LATERALIZATION OF ANTERIOR CRUCIATE LIGAMENT INJURIES OF THE KNEE – ANALYSIS BY SEX, SPORTS ACTIVITY, TYPE OF SPORT, AND INJURY MECHANISM

LATERALIZACIJA POVREDA PREDNJEG UKRŠTENOG LIGAMENTA KOLENA – ANALIZA PREMA POLU, SPORTSKOJ AKTIVNOSTI, VRSTI SPORTA I MEHANIZMU POVREĐIVANJA

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Abstract

Introduction. Anterior cruciate ligament injuries represent a major concern among athletes, with recent studies suggesting that sex, sport type, and injury mechanism influence their incidence and characteristics. This study aimed to investigate the lateralization of anterior cruciate ligament injuries and assess associations between the injured side and sex, level of sports activity, sport type, injury mechanism, and playing surface. **Material and Methods.** A retrospective analysis was performed on 1,011 athletes with confirmed anterior cruciate ligament injury. Data were obtained from medical records and included variables as sex, injury side, level of sports activity, type of sport, injury mechanism, and playing surface. Associations were analyzed using chi-square tests. **Results.** A statistically significant association was found between sex and injury side (p = 0.0066), with females more frequently sustaining injuries to the left knee and males to the right. Professional athletes had a significantly higher incidence of right-sided injuries compared to recreational athletes (p = 0.005). Among sports, rugby and american football showed a predominance of right knee injuries (76.2%), while volleyball exhibited a higher rate of left-sided injuries (71.4%). Contact injuries were more common on the right side (62.7%), whereas non-contact injuries predominantly affected the left side. Injuries occurring on grass surfaces were significantly more frequent on the right side (p = 0.028). **Conclusion.** Sex, level of sports activity, type of sport, and playing surface are significantly associated with the lateralization of anterior cruciate ligament injuries. These findings may contribute to improved better understanding of injury risk factors and inform targeted prevention strategies. Further studies incorporating leg dominance are recommended to refine injury risk assessments.

Key words: Anterior Cruciate Ligament Injuries; Knee Injuries; Sports; Athletic Injuries; Functional Laterality; Sex Factors; Risk Factors

Sažetak

Uvod. Povrede prednjeg ukrštenog ligamenta predstavljaju značajan problem kod sportista, a sve više istraživanja ukazuje na ulogu polnih razlika, vrste sporta i mehanizma povređivanja u njihovoj učestalosti i karakteristikama. Cilj ovog istraživanja bio je da se ispita lateralizacija povreda prednjeg ukrštenog ligamenta kod sportista, kao i povezanost strane povrede sa polom, sportskom aktivnošću, vrstom sporta, mehanizmom povrede i podlogom. **Materijal i metode.** Sprovedena je retrospektivna analiza 1.011 ispitanika sa povredom prednjeg ukrštenog ligamenta. Podaci su prikupljeni iz medicinske dokumentacije i obuhvatali su pol, stranu povrede, nivo sportske aktivnosti, vrstu sporta, mehanizam povrede i podlogu. Statistička analiza je obuhvatila hi-kvadrat test za ispitivanje značajnosti povezanosti posmatranih faktora. **Rezultati.** Analiza je pokazala statistički značajnu povezanost između pola i strane povrede (p = 0,0066), pri čemu su žene češće povređivale levo koleno, a muškarci desno. Profesionalni sportisti su imali značajno veću učestalost povreda desnog kolena u poređenju sa rekreativcima (p = 0,005). Ragbi i američki fudbal su pokazali izraženiju asimetriju povreda desnog kolena (76,2%), dok je kod odbojke bila veća učestalost levostranih povreda (71,4%). Kontaktni mehanizmi su bili povezani s povredom desnog kolena (62,7%), dok su nekontaktni mehanizmi češće uzrokovali levostrane povrede. Travnata podloga bila je značajno povezana sa povredama desnog kolena (p = 0,028). **Zaključak.** Rezultati ukazuju na značajnu ulogu pola, nivoa sportske aktivnosti, vrste sporta i podloge u lateralizaciji povreda prednjeg ukrštenog ligamenta kod sportista. Ova saznanja mogu doprineti boljem razumevanju faktora rizika i razvoju ciljane prevencije. Potrebna su dalja istraživanja koja uključuju i dominaciju noge radi sveobuhvatnijeg sagledavanja rizika za povrede prednjeg ukrštenog ligamenta.

Ključne reči: povrede prednjeg ukrštenog ligamenta; povrede kolena; sport; sportske povrede; funkcionalna lateralizacija; pol; faktori rizika

Introduction

Injuries to the anterior cruciate ligament (ACL) of the knee (*lat. ligamentum cruciatum anterior – LCA*) are among the most frequent sports-related knee injuries, with an increasing incidence observed in both professional and recreational athletes [1,2]. Numerous studies have identified a variety of internal and external risk factors, which can be broadly categorized into four main groups: environmental, anatomical, hormonal, and biomechanical [3–7]. ACL rupture risk is multifactorial, and the interplay of these contribut-

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ing factors offers a more accurate prediction of injury likelihood [8–10].

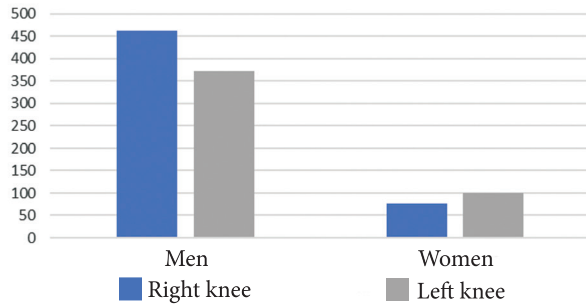
Laterality, or the functional dominance of one side of the body, is a well-established neurological phenomenon reflected in the preferential use of one hand, leg, or eye. Although left-handedness is present in approximately 10% of the population [11], it has been historically misunderstood and stigmatized. Despite this, many notable figures – including Leonardo da Vinci, Nikola Tesla, Marie Curie, Isaac Newton, Ludwig van Beethoven, Jimi Hendrix, and Kurt Cobain – exemplify the diverse capabilities associated with left-side dominance. In political and military history, notable left-handers include Alexander the Great, Napoleon Bonaparte, Winston Churchill, and Barack Obama. Modern sports offer numerous examples of successful left-handed or left-footed athletes such as Rafael Nadal, Lionel Messi, Martina Navratilova, Monica Seles, and Mike Tyson. Their advantage often lies in unusual attack angles, distinct biomechanical patterns, and tactical superiority over predominantly right-handed opponents. These biomechanical and neurological variations may influence movement patterns, balance, and injury risk. Thus, understanding laterality as a broader neurophysiological concept provides foundation for studies exploring differences in sports injury mechanisms. ACL injury lateralization refers to the tendency for injuries to affect one side of the body more frequently [12]. While such injuries are often perceived as random, emerging research suggests a potential association between leg dominance and injury side, influenced by asymmetrical biomechanics, neuromuscular control, and movement strategies [13].

Notably, sex appears to play a critical role: some studies suggest that female athletes more commonly injure the non-dominant, supporting leg [3,14], whereas in male athletes – particularly in sports such as football – injuries tend to occur on the dominant side [15]. These findings highlight the need to explore sex-specific biomechanics and load distribution in ACL injury mechanisms.

The aim of this study was to investigate the lateralization of anterior cruciate ligament injuries and examine its association with sex, level of sports activity, type of sport, injury mechanism, and playing surface.

Material and Methods

The retrospective study was conducted at the Clinic for Orthopedic Surgery and Traumatology, University Clinical Center of Vojvodina. Data were collected from the institutional database of the Clinic, and the study was carried out in accordance with the Declaration of Helsinki [16]. Ethical approval was obtained from the Ethics Committee of the University Clinical Center of Vojvodina.



Graph 1. Distribution of right/left knee injuries by gender

The study included a total of 1,011 participants of both sexes, aged 18 to 45 years, who underwent anterior cruciate ligament (ACL) reconstruction due to sports-related injuries. Exclusion criteria were previous ACL reconstruction (i.e., re-injury of a reconstructed ligament) and ACL injures not related to sports activity. Among the participants, 835 were male and 176 were female. Injuries to the right knee were recorded in 539 cases, while 472 cases involved the left knee **(Graph 1).**

The most commonly represented sport was football ($n = 507$), followed by basketball ($n = 153$) and handball ($n = 102$). Other sports were represented in smaller numbers.

Statistical analysis was performed using the chi-square test of independence to assess the association between the side of the injured knee and categorical variables, including sex, level of sports activity, type of sport, playing surface, and injury mechanism. Descriptive statistics are presented as absolute numbers (N) and percentages (%). All analyses were conducted using SPSS software, version 26. A p-value of <0.05 was considered statistically significant.

Results

The majority of participants were male, with a higher frequency of right knee injuries (55.3%). In contrast, female participants more frequently sustained left knee injuries (55.2%). A chi-square test of independence revealed a statistically significant association between sex and the side of ACL injury ($\chi^2 = 7.37$; $p = 0.0066$) **(Table 1).**

A statistically significant association was also observed between the side of the injured knee and the level of sports activity ($\chi^2(2) = 10.5$, $p = 0.005$) **(Table 2).** Professional athletes more often sustained right-sided ACL injuries compared to recreational athletes.

Abbreviations

ACL – anterior cruciate ligament (*LCA – lat. ligamentum cruciatum anterior*)

While non-athletes showed a higher proportion of right-sided injuries (65.4%) than professionals (56.9%), the difference was not statistically significant due to the small sample size of the non-athlete subgroup (N = 26). Overall, the chi-square test confirmed that professionals had a significantly higher frequency of right knee injuries than recreational athletes (p = 0.005), whereas the influence of non-athletes on this association was negligible.

The distribution of knee injuries varied significantly across different sports **(Table 3).** The greatest side-to-side asymmetry was observed in rugby and american football, where 76.2% of injuries affected the right knee. In contrast, volleyball showed a predominance of left-sided injuries (71.4%). Football and basketball demonstrated a moderate predominance of right knee injuries (56.6% and 55.6% respectively), while handball and combat sports showed a more balanced distribution between sides. The chi-square test confirmed a statistically significant association between the side of injury and the type of sport ($\chi^2(8) = 45.2$, $p < 0.001$).

Although the chi-square test did not show a statistically significant association between injury mechanism and the side of injury ($\chi^2(4) = 8.24$, $p = 0.083$), certain trends were noted **(Table 4)**. Contact injuries, particularly collisions, were more frequently associated with right knee injuries (62.7%), while "other" mechanisms were more commonly linked to left-sided injuries (61.5%). Cutting and landing mechanisms were more evenly distributed. The small number of injuries resulting from falls (n = 9) limits the liability of conclusions in this category and underscores the need for further research with larger sample.

A statistically significant association was identified between playing surface and the injured side ($\chi^2(5) = 12.5$, $p = 0.028$) **(Table 5).** The most notable difference occurred on grass surfaces, where right knee injuries predominated (58.4%). In contrast, "other" surfaces showed a higher incidence of left-sided injuries (57.5%). Mat surfaces had a completely balanced injury distribution (50%-50%). These findings suggest that the biomechanical properties of the playing surface may influence the lateralization of ACL injures.

Discussion

The human body naturally exhibits asymmetry, both morphologically and functionally. Limb dominance – whether of the leg, arm, or eye – results from complex neurological and biomechanical interactions. While biologically determined, dominance is also shaped by cultural and functional factors. Measuring leg preference and understanding laterality hold clinical and sports medicine relevance, particularly in the prevention and rehabilitation of lower extremity injuries [17].

Table 1. Distribution of ACL injuries by gender and side of the injured knee

			Sex	
			Female	Male
Side	Right Knee	N	77	462
	Left Knee	N	99	373

Table 2. Distribution of knee injuries by side and category of sports activity

			Sports activity		
			Recreational athlete	Professional athlete	Non-athlete
Side	Right Knee	N	298	228	17
		%	50.70%	56.90%	65.40%
	Left Knee	N	286	173	9
		%	49.30%	43.10%	34.60%

Table 3. Distribution of knee injuries according to the type of sports activity

			Sports								
			Skiing	Handball	Rugby; American Football	Volleyball	Non-athlete	Basketball	Football	Other	Combat sport
Side	Right Knee	N	15	51	16	10	23	85	287	23	33
		%	38.50%	50%	76.20%	28.60%	46.90%	55.60%	56.60%	50%	55.90%
	Left Knee	N	24	51	5	25	26	68	220	23	26
		%	61.50%	50%	23.80%	71.40%	53.10%	44.40%	43.40%	50%	44.10%

Table 4. Distribution of knee injuries according to the injury mechanism

			Mechanism of injury				
			Collision	Fall	Change of direction	Landing	Other
Side	Right Knee	N	133	5	247	148	10
		%	62.70%	55.60%	52%	51.20%	38.50%
	Knee	N	79	4	228	141	16
		%	37.30%	44.40%	48%	48.80%	61.50%

Table 5. Incidence of right and left knee injuries on different surfaces

			Surface					
			Grass	Taraflex	Mat	Parquet	Other	Concrete
Side	Right Knee	N	240	22	24	141	48	68
		%	57.80%	53.70%	50%	52%	42.50%	55.30%
	Left Knee	N	175	19	24	130	65	55
		%	42.20%	46.30%	50%	48%	57.50%	44.70%

In sports, especially football, leg dominance is typically described in terms of a "stronger" or "weaker" leg, with the dominant leg more frequently used for powerful and accurate actions such as kicking. Although bilateral proficiency is advantageous, most athletes exhibit significant functional asymmetry, which can alter movement biomechanics and elevate injury risk. The role of laterality is especially crucial in understanding the mechanism underlying ACL injuries [15,18].

Lower extremity injuries are the most common in many sports, and functional asymmetry and limb dominance have been identified as potential predisposing factors. Wong and Hong [19] emphasized that most football injuries occur through non-contact mechanisms, where body control and stabilization are vital, particularly in athletes with pronounced limb dominance. Extremity dominance has also been shown to play a role in ACL injuries, as uneven biomechanical loading between limbs may lead to increased vulnerability [18].

Additionally, hormonal influences – especially in women – may contribute to injury incidence, raising additional questions about the complex interaction between laterality, sex, and injury risk [20]. Asymmetries are also present in the trunk, where differences in muscle endurance can result in load imbalances that further exacerbate injury risk, particularly in sports requiring repetitive unilateral movements [21].

In our study, we observed a statistically significant association between sex and the side of ACL injury ($p = 0.007$). Left-sided injuries were more frequent among female athletes (55.2%), while male athletes predominantly sustained right-sided injuries (55.3%). These findings align with the hypothesis that neuromuscular differences between sexes and the tendency to rely on the dominant leg in sport-specific tasks [15] contribute to injury lateralization. However, the relatively small asymmetry in our sample, compared to some previous studies [3], underscores the importance of considering sport-specific biomechanics and movement pattern [22].

Professional athletes in our study (56.9%) had a higher proportion of right-sided ACL injuries compared to recreational athletes (50.7%). This difference may reflect the greater loading of the dominant leg in high-performance environments [23], supporting previous findings that suggest increased injury risk among professional athletes due to sport-specific demands [24]. Non-athletes also exhibited a predominance of right-sided injuries, though due to the small sample size ($N = 26$), this finding warrants cautious interpreted.

The relationship between the type of sport and the side of injury indicates that specific movement patterns in certain sports may significantly contribute to injury lateralization [1]. Rugby and American football, which involve frequent directional changes and repetitive loading of the dominant leg, showed a strong predominance of right-side injuries. Grindem et al. [25] reported that the right knee is up to three times more likely to be injured in football and basketball, which aligns with our results (football – 55.6% right knee injuries; basketball – 55.6%). In contrast, volleyball was associated with more left-sided injuries, possibly due to the biomechanics of landing and body rotation. Handball injuries in our sample demonstrated a near-equal distribution, consistent with previous findings by Olsen et al. [26].

In our study, non-contact injury mechanisms were significantly more common, accounting for 79% of all ACL injuries, compared to only 21% caused by contact (collision) events. This finding is consistent with previous epidemiological research which found that non-contact mechanisms accounted for over 50% of ACL injuries in team sports [27]. These injuries typically occur during activities such as cutting, sudden deceleration, or landing – movements that involve high biomechanical load without external contact. Although our chi-square analysis did not show a statistically significant association between injury mechanism and the side of injury ($p = 0.083$), we observed that contact injuries were more frequently associated with right-sided injuries, while non-contact injuries tended to occur on the left. This asymmetry may reflect neuromuscular and biomechanical differences related to limb dominance and movement strategy. The predominance of non-contact injuries in our cohort underscores the importance of targeted neuromuscular training programs aimed at optimizing lower limb control and reducing asymmetry-related risk.

A statistically significant association was also observed between playing surface and the side of injury, with grass fields linked to a higher frequency of right-sided injuries. This is consistent with Agel et al. [28], who found that grass surfaces increase the likelihood of right-sided ACL injuries by 22%. These findings underscore the potential influence of surface biomechanics on injury lateralization and emphasize the need to consider environmental factors when designing injury prevention strategies and adapting training programs.

The practical implications of our findings are substantial. Recognizing patterns in ACL injury lateralization can inform individualized prevention and rehabilitation programs. Targeted training aimed at enhancing knee stability and control may enhance "prehabilitation" and reduce injury risk. Additionally, these may serve as a foundation for educating coaches and athletes about biomechanical movement patterns that increase injury risk.

However, several limitations should be acknowledged. Small sample sizes in some groups, such as non-athletes, may affect the stability of statistical estimates. Furthermore, the absence of data on leg dominance precluded deeper analysis of the biomechanical and functional differences contributing to injury lateralization.

For future studies should aim to incorporate larger sample sizes and incorporate data on leg dominance. Comparing results across different sports may also improve understanding of injury risk, and support the development of targeted prevention strategies.

Conclusion

This study demonstrated a statistically significant association between sex and the side of anterior cruciate ligament injury, with male athletes more frequently injuring the right knee (55.3%), and female athletes showing a higher proportion of left-sided injuries (55.2%).

A statistically significant relationship was also observed between the side of injury and the level of sports activity ($p = 0.005$), with professional athletes sustaining right-sided injuries more often than recreational athletes and non-athletes.

The chi-square test confirmed a statistically significant association between the side of injury and the type of sport ($p < 0.001$), with the most pronounced right-sided asymmetry found in rugby and American football.

Non-contact injury mechanisms (79%) were significantly more common than contact injuries (21%). Although contact injuries (collisions) were more common (62.7%), there was no statistically significant association between the mechanism of injury and the side of the injured knee ($p = 0.083$).

Lastly, a significant correlation was found between the playing surface and injury lateralization ($p = 0.028$). Right-sided injuries were more frequent on grass surfaces (58.4%), while mat surfaces exhibited an even distribution (50%-50%).

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