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Predictive Models of Hamstring Performance in Adolescent Athletes

Adolesan Sporcularda Hamstring Performansının Tahmin Modelleri

Research Article / Araştırma Makalesi

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Abstract

This study investigated the relationships between hamstring strength, flexibility, core endurance, jumping performance, single-leg bridge endurance, and knee joint range of motion (ROM) across six sports disciplines, including football, swimming, volleyball, karate, wrestling, and athletics. A total of 249 athletes (144 men, 105 women) aged 10–18 years participated, with a mean BMI of 22,6 kg/m² and an average of 4.9 years of sports experience. Regression analyses revealed sport-specific predictors of performance and injury risk. Dominant hamstring strength and torque were strong predictors of explosive movements like squat jumps in football (R^2=0.74, p <0.001) and volleyball (R^2=0.71, p <0.001), while balanced hamstring strength was critical for core stability in swimming (R^2=0.62, p<0.05). Non-dominant hamstring strength influenced squat jump performance in wrestling (R^2=0.66, p <0.01), and hamstring torque was significantly associated with knee flexion ROM in athletics (R^2=0.72, p<0.001). Inter-limb asymmetry exceeding 10% correlated with in-creased injury risk, highlighting the importance of symmetry. The findings emphasize the need for tailored training protocols that address sport-specific demands, integrating strength, flexibility, and endurance.

Keywords: Hamstring strength, Sports performance, Injury prevention, Inter-limb asymmetry, Core endurance

Öz

Bu çalışma, futbol, yüzme, voleybol, karate, güreş ve atletizm dahil olmak üzere altı farklı spor branşında hamstring kuvveti, esneklik, core dayanıklılığı, sıçrama performansı, tek bacak köprü dayanıklılığı ve diz eklem hareket açıklığı (ROM) arasındaki ilişkileri araştırmıştır. Çalışmaya, yaşları 10–18 arasında değişen toplam 249 sporcu (144 erkek, 105 kadın) katılmıştır. Sporcuların ortalama vücut kitle indeksi (BMI) 22,6 kg/m² ve spor tecrübeleri ortalama 4,9 yıl olarak kaydedilmiştir. Regresyon analizleri, performans ve sakatlık riskinin branşa özgü belirleyicilerini ortaya koymuştur. Futbol (R^2=0,74, p<0,001) ve voleybolda (R^2=0,71, p<0,001) dominant hamstring kuvveti ve torku, squat sıçrama gibi patlayıcı hareketlerin güçlü belirleyicisi olurken, yüzmede (R^2=0,62, p<0,05) dengeli hamstring kuvveti core stabilitesi için kritik bulunmuştur. Güreşte (R^2=0,66, p<0,01) baskın olmayan hamstring kuvveti, squat sıçrama performansını etkilerken, atletizmde hamstring torku diz fleksiyon ROM'u ile anlamlı bir ilişki göstermiştir (R^2=0,72, p<0,001). %10'u aşan ekstremiteler arası asimetri, artan sakatlık riski ile ilişkilendirilmiş ve simetrinin önemini vurgulamıştır. Bulgular, spor branşına özgü ihtiyaçları ele alan, kuvvet, esneklik ve dayanıklılığı içeren bireyselleştirilmiş antrenman protokollerinin gerekliliğini ortaya koymaktadır.

Anahtar Kelimeler: Hamstring kuvveti, Spor performansı, Sakatlık önleme, Ekstremiteler arası asimetri, Core dayanıklılığı

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Introduction

Hamstring strength, flexibility, and endurance are foundational components of athletic performance, playing pivotal roles in power generation, injury prevention, and overall functional capacity. However, the interplay between hamstring metrics and sport-specific performance demands remains an area requiring further exploration. While previous studies have extensively examined hamstring strength's role in injury risk reduction and explosive activities, a comprehensive understanding of how hamstring flexibility, core endurance, single-leg bridge endurance, and knee joint range of motion (ROM) influence performance across different sports is lacking. This gap underscores the need for targeted investigations into these relationships to enhance training and rehabilitation strategies.

Hamstring flexibility, as a determinant of joint mobility and muscle efficiency, has been shown to influence both performance and injury risk. Limited flexibility can disrupt movement patterns, increasing the likelihood of overuse injuries, particularly in sports requiring high speed running or jumping, such as football and track and field (Malliaropoulos et al., 2010). Conversely, excessive flexibility without corresponding strength can compromise muscle stiffness, impairing explosive performance in sports like volleyball (Marques, Van den Tillaar, Gabbett, Reis, & González-Badillo, 2009). Core endurance, on the other hand, provides the stability necessary for force transmission through the kinetic chain, which is critical in swimming and karate, where sustained stability is essential for optimal technique (Chaouachi et al., 2014; Ebben, Carroll, & Simenz, 2004). Despite its importance, the relationship between core endurance and hamstring function remains underexplored in the context of specific sports, such as football, swimming, volleyball, karate, wrestling, and track and field sports.

Jumping performance, a hallmark of explosive strength, relies heavily on hamstring strength and torque. Sports such as football and volleyball demand a high degree of explosive power, with imbalances in hamstring strength often leading to reduced jump height and increased injury risk during dynamic actions (Bishop, Read, Chavda, & Turner, 2016; Hewett, 2004). Similarly, the single-leg bridge endurance test, which assesses hamstring endurance and inter limb strength symmetry, has been identified as a valuable predictor of performance in sports requiring prolonged muscular contractions (Freckleton, Cook, & Pizzari, 2014). Despite these insights, the role of inter-limb asymmetry in functional performance across various sports has not been thoroughly examined.

Knee flexion and extension ROM are critical for maintaining dynamic flexibility and control, especially in sports with complex technical demands, such as track and field, karate, and wrestling. Limited ROM can hinder efficient movement patterns and increase the risk of compensatory injuries, while optimal flexibility enables athletes to perform complex maneuvers and maintain stability during high-intensity actions (Kay & Blazevich, 2012; Malliaropoulos et al., 2010). However, the relationship between hamstring flexibility and ROM in different adolescent athletes and sports disciplines has not been sufficiently explored.

This study seeks to address these gaps by investigating the relationships between hamstring strength, flexibility, core endurance, jumping performance, single-leg bridge endurance, and knee joint ROM across multiple sports, including football, swimming, volleyball, karate, wrestling, and track and field. By adopting a sport-specific approach, this research aims to provide a nuanced understanding of how these parameters interact to influence performance and injury risk. It is hypothesized that hamstring strength and flexibility will have distinct impacts depending on the biomechanical and functional demands of each sport, with dominant leg strength being considered more critical for explosive activities, while inter-limb symmetry and endurance are regarded as more significant in stability-intensive sports. This study's findings will contribute to the development of tailored training and rehabilitation programs, ultimately enhancing performance and reducing injury risk across diverse athletic disciplines.

Methods

Research Model

This study was conducted using a prospective regression design to examine the relationships between athletes' functional and performance parameters and their predictors of athletic performance and injury risk. The study can be classified as descriptive, quantitative, and cross-sectional. To enhance the reliability of the findings, all measurements were conducted at the Exercise Physiology and Performance Laboratory of Kütahya Dumlupınar University.

To prevent physical fatigue, the tests were divided into three separate days, ensuring adequate rest periods between trials and assessments. On the first day, participants underwent a comprehensive evaluation, including demographic data, anthropometric measurements, sports history, and injury history. On the same day, knee joint range of motion (ROM) measurements and the Squat Jump Double test were conducted to assess lower limb explosive power. On the second day, core endurance was assessed using the Horizontal Trunk Flexion Test and the Wall Sit Test. Additionally, hamstring endurance was evaluated using the Single-Leg Bridge Test. On the third day, eccentric hamstring strength was measured during the Nordic Hamstring Exercise using the IVMES H-Board device. This structured testing protocol ensured a comprehensive and reliable assessment of athletes' performance and injury risk factors.

Participants

The participants in this study consisted of 249 athletes from various sports disciplines, including 144 men and 105 women. The athletes represented different sports: athletics (n = 19; 10 men, 9 women), karate (n = 15; 4 men, 11 women), soccer (n = 116; 93 men, 23 women), swimming (n = 13; 8 men, 5 women), volleyball (n = 66; 11 men, 55 women), and wrestling (n = 15; 13 men, 2 women). The participants' ages ranged from 10 to 18 years, with a mean age of 14.7 ± 2.3 years. When analyzed by sport, the mean age was as follows: athletics (14.9 ± 2.5 years, range: 10–18 years), soccer (14.2 ± 2.0 years, range: 10–18 years), wrestling (13.3 ± 1.9 years, range: 10–18 years), and karate (13.3 ± 1.3 years, range: 10–18 years). These values indicate that the distribution of ages among the sports remains within the adolescent range, with slight variations based on sport-specific participation trends. The average height of all participants was 163.2 ± 8.3 cm, and the average body mass was 52.8 ± 10.6 kg, leading to a mean BMI of 19.8 ± 2.7 kg/m². These characteristics provide an overview of the physical development of the adolescent athletes and their potential impact on sports performance. Thus, on average, participants trained for 4. 9 ± had 3. training 2 frequency years of and three to six sessions in a week. Inclusion Criteria: To improve the relevance of the sample while acknowledging the potential heterogeneity due to the inclusion of both pre-adolescent and adolescent participants, only athletes aged between 10 and 18 years who had been engaged in sports for at least six months and trained three or more times per week were included. Furthermore, be all members the of athletes Kütahya had Youth to and be study Sports capable without Directorate of experiencing to undergoing discomfort enable the or the physical limitations researcher tests in to required order reach for to the ensure the validity and reliability of the data collected. Exclusion Criteria: The participants were excluded if they had lower limb injury within the last six months as such injuries may affect the performance metrics. Other exclusion criteria included history of surgery on the lower limbs which may alter the biomechanical function and range of motion, neurological disorders or systemic diseases such as neurological disorders or metabolic syndrome that may affect the physical well-being or bias the results. The athletes with chronic pain or musculoskeletal disorders affecting the lower extremities were also excluded if they had medical complaints or conditions that prevented them from participating in the study or which made them unfit for the physical examinations. The sample size calculations were done using G*Power software version 3.1.9.7 since it would provide enough statistical power for detecting the differences that would be of interest. The calculations were based on an anticipated medium effect size of 0.5, a significance level of 0.05, and a statistical power of 0.8. Prior to these calculations, a pilot study was conducted with 50 participants, and the results were used to refine the effect size estimation. Based on these parameters, the minimum sample size that was needed to achieve the desired level of precision was computed to be 210 participants. To ensure that the participants' data was not lost through dropout or any other means, a total of 249 athletes were enrolled in the study, which is beyond the required sample size. This number of participants was adequate to ensure the strength of the research and allowed for analysis of sub-groups by type of sport. The design of the study and the power analysis provided a solid methodological basis for making conclusions that are robust and comparable.

Data Collection Tools

Measurement of Knee Joint Range of Motion (ROM): The functional range of motion (ROM) of the knee joint was measured to detect any pre-existing deficits in flexion and extension, as these are critical for optimal athletic performance, particularly in activities such as sprinting, jumping, and kicking. Additionally, the flexibility of the hamstring—a key determinant of knee joint ROM—was evaluated to explore its potential influence on knee function(Moltubakk, Eriksrud, Paulsen, Seynnes, & Bojsen-Møller, 2016).

Knee Flexion ROM Measurement: Participants lay prone (face-down) on an examination table for the assessment. Starting with the knee in full extension, active and passive flexion was performed while maintaining the hip in a neutral position. A digital inclinometer was aligned with the lateral midline of the tibia and tracked the movement throughout the range of motion. The maximum angle reached during both active and passive flexion was recorded. Each leg was measured twice, and the mean value was calculated for analysis.

Knee Extension ROM Measurement: To assess knee extension, participants were positioned supine (face-up) on an examination table with their hip flexed at 90°. They were instructed to actively extend the knee to the maximum angle they could achieve. Passive extension was then evaluated by carefully moving the leg further until resistance prevented additional movement. A digital inclinometer was utilized for angle measurements, ensuring consistent evaluation across both active and passive movements. Each leg was assessed twice, and the average of the measurements was calculated. These ROM assessments were instrumental in detecting asymmetries or deficits that might contribute to movement inefficiencies or an increased risk of injury in athletes.

Eccentric Hamstring Muscle Strength: Eccentric hamstring strength was assessed using the Nordic Hamstring Exercise (NHE) and the IVMES H-Bord device (IVMES, Ankara, Turkey), a validated and reliable tool (ICC = 0.90–0.97) for measuring eccentric strength (Akarçeşme et al., 2024) (Figure 1.). This evaluation focused on the hamstring muscles' capacity to resist elongation under load, a crucial aspect of deceleration and injury prevention during high-intensity athletic activities. A familiarization phase was conducted to ensure proper technique, during which participants performed one set of three submaximal NHE repetitions. In the testing phase, three maximal eccentric repetitions were completed, with a two-minute rest interval between attempts to minimize fatigue and maintain consistent performance. Participants started in an upright kneeling position with knees bent at 90°, while their ankles were secured with supports above the lateral malleoli. They were instructed to lean forward as slowly as possible, resisting the downward force with maximum effort, all while maintaining a neutral trunk and hip alignment.

To enhance accuracy, reflective markers were positioned on key anatomical landmarks, including the greater trochanter, lateral femoral condyle, and lateral malleolus. Video recordings captured at 50 Hz were used to perform angular analyses. Strict criteria were applied to ensure data quality: repetitions were excluded if hip flexion exceeded 20°, forward bending velocity was outside the range of 20–40°/s, or if participants lost control during landing or displayed excessive lumbar movement. The IVMES H-Bord device measured peak force, mean force, and inter-limb strength asymmetries for the right and left hamstring muscles during valid repetitions. The average values from three valid trials were used for further analysis, providing a comprehensive assessment of eccentric hamstring strength (Akarçeşme et al., 2024).

Figure 1. Eccentric hamstring strength assessment during Nordic Hamstring Exercise using IVMES H-Bord device

Single-Leg Bridge Endurance Test: Hamstring endurance was assessed using the Single-Leg Bridge Test, a reliable and validated method for evaluating hamstring function and identifying potential injury risk (ICC = 0.85). This test is widely recognized for its relevance in predicting hamstring injuries, particularly in sports like football and athletics. Participants began in a supine position on a flat surface, with their arms crossed over their chest to minimize upper body involvement. One heel was placed on a 60 cm platform, while the opposite leg was held upright to avoid using momentum. The task required participants to repeatedly lift and lower their hips, maintaining a neutral alignment (0°) at the top of each lift, until they could no longer perform the movement correctly. Failure was defined as an inability to maintain proper form or complete another repetition without resting. To ensure accuracy, feedback was provided during the test, and the exercise was stopped if participants demonstrated improper technique, such as pelvic tilting, lateral movement, or reliance on momentum. The total number of successful repetitions was recorded for each leg, with the order of testing between the dominant and non-dominant legs randomized. This protocol allowed for a detailed assessment of hamstring endurance, capturing potential imbalances and weaknesses (Freckleton & Pizzari, 2013).

Figure 2. Hamstring endurance assessment (Single-Leg Bridge Test)

Core Endurance Evaluation: Core endurance, a critical component for preventing lower extremity injuries (Schuermans, Van Tiggelen, Danneels, & Witvrouw, 2014; Shield & Bourne, 2018), was assessed using two validated tests: the Wall Sit Test and the Horizontal Trunk Flexion Test.

Wall Sit Test: Participants performed the test by positioning their back against a wall, with their feet shoulder-width apart and arms crossed over their chest. They slid down the wall until both hips and knees were flexed to 90° (Figure 3). The non-tested leg was elevated 3–6 inches off the ground, requiring participants to maintain balance on a single leg. The test was stopped when participants were unable to hold the position or lost their balance. The duration (in seconds) that each participant maintained the position was recorded for both legs separately. The test was performed for both the dominant and non-dominant legs, and the average duration for each leg was calculated. This assessment demonstrated strong reliability (ICC = 0.80–0.89) and provided valuable insights into lower limb strength and endurance (Bruce, Rush, Torres, & Lipscomb, 2017).

Figure 3. Core endurance assessment (Wall Sit Test)

Horizontal Trunk Flexion Test: Participants assumed a quadruped position with their shoulders, hips, and knees flexed at 90°. To ensure stability, an assistant secured the lower legs while participants extended their arms to a 90° abduction position, maintaining a horizontal posture (Figure 4). The test continued until participants were unable to sustain proper form or experienced fatigue. The duration (in seconds) was recorded, providing a measure of endurance and control. This method demonstrated strong reliability (ICC = 0.85)(Bruce et al., 2017).

Figure 4. Core endurance assessment (Horizontal Trunk Flexion Test)

Squat Jump Double: Lower limb explosive power was evaluated using the Squat Jump Double test, a well-established method for measuring vertical force production with high reliability and validity (ICC = 0.91–0.96) (McMahon, Jones, & Comfort, 2022). Participants started in a static squat position with their knees bent at 90° and their hands placed on their hips to eliminate the influence of arm movement. From this position, they executed a vertical jump with maximum effort, ensuring both feet left the ground simultaneously (Figure 5). The test was performed using the İvmes Athlete motion-sensitive sensor, which was securely fastened to the participant's waist with a belt to maintain stability and accuracy during measurements. This advanced system captured and analyzed all movements throughout the jump. Participants completed multiple trials, and the highest vertical jump height was recorded as the result. To ensure precision, counter-movements before the jump were strictly avoided, and participants were provided with 1–2 minutes of rest between attempts to reduce fatigue. This protocol provided an accurate and reliable assessment of lower limb explosive power (Markovic, Dizdar, Jukic, & Cardinale, 2004).

Figure 5. Lower limb explosive power assessment (Squat Jump test)

Statistical Analysis

All statistical analyses were performed using SPSS version 26.0 (IBM, Armonk, NY, USA) for computation and GraphPad Prism version 9.0 for data visualization. The significance threshold was set at $p < 0.05$. Prior to analysis, data normality was evaluated using the Kolmogorov Smirnov test, and variance homogeneity was checked with Levene's test. For variables that did not follow a normal distribution, log transformations were applied, or non-parametric tests were used when appropriate. Descriptive statistics, including means, standard deviations, and ranges, were calculated to summarize the demographic and performance characteristics of participants. Multiple linear regression analyses were conducted to identify factors influencing athletic performance and injury risk. Dependent variables included performance outcomes such as squat jump height, knee range of motion (ROM), hamstring endurance, and core stability, while independent variables consisted of eccentric hamstring strength (dominant and non-dominant), inter-limb asymmetry, and demographic factors such as age, BMI, and training experience. Both forward and backward selection methods were utilized to optimize the models, retaining only predictors with significant contributions ($p<0.05$). Adjusted R^2 values were reported to reflect the proportion of variance explained by the models. Differences between sports disciplines were analyzed using one-way ANOVA with Bonferroni post hoc tests for continuous variables. If the assumptions of normality or homogeneity of variances were not met, the Kruskal-Walli's test was applied, followed by pairwise Mann-Whitney U tests with Bonferroni adjustments. Pearson or Spearman correlation coefficients were used to examine the relationships between hamstring metrics (e.g., strength, flexibility) and functional outcomes (e.g., jump height, endurance). Correlations were categorized as weak (r=0.1–0.3), moderate (r=0.3–0.5), or strong (r>0.5) (Cohen, 1988).

To assess inter-limb asymmetry, the percentage difference between dominant and non-dominant hamstrings was calculated using the formula 3 (Bishop, C., Read, P., Chavda, S., & Turner, A., 2016):

Asymmetry (%) = ((Dominant- Non-Dominant) / Average of Dominant and Non-Dominant) × 100

An asymmetry greater than 10% was used as a threshold to identify athletes at a higher risk for performance issues or injury. Effect sizes were reported to complement significant findings: Cohen's f^2 for regression models, partial eta squared (η^2) for ANOVA, and r^2 for correlations. Effect sizes were classified as small (0.02), medium (0.13), or large (0.26) following standard conventions. Subgroup analyses were performed to explore sport-specific trends. Separate regression models were created for each sport, and interaction effects between predictors (e.g., strength and flexibility) were examined using generalized linear models (GLM). Results were visualized through scatter plots with regression lines, bar graphs showing group means with standard deviations, and heatmaps highlighting p-values across variables and sports. These visualizations facilitated the interpretation of relationships and key findings in the context of different sports disciplines.

Ethical Approval

This study received ethical approval from the Ethical Committee of Kütahya Dumlupınar University, under the decision number 12.08.2024–388.

Findings

The heatmap below illustrates the coefficient of determination (R^2) and corresponding p-values for the relationship between various hamstring strength metrics and different sports disciplines. Darker shades represent lower p-values, indicating stronger statistical significance, while R^2 values reflect the strength of the explained variance across the measured variables.

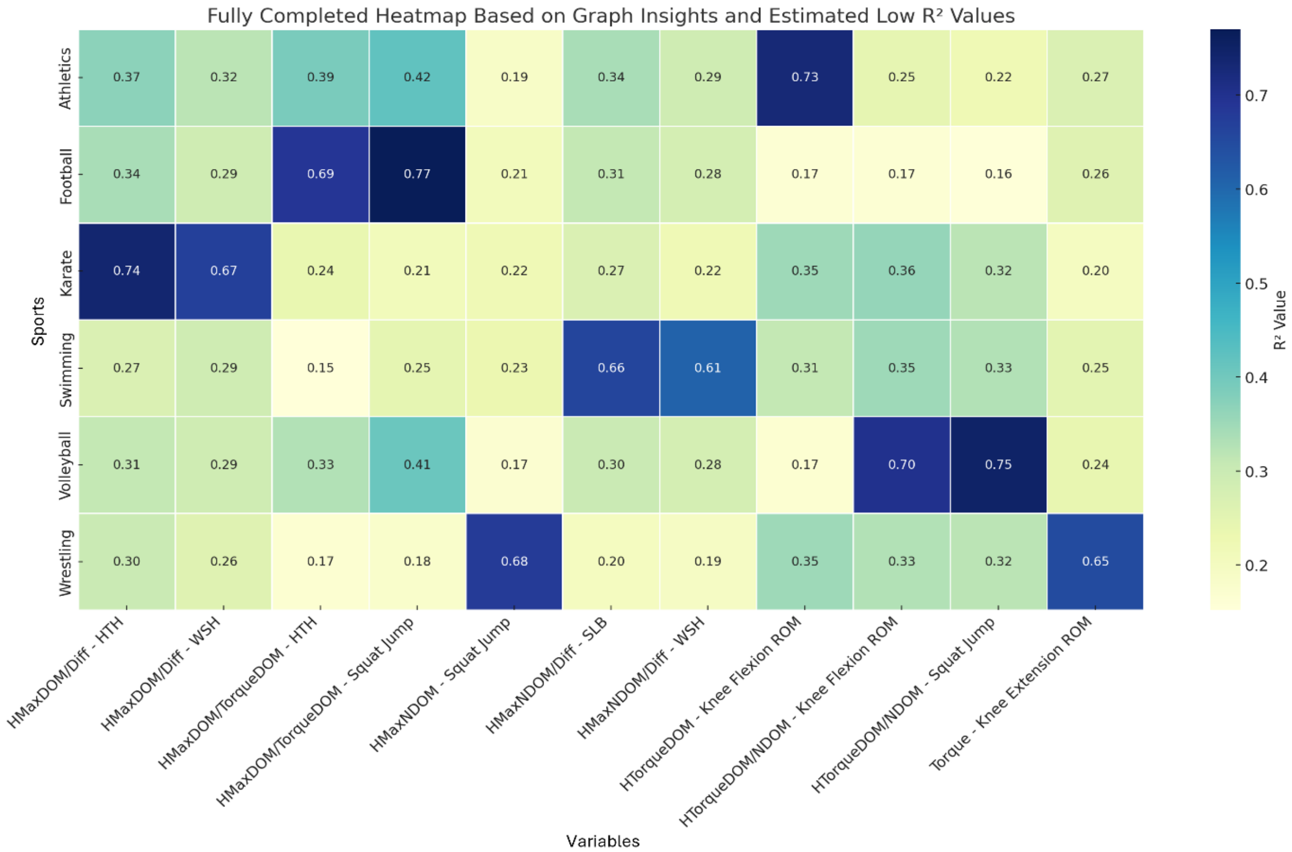

Figure 6. Heatmap of Sport-Specific Associations Between Hamstring Metrics and Functional Performance Outcomes (R^2 Values)

HMaxDOM: Maximal Hamstring Strength – Dominant Leg; HMaxNDOM: Maximal Hamstring Strength – Non-Dominant Leg; HMaxDiff: Interlimb Strength Difference; HTorqueDOM/NDOM: Hamstring Torque – Dominant/Non-Dominant Leg; HTH: Horizontal Trunk Hold; WSH: Wall Sit Hold; SLB: Single Leg Balance; ROM: Range of Motion

In volleyball, dominant and non-dominant hamstring torque values (HTorqueDOM, HTorqueNDOM) displayed strong positive correlations with Squat Jump (R^2=0.75, $p<0.001$) and Knee Flexion Range of Motion (ROM) (R^2=0.70, $p<0.01$) (Figure 6). These results emphasize the role of balanced hamstring strength in explosive jumping and lower-limb mobility, aligning with the sport's high demands for vertical power and flexibility.

In karate, dominant hamstring maximal strength (HMaxDOM) and inter-limb strength symmetry (HMaxDiff) had significant associations with Horizontal Trunk Hold (HTH) (R^2=0.74, $p<0.01$) and Wall Sit Hold (WSH) (R^2=0.67, $p<0.01$) (Figure 6), suggesting that core stabilization and endurance are influenced by hamstring strength symmetry and dominant leg stability.

In football, dominant hamstring maximal strength (HMaxDOM) and torque (HTorqueDOM) were strong predictors of Horizontal Trunk Hold (HTH) (R^2=0.69, $p<0.01$) and Squat Jump (R^2=0.77, $p<0.001$), underlining the importance of hamstring power for explosive sprinting and directional changes (Figure 6). The relationship highlights how lower-limb strength directly affects core stability and jumping ability, both critical in football.

For swimming, non-dominant hamstring strength (HMaxNDOM) and inter-limb asymmetry (HMaxDiff) significantly influenced Single Leg Bridge (SLB) (R^2=0.66, $p<0.05$) and Wall Sit Hold (WSH) (R^2=0.61, $p<0.05$) (Figure 6), demonstrating the necessity of balanced muscle engagement for optimal body positioning and endurance in the water.

In wrestling, non-dominant hamstring strength (HMaxNDOM) was a key determinant of Squat Jump (R^2=0.68, p<0.01), while hamstring torque values showed a notable effect on Knee Extension ROM (R^2=0.65, p<0.05) (Figure 6). These findings suggest that greater flexibility and strength in the non-dominant leg contribute to powerful and controlled takedown maneuvers

Finally, in athletics, dominant hamstring torque (HTorqueDOM) was a significant predictor of Knee Flexion ROM (R^2=0.73, p<0.001), reinforcing its critical role in enhancing knee mobility for running and jumping performance (Figure 6).

Discussion

This study examined the influence of hamstring strength and flexibility on functional performance across six different sports, revealing distinct, sport-specific relationships. Our findings demonstrate that hamstring strength and flexibility are crucial components of athletic performance, but their specific roles and importance vary considerably depending on the biomechanical demands of each sport. Regression analyses revealed that various aspects of hamstring strength significantly influence functional performance in a sport-specific manner. Specifically, we found that dominant leg hamstring strength was key for explosive movements in football, balanced hamstring strength was crucial for stability and endurance in swimming, both strength and flexibility were important in volleyball, dominant leg strength and inter-limb balance were important for static stability in karate, non-dominant leg strength and flexibility were critical in wrestling, and hamstring torque was significantly associated with knee flexion range of motion in athletics. These findings highlight the need for tailored training programs that address the specific needs of athletes in different sports.

In football, the association between dominant hamstring strength (HMaxDOM and HTorqueDOM) and explosive movements like squat jump was particularly strong. HMaxDOM showed a high coefficient of determination with squat jump (R^2= 0.77, p< 0.001), while the combination of HMaxDOM and torque measures also revealed a strong link with squat jump performance (R^2=0.69). These results align with previous findings that highlighted the importance of hamstring strength for sprinting and high-velocity actions in football (Mendiguchia, Alentorn-Geli, & Brughelli, 2012). Furthermore, hamstring strength plays a major role in pelvic stability and trunk control during fast movements such as kicking and sprinting (Hewett, 2004). The dominant leg's superior contribution supports the findings of Bloomfield, Polman, and O'Donoghue (2007), who emphasized the kicking leg's force production demands. Exercises that enhance both maximal and eccentric hamstring strength—such as Nordic hamstring curls and eccentric squats—are therefore essential (Askling, Tengvar, & Thorstensson, 2013). Regular monitoring of hamstring strength throughout the season can also help reduce injury risk (Gabbett, 2016).

In swimming, balanced hamstring strength was a significant factor for core stability and muscular endurance. The difference between dominant and non-dominant leg strength (HMaxDiff) was significantly associated with wall sit performance (R^2=0.66, p = 0.003), while HMaxNDOM also demonstrated a relevant association (R^2=0.61, p<0.05). Although swimming relies heavily on upper-body propulsion, hamstring strength supports streamlined positioning and propulsion through hip extension (Zhou et al., 2024). Imbalances in hamstring strength may result in compensatory trunk movements and inefficiencies. Similar conclusions were drawn by Wanivenhaus, Fox, Chaudhury, and Rodeo (2012), who recommended preseason screening of hamstring function. For swimmers, unilateral strengthening and core-focused exercises are key components of injury prevention strategies.

In volleyball, both hamstring strength and flexibility were critical. HTorqueNDOM and HTorqueDOM were significantly associated with squat jump height (R^2=0.75 and R^2=0.70, respectively; p=0.001). These findings support the idea that volleyball requires both high torque generation and dynamic range of motion in the lower limbs. Hamstring strength influences jump performance, while flexibility contributes to efficient movement mechanics (Hewett, 2004). Marques et al. (2009) similarly showed that hamstring stiffness affects explosive actions. As such, training plans for volleyball players should incorporate plyometrics and mobility drills such as proprioceptive neuromuscular facilitation (PNF) stretching.

In karate, static control and postural endurance were significantly associated with hamstring parameters. Dominant hamstring strength was associated with trunk hold time (R^2=0.74, p=0.012), and inter-limb asymmetry (HMaxDiff) was linked with wall sit performance (R^2=0.67, p=0.002). Karate relies heavily on balance and postural precision, particularly in stances and technique execution. Hamstring strength contributes to core stabilization and efficient force transfer (Chaouachi et al., 2014; Hewett, 2004). Karate practitioners may benefit from single-leg strength exercises, bridges, and isometric stability training.

In wrestling, non-dominant hamstring strength and flexibility were notably important. HMaxNDOM was significantly associated with squat jump performance (R^2=0.68, p=0.008), while hamstring torque also correlated with knee extension range of motion (R^2=0.65, p<0.05). These results are consistent with the sport's mechanical demands, where athletes frequently use the non-dominant leg to generate force and maintain balance during takedowns and grappling transitions (Maniar, Shield, Williams, Timmins, & Opar, 2016). A combination of non-dominant leg strengthening and hamstring flexibility is essential for optimizing wrestling performance and reducing injury risk.

Finally, in athletics, a significant association was observed between dominant hamstring torque and knee flexion range of motion (R^2=0.73, p<0.001). This reflects the need for both strength and mobility in sprinting, hurdling, and jumping events. Strong hamstrings contribute to hip extension and knee stabilization during high-speed movements, while flexibility allows for efficient biomechanics and injury prevention (Malliaropoulos et al., 2010). Similar recommendations are made by Edouard et al. (2022) and Shield & Bourne (2018), who emphasized hamstring mobility and eccentric strength development in track-based sports.

Despite its contributions, this study has several limitations. The sample size was limited and sport-specific, potentially restricting the generalizability of the results. The cross-sectional design precludes causal inferences about the relationships between hamstring metrics and performance. Additionally, the analysis did not account for individual biomechanical variations or training history, which could influence outcomes. Future research should incorporate larger and more diverse cohorts and employ longitudinal designs to explore these relationships over time. Advanced biomechanical tools, such as motion capture and electromyography, could provide more detailed insights into hamstring function during sports activities.

Conclusions

This study highlights the critical role of hamstring strength, flexibility, and endurance in shaping sport-specific performance outcomes across diverse athletic disciplines. The findings emphasize how different sports place unique biomechanical and functional demands on the hamstring muscle group. For instance, sports requiring explosive power, such as football and volleyball, rely heavily on dominant hamstring strength, while disciplines like swimming and wrestling demand balanced strength, flexibility, and endurance for stability and efficient movement. These insights offer valuable guidance for clinicians and coaches in designing tailored training and rehabilitation protocols that address the distinct needs of athletes in their respective sports. Future research should prioritize investigating the long-term effects of sport-specific training interventions targeting hamstring function. Moreover, a deeper exploration into the interactions between hamstring metrics, such as strength symmetry, joint range of motion, and core endurance, could provide a more comprehensive understanding of their influence on performance and injury prevention. Incorporating advanced biomechanical tools and longitudinal designs could further clarify the dynamic relationships between hamstring function and sport-specific demands, ultimately enhancing athletic success and reducing injury risks.

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Conflict of Interest

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Authors Contributions

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