure 3: Participation-Normalized Injury Analysis

Comparing raw counts vs. rate per 100 sports participants

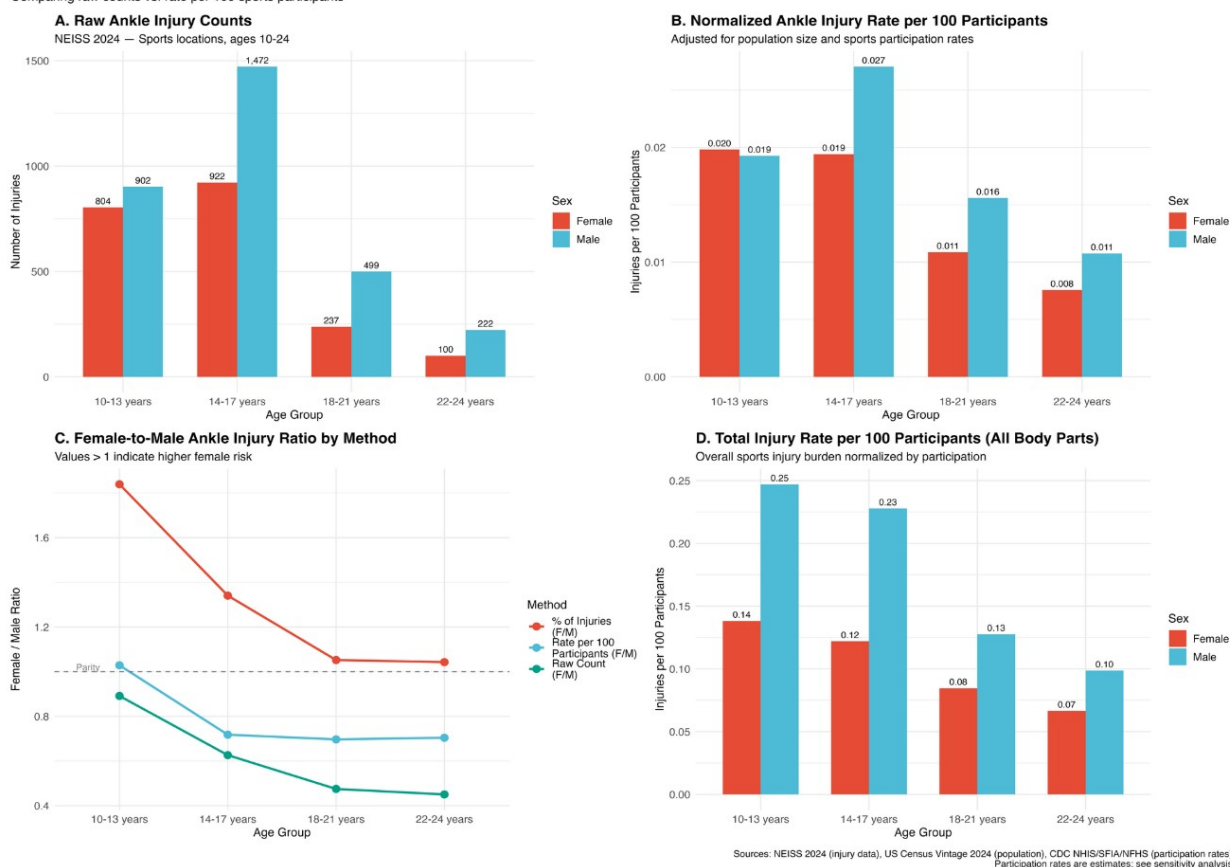


Figure 3. Participation-Normalized Injury Analysis. Four-panel figure comparing raw counts, normalized scaled injury rates per 100 participants, sex ratios by method, and total injury rates. Note: Panel A shows raw ankle injury counts by age group and sex. Panel B shows ankle injury counts scaled relative to estimated sports participation levels. Panel C shows female-to-male sex ratios based on raw counts, participation-scaled counts, and percentage of injuries. Panel D shows total sports injury counts scaled relative to estimated participation levels. Because NEISS provides unweighted sample counts rather than national injury totals, the scaled values should be interpreted as relative comparisons rather than incidence rates.

3.4.1 Exploratory analysis of physiological mechanisms

An exploratory ecological analysis examined age-group-level patterns between population-average physiological factors (Q-angle and estrogen levels) and female ankle injury rates across four age strata (Table 4). Because these analyses were based on only four aggregated age

groups, they are descriptive only and are not suitable for formal statistical inference.

Across the four age groups, both Q-angle and estrogen showed inverse ecological correlations with female ankle injury rates (both $r = -0.635$). When participation-normalized rates were examined, the inverse correlations were stronger (Q-angle: $r = -0.971$; estrogen: $r = -0.968$).

However, because these estimates were derived from only four aggregated age groups, they are unstable and should be interpreted descriptively rather than inferentially.

Table 4. An exploratory ecological-level analysis examined relationships between population-level physiological factors (Q-angle, estrogen levels) and age-stratified ankle injury rates in females.

Factor	r (Raw)	p (Raw)	r (Normalized)	p (Normalized)
<i>Q-angle</i>	-0.635	0.3652	-0.971	0.0290
<i>Estrogen</i>	-0.635	0.3653	-0.968	0.0319

Note: Pearson correlation coefficients (r) and associated p-values for each factor (reported for completeness, not inferential validity). Raw correlations are computed across 8 age-sex strata (4 age groups $\times$ 2 sexes) using ankle injury percentages among all sports-related injuries. Normalized correlations use participation-normalized ankle injury rates (per 100 estimated sports participants) across 4 female-only age strata. Hence, raw and normalized correlations are not directly comparable due to differing sample structures. Q-angle reference values from Sharma et al. (2023); estrogen (estradiol, pg/mL) reference values from West Virginia University Health Database. Regression analyses yielded negative coefficients for both variables (Q-angle: -0.91% per degree, 95% CI: $[-4.28, 2.46]$; estrogen: -2.36% per log-unit, 95% CI: $[-11.92, 7.21]$). Sex difference adjustments: raw female–male difference = 5.47 pp; after Q-angle adjustment = 6.99 pp; after estrogen adjustment = 10.82 pp; after combined adjustment = 12.34 pp. Negative variance explained values (Q-angle: -27.9% ; combined: -125.8%) indicate that physiological adjustment paradoxically increased the sex difference, consistent with ecological confounding by age. * $p < 0.05$.

Overall, age groups with higher average Q-angle and estrogen levels tended to have lower female ankle injury rates, and a similar inverse pattern was observed when injury rates were normalized per 100 estimated sports participants (Supplementary Figures S2 and S3). These aggregate-level findings run counter to individual-level mechanistic hypotheses and should not be interpreted as evidence that higher Q-angle or estrogen is protective against ankle injury.

The most likely explanation for these inverse ecological patterns is age-related confounding. Q-angle and estrogen generally increase across female development, whereas ankle injury rates may decline across later adolescence and young adulthood because of neuromuscular maturation, training adaptation, and sport-

specific skill development. As a result, age-group-level comparisons may produce associations that do not reflect individual-level causal relationships.

Accordingly, this ecological analysis should be interpreted as descriptive and hypothesis-generating only. These findings illustrate the limitations of surveillance-based aggregate analyses for evaluating physiological mechanisms and underscore the need for prospective studies with individual-level physiological measurements, exposure data, and longitudinal follow-up.

4. Discussion

This study examined sex differences in sports-related injury patterns among youth aged 10–24 years using unweighted NEISS 2024 data from

a national sample of hospital emergency departments, with a particular focus on ankle and foot injuries across developmental stages. The analysis revealed a developmental pattern in injury distribution: among adolescents aged 10–17 years, females had higher adjusted odds than males that an injury involved the ankle/foot rather than another body region, whereas this difference was attenuated and no longer statistically significant among young adults aged 18–24 years. Consistently, ankle/foot injuries accounted for a greater proportion of injuries among females during early and mid-adolescence, with convergence by young adulthood. This developmental convergence represents the study's primary empirical contribution.

Importantly, participation-normalized analyses indicate that this pattern should not be interpreted as elevated absolute ankle injury risk among females. After scaling injury counts relative to estimated sports participation levels, females had ankle injury values comparable to males at ages 10–13 and lower than males from mid-adolescence onward. Thus, while ankle/foot injuries represented a larger share of injuries among adolescent females within the ED injury sample, the available denominator-based analyses do not support higher per-participant ankle injury risk among females. Together, these findings indicate that observed sex differences vary across developmental stages and primarily reflect injury distribution rather than female-specific biological susceptibility.

These findings suggest a more nuanced interpretation than prior frameworks that

implied greater female vulnerability. The pronounced adolescent pattern may reflect differences in injury distribution within the injured sample rather than uniformly elevated absolute risk. Although hormonal, anatomical, and neuromuscular mechanisms have been proposed, the present analyses do not permit causal inference regarding these factors. The convergence observed by young adulthood, together with participation-normalized findings showing comparable or lower female per-participant ankle injury rates, suggests substantial developmental convergence. This pattern supports prevention strategies that are developmentally targeted rather than based on assumptions of persistent female-specific susceptibility.

The convergence in the distribution of ankle/foot injuries by young adulthood, together with participation-normalized findings showing comparable or lower female per-participant ankle injury rates, suggests substantial developmental convergence by early adulthood. These findings indicate that the sex differences observed during adolescence are not fixed and support developmentally targeted prevention strategies, particularly during adolescence when differences in injury distribution are most pronounced. Neuromuscular and balance-based training programs have previously demonstrated efficacy in reducing ankle sprain incidence among high school athletes (25). Although participation-normalized analyses suggest comparable or lower per-participant ankle injury rates among females in young adulthood, ankle injuries remain common in both sexes, indicating that preventive strategies should continue beyond adolescence.

Beyond ankle and foot injuries, the analysis also suggested broader anatomical patterning in injury distribution. Females had higher odds of knee injuries during adolescence, with this difference attenuating by young adulthood. In contrast, females had lower odds than males of injuries involving upper-body regions, including the shoulder and upper trunk, arm and elbow, and wrist and hand, across both age strata. Together, these findings suggest that sex-based differences were anatomically specific rather than indicative of a generalized increase in injury susceptibility. The concentration of lower-extremity injuries among females during adolescence, alongside lower representation of upper-body injuries, may reflect differences in sport participation patterns, movement demands, or injury mechanisms.

Females were also less likely than males to sustain injuries involving multiple products, which may reflect differences in participation patterns, injury mechanisms, or environmental exposures.

This study had several important limitations. First, this study used unweighted NEISS data, which reflects injury patterns in sampled hospitals but does not produce nationally representative population-based estimates. Second, NEISS was a surveillance system designed for injury monitoring rather than etiological research. It lacked detailed information about individual-level exposures, training characteristics, playing time, sport-specific positions, skill levels, prior injury history, and individual physiological measurements. The inability to account for these factors limited the ability to draw causal

inferences about specific mechanisms underlying observed patterns. Third, the ecological-level analysis of Q-angle and estrogen effects was constrained by the use of population-average values from published literature rather than individual-level measurements, the small number of age-sex strata providing limited statistical power, and the inherent ecological fallacy problem, whereby aggregate-level associations did not establish individual-level causation. The negative correlations and paradoxical normalization results underscore these limitations rather than indicating the protective effects of these physiological factors. Fourth, Q-angle normative data were derived from a study of adolescents with short stature, which may limit their generalizability to broader athletic populations. Fifth, the participation-scaled analysis relied on estimated participation rates from published surveys rather than directly measured denominators for the NEISS catchment population. Participation rates vary by data source and methodology; sensitivity analyses using multiple assumptions were conducted to assess robustness. Sixth, NEISS recorded only emergency department visits, potentially underrepresenting less severe injuries treated in other settings and introducing selection bias toward more acute or severe injury presentations. Seventh, the cross-sectional design precluded assessment of within-individual changes in injury risk over developmental stages or evaluation of longitudinal risk trajectories. Eighth, detailed information about menstrual cycle phase, hormonal contraceptive use, pubertal stage, and other potentially relevant physiological variables was unavailable in NEISS data.

Finally, the analysis could not distinguish between contact and non-contact injury mechanisms, account for differences in training load or competition intensity across age groups and sexes, or assess the influence of sport-specific factors, coaching quality, or environmental conditions. These unmeasured confounders may have influenced observed associations and limited the specificity of conclusions about underlying mechanisms.

5. Conclusion

This analysis of sports-related injuries in NEISS-participating hospitals indicates that sex differences in ankle/foot injuries are largely developmental and primarily reflect injury distribution rather than elevated absolute per-participant risk among females. During adolescence, ankle/foot injuries accounted for a greater proportion of injuries among females than among males, but this difference converged by young adulthood. Participation-scaled analyses further indicated comparable per-participant ankle injury rates in early

adolescence and lower female per-participant ankle injury rates from mid-adolescence onward.

Together, these findings underscore the importance of distinguishing within-sample injury distribution from denominator-based absolute risk when interpreting sex differences in sports injuries. The observed developmental pattern suggests that differences during adolescence are not fixed and supports developmentally targeted prevention strategies during this period, when differences in injury distribution are most pronounced.

Exploratory ecological analyses of Q-angle and estrogen yielded inverse age-group-level associations consistent with ecological confounding by age rather than causal relationships. These findings further highlight the limitations of surveillance data for establishing individual-level mechanisms and underscore the need for studies incorporating individual-level physiological and exposure data.

Data availability

All analysis scripts are available in a public GitHub repository at <https://github.com/elliegkong/NEISS>. This study utilized de-identified, publicly available surveillance data and was exempt from institutional review board approval since NEISS data contain no direct patient identifiers and are collected as part of routine public health surveillance activities.

6. References

1. Fong, D. T., Hong, Y., Chan, L. K., Yung, P. S., Chan, K. M. (2007). A systematic review on ankle injury and ankle sprain in sports. *Sports Med*, 37(1), 73-94.
<https://doi.org/10.2165/00007256-200737010-00006>

2. Caldwell, K., Houlihan, N., Whitfield, T., Williams, B. A. (2022). Track and Field Injuries in Children and Adolescents Presenting to us Emergency Departments-An Updated Review of the National Electronic Injury Surveillance System. *Orthopaedic Journal of Sports Medicine*, 10(5_suppl2), 2325967121S2325900536. <https://doi.org/10.1177/2325967121s00536>
3. Waterman, B. R., Owens, B. D., Davey, S., Zacchilli, M. A., Belmont, P. J., Jr. (2010). The epidemiology of ankle sprains in the United States. *J Bone Joint Surg Am*, 92(13), 2279-2284. <https://doi.org/10.2106/jbjs.I.01537>
4. Delahunt, E., Bleakley, C. M., Bossard, D. S., Caulfield, B. M., Docherty, C. L., Doherty, C., et al. (2018). Clinical assessment of acute lateral ankle sprain injuries (ROAST): 2019 consensus statement and recommendations of the International Ankle Consortium. *Br J Sports Med*, 52(20), 1304-1310. <https://doi.org/10.1136/bjsports-2017-098885>
5. Gribble, P. A., Bleakley, C. M., Caulfield, B. M., Docherty, C. L., Fourchet, F., Fong, D. T., et al. (2016). Evidence review for the 2016 International Ankle Consortium consensus statement on the prevalence, impact and long-term consequences of lateral ankle sprains. *Br J Sports Med*, 50(24), 1496-1505. <https://doi.org/10.1136/bjsports-2016-096189>
6. Carmichael, M. A., Thomson, R. L., Moran, L. J., Wycherley, T. P. (2021). The Impact of Menstrual Cycle Phase on Athletes' Performance: A Narrative Review. *International Journal of Environmental Research and Public Health*, 18(4), 1667. <https://doi.org/10.3390/ijerph18041667>
7. Chidi-Ogbolu, N., Baar, K. (2019). Effect of Estrogen on Musculoskeletal Performance and Injury Risk [Review]. *Frontiers in Physiology*, Volume 9 - 2018. <https://www.frontiersin.org/journals/physiology/articles/10.3389/fphys.2018.01834>
8. Attenborough, A. S., Hiller, C. E., Smith, R. M., Stuelcken, M., Greene, A., Sinclair, P. J. (2014). Chronic Ankle Instability in Sporting Populations. *Sports Medicine*, 44(11), 1545-1556. <https://doi.org/10.1007/s40279-014-0218-2>
9. Hiller, C. E., Kilbreath, S. L., Refshauge, K. M. (2011). Chronic ankle instability: evolution of the model. *J Athl Train*, 46(2), 133-141. <https://doi.org/10.4085/1062-6050-46.2.133>
10. Brant, J. A., Johnson, B., Brou, L., Comstock, R. D., Vu, T. (2019). Rates and Patterns of Lower Extremity Sports Injuries in All Gender-Comparable US High School Sports. *Orthop J Sports Med*, 7(10), 2325967119873059. <https://doi.org/10.1177/2325967119873059>

11. Bunstine, J. L., Yang, J., Kistamgari, S., Collins, C. L., Smith, G. A. (2024). Differences in Overuse Injuries in Gender-Comparable Sports: A Nationally Representative Sample of High School Athletes. *J Athl Train*, 59(9), 962-968. <https://doi.org/10.4085/1062-6050-0040.23>
12. Doherty, C., Delahunt, E., Caulfield, B., Hertel, J., Ryan, J., Bleakley, C. (2014). The Incidence and Prevalence of Ankle Sprain Injury: A Systematic Review and Meta-Analysis of Prospective Epidemiological Studies. *Sports Medicine*, 44(1), 123-140. <https://doi.org/10.1007/s40279-013-0102-5>
13. Emery, C. A., Tyreman, H. (2009). Sport participation, sport injury, risk factors and sport safety practices in Calgary and area junior high schools. *Paediatrics & Child Health*, 14(7), 439-444. <https://doi.org/10.1093/pch/14.7.439>
14. Swenson, D. M., Collins, C. L., Fields, S. K., Comstock, R. D. (2013). Epidemiology of U.S. high school sports-related ligamentous ankle injuries, 2005/06-2010/11. *Clin J Sport Med*, 23(3), 190-196. <https://doi.org/10.1097/JSM.0b013e31827d21fe>
15. Fernandez, W. G., Yard, E. E., Comstock, R. D. (2007). Epidemiology of lower extremity injuries among U.S. high school athletes. *Acad Emerg Med*, 14(7), 641-645. <https://doi.org/10.1197/j.aem.2007.03.1354>
16. Sun, L., Luo, L., Yang, Y., Wangchuan, Q., Luo, J. (2025). Gender Differences in the Incidence and Types of Sports Injuries Among Female Athletes: A Scoping Review. *J Nurs Manag*, 2025, 6416101. <https://doi.org/10.1155/jonm/6416101>
17. Ericksen, H., Gribble, P. A. (2012). Sex Differences, Hormone Fluctuations, Ankle Stability, and Dynamic Postural Control. *Journal of Athletic Training*, 47(2), 143-148. <https://doi.org/10.4085/1062-6050-47.2.143>
18. John, G., AlNadwi, A., Georges Abi Antoun, T., Ahmetov, II. (2025). Injury Prevention Strategies in Female Football Players: Addressing Sex-Specific Risks. *Sports (Basel)*, 13(2). <https://doi.org/10.3390/sports13020039>
19. Pizzarro, J. N., Chiang, B. J. L., Monroig-Rivera, C. A., Mehran, N., Tabaie, S. (2024). Epidemiology of Sports Injuries Among High School Athletes in the United States: Data From 2015 to 2019. *Orthopaedic Journal of Sports Medicine*, 12(5), 23259671241252637. <https://doi.org/10.1177/23259671241252637>

20. Wojtys, E. M., Huston, L. J., Lindenfeld, T. N., Hewett, T. E., Greenfield, M. L. (1998). Association between the menstrual cycle and anterior cruciate ligament injuries in female athletes. *Am J Sports Med*, 26(5), 614-619. <https://doi.org/10.1177/03635465980260050301>
21. Hansen, M., Kongsgaard, M., Holm, L., Skovgaard, D., Magnusson, S. P., Qvortrup, K., et al. (2009). Effect of estrogen on tendon collagen synthesis, tendon structural characteristics, and biomechanical properties in postmenopausal women. *J Appl Physiol* (1985), 106(4), 1385-1393. <https://doi.org/10.1152/jappphysiol.90935.2008>
22. Romero-Moraleda, B., Morencos-Martínez, E., Varón, P., Lara, B., Jiménez-Ormeño, E., Peinado, A. B., González-García, J. (2025). The influence of menstrual cycle phase on neuromuscular performance and subjective perception of effort in elite football players. *Biol Sport*, 42(3), 89-98. <https://doi.org/10.5114/biolSport.2025.146781>
23. Sharma, R., Khorwal, G., Vaibhav, V., Singh, B., Meshram, R. (2023). Quadriceps Angle Measurement in Adolescents With Short Stature: Exploring the Relationship Between Postural Alignment and Lower Limb Mechanics. *Cureus*, 15(8), e43953. <https://doi.org/10.7759/cureus.43953>
24. Shultz, S. J., Sander, T. C., Kirk, S. E., Perrin, D. H. (2005). Sex differences in knee joint laxity change across the female menstrual cycle. *J Sports Med Phys Fitness*, 45(4), 594-603.
25. McGuine, T. A., Keene, J. S. (2006). The effect of a balance training program on the risk of ankle sprains in high school athletes. *Am J Sports Med*, 34(7), 1103-1111. <https://doi.org/10.1177/0363546505284191>

Supplemental material

Supplementary Table S1. Female-to-male sex ratio comparison across normalization methods

Age Group	Ankle Injuries (Female)	Ankle Injuries (Male)	Raw Count Ratio (F/M)	Normalized Rate Ratio (F/M)	Normalized Rate Ratio (F/M, Reviewer)	% of Injuries Ratio (F/M)
10-13	804	902	0.89	1.03	0.94	1.84
14-17	922	1,472	0.63	0.72	0.66	1.34
18-21	237	499	0.47	0.70	0.50	1.05
22-24	100	222	0.45	0.70	0.47	1.04

Note: Female-to-male ratios of ankle injury metrics across four age groups. Raw Count Ratio = female ankle injury count / male ankle injury count. Normalized Rate Ratio = female ankle rate per 100 participants / male ankle scaled injury rate per 100 participants (primary assumptions and reviewer assumptions). % of Injuries Ratio = female ankle-as-percentage-of-all-injuries / male ankle-as-percentage-of-all-injuries. A ratio > 1.0 indicates higher female

values; < 1.0 indicates higher male values. The raw count and normalized rate ratios are consistently < 1.0 from ages 14 onward, indicating males have more absolute ankle injuries and higher per-participant rates. However, the % of injuries ratio remains > 1.0 across all age groups (declining from 1.84 to 1.04), confirming that ankle injuries constitute a disproportionately larger share of female injuries, consistent with the within-sample regression findings.

Supplementary Table S2. Sensitivity analysis of participation rate assumptions on female ankle injury rates (per 100 participants)

Scenario	Ages 10–13	Ages 14–17	Ages 18–21	Ages 22–24	% Change (10–13 to 22–24)
Primary	0.0198	0.0194	0.0109	0.0076	-61.8%
Reviewer	0.0162	0.0191	0.0109	0.0061	-62.7%
High female	0.0180	0.0178	0.0091	0.0061	-66.4%
Low female	0.0220	0.0214	0.0136	0.0101	-54.1%

Note: Female ankle scaled injury rates per 100 estimated sports participants under four participation rate scenarios. Primary: 50%/55%/25%/20% for ages 10–13/14–17/18–21/22–24. Reviewer: 61%/56%/25%/25% (derived from reviewer’s suggested rates). High female: primary rates + 10 percentage points. Low female: primary rates – 10 percentage points. All scenarios show a monotonic decline in per-participant ankle injury rates with age. The percentage decline from ages 10–13 to 22–24 ranges from –54.1% (low female) to –66.4% (high female), demonstrating that the developmental convergence pattern is robust to participation rate assumptions. Population data from U.S. Census Bureau Vintage 2024 estimates.

Supplementary Table S3. Physiological correlations: raw vs. participation-normalized

Physiological Factor	r (Raw)	p (Raw)	r (Normalized)	p (Normalized)	Change After Normalization
Q-angle	-0.844	0.1562	-0.971	0.0290	Strengthened
Estrogen	-0.832	0.1683	-0.968	0.0319	Strengthened

Note: Pearson correlation coefficients between female ankle injury rates and physiological factors using raw injury proportions (% of all sports injuries that are ankle injuries, across 4 female age strata) versus participation-normalized rates (ankle injuries per 100 estimated sports participants). Both correlations are negative, indicating that higher physiological values (which increase with age) correspond to lower ankle injury rates (which decrease with age). The strengthening of negative correlations after participation normalization demonstrates that the ecological associations were not artifacts of declining sports participation at older ages but reflect genuine ecological confounding by age. Q-angle reference values from Sharma et al. (2023); estrogen (estradiol, pg/mL) reference values from West Virginia University Health Database. * $p < 0.05$.