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Sex-Based Differences and Associations in Muscle Stiffness and Reactive Strength Index Among Elite Male and Female Soccer Players

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Abstract

The aim of this study was to compare reactive strength index (RSI), muscle stiffness, and aerobic capacity between male and female soccer players, and to examine their relationships with physical performance. A total of 32 soccer players participated in the study, including 16 female players (age: 18.06 ± 3.21 years; height: 1.66 ± 0.09 m; body mass: 56.87 ± 7.51 kg; BMI: 20.78 ± 2.03 kg/m²; training experience: 7.09 ± 2.49 years) and 16 male players (age: 21.37 ± 3.86 years; height: 1.79 ± 0.06 m; body mass: 71.87 ± 8.93 kg; BMI: 22.51 ± 2.20 kg/m²; training experience: 11.37 ± 4.22 years). To compare performance characteristics between sexes, several key physical parameters were assessed, including linear sprint velocity, aerobic capacity (via the 30-15 Intermittent Fitness Test), maximal ball velocity, leg stiffness, and Reactive Strength Index (RSI). Group differences were assessed using independent t-tests or Mann–Whitney U tests, based on distribution characteristics. Within-group associations were analyzed through Pearson or Spearman correlation coefficients, as appropriate. Significant sex-based differences were found in sprint (p = 0.000, ES = 2.34), 30-15 IFT (p = 0.005, ES = 1.07), kicking velocity (p = 0.000, ES = 3.31), RSI (p = 0.043, ES = 0.75), and stiffness (p = 0.007, ES = 1.02). In females, stiffness was negatively correlated with kicking velocity (p = 0.017, ES = –8.34), while in males, RSI (p = 0.013, r = 0.604, ES = 2.47) and stiffness (p = 0.028, r = 0.548, ES = 1.82) were positively correlated with kicking velocity. Additionally, stiffness was positively related to 30-15 IFT performance in males (p = 0.049, r = 0.499, ES = 1.98). Male players showed higher RSI and stiffness values, which were more strongly associated with performance, while lower stiffness in females may support technical skills but increase injury risk. These findings highlight the importance of sex-specific training approaches that consider neuromechanical differences in performance and injury prevention. Future studies should include physiological variables such as muscle cross-sectional area to clarify sex-specific neuromechanical adaptations.

Keywords: Aerobic capacity, Injury risk, Kicking performance, Neuromechanical characteristics, Sprint.

Özet

Elit Erkek ve Kadın Futbol Oyuncuları Arasında Kas Sertliği ve Reaktif Güç Endeksindeki Cinsiyete Dayalı Farklılıklar ve İlişkiler

Bu çalışmanın amacı, erkek ve kadın futbolcular arasında reaktif kuvvet indeksi (RSI), kas sertliği ve aerobik kapasiteyi karşılaştırmak ve bu parametrelerin fiziksel performansla olan ilişkilerini incelemektir. Çalışmaya 32 futbolcu katılmıştır; bunların 16'sı kadın (yaş: 18.06 ± 3.21 yıl; boy: 1.66 ± 0.09 m; vücut ağırlığı: 56.87 ± 7.51 kg; BKİ: 20.78 ± 2.03 kg/m²; antrenman yaşı: 7.09 ± 2.49 yıl) ve 16'sı erkektir (yaş: 21.37 ± 3.86 yıl; boy: 1.79 ± 0.06 m; vücut ağırlığı: 71.87 ± 8.93 kg; BKİ: 22.51 ± 2.20 kg/m²; antrenman yaşı: 11.37 ± 4.22 yıl). Cinsiyete bağlı performans farklılıklarını karşılaştırmak amacıyla doğrusal sprint hızı, aerobik kapasite (30-15 Aralıklı Fitness Testi), maksimum şut hızı, bacak sertliği ve reaktif kuvvet indeksi gibi temel fiziksel parametreler değerlendirilmiştir. Gruplar arası farklar, dağılım özelliklerine bağlı olarak bağımsız örneklem t-testi veya Mann–Whitney U testi ile analiz edilmiştir. Grup içi ilişkiler ise uygunluğa göre Pearson veya Spearman korelasyon katsayıları ile değerlendirilmiştir. Sprint (p = 0.000, ES = 2.34), 30-15 IFT (p = 0.005, ES = 1.07), maksimum şut hızı (p = 0.000, ES = 3.31), RSI (p = 0.043, ES = 0.75) ve bacak sertliği (p = 0.007, ES = 1.02) performanslarında cinsiyetler arasında anlamlı farklar bulunmuştur. Kadın futbolcularda, bacak sertliği ile topa vurma hızı arasında negatif korelasyon saptanmıştır (p = 0.017, ES = –8.34); erkek futbolcularda ise RSI (p = 0.013, r = 0.604, ES = 2.47) ve sertlik (p = 0.028, r = 0.548, ES = 1.82) şut hızı ile pozitif ilişkili bulunmuştur. Ayrıca, erkeklerde sertlik, 30-15 IFT performansı ile anlamlı pozitif ilişki göstermiştir (p = 0.049, r = 0.499, ES = 1.98). Erkek futbolcular daha yüksek RSI ve sertlik değerlerine sahipken, bu parametreler performansla daha güçlü ilişkiler göstermiştir. Kadınlarda ise daha düşük kas sertliği teknik becerilere katkı sağlayabilirken, yaralanma riskini artırabileceği görülmüştür. Bu bulgular, performans ve sakatlanma riskine yönelik cinsiyete özgü antrenman yaklaşımlarının önemini ortaya koymaktadır. Gelecek çalışmalar, cinsiyete özgü nöromekanik uyumları daha iyi anlamak için kas kesit alanı gibi fizyolojik değişkenleri de içermelidir.

Anahtar Kelimeler: Aerobik kapasite, Yaralanma riski, Vuruş performansı, Nöromekanik özellikler, Sprint.

INTRODUCTION

Analyses of match-related performance indicators in both women's and men's soccer suggest a temporal advancement in technical, tactical, and physical aspects of team performance (4,16, 29). A comprehensive understanding of this evolutionary progression holds significant value for coaches and sports scientists alike, as the monitoring, assessment, and optimization of player performance rely heavily on the systematic analysis of such key performance indicators. Long-term performance development and its systematic monitoring have become one of the most emphasized and extensively studied topics in modern football, as they are considered crucial for enabling athletes to reach and maintain elite-level performance (2, 23, 26). Consequently, the integration of neuromechanical parameter monitoring into performance assessment has become a fundamental aspect of modern athlete monitoring systems, ensuring that training prescriptions are based on scientifically grounded evidence (7).

One of the fundamental neuromechanical mechanisms underlying football performance is the stretch-shortening cycle (SSC) (18). The SSC is typically defined as the ability of the musculotendinous unit to produce a rapid and forceful concentric contraction immediately following a fast eccentric action, and is effectively utilized in football-specific movements (15). This typically occurs during movements in which body segments are exposed to impact forces that induce a rapid stretch of the musculotendinous structures (11, 27). The magnitude of impact or stretch forces, task constraints, and the individual's capacity to tolerate such forces collectively determine the nature of the SSC—classified as either fast (≤ 250 ms) or slow (> 250 ms) (17). Reactive strength is a key parameter that reflects an athlete's ability to generate force rapidly. It becomes particularly prominent in sport-specific actions such as cutting, sprinting, and jumping, and is commonly associated with changes in muscle contraction velocity or force output. In sports where time-constrained actions are prevalent, the assessment of this quality provides valuable insights for exercise programming and athlete monitoring (15). Stiffness is an estimate of the resistance force a muscle exhibits in response to a given change in length. Mechanically, stiffness is defined as the ratio of change in force to change in length (stiffness [k] = Δ force / Δ length) (3). The primary source of resistance encountered during passive muscle elongation is attributed to the parallel elastic components of the muscle, including connective tissues such as the sarcolemma, endomysium, perimysium, and epimysium (17). A significant portion of passive muscle stiffness arises from the series elastic components, primarily tendons and the myofibrillar cross-bridge structures (25).

In contrast, active stiffness refers to the level of resistance a muscle exhibits against external forces during voluntary contraction, and is primarily determined by the number of cross-bridges formed in parallel within the muscle fibers (8).

Muscle stiffness and the Reactive Strength Index (RSI) are neuromechanical parameters closely associated with high-intensity actions in football, such as sprinting, jumping, and change of direction. Although these variables have received increasing attention in performance science in recent years, studies that directly compare male and female soccer players in terms of these parameters remain scarce. Nevertheless, to date, no studies have directly investigated the relationship between RSI and/or muscle stiffness with key performance components such as kicking velocity, sprint time, or aerobic capacity specifically in female athletes, highlighting the originality and relevance of the current research. This study aimed to provide a broader analysis of physical performance by evaluating not only neuromechanical characteristics but also aerobic capacity. In doing so, the relationships between variables such as RSI and stiffness and both anaerobic and aerobic performance indicators were examined in a sex-specific context. This research seeks to (i) compare RSI, muscle stiffness, and aerobic capacity between male and female soccer players, and (ii) investigate how these parameters relate to physical performance outcomes. The results aim to inform sex-specific training strategies and performance monitoring practices.

METHOD

Prior to the implementation of the study, the necessary approval was obtained from the Ethics Committee of Çukurova University, Faculty of Medicine (Decision No: 155; Date: 16.05.2025). Prior to the study, all athletes were informed about the measurement protocols and provided written consent in accordance with the Declaration of Helsinki.

Participants

A total of 32 soccer players voluntarily participated in this study, including 16 females (age = 18.06 ± 3.21 years, height = 1.66 ± 0.09 m, body mass = 56.87 ± 7.51 kg, BMI = 20.78 ± 2.03 kg/m², training experience = 7.09 ± 2.49 years) and 16 males (age = 21.37 ± 3.86 years, height = 1.79 ± 0.06 m, body mass = 71.87 ± 8.93 kg, BMI = 22.51 ± 2.20 kg/m², training experience = 11.37 ± 4.22 years). Inclusion criteria were: (i) being an active soccer player registered with a club or federation, (ii) having at least three years of systematic training history, (iii) participating in training regularly (minimum three sessions per week), and (iv) providing informed consent. Exclusion criteria included: (i) current musculoskeletal injury or pain affecting performance, (ii) any neurological, cardiovascular, or metabolic condition, and (iii) absence from training for more than two consecutive weeks in the past three months.

Procedure

The implemented protocol consisted of two separate testing sessions conducted on non-consecutive days, with a minimum 48-hour rest period between sessions to prevent fatigue-related effects. In the first session, sprint performance, maximum ball kicking velocity, and the 30-15 Intermittent Fitness Test (30-15 IFT) were conducted in that order. In the second session, the RSI and muscle stiffness measurements were carried out. Prior to each session, participants completed a standardized warm-up routine lasting approximately 10 minutes, which included self-selected dynamic stretching and submaximal trial efforts related to the upcoming tests (e.g., trial sprints or jumps). Additionally, 3 to 5-minute passive rest intervals were provided between each test within the sessions to ensure adequate recovery and minimize fatigue's influence on performance outcomes.

Linear Sprint Test

A 30-meter distance was precisely measured and marked, and necessary adjustments were made prior to the placement of electronic timing gates (TC Photogate; Brower Timing Systems LLC, Draper, UT, USA). The timing gates were positioned at the start of the 30-meter track, and each player began the sprint from a standing position 30 cm behind the first gate. Two plastic markers were placed 2 meters beyond the finish line to encourage players not to decelerate before crossing the line. Each participant performed three maximal-effort sprints, and the best time over the 30-meter distance was recorded for analysis (10).

30–15 Intermittent Fitness Test

The original 30–15 Intermittent Fitness Test was employed to assess participants' aerobic fitness levels. This protocol was selected due to its suitability for evaluating locomotor performance in soccer players. The test was conducted 48 hours after the participants' last official match, on a synthetic turf surface. Prior to the test, all participants completed a 5-minute self-paced running warm-up protocol. This test consists of alternating intervals of 30 seconds of high-intensity running and 15 seconds of active recovery. The running speed increases progressively at each stage. The initial speed was set at 8 km/h, and it was increased by 0.5 km/h every 30-second stage. The test was terminated when participants could no longer keep pace with the audio signal system. The primary outcome for aerobic performance was the velocity at the final completed stage (5).

Maximum Ball Kicking Velocity Test

Participants' ball kicking velocities were measured using a portable radar-based velocity measurement device (Bushnell 101911, Overland Park, KS, USA), which has previously demonstrated high validity ($r = 0.88$) (14). FIFA-approved size 5 footballs (circumference: 68–70 cm; weight: 420–445 g), specifically designed for the respective player category, were used for all attempts. Each participant performed three maximal-effort kicks from a distance of 11 meters, with a fixed 2-meter run-up. Regardless of shot accuracy, the highest ball velocity recorded among the three trials was used for analysis.

Leg Stiffness Test

Leg stiffness was assessed during a submaximal bilateral hopping test. The test was performed at a fixed hopping frequency of 2.5 Hz, selected to elicit movement patterns that resemble typical spring-mass model behavior (20). Participants were instructed to perform 20 consecutive bilateral hops on a mat. The hopping frequency was maintained using a quartz metronome (SQ-44, Seiko, Berkshire, UK). Leg stiffness (kNm^{-1}) was calculated using body mass, ground contact time, and flight time measurements (9) (Equation 1).

Kn=Mπ [(Tf+Tc)]/T■(2@c)[(Tf+Tc/π)-(Tc/4)](Equ 1).

In the equation, K_n represents leg stiffness, M denotes body mass, Tc refers to ground contact time, and T$\boldsymbol{f}$ indicates flight time.

Reactive Strength Index (RSI)

The RSI was calculated based on data obtained during a maximal vertical jump test. In this test, participants performed five consecutive bilateral maximal vertical jumps on a contact mat. They were instructed to minimize ground contact time while maximizing jump height (21). The first jump of each trial was excluded from analysis, and the mean value of the remaining four jumps was used in the RSI calculation (20). RSI was computed using the formula proposed by (11) (Equation 2).

RSI=Contact Time (ms)÷Jump Heigth (cm) (Equ 2).

Statistical Analysis

Data were analyzed using IBM SPSS Statistics version 20.0. For all variables, mean ($\bar{X}$) and standard deviation (SD) values were calculated. Following the assessment of normality, independent samples t-tests were used for variables meeting parametric assumptions, while the Mann–Whitney U test was applied for those that did not. Group comparisons were conducted to evaluate differences between male and female participants. Additionally, within-group relationships among variables were examined using correlation analyses (Pearson or Spearman, as appropriate). Effect sizes (Cohen's d) were calculated for all between-group comparisons, and interpreted using the following criteria: $d < 0.20$ = very small effect, $0.20 \le d < 0.50$ = small effect, $0.50 \le d < 0.80$ = moderate effect, and $d \ge 0.80$ = large effect (Cohen, 1988). The level of statistical significance was set at $p < 0.05$ for all analyses.

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FINDINGS

Comparisons Between Female and Male Soccer Players

The mean, standard deviation, p-value, and effect size (Cohen's d) results for the 30 m sprint, 30-15 Intermittent Fitness Test (IFT), maximum kicking velocity, RSI, and stiffness tests of female and male soccer players were presented in Table 1. According to the statistical analysis, significant differences were found between female and male athletes in the 30 m sprint (p = 0.000, ES = 2.34, large), 30-15 IFT (p = 0.005, ES = 1.07, large), maximum kicking velocity (p = 0.000, ES = 3.31, large), RSI (p = 0.043, ES = 0.75, moderate), and stiffness (p = 0.007, ES = 1.02, large) performance levels.

Table 1. Comparative mean and standard deviation values of female and male athletes in physical performance tests.

Test	Female (Mean ± SD)	Male (Mean ± SD)	p-value	Cohen's d
RSI (ms / cm)	135.08 ± 36.61	162.81 ± 37.43*	0.043	0.75
Stiffness (kN·m^{-1})	23.41 ± 4.29	28.81 ± 6.12*	0.007	1.02
30m Sprint (s)	4.63 ± 0.30	4.09 ± 0.13*	0.000	-2.34
30-15 IFT (km/h)	17.31 ± 1.48	18.81 ± 1.33*	0.005	1.07
Maximal Kick (km/h)	74.94 ± 7.61	96.69 ± 5.34*	0.000	3.31

*Indicates statistical significance between the two groups (p < 0.05).

Correlations Within Female and Male Soccer Players

In the analyses conducted on data from female soccer players, a moderate but significant negative correlation was found between stiffness and maximum kicking velocity (p = 0.017, ES = –8.34, large). No significant relationships were observed between RSI and maximum kicking velocity (p = 0.226, ES = 2.27, large), RSI and sprint time (p = 0.853, ES = 5.04, large), RSI and 30-15 IFT (p = 0.464, ES = 4.54, large), stiffness and sprint time (p = 0.434, ES = 6.17, large), or stiffness and 30-15 IFT (p = 0.819, ES = 1.90, large) (Figure 1A and 1B).

According to the Pearson correlation analysis conducted on data from male soccer players, a significant and positive correlation was found between RSI and maximum kicking velocity (r = 0.604, p = 0.013, ES = 2.47, large). A significant and positive correlation was also observed between stiffness and kicking velocity (r = 0.548, p = 0.028, ES = 1.82, large). Additionally, stiffness showed a significant and positive relationship with 30-15 IFT performance (r = 0.499, p = 0.049, ES = 1.98, large). On the other hand, no significant relationships were found between RSI and sprint time (r = –0.250, p = 0.350, ES = 1.62) or between RSI and 30-15 IFT (r = 0.034, p = 0.901, ES = 0.86) (Figure 1A and 1B).

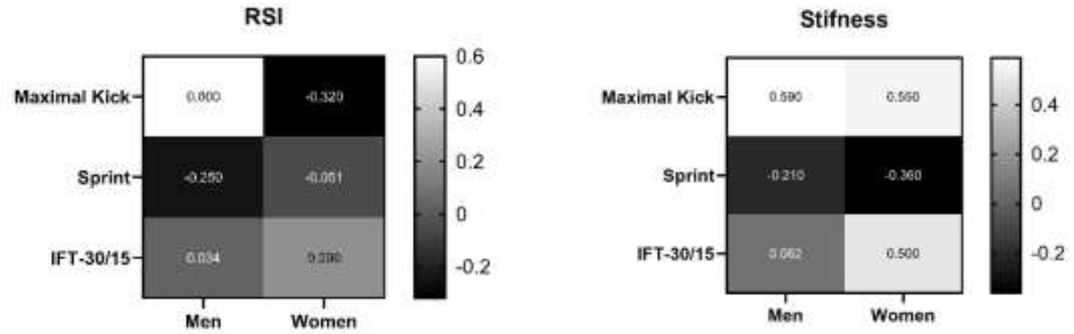

Figure 1. Correlation analysis of RSI and stiffness with performance variables based on gender.

DISCUSSION AND CONCLUSION

The primary objective of this study was to compare muscle stiffness and RSI between female and male soccer players and to investigate the associations between these neuromuscular variables and performance outcomes in a sex-specific context. The results demonstrated statistically significant differences between sexes in sprint, IFT 30/15, maximal kicking velocity, RSI, and muscle stiffness performance. Moreover, a significant negative relationship was identified between muscle stiffness and kicking velocity among female athletes, whereas in male athletes, both RSI and muscle stiffness exhibited significant positive correlations with maximal kicking velocity and aerobic capacity. These findings suggest that sex-based neuromuscular characteristics may differentially influence performance parameters in soccer.

In our study, male athletes demonstrated higher levels of muscle stiffness and reactive strength index (RSI) compared to their female counterparts. The literature investigating sex-based differences in these parameters remains limited. Lehnert et al. (19) reported that males aged 13–16 exhibited greater leg stiffness, with significant RSI differences observed only in the 15–16 age group. Similarly, Beckham et al. (6) found that male athletes showed higher RSI values than females, attributing these differences to physiological factors such as increased muscle mass, greater muscle–tendon unit stiffness, and enhanced neuromuscular control. These physiological advantages enable male athletes to utilize the stretch-shortening cycle (SSC) mechanism more effectively. Similarly, Granata et al. (13) reported that males exhibited greater leg stiffness than females during functional jumping tasks. In line with these findings, Padua et al. (24) observed higher leg stiffness in males compared to females during double-leg jumping, suggesting that this difference might be due to limited hamstring contribution in females despite higher quadriceps and soleus activation levels measured via surface EMG. Consistent with these observations, Zhang et al. (30) found that female athletes demonstrated lower leg and knee stiffness during single-leg landings compared to their male counterparts, which may compromise knee joint stability and increase the risk of anterior cruciate ligament (ACL) injuries. The findings indicate that sex-related differences in muscle–tendon architecture are associated not only with performance outcomes but also with injury risk. Another key result of the study was that male athletes exhibited significantly superior performance compared to female athletes in sprint time, maximal kicking velocity, and aerobic endurance tests. This highlights the importance of neuromechanical characteristics such as RSI and muscle stiffness in lower limb functionality and rapid force production. Effective utilization of the stretch-shortening cycle (SSC) contributes to reduced ground contact time and enables greater force generation by exploiting the elastic properties of the muscle–tendon unit (22). This mechanism provides a distinct advantage, particularly in sprint performance (28). Indeed, the ability to generate high force in a short ground contact phase is a fundamental determinant of the reactive strength index, reflecting the efficiency of SSC utilization (12).

Comparative analyses between sexes reveal that the relationships between neuromuscular and mechanical properties and field-based performance tests operate through different dynamics in male and female athletes. Notably, the significant positive associations observed between RSI and muscle stiffness with performance outcomes such as kicking velocity and aerobic endurance in male athletes suggest that these parameters may serve as key performance determinants in this population. These findings are supported by previous literature. For instance, Başkaya et al. (1), in their study on young male soccer players, reported significant positive correlations between RSI, leg strength, and eccentric utilization ratio, yet found no significant relationships between RSI and field-based performance tests such as sprint time, acceleration, or change of direction. Similarly, in the present study, no significant correlation was found between RSI and sprint time. Nevertheless, existing literature also includes studies reporting strong associations between RSI and sprint performance, indicating that the nature of this relationship may be context-dependent and influenced by factors such as age, training background, or test methodology. Indeed, Ciacci et al. (7) reported strong negative correlations between RSI—calculated using ground reaction force data during sprinting—and 100-meter sprint times ($r = -0.90$ to -0.96). These discrepancies suggest that the relationship between RSI and field-based performance may vary depending on factors such as the athlete's competitive level, the specific testing protocol, and the method used to assess RSI. Supporting this, a meta-analysis conducted by Jarvis et al. (15) demonstrated that RSI is significantly and moderately correlated with both strength ($r = 0.356$) and endurance ($r = 0.401$) performance.

These associations are thought to be underpinned by physiological mechanisms: in strength-related performance, muscle–tendon stiffness and explosive force capacity play a critical role, whereas in endurance performance, elastic energy reutilization and mechanical efficiency are key contributors. To date, no studies have directly examined the relationship between RSI, stiffness, and kicking velocity. This study offers a novel contribution by addressing these associations. Notably, a significant negative correlation was identified between muscle stiffness and kicking velocity in female athletes, whereas no statistically significant associations were observed between RSI and any performance variables in the same group. The negative association between muscle stiffness and kicking velocity among female players may suggest that more compliant muscle–tendon structures could favor technical performance outcomes. On the other hand, the lack of significant relationships between RSI and performance parameters may imply that the role of explosive strength in determining performance could be limited in female athletes.

Limitations and Future Directions

This study has certain limitations, including a relatively small sample size, a cross-sectional design, and the exclusion of other biomechanical and physiological variables such as muscle cross-sectional area or hormonal status. These factors may limit the generalizability and causal interpretation of the findings. Future research should include larger, more diverse samples, incorporate physiological measures (e.g., muscle architecture, hormonal profiles), and adopt longitudinal designs to better understand sex-specific adaptations in neuromechanical performance.

CONCLUSION

In conclusion, male soccer players demonstrated higher levels of RSI and muscle stiffness compared to female players, and these parameters exhibited stronger associations with performance outcomes in males. While force-based performance advantages were more prominent among male athletes, lower muscle stiffness in females appeared to contribute positively to technical skills, albeit potentially increasing injury risk. In this study, dynamic muscle stiffness was evaluated, and it is suggested that although lower stiffness may be advantageous for executing technical movements, it could also impair effective force transmission during sudden loads, thereby elevating the risk of injury. The absence of significant associations between RSI and performance variables in female athletes may reflect the limited role of explosive strength in determining performance within this population. To date, no studies have directly examined the relationships between RSI and/or muscle stiffness and performance components such as sprint time, kicking velocity, or aerobic capacity specifically in female athletes. Therefore, the present study offers a novel contribution by addressing this gap and highlighting the influence of sex-specific neuromechanical differences on sport performance.

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