applied sciences

MDPI

Article

The Effects of Skill Level on Lower-Limb Injury Risk During the Serve Landing Phase in Male Tennis Players

Jianqi Pan [1], Dong Sun [1,*], Fengping Li [1], Zhanyi Zhou [1], Yucheng Wang [1], Xuanzhen Cen [1], Yang Song [2] and Gusztáv Fekete [3,*]

1 Faculty of Sports Science, Ningbo University, Ningbo 315211, China; 2411040017@nbu.edu.cn (J.P.); 2211040065@nbu.edu.cn (F.L.); zhouzhanyi630@hotmail.com (Z.Z.); 2411040024@nbu.edu.cn (Y.W.)
2 Department of Biomedical Engineering, Faculty of Engineering, The Hong Kong Polytechnic University, Hong Kong, China; yangsong@polyu.edu.hk
3 Department of Materials Science and Technology, Audi Hungaria Faculty of Automotive Engineering, Széchenyi István University, 9026 Gyor, Hungary
* Correspondence: sundong@nbu.edu.cn (D.S.); fekete.gusztav@sze.hu (G.F.)

Abstract: The kinematic and kinetic performance of tennis players differs across skill levels, with joint range of motion (ROM), moments, and stiffness being strongly linked to injury risk. Focusing on the biomechanical characteristics of lower-limb joints throughout the landing stage, especially among athletes of different skill levels, aids in understanding the link between injury risk and performance level. This study recruited 15 male campus tennis enthusiasts and 15 male professional tennis players. The kinematic and kinetic differences between amateur and professional players during the landing phase of the tennis serve were analyzed using SPM1D 0.4.11 and SPSS 27.0.1, with independent-sample *t*-tests applied in both cases. Throughout the tennis serve's landing stage, the professional group exhibited significantly greater sagittal plane hip-joint stiffness ($p < 0.001$), horizontal plane moment (59~91%; $p = 0.036$), and a significantly higher peak moment ($p = 0.029$) in comparison with the amateur group. For the knee joint, the professional group exhibited significantly larger ROM in flexion–extension (0~82%; $p = 0.003$); along with greater ROM (0~29%; $p = 0.042$), moment (12~100%; $p < 0.001$), peak moment ($p < 0.001$) in adduction-abduction; and internal–external rotational moments (19~100%; $p < 0.001$) were markedly higher. The professional group showed significantly higher ankle joint ROM ($p < 0.001$) and moments (6~74%; $p = 0.004$) in the sagittal plane, as well as greater horizontal-plane ROM (27~67%; $p = 0.041$) and peak moments ($p < 0.001$). Compared with amateur tennis players, professional tennis players exhibit greater ROM, joint moments, and stiffness in specific planes, potentially increasing their risk of injury during the landing phase.

Keywords: kinematics; dynamics; tennis; platform serve; lower limbs; sports injury

check for updates

Academic Editor: Arkady Voloshin

Received: 7 February 2025
Revised: 25 February 2025
Accepted: 28 February 2025
Published: 3 March 2025

Citation: Pan, J.; Sun, D.; Li, F.; Zhou, Z.; Wang, Y.; Cen, X.; Song, Y.; Fekete, G. The Effects of Skill Level on Lower-Limb Injury Risk During the Serve Landing Phase in Male Tennis Players. *Appl. Sci.* **2025**, *15*, 2681. https://doi.org/10.3390/app15052681

1. Introduction

Tennis, a ball sport with its origins in France, was reintroduced as an official competition event at the 1988 Summer Olympics in Seoul [1]. The serve is a critical element in tennis, with an effective serve enabling athletes to gain points rapidly [2]. However, due to the unique nature of the tennis serve motion and its repetitive execution during competition, this movement is a common source of sports injuries [3]. During the tennis serve landing phase, in order to effectively absorb impact, the lower-limb joints must not only flex but also withstand torsional forces. Prolonged exposure to these forces can easily lead to joint injuries.

Pluim et al. [4] and Sell et al. [5] propose that compared with upper-limb and trunk injuries, lower-limb injuries occur at a higher rate in tennis. Renström's study [6] shows that one in five tennis injuries occur at the knee joint. Chronic injuries are more prevalent, accounting for the majority of cases [7]. Furthermore, Hjelm et al. [8] report that 80% of chronic tennis-related injuries lack a well-defined pathogenesis. Therefore, this underscores the necessity of investigating lower-limb injury risks when the serve landing occurs. This phase represents a characteristic jump–landing movement, during which frequently reported lower-limb injuries among players consist of patellofemoral issues, tendinopathy of the knee, meniscus damage, inflammation of the bursae, tennis leg, medial tibial stress syndrome, plantar fasciitis, and tennis toe [9–12]. From a biomechanical viewpoint, musculoskeletal injuries are the result of forces acting on the body [13]. Excessive mechanical stress on the musculoskeletal system can lead to overuse injuries, affecting bones, muscles, tendons, and ligaments [14]. Therefore, biomechanical metrics are commonly regarded as key tools for assessing injury risk. Van Mechelen et al. [15] suggest that ROM can serve as a relatively stable anthropometric measure to aid in the prediction of injuries. Aicale et al. [16] demonstrated that athletes with reduced ROM in the hip and knee joints have an increased likelihood of muscle strain. Many sports that require jumping frequently result in lower-limb injuries during landing, with the application of forces and moments to the body playing a significant role in causing these injuries [17]. Nigg et al. [18] suggest that in biomechanical injury analysis, both the force magnitude and anatomical geometry must be considered. Indicators such as stiffness, which integrate both the dynamics and kinematics of movement, provide more precise identification of individuals at risk of musculoskeletal injuries and can elucidate specific injury mechanisms through subsequent analysis [19]. An increase in lower-limb stiffness may elevate the risk of bone injury, as it is typically associated with a reduction in lower-limb joint displacement (ROM) and an increase in peak force. This combination results in a higher loading rate, subsequently raising the risk of injury [20]. Therefore, our study examined the ROM of lower extremity joints, joint moments (including peak moments), and lower extremity stiffness during the serve landing action of male tennis players.

Söğüt [21] found that although tennis players of different competitive levels demonstrate the same explosiveness during serves, there are significant differences in coordination during the serve. Such variations could affect lower-limb biomechanics during the serve landing phase, potentially increasing the risk of injury during both practice and matches. Lower-limb mechanics are a critical factor in determining the racket speed and ball velocity [22], with the biomechanics during serving varying across players of different skill levels, as reported in numerous studies on the effects of skill level differences on serve performance [23,24]. Chen et al. [25] indicate that professional athletes generate higher ball velocity and rotational velocity during the serving motion by employing greater knee flexion and extension velocities to strike the ball at a higher position. According to Martin et al. [26], high-level players generate higher ball speeds while serving, despite exhibiting similar forces and torques in the upper-body joints. Hernández-Davó et al. [27] found that professional players' serves exhibited both higher ball speed and greater accuracy compared with those of amateur players. Differences in the serve performance due to varying lower-limb biomechanics suggest that athletes of different skill levels exhibit distinct dynamic kinetic chains, which result in different muscle recruitment patterns and associated risks of musculoskeletal injuries and related conditions [28]. Injuries to the lower-limb joints can severely affect athletes' daily training and competition performance, potentially leading to psychological challenges and, ultimately, hindering their professional careers [29,30]. Currently, the relationship between lower-limb joint injuries caused by tennis and an athlete's skill level remains unclear. Examining the kinematics and dynamics of the lower limbs in professional and amateur tennis players during the landing phase of the serve can reveal injury mechanisms, aid in predicting sports injuries, and support the effective prevention of lower-limb joint injuries in tennis.

This study aims to examine and compare the kinematic and kinetic variations in lower-limb joints during the serve impact phase between professional and amateur male tennis players and to evaluate the related injury risks. We hypothesize that professional male tennis players perform more powerful movements during the serve phase, leading to a higher likelihood of lower-limb joint injuries.

2. Materials and Methods

2.1. Participants

The effect size for hip-joint stiffness in the sagittal plane was calculated as 1.158 based on preliminary study results, with the statistical power set at 0.8 and the significance level (α) at 0.05. According to G*Power 3.1 calculations, 13 participants per group are required, for a total of 26 participants across two groups. This study recruited 30 male tennis players (Table 1), including 15 amateur-level players (tennis majors) and 15 professional-level players (national level). All participants voluntarily took part in the experiment and provided signed informed consent. The amateur-level tennis players (tennis majors) had undergone at least five years of professional training. The national tennis players had finished in the top three at national-level competitions, as outlined in the "Tennis Athlete Technical Level Standard" released by the General Administration of Sport of China in 2021 (www.sport.gov.cn, accessed on 10 October 2024). The participant recruitment criteria were as follows: (1) The dominant hand is the right hand, and the landing leg for all subjects is the left leg; (2) At least one year of professional tennis training experience; (3) No history of lower-limb motor injuries within six months; (4) No other conditions that would interfere with completing a platform-style serve. This study protocol received approval from Ningbo University's Ethics Committee (TY2024044).

Table 1. Participants' demographic data.

Variable	n	Age (years)	Height (cm)	Weight (kg)	Years of Training
Amateur	15	21 ± 1.94	176 ± 2.67	70 ± 3.65	6.67 ± 1.29
Professional	15	20 ± 1.05	177 ± 2.69	71 ± 4.15	11.73 ± 0.96

The values are presented as the mean ± SD.

2.2. Experimental Procedure

During the athlete's serve landing phase, the motion dynamics and kinematics of their lower extremities were recorded by the Vicon motion-tracking system (Oxford Metrics Ltd., Oxford, UK) operating at 200 Hz, along with a Kistler force plate (Kistler Instrumente AG, Winterthur, Switzerland) recording at 1000 Hz. The marker model included 49 points, which were as follows: thoracic vertebrae 10, scapular—inferior angles, scapula—acromial edge, deltoid tuberosity, humeral lateral epicondyle, styloid tips of the radius and ulna, base of the index finger, anterior superior iliac spine, iliac crest, posterior superior iliac spine, three points of the thigh, lateral and medial epicondyles of the femur, fibular head, tibial tuberosity, calf triad, lateral and medial projections of malleoli, heel bone, dorsal margins of the first and fifth metatarsal heads, and dorsal side of the second metatarsal head.

Initially, the resting state of each athlete was individually recorded, which was defined as a period with no significant joint or muscle activity. This resting state was then used as the baseline for analyzing the athlete's dynamic serving motion. After the athlete had completed a full dynamic warm-up (DWU) [31], consisting of 4–5 min of self-directed general warm-up, 6–8 min of dynamic stretching, 10 min of tennis-specific high-intensity exercises, and 3 rounds of explosive movements with a 15 s rest between each round, a platform-style serve was simulated on the force platform, ensuring that the subject applied the same magnitude of force for each serve as they had for the first one. As shown in Figure 1, data analysis was conducted using the first five successful serves [32]. This study selected kinematic and dynamic indicators for the three joints of the lower limb in the sagittal, coronal, and horizontal planes [33], including ROM in degrees (°), moment and peak moment in Nm/kg, and stiffness in Nm/kg°, which was calculated using the formula shown below [20]:

$$K = \frac{\Delta M}{\Delta \theta} \tag{1}$$

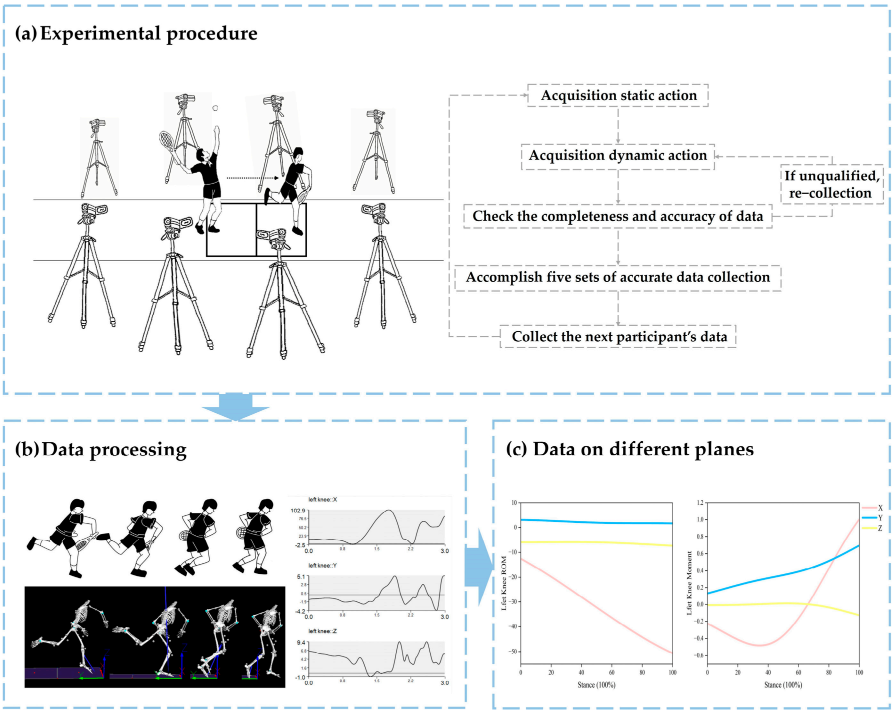

Figure 1. Experimental procedure and data analysis: (**a**) Experimental procedure: The Vicon system combined with a Kistler force plate was used to record kinematic and dynamic data of the serving motion; (**b**) Data processing using Visual 3D software, version 6; (**c**) Data analysis on different planes using the first five successful serves.

2.3. Data Processing

The experimental data, collected and converted simultaneously, were analyzed with Vicon Nexus 2.6.1 software. The process involved marker labeling, identification, trajectory gap interpolation, and the assigning of names. Finally, the entire dataset was transferred in "*c3d" format to Visual 3D (version 6; C-Motion, Inc., Germantown, MD, USA) for detailed examination. The data underwent processing via a low-pass filter of the fourth order, featuring a 10 Hz cut-off frequency, as cited in reference [34]. Joint moments were calibrated in relation to the body weights of the participants. All the data points from every phase of motion were standardized to a total of 101.

2.4. Statistical Analysis

Following standardization, a normality test was performed, and data are shown as the mean ± SD, with a significance threshold of 0.05. Independent-sample t-tests were applied in both analyses. ROM and joint moment differences between the two groups of tennis players were analyzed using Spm1d 0.4.11 in MATLAB R2024a (The MathWorks, Natick, MA, USA), while peak moments and joint stiffness were examined using SPSS 27.0.1 (IBM Corp, Armonk, NY, USA).

3. Results

3.1. ROM

Figure 2 illustrates the left hip-joint ROM of male professional and amateur tennis players during the serve's landing phase. The degree of hip flexion in professional tennis players is greater than that of amateur tennis players; however, there is no notable difference ($p > 0.05$) (Figure 2a). During the landing phase of a tennis serve on the horizontal plane, amateur male tennis players demonstrate significantly greater hip external rotation ROM compared with professional players (45~100%; $p = 0.026$) (Figure 2c).

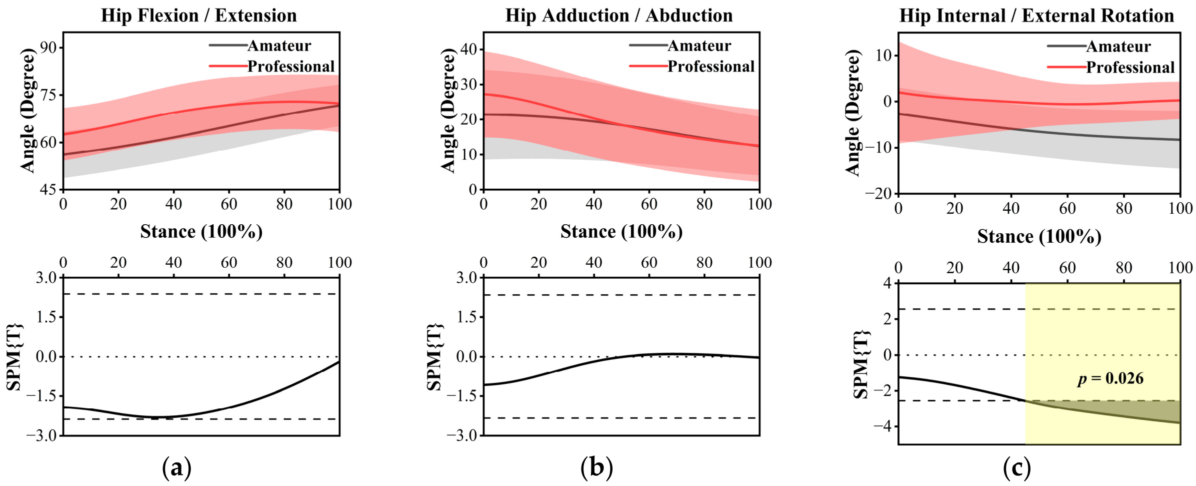

Figure 2. The three-plane ROM of the left hip joint: (**a**) Sagittal plane; (**b**) Coronal plane; (**c**) Horizontal plane.

During the landing phase of the serve, professional male tennis players exhibit a significantly larger ROM of the left knee joint compared with amateur male players in the sagittal plane (0~82%; $p = 0.003$) (Figure 3a) and the coronal plane (0~29%; $p = 0.042$) (Figure 3b). As shown in Figure 3c, no notable difference in ROM of the left knee in the horizontal plane is observed between professional and amateur male tennis players ($p > 0.05$).

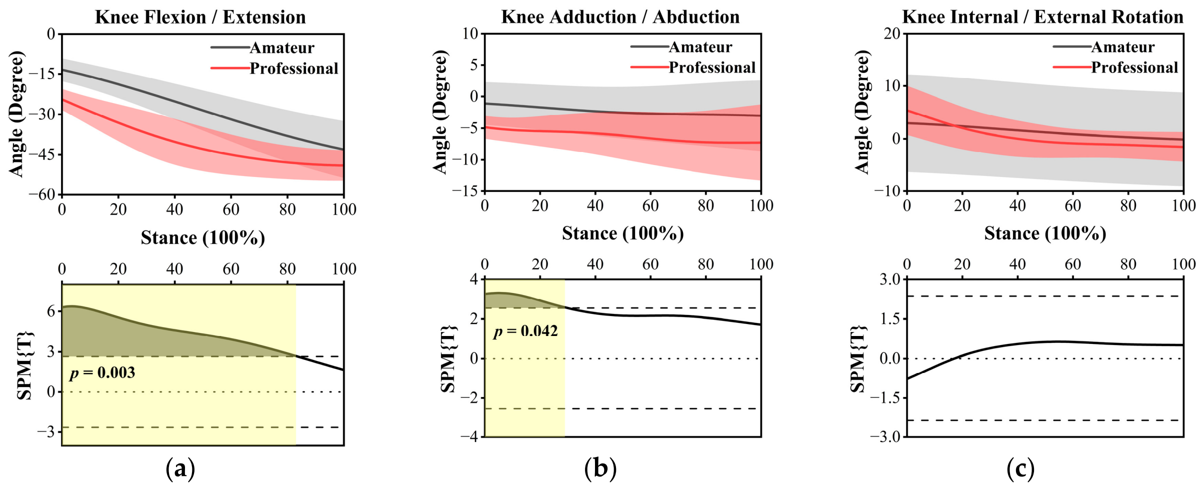

Figure 3. Three-plane ROM of the left knee joint: (**a**) sagittal plane; (**b**) coronal plane; (**c**) horizontal plane.

Throughout the serve's landing phase, the left ankle joint's sagittal-plane ROM differs significantly between male tennis players of varying competitive levels ($p < 0.001$), with professional players exhibiting a greater ankle-joint ROM (Figure 4a). There is no significant difference in the left ankle inversion–eversion ROM between professional and amateur male tennis players ($p \geq 0.05$) (Figure 4b). During the landing phase of the serve, the horizontal-plane ROM of the left ankle joint is significantly greater in professional male tennis players compared with that of amateurs (27~67%; $p = 0.041$) (Figure 4c).

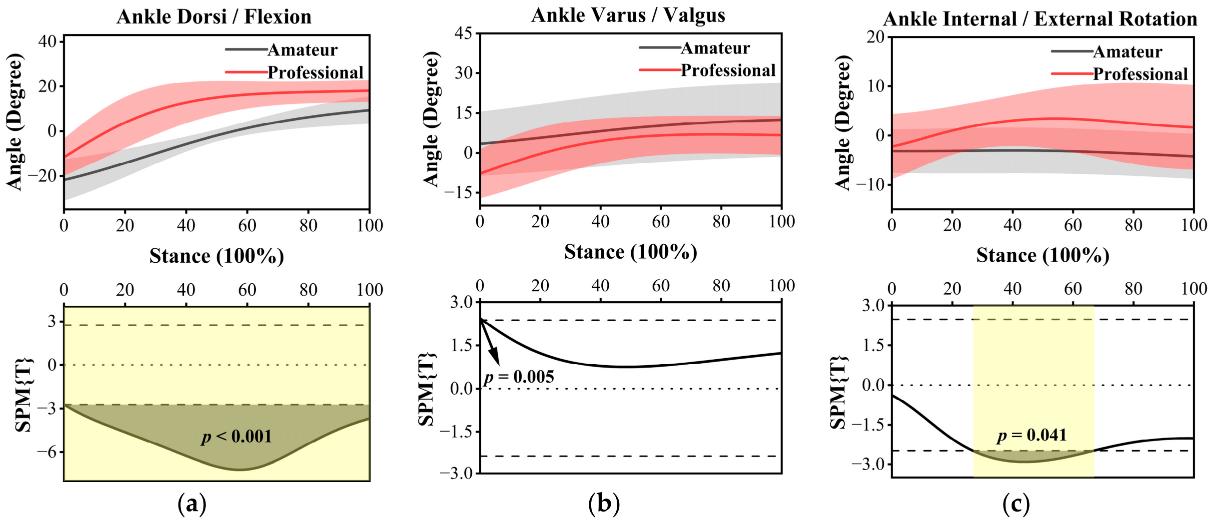

Figure 4. Three-plane ROM of the left ankle joint: (**a**) Sagittal plane; (**b**) Coronal plane; (**c**) Horizontal plane.

3.2. Joint Moment

Though the difference is not significant ($p > 0.05$), in the landing phase of the serve, a larger left hip-joint moment in the sagittal plane is observed in professional male tennis players compared with amateurs (Figure 5a). The moment variations of the left hip joint in the coronal plane among male tennis players of two performance levels also show no significant differences ($p > 0.05$) (Figure 5b). Professional male tennis players demonstrate a significantly higher left hip internal rotation moment during the serve's landing phase than amateur male players (59~91%; $p = 0.036$) (Figure 5c).

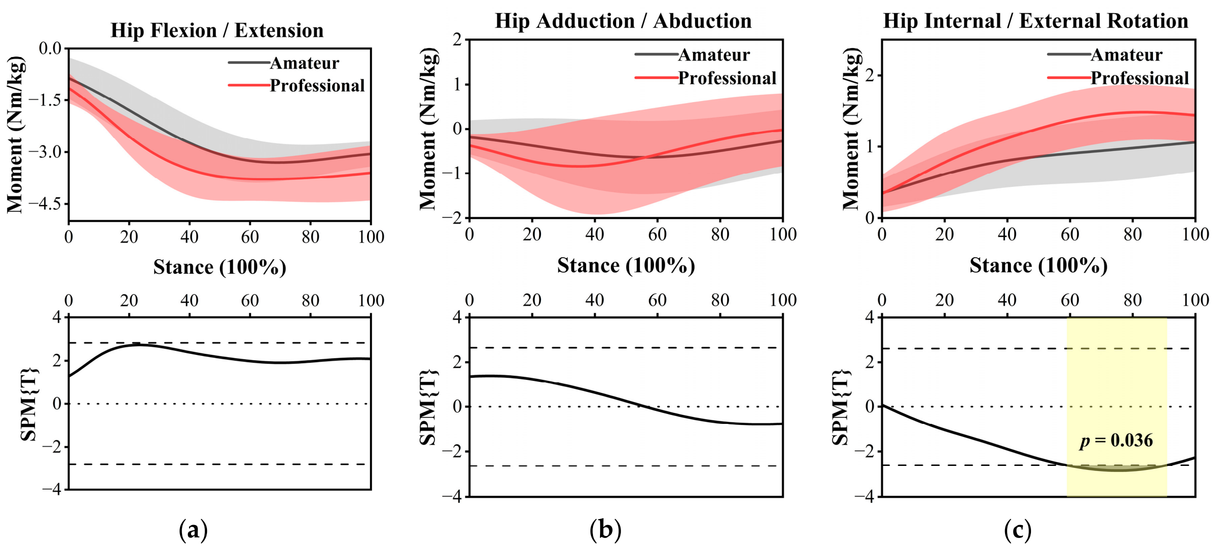

Figure 5. Three-plane moment of the left hip joint: (**a**) Sagittal plane; (**b**) Coronal plane; (**c**) Horizontal plane.

The variations in the left knee flexion–extension moment throughout the serve's landing phase show no significant differences between professional and amateur male tennis players ($p > 0.05$) (Figure 6a). Throughout the landing phase of the tennis serve, professional male tennis players exhibit a significantly higher left knee adduction moment compared with amateur male players (12~100%; $p < 0.001$) (Figure 6b). The horizontal plane moment at the left knee joint of professional male tennis players is markedly higher than that of amateur players (19~100%; $p < 0.001$) (Figure 6c).

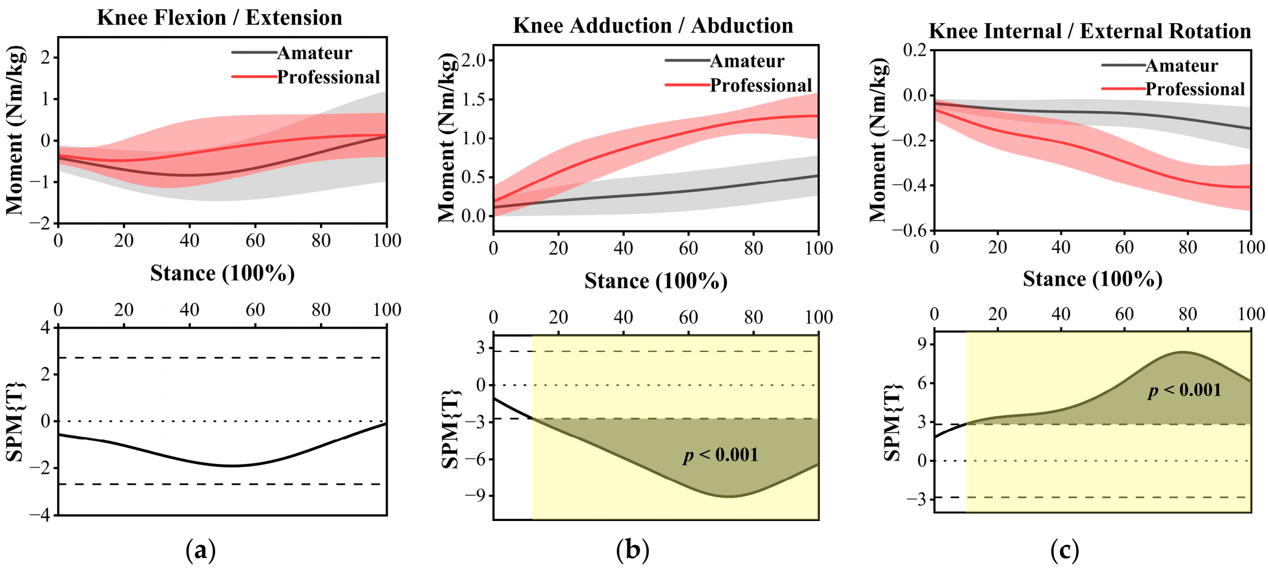

Figure 6. Three-plane moment of the left knee joint: (**a**) Sagittal plane; (**b**) Coronal plane; (**c**) Horizontal plane.

Professional male tennis players demonstrate a significantly higher plantarflexion moment in the left ankle joint throughout the landing phase of serving than amateur male players (6~74%; $p = 0.004$) (Figure 7a). In the coronal and horizontal planes, no significant differences in the moments of the left ankle joint are observed between male tennis players at professional and amateur levels ($p > 0.05$) (Figure 7b,c).

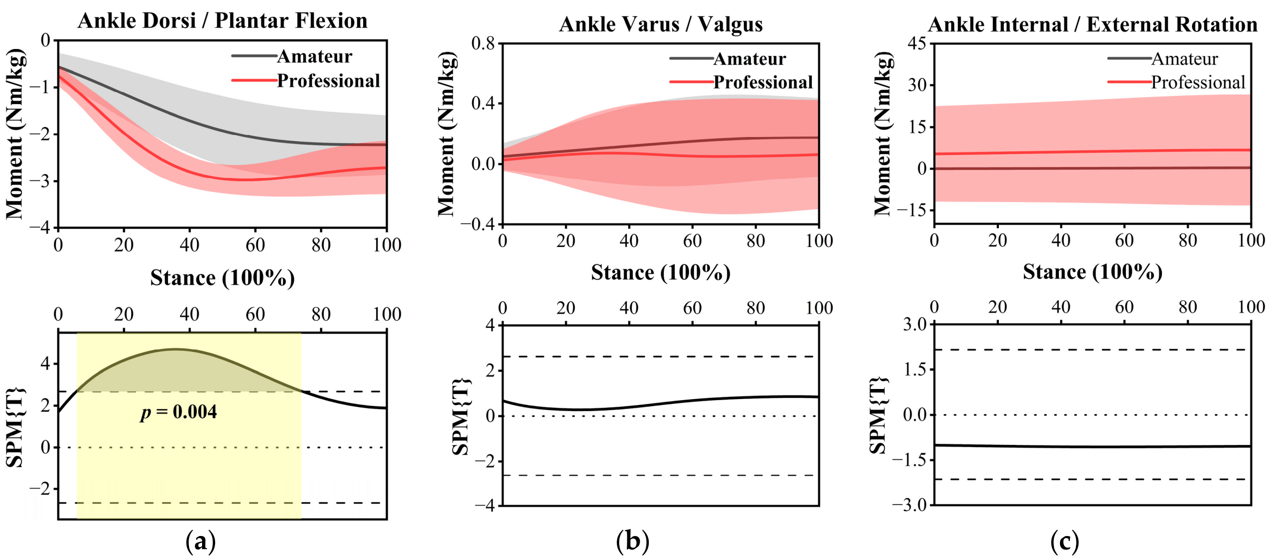

Figure 7. Three-plane moment of the left ankle joint: (**a**) Sagittal plane; (**b**) Coronal plane; (**c**) Horizontal plane.

As shown in Table 2, during the landing phase of the serve, except for the peak moment in the frontal plane of the left ankle joint, professional male tennis players exhibit higher peak moments compared with amateur players. However, significant differences are noted solely in peak moments of the left hip joint in the horizontal plane ($p = 0.029$), the knee joint within the coronal plane ($p < 0.001$), and the ankle joint within the horizontal plane ($p < 0.001$) between the two groups. Skill differences do not have a significant impact on the peak moments of the three lower-limb joints in professional male tennis players during the landing phase of the serve in other planes ($p > 0.05$).

Table 2. Peak joint moments of the left lower limb.

Joint	Plane	Amateur	Professional	*p*
Hip	X	−0.866 ± 0.589	−1.151 ± 0.438	0.212
	Y	−0.069 ± 0.506	0.110 ± 0.661	0.482
	Z	1.094 ± 0.417	1.511 ± 0.417	0.029
Knee	X	0.235 ± 0.955	0.337 ± 0.608	0.764
	Y	0.521 ± 0.259	1.354 ± 0.244	<0.001
	Z	−0.034 ± 0.257	−0.063 ± 0.468	0.087
Ankle	X	−0.569 ± 0.296	−0.755 ± 0.211	0.104
	Y	0.217 ± 0.215	0.173 ± 0.287	0.690
	Z	0.360 ± 0.175	0.678 ± 0.137	<0.001

The values are presented as the mean ± SD; $n = 30$ ($n = 15$ per group).

3.3. Stiffness of Lower Extremities

In the sagittal plane, professional male tennis players demonstrate significantly greater left hip-joint stiffness compared with amateur players ($p < 0.05$) (Table 3). However, no significant differences in stiffness of left lower-limb joints are observed among the two groups of male tennis players during the serve's landing phase in other planes.

Table 3. Joint stiffness of the left lower limb.

Joint	Plane	Amateur	Professional	*p*
Hip	X	0.166 ± 0.049	0.278 ± 0.079	<0.001
	Y	0.088 ± 0.054	0.075 ± 0.022	0.478
	Z	0.161 ± 0.112	0.162 ± 0.065	0.987
Knee	X	0.036 ± 0.009	0.037 ± 0.008	0.761
	Y	0.253 ± 0.177	0.249 ± 0.123	0.954
	Z	0.063 ± 0.066	0.076 ± 0.095	0.732
Ankle	X	0.094 ± 0.129	0.076 ± 0.011	0.658
	Y	0.027 ± 0.013	0.036 ± 0.046	0.540
	Z	0.265 ± 0.278	0.429 ± 1.010	0.609

The values are presented as the mean ± SD; $n = 30$ ($n = 15$ per group).

4. Discussion

In tennis matches, the number of serves in each service game exceeds that of any other stroke type [35]. Serves directly influence match outcomes [36], as players strive to score points through serves to secure victory. Tennis serving requires the coordination of lower-limb joints [37]. The serve motion is categorized into three stages: the pre-serve jump, lift-off, and the landing phase [38]. The landing phase primarily relies on the action of a single lower limb [39], imposing significant demands on the muscular control of the athlete's lower limb, potentially leading to an elevated injury risk. Differences in the serve performance among tennis players with varying skill levels [40] may result in varying risks of lower-limb joint injuries. Thus, the study investigated differences in ROM, joint moments (including peak moments), and lower-limb joint stiffness in the landing phase of the serve between professional and amateur male tennis players (Table 4), highlighting differences in lower-limb movements and force dynamics during this phase for players with varying skill levels. Consistent with the hypothesis, professional male tennis players adopt a more aggressive approach during the serve phase.

Table 4. Variations in lower-limb joint mechanics between male tennis players of two skill levels.

Joint	Plane	ROM	Joint Moment	Peak Joint Moment	Joint Stiffness
Hip	X	-	-	-	<0.001
	Y	-	-	-	-
	Z	0.026 (45~100%)	0.036 (59~91%)	0.029	-
Knee	X	0.003 (0~82%)	-	-	-
	Y	0.042 (0~29%)	<0.001 (12~100%)	<0.001	-
	Z	-	<0.001 (19~100%)	-	-
Ankle	X	<0.001	0.004 (6~74%)	-	-
	Y	-	-	-	-
	Z	0.041 (27~67%)	-	<0.001	-

The values are presented as *p*, with only significant *p*-values reported.

At the hip joint, professionals exhibit significantly higher internal–external rotation moments and peak moments in the horizontal plane, whereas amateurs demonstrate a significantly greater ROM. This suggests that professionals can generate greater force with a smaller joint ROM, reflecting more efficient force transmission and control, as confirmed by the findings of Muaidi et al. [41]. However, prolonged exposure of the hip joint to high-load forces may result in chronic injuries, while atypical force trajectories in the hip joint could potentially impact the knee joint as well, consequently increasing the likelihood of knee injuries [42]. The results indicate that during the landing phase of the serve, professional male tennis players demonstrate greater hip flexion–extension stiffness. Durand et al. [43] found a positive relationship between lower-limb stiffness and explosive strength. However, excessive joint stiffness, which limits ROM, may increase the risk of joint injuries under impact [44,45]. During the landing phase, athletes experience substantial ground reaction forces and internal muscle forces, which could pose a higher risk of hip injuries for professional male tennis players.

The results indicate that during the landing phase of the serve, professional male tennis players exhibit significantly greater knee-joint ROM in the sagittal plane compared with amateur male tennis players. An excessive ROM may increase the load on the lower-limb extensor muscles [46], thereby elevating the risk of injury. Dynamic valgus and increased valgus moments during landing are considered to be contributing factors to anterior cruciate ligament (ACL) injuries, based on research carried out by Hewett et al. [47]. In this study, professional male tennis players show significantly increased knee abduction ROM, moments, and peak moments compared with amateur players, indicating that the professional group might face an elevated risk of knee injury. Ueno et al. [48] also observes that a larger knee abduction moment raises the likelihood of ACL injury. Excessive external moments are recognized to increase knee-joint laxity, which may result in damage to medial and lateral collateral ligaments, the anterior cruciate ligament, and the posterolateral region [49]. This study's findings reveal that knee-joint moment in the horizontal plane is significantly greater in the professional group. This implies that professional male tennis players may face a greater risk of knee-joint injuries compared with amateur players.

Inversion is the most common mechanism of injury for ankle joints [50]. However, this study finds no notable variation in ROM in the frontal plane when comparing professional and amateur male tennis players. Excessive peak forces and training loads have been recognized as contributing factors that elevate the likelihood of muscle injuries and bone tissue damage in professional athletes [51,52]. The findings of this study indicate that professional male tennis players exhibit considerably higher ROM and moments in the sagittal plane, along with higher ROM and peak moments at the ankle joint in the transverse plane compared with amateur male players. It is speculated that the landing phase of the serve may pose a higher risk of ankle injuries to professional male tennis players.

Athletes must control and optimize the efficiency and stability of their movements during the serve to sustain optimal performance levels [37]. The lower-limb movement and pelvic thrust initiate the kinetic chain during the serve, playing a vital role in generating powerful trunk rotational moments [53,54]. Athletes' leg strength positively correlates with serve speed, as found by Kaya et al. [55]. Furthermore, it is important to note that upper-limb and trunk movements also influence lower-limb biomechanics [56,57]. Improvements in upper-limb function help to enhance overall stability [58,59], which affects the joint angles, forces, and overall biomechanics during landing. Therefore, additional studies are required to gain a comprehensive understanding of the complex relationships among upper-limb, trunk, and lower-limb biomechanics, especially in the context of injury prevention. This study focuses on lower-limb injury risks during the serve landing phase. Aligning with the results of this study, Chéron et al. [60] found that lower limbs are more prone to injury during athletic activities, and Hopper et al. [61] observed that young high-level athletes are more susceptible to lower-extremity injuries. This might be because athletes with higher skill levels are more likely to display greater intensity or to engage in risk-taking behaviors compared with their amateur counterparts, thereby increasing their injury risk. However, further research is required to identify effective strategies for preventing sports-related injuries. Uninjured tennis players typically demonstrate greater efficiency in energy transfer [26], highlighting the importance of studying lower-extremity injury prevention during specific landing phases, such as after jumps or quick directional changes. Previous studies have primarily focused on systematically developing tennis injury prevention programs [62], but there remains a lack of personalized strategies that account for individual differences. Future research should further investigate how to tailor prevention plans based on athletes' specific characteristics, thereby enhancing athletic performance while preventing injuries and maintaining health.

While further investigation is necessary to create more effective injury prevention measures for sports, present injury prevention guidelines for tennis include strengthening the lower-limb muscles [63], enhancing flexibility [64], and optimizing the method of training [65]. Hewett et al. [66] have also found that enhanced proprioception and neuromuscular control can effectively decrease the risk of injury. Daily recovery routines like stretching, relaxation, as well as adequate warming up and cooling down, contribute considerably toward the reduction in injuries of the lower extremities when engaged in sports like tennis [67,68]. Modification of these protective measures according to the specific athletes can also optimize their effectiveness [4]. Additionally, specific training aimed at correcting injury-prone movement patterns and preventing muscle imbalances along the kinetic chain can significantly lower the occurrence of both acute and chronic injuries in tennis players [69]. Therefore, when designing training and research programs for tennis players, it is crucial to thoroughly comprehend the physiological requirements of the sport and to adopt a holistic approach to injury prevention [70].

During the serve landing phase, professional-level male tennis players in this study demonstrate greater ROM, joint moments, peak moments, and stiffness in certain planes of the lower limbs. It is hypothesized that this increased lower-limb involvement is intended to enhance the serve performance and scoring potential, but it may also contribute to a heightened risk of injury. Kinematic and dynamic assessments confirm the hypothesis of this study, highlighting notable differences in the lower-limb biomechanical performance between male tennis players of varying skill levels during the serve landing phase. However, several limitations exist in this study. The analysis of tennis serving biomechanics may be constrained, as the tests were conducted in a controlled laboratory environment that did not account for the variable conditions found in actual tennis matches, such as differences in surfaces like clay, grass, and hard courts. These environmental differences were not replicated in the lab. Future research could explore real-world scenarios or apply finite element analysis to better simulate these conditions. Finite element analysis, along with musculoskeletal modeling, has been widely applied to explore the biomechanical behavior of human internal tissues during movement [71–74]. Therefore, we will incorporate this method to examine the biomechanical impact of serve landing on lower-limb injury risks and further clarify potential injury mechanisms. Specifically, finite element analysis can simulate the responses of bones, muscles, and tissues to dynamic forces during the serve landing [75], providing deeper insights into the forces contributing to injury risk. Musculoskeletal analysis can help identify muscle imbalances or improper joint movements that may increase injury susceptibility [76], offering a more comprehensive understanding of injury mechanisms while complementing the current study.

The findings of this study can inform practical applications in tennis injury prevention and performance optimization. Understanding the kinematic and kinetic differences between professional and amateur players can guide the development of personalized training programs. Adjusting training plans based on athletes' specific biomechanical needs can effectively reduce the risk of lower-extremity injuries in tennis players.

5. Conclusions

This study analyzes the kinematic and dynamic performance of male tennis players across various skill levels during the serve landing phase, revealing distinct differences in lower-limb biomechanics between professionals and amateurs. Compared with amateur tennis players, professional tennis players showed greater ROM, joint moments, and stiffness in some lower-limb joint planes during the serve landing phase. These findings help predict lower-limb injury risks in tennis players during the serve landing phase. Future biomechanical research could focus on developing personalized, biomechanically informed exercise programs for tennis players to prevent and mitigate lower-limb joint injuries.

Author Contributions: Conceptualization, J.P., Z.Z. and Y.W.; methodology, F.L. and Z.Z.; formal analysis, J.P.; investigation, J.P. and Y.W.; resources, D.S. and Y.W.; data curation, Z.Z.; writing—original draft preparation, J.P.; writing—review and editing, D.S., F.L., Z.Z., Y.W., X.C., Y.S. and G.F.; visualization, J.P. and Z.Z.; supervision, D.S. and F.L.; project administration, D.S. and F.L.; funding acquisition, D.S. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Zhejiang Province Science Fund for Distinguished Young Scholars, grant number LR22A020002; the Ningbo Key Research and Development Program, grant number 2022Z196; the Zhejiang Rehabilitation Medical Association Scientific Research Special Fund, grant number ZKKY2023001, ZKKY2024012; the Research Academy of Medicine Combining Sports, Ningbo, grant number No.2023001; the Project of Ningbo Leading Medical & Health Discipline, grant number No.2022-F15, No.2022-F22; the Ningbo No.2 Hospital Huamei Research Fund, grant number 2024HMKYA53; the Ningbo Natural Science Foundation, grant number 2022J065; and the K. C. Wong Magna Fund from Ningbo University.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Ningbo University (TY2024044; 13 December 2024).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are only available upon request from the corresponding author due to privacy considerations.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Llewellyn, M.P.; Lake, R.J. *Tennis and the Olympics: An Historical Examination of Their On-Off Relationship Since 1896*; Routledge International Handbooks; First Issued in Paperback 2020; Routledge: London, UK; New York, NY, USA, 2020; ISBN 978-1-315-53357-5.
2. Chow, J.; Carlton, L.; Lim, Y.-T.; Chae, W.-S.; Shim, J.-H.; Kuenster, A.; Kokubun, K. Comparing the Pre- and Post-Impact Ball and Racquet Kinematics of Elite Tennis Players' First and Second Serves: A Preliminary Study. *J. Sports Sci.* **2003**, *21*, 529–537. [CrossRef] [PubMed]
3. Abrams, G.D.; Sheets, A.L.; Andriacchi, T.P.; Safran, M.R. Review of Tennis Serve Motion Analysis and the Biomechanics of Three Serve Types with Implications for Injury. *Sports Biomech.* **2011**, *10*, 378–390. [CrossRef] [PubMed]
4. Pluim, B.M.; Staal, J.B.; Windler, G.E.; Jayanthi, N. Tennis Injuries: Occurrence, Aetiology, and Prevention. *Br. J. Sports Med.* **2006**, *40*, 415–423. [CrossRef] [PubMed]
5. Sell, K.; Hainline, B.; Yorio, M.; Kovacs, M. Injury Trend Analysis from the US Open Tennis Championships between 1994 and 2009. *Br. J. Sports Med.* **2014**, *48*, 546–551. [CrossRef]
6. Renström, P.A.F.H. Knee Pain in Tennis Players. *Clin. Sports Med.* **1995**, *14*, 163–175. [CrossRef]
7. Pluim, B.M.; Loeffen, F.G.J.; Clarsen, B.; Bahr, R.; Verhagen, E.A.L.M. A One-season Prospective Study of Injuries and Illness in Elite Junior Tennis. *Scand. Med. Sci. Sports* **2016**, *26*, 564–571. [CrossRef]
8. Hjelm, N.; Werner, S.; Renstrom, P. Injury Profile in Junior Tennis Players: A Prospective Two Year Study. *Knee Surg. Sports Traumatol. Arthrosc.* **2010**, *18*, 845–850. [CrossRef]
9. Delgado, G.J.; Chung, C.B.; Lektrakul, N.; Azocar, P.; Botte, M.J.; Coria, D.; Bosch, E.; Resnick, D. Tennis Leg: Clinical US Study of 141 Patients and Anatomic Investigation of Four Cadavers with MR Imaging and US. *Radiology* **2002**, *224*, 112–119. [CrossRef]
10. Perkins, R.H.; Davis, D. Musculoskeletal Injuries in Tennis. *Phys. Med. Rehabil. Clin.* **2006**, *17*, 609–631. [CrossRef]
11. Abrams, G.D.; Renstrom, P.A.; Safran, M.R. Epidemiology of Musculoskeletal Injury in the Tennis Player. *Br. J. Sports Med.* **2012**, *46*, 492–498. [CrossRef]
12. van der Does, H.T.D.; Brink, M.S.; Benjaminse, A.; Visscher, C.; Lemmink, K.A.P.M. Jump Landing Characteristics Predict Lower Extremity Injuries in Indoor Team Sports. *Int. J. Sports Med.* **2016**, *37*, 251–256. [CrossRef] [PubMed]
13. Getgood, A.; Hoshino, Y.; Roessler, P.P.; Kuroroda, R.; Piedade, S.R. Biomechanics of Musculoskeletal Injuries. In *The Sports Medicine Physician*; Rocha Piedade, S., Imhoff, A.B., Clatworthy, M., Cohen, M., Espregueira-Mendes, J., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 27–35, ISBN 978-3-030-10432-0.
14. Aicale, R.; Tarantino, D.; Maffulli, N. Overuse Injuries in Sport: A Comprehensive Overview. *J. Orthop. Surg. Res.* **2018**, *13*, 309–319. [CrossRef] [PubMed]
15. van Mechelen, W.; Hlobil, H.; Zijlstra, W.P.; de Ridder, M.; Kemper, H.C.G. Is Range of Motion of the Hip and Ankle Joint Related to Running Injuries? *Int. J. Sports Med.* **1992**, *13*, 605–610. [CrossRef] [PubMed]
16. Bradley, P.S.; Portas, M.D. The Relationship Between Preseason Range of Motion and Muscle Strain Injury in Elite Soccer Players. *J. Strength Cond. Res.* **2007**, *21*, 1155–1159.
17. Dufek, J.S.; Bates, B.T. Biomechanical Factors Associated with Injury During Landing in Jump Sports. *Sports Med.* **1991**, *12*, 326–337. [CrossRef]
18. Nigg, B.M. Biomechanics, Load Analysis and Sports Injuries in the Lower Extremities. *Sports Med.* **1985**, *2*, 367–379. [CrossRef]
19. Lorimer, A.V.; Keogh, J.W.L.; Hume, P.A. Using Stiffness to Assess Injury Risk: Comparison of Methods for Quantifying Stiffness and Their Reliability in Triathletes. *PeerJ* **2018**, *6*, e5845. [CrossRef]
20. Butler, R.J.; Crowell, H.P.; Davis, I.M. Lower Extremity Stiffness: Implications for Performance and Injury. *Clin. Biomech.* **2003**, *18*, 511–517. [CrossRef]
21. Söğüt, M. A Comparison of Serve Speed and Motor Coordination between Elite and Club Level Tennis Players. *J. Hum. Kinet.* **2017**, *55*, 171–176. [CrossRef]
22. Reid, M.; Elliott, B.; Alderson, J. Lower-Limb Coordination and Shoulder Joint Mechanics in the Tennis Serve. *Med. Sci. Sports Exerc.* **2008**, *40*, 308–315. [CrossRef]
23. Colomar, J.; Corbi, F.; Brich, Q.; Baiget, E. Determinant Physical Factors of Tennis Serve Velocity: A Brief Review. *Int. J. Sports Physiol. Perform.* **2022**, *17*, 1159–1169. [CrossRef] [PubMed]

24. Pluim, B.M.; Jansen, M.G.T.; Williamson, S.; Berry, C.; Camporesi, S.; Fagher, K.; Heron, N.; Van Rensburg, D.C.J.; Moreno-Pérez, V.; Murray, A.; et al. Physical Demands of Tennis Across the Different Court Surfaces, Performance Levels and Sexes: A Systematic Review with Meta-Analysis. *Sports Med.* **2023**, *53*, 807–836. [CrossRef]
25. Chen, Y.; Wang, T.; Zhao, Y.; Zhan, G.; Tang, Y.; Wang, Z. Kinematic Differences between Female National and Provincial Athletes in the Tennis Serve. *PeerJ* **2024**, *12*, e18410. [CrossRef] [PubMed]
26. Martin, C.; Bideau, B.; Ropars, M.; Delamarche, P.; Kulpa, R. Upper Limb Joint Kinetic Analysis during Tennis Serve: Assessment of Competitive Level on Efficiency and Injury Risks. *Scand. Med. Sci. Sports* **2014**, *24*, 700–707. [CrossRef] [PubMed]
27. Hernández-Davó, J.L.; Moreno, F.J.; Sanz-Rivas, D.; Hernández-Davó, H.; Coves, Á.; Caballero, C. Variations in Kinematic Variables and Performance in the Tennis Serve According to Age and Skill Level. *Int. J. Perform. Anal. Sport* **2019**, *19*, 749–762. [CrossRef]
28. Liang, Z.; Wu, J.; Yu, J.; Ying, S.; Liu, Z.; Zhang, Y.; Gu, Y.; Li, J. Comparison and Analysis of the Biomechanics of the Lower Limbs of Female Tennis Players of Different Levels in Foot-up Serve. *Front. Physiol.* **2023**, *14*, 1125240. [CrossRef]
29. Olmedilla Zafra, A.; Prieto Andreu, J.M.; Blas Redondo, A. Relaciones entre estrés psicosocial y lesiones deportivas en tenistas. *Univ. Psychol.* **2010**, *10*, 909–922. [CrossRef]
30. Guevara, S.; Sheehy, D.; Waddington, G.; Drew, M.; Keegan, R.; Toohey, L. Injuries Impacted a Third of Athletes Who Left the High-Performance Sport Pathway. A 4-Year Retrospective Study. *J. Sci. Med. Sport* **2024**, *27*, S40. [CrossRef]
31. Ayala, F.; Moreno-Pérez, V.; Vera-Garcia, F.J.; Moya, M.; Sanz-Rivas, D.; Fernandez-Fernandez, J. Acute and Time-Course Effects of Traditional and Dynamic Warm-Up Routines in Young Elite Junior Tennis Players. *PLoS ONE* **2016**, *11*, e0152790. [CrossRef]
32. Fong, C.-M.; Blackburn, J.T.; Norcross, M.F.; McGrath, M.; Padua, D.A. Ankle-Dorsiflexion Range of Motion and Landing Biomechanics. *J. Athl. Train.* **2011**, *46*, 5–10. [CrossRef]
33. Blackburn, J.T.; Padua, D.A. Sagittal-Plane Trunk Position, Landing Forces, and Quadriceps Electromyographic Activity. *J. Athl. Train.* **2009**, *44*, 174–179. [CrossRef] [PubMed]
34. Pan, J.; Ho, M.M.Y.; Loh, R.B.C.; Iskandar, M.N.S.; Kong, P.W. Foot morphology and running gait pattern between the left and right limbs in recreational runners. *Phys. Act. Health* **2023**, *7*, 43–52. [CrossRef]
35. Johnson, C.D. Performance Demands of Professional Male Tennis Players. *Br. J. Sports Med.* **2006**, *40*, 696–699. [CrossRef] [PubMed]
36. Kovalchik, S.A.; Reid, M. Comparing Matchplay Characteristics and Physical Demands of Junior and Professional Tennis Athletes in the Era of Big Data. *J. Sports Sci. Med.* **2017**, *16*, 489–497.
37. Chang, H.; Cen, X. Can running technique modification benefit patellofemoral pain improvement in runners? A systematic review and meta-analysis. *Int. J. Biomed. Eng. Technol.* **2024**, *45*, 83–101. [CrossRef]
38. Kovacs, M.; Ellenbecker, T. An 8-Stage Model for Evaluating the Tennis Serve: Implications for Performance Enhancement and Injury Prevention. *Sports Health A Multidiscip. Approach* **2011**, *3*, 504–513. [CrossRef]
39. Lambrich, J.; Muehlbauer, T. Biomechanical Analyses of Different Serve and Groundstroke Techniques in Tennis: A Systematic Scoping Review. *PLoS ONE* **2023**, *18*, e0290320. [CrossRef]
40. Girard, O.; Micallef, J.-P.; Millet, G.P. Lower-Limb Activity during the Power Serve in Tennis: Effects of Performance Level. *Med. Sci. Sports Exerc.* **2005**, *37*, 1021.
41. Muaidi, Q.I.; Nicholson, L.L.; Refshauge, K.M. Do Elite Athletes Exhibit Enhanced Proprioceptive Acuity, Range and Strength of Knee Rotation Compared with Non-Athletes? *Scand. J. Med. Sci. Sports* **2009**, *19*, 103–112. [CrossRef]
42. Powers, C.M. The Influence of Abnormal Hip Mechanics on Knee Injury: A Biomechanical Perspective. *J. Orthop. Sports Phys. Ther.* **2010**, *40*, 42–51. [CrossRef]
43. Durand, S.; Ripamonti, M.; Beaune, B.; Rahmani, A. Leg Ability Factors in Tennis Players. *Int. J. Sports Med.* **2010**, *31*, 882–886. [CrossRef] [PubMed]
44. Devita, P.; Skelly, W.A. Effect of Landing Stiffness on Joint Kinetics and Energetics in the Lower Extremity. *Med. Sci. Sports Exerc.* **1992**, *24*, 108–115. [CrossRef] [PubMed]
45. Pruyn, E.C.; Watsford, M.L.; Murphy, A.J.; Pine, M.J.; Spurrs, R.W.; Cameron, M.L.; Johnston, R.J. Relationship between Leg Stiffness and Lower Body Injuries in Professional Australian Football. *J. Sports Sci.* **2012**, *30*, 71–78. [CrossRef] [PubMed]
46. Rice, R.P.; Roach, K.; Kirk-Sanchez, N.; Waltz, B.; Ellenbecker, T.S.; Jayanthi, N.; Raya, M. Age and Gender Differences in Injuries and Risk Factors in Elite Junior and Professional Tennis Players. *Sports Health A Multidiscip. Approach* **2022**, *14*, 466–477. [CrossRef]
47. Hewett, T.E.; Myer, G.D.; Ford, K.R.; Heidt, R.S.; Colosimo, A.J.; McLean, S.G.; van den Bogert, A.J.; Paterno, M.V.; Succop, P. Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study. *Am. J. Sports Med.* **2005**, *33*, 492–501. [CrossRef]
48. Ueno, R.; Navacchia, A.; DiCesare, C.A.; Ford, K.R.; Myer, G.D.; Ishida, T.; Tohyama, H.; Hewett, T.E. Knee Abduction Moment Is Predicted by Lower Gluteus Medius Force and Larger Vertical and Lateral Ground Reaction Forces during Drop Vertical Jump in Female Athletes. *J. Biomech.* **2020**, *103*, 109669. [CrossRef]

49. Csintalan, R.P.; Ehsan, A.; McGarry, M.H.; Fithian, D.F.; Lee, T.Q. Biomechanical and Anatomical Effects of an External Rotational Torque Applied to the Knee: A Cadaveric Study. *Am. J. Sports Med.* **2006**, *34*, 1623–1629. [CrossRef]
50. van den Bekerom, M.P.J.; Oostra, R.J.; Alvarez, P.G.; van Dijk, C.N. The Anatomy in Relation to Injury of the Lateral Collateral Ligaments of the Ankle: A Current Concepts Review. *Clin. Anat.* **2008**, *21*, 619–626. [CrossRef]
51. Windt, J.; Gabbett, T.J. How Do Training and Competition Workloads Relate to Injury? The Workload—Injury Aetiology Model. *Br. J. Sports Med.* **2017**, *51*, 428–435. [CrossRef]
52. Sugimoto, D.; McCartney, R.E.; Parisien, R.L.; Dashe, J.; Borg, D.R.; Meehan, W.P. Range of Motion and Ankle Injury History Association with Sex in Pediatric and Adolescent Athletes. *Physician Sportsmed.* **2018**, *46*, 24–29. [CrossRef]
53. Elliott, B. Biomechanics and Tennis. *Br. J. Sports Med.* **2006**, *40*, 392–396. [CrossRef] [PubMed]
54. Reid, M.; Whiteside, D.; Gilbin, G.; Elliott, B. Effect of a Common Task Constraint on the Body, Racket, and Ball Kinematics of the Elite Junior Tennis Serve. *Sports Biomech.* **2013**, *12*, 15–22. [CrossRef] [PubMed]
55. Kaya, M.; Soyal, M.; Karakuş, M. The Effect of the Leg and Back Strength of the Serve and Tennis Players to the Serve Throwing Speed and Agility. *Phys. Educ. Stud.* **2018**, *22*, 237–242. [CrossRef]
56. Leteneur, S.; Gillet, C.; Sadeghi, H.; Allard, P.; Barbier, F. Effect of Trunk Inclination on Lower Limb Joint and Lumbar Moments in Able Men during the Stance Phase of Gait. *Clin. Biomech.* **2009**, *24*, 190–195. [CrossRef]
57. Müller, R.; Ertelt, T.; Blickhan, R. Low Back Pain Affects Trunk as Well as Lower Limb Movements during Walking and Running. *J. Biomech.* **2015**, *48*, 1009–1014. [CrossRef]
58. Sciascia, A.; Cromwell, R. Kinetic Chain Rehabilitation: A Theoretical Framework. *Rehabil. Res. Pract.* **2012**, *2012*, 853037. [CrossRef]
59. Sidiropoulos, A.; Magill, R.; Gordon, A. Coordination of the Upper and Lower Extremities during Walking in Children with Cerebral Palsy. *Gait Posture* **2021**, *86*, 251–255. [CrossRef]
60. Chéron, C.; Le Scanff, C.; Leboeuf-Yde, C. Association between Sports Type and Overuse Injuries of Extremities in Adults: A Systematic Review. *Chiropr. Man. Ther.* **2017**, *25*, 4–13. [CrossRef]
61. Hopper, D.M.; Hopper, J.L.; Elliott, B.C. Do Selected Kinanthropometric and Performance Variables Predict Injuries in Female Netball Players? *J. Sports Sci.* **1995**, *13*, 213–222. [CrossRef]
62. Pas, H.I.M.F.L.; Bodde, S.; Kerkhoffs, G.M.M.J.; Pluim, B.; Tiemessen, I.J.H.; Tol, J.L.; Verhagen, E.; Gouttebarge, V. Systematic Development of a Tennis Injury Prevention Programme. *BMJ Open Sport Exerc. Med.* **2018**, *4*, e000350. [CrossRef]
63. Fleck, S.J.; Falkel, J.E. Value of Resistance Training for the Reduction of Sports Injuries. *Sports Med.* **1986**, *3*, 61–68. [CrossRef] [PubMed]
64. Zheng, Z.; Xia, Q. Effcets of Flexibility Exercises to Prevent Knee Injuries in Tennis Players. *Rev. Bras. Med. Esporte* **2023**, *29*, e2023_0040. [CrossRef]
65. Pluim, B.M.; Drew, M.K. It's Not the Destination, It's the 'Road to Load' That Matters: A Tennis Injury Prevention Perspective. *Br. J. Sports Med.* **2016**, *50*, 641–642. [CrossRef] [PubMed]
66. Hewett, T.E.; Lindenfeld, T.N.; Riccobene, J.V.; Noyes, F.R. The Effect of Neuromuscular Training on the Incidence of Knee Injury in Female Athletes. A Prospective Study. *Am. J. Sports Med.* **1999**, *27*, 699–706. [CrossRef]
67. McHugh, M.P.; Cosgrave, C.H. To Stretch or Not to Stretch: The Role of Stretching in Injury Prevention and Performance. *Scand. J. Med. Sci. Sports* **2010**, *20*, 169–181. [CrossRef]
68. Ayala, F.; Calderón-López, A.; Delgado-Gosálbez, J.C.; Parra-Sánchez, S.; Pomares-Noguera, C.; Hernández-Sánchez, S.; López-Valenciano, A.; Croix, M.D.S. Acute Effects of Three Neuromuscular Warm-Up Strategies on Several Physical Performance Measures in Football Players. *PLoS ONE* **2017**, *12*, e0169660. [CrossRef]
69. Dines, J.S.; Bedi, A.; Williams, P.N.; Dodson, C.C.; Ellenbecker, T.S.; Altchek, D.W.; Windler, G.; Dines, D.M. Tennis Injuries: Epidemiology, Pathophysiology, and Treatment. *J. Am. Acad. Orthop. Surg.* **2015**, *23*, 181–189. [CrossRef]
70. Kovacs, M.S. Applied Physiology of Tennis Performance. *Br. J. Sports Med.* **2006**, *40*, 381–386. [CrossRef]
71. Sun, D.; Song, Y.; Cen, X.; Wang, M.; Baker, J.S.; Gu, Y. Workflow Assessing the Effect of Achilles Tendon Rupture on Gait Function and Metatarsal Stress: Combined Musculoskeletal Modeling and Finite Element Analysis. *Proc. Inst. Mech. Eng. H* **2022**, *236*, 676–685. [CrossRef]
72. Song, Y.; Cen, X.; Sun, D.; Bálint, K.; Wang, Y.; Chen, H.; Gao, G.; Bíró, I.; Zhang, M.; Gu, Y. Curved carbon-plated shoe may further reduce forefoot loads compared to flat plate during running. *Sci. Rep.* **2024**, *14*, 13215. [CrossRef]
73. Cen, X.; Song, Y.; Yu, P.; Sun, D.; Simon, J.; Bíró, I.; Gu, Y. Effects of Plantar Fascia Stiffness on the Internal Mechanics of Idiopathic Pes Cavus by Finite Element Analysis: Implications for Metatarsalgia. *Comput. Methods Biomech. Biomed. Eng.* **2024**, *27*, 1961–1969. [CrossRef] [PubMed]
74. Song, Y.; Cen, X.; Wang, M.; Bálint, K.; Tan, Q.; Sun, D.; Gao, S.; Li, F.; Gu, Y.; Wang, Y.; et al. The Influence of Simulated Worn Shoe and Foot Inversion on Heel Internal Biomechanics during Running Impact: A Subject-Specific Finite Element Analysis. *J. Biomech.* **2025**, *180*, 112517. [CrossRef] [PubMed]

75. Shu, L.; Yamamoto, K.; Yoshizaki, R.; Yao, J.; Sato, T.; Sugita, N. Multiscale Finite Element Musculoskeletal Model for Intact Knee Dynamics. *Comput. Biol. Med.* **2022**, *141*, 105023. [CrossRef] [PubMed]
76. Bulat, M.; Korkmaz Can, N.; Arslan, Y.Z.; Herzog, W. Musculoskeletal Simulation Tools for Understanding Mechanisms of Lower-Limb Sports Injuries. *Curr. Sports Med. Rep.* **2019**, *18*, 210–216. [CrossRef]