SIN-CHN SCIENTIFIC PRESS PTE.LTD.

Molecular & Cellular Biomechanics 2025, 22(3), 1306.
https://doi.org/10.62617/mcb1306

Article

Finite element analysis of stress distribution in knee joint structures during soccer instep kick

Lifu Xing[1,†], Fengping Li[2,†], Dong Sun[2,*], Zixiang Gao[3], Monèm Jemni[4], Yang Song[5,*], Yaodong Gu[2]

[1] Department of Physical Education, Ningbo University of Finance and Economics, Ningbo 315175, China
[2] Faculty of Sports Science, Ningbo University, Ningbo 315211, China
[3] Faculty of Kinesiology, University of Calgary, Calgary, AB T2N 1N4, Canada
[4] Centre for Mental Health Research in Association, University of Cambridge, Cambridge CB2 1TN, United Kingdom
[5] Faculty of Engineering, The Hong Kong Polytechnic University, Hong Kong, China
*** Corresponding authors:** Dong Sun, nbusundong@hotmail.com; Yang Song, yangsong@polyu.edu.hk
[†] Equally contributed first author.

CITATION

Xing L, Li F, Sun D, et al. Finite element analysis of stress distribution in knee joint structures during soccer instep kick. Molecular & Cellular Biomechanics. 2025; 22(3): 1306. https://doi.org/10.62617/mcb1306

ARTICLE INFO

Received: 6 January 2025
Accepted: 6 February 2025
Available online: 20 February 2025

Abstract: This observational study investigates the stress distribution in knee joint structures, specifically focusing on the meniscus and primary ligaments of the supporting leg during the support phase of a maximal-effort soccer instep kick executed by an elite-level player. Understanding these stress patterns is crucial for injury prevention and enhancing performance in high-impact soccer actions. A three-dimensional (3D) knee model was developed utilizing CT and MRI data. Finite element (FE) analysis was conducted to evaluate stress distribution patterns across the lateral and medial menisci, medial collateral ligament (MCL), and anterior cruciate ligament (ACL). The analysis revealed peak von Mises stresses of 16.127 MPa in the lateral meniscus, 10.845 MPa in the medial meniscus, 36.613 MPa in the MCL, and 22.863 MPa in the ACL. These findings indicate significant stress concentrations in the lateral meniscus, proximal MCL, and femoral insertion of the ACL. The identified stress distribution patterns specifically related to the knee joint during the instep kicking phase provide critical insights into the internal mechanical demands placed on the joint structures. This study enhances the understanding of stress concentrations in the meniscus and ligaments during soccer kicks, emphasizing the potential for targeted analysis of these stress patterns to inform injury prevention strategies. It suggests that a deeper comprehension of the stress distribution mechanics could contribute to more effective training protocols and rehabilitation approaches for athletes, ultimately improving performance and reducing the likelihood of knee injuries during soccer activities.

Keywords: soccer; knee joint; finite element analysis; biomechanics

1. Introduction

In soccer, the kicking action, particularly the instep kick, is critical for achieving accuracy and power, both essential for high-level performance [1]. Moreover, the instep kick is one of the most fundamental and frequently executed movements in soccer, serving as a critical skill for passing, shooting, and other essential game scenarios. Its biomechanical significance has been widely documented, particularly regarding the generation of substantial valgus forces, shear stresses, and rotational moments acting on the supporting leg. These forces have been strongly associated with common knee injuries, including damage to the anterior cruciate ligament (ACL), medial collateral ligament (MCL), and meniscus. Research has shown that the instep kick requires precise neuromuscular coordination and places significant mechanical demands on the knee joint, resulting in increased susceptibility to injury under high-loading conditions [2]. Specifically, the valgus forces and rotational moments generated during the movement have been closely linked to strain and potential failure of the ACL and MCL [3]. This movement is known to generate substantial biomechanical loads on the knee joint, particularly in the supporting leg, which undergoes complex interactions between muscles, ligaments, and bone structures during dynamic actions like kicking [4]. The stability of the knee joint during these actions relies heavily on key ligaments, including the ACL and the MCL, and cartilage structures that buffer forces and assist in joint stability [5]. Understanding the stress and strain distributions in these components can offer valuable insights into injury mechanisms, as soccer players are prone to knee injuries, with the ACL and MCL being particularly susceptible due to the high valgus and rotational forces exerted during play [6–8].

In previous biomechanical studies on the supporting leg during soccer shooting, Tamura et al. utilized a three-dimensional motion analysis system to examine the relationship between supporting leg stiffness and trunk kinematics of the kicking leg [3]. Their findings indicated that the stiffness of the supporting leg may restrict trunk rotation during the kicking motion. Sakamoto et al. focused on gender differences, investigating the instep kick mechanics of female soccer players. They discovered a significant negative correlation between the speed of the kicking leg and the range of motion of the supporting leg's knee joint, with a correlation coefficient of $r = -0.73$ [9]. They recommended that female soccer players should minimize the flexion angle of the supporting leg's knee joint during the preparatory phase of the instep kick. While these analyses optimize shooting mechanics for the supporting leg, it is important to recognize that enhancing athletic performance often brings an increased risk of injury. Studies indicate that one in every four MCL injuries in soccer is a non-contact injury [7].

Historically, video analysis has been a common method for exploring injury factors. For instance, Zago et al. conducted a large-scale reconstruction of three-dimensional (3D) whole-body kinematics in male elite soccer players to investigate the biomechanical factors associated with ACL injuries, comparing joint angle time courses across various scenarios [10]. However, research focusing on the biomechanical state of the knee joint during athletic movements, particularly concerning the internal forces acting on the supporting leg's knee joint during shooting, remains limited.

A comprehensive analysis of the internal force conditions of structures under high-risk movements can contribute to the prevention of related injuries, thereby enhancing athlete safety and performance. Finite element (FE) analysis has become a pivotal tool for investigating internal joint mechanics and understanding injury risks in sports [11–13]. By simulating realistic boundary conditions and applying accurate joint loads, FEA allows researchers to analyze stress and strain distributions across joint structures in ways that are not feasible with experimental methods alone. Studies utilizing FEA to model knee mechanics have revealed essential information regarding load distribution patterns in ligamentous and cartilaginous structures, contributing to a better understanding of how specific movements, such as cutting, landing, or pivoting, impact knee integrity [14–16]. However, while many studies have focused on general lower-limb mechanics or knee joint loads during jumping and landing, less attention has been devoted to the impact of soccer-specific actions, such as the instep kick, on knee joint mechanics.

The present study leverages FEA to simulate the knee joint of an elite soccer player during the support phase of an instep kick, focusing on stress and strain distributions in the ACL, MCL, and meniscus. By applying the specific boundary conditions and knee joint loads derived from motion capture data collected during the instep kick, we aim to provide a precise analysis of how these structures respond to load under soccer-specific conditions. Such findings can expand upon existing knowledge of joint mechanics in soccer instep kicks, providing crucial insights into injury prevention strategies. Identifying high-stress areas within the knee joint during support-phase actions could contribute to more targeted conditioning, ultimately reducing the incidence of injuries among soccer players. This research also builds on the findings of previous studies by incorporating high-resolution MRI and CT data to enhance the accuracy of anatomical modeling. By integrating advanced imaging techniques, we reinforce the study's relevance for understanding the complex biomechanics of specific moves of soccer, contributing to future investigations into injury mechanisms and rehabilitation practices.

2. Methods

2.1. Participant information

A single elite-level soccer player (age 22, height 176 cm, weight 64 kg) was recruited for this study. The participant was free of musculoskeletal disorders and had no history of orthopedic surgeries. Analysis was conducted on the participant's dominant (left) foot. Before participation, informed consent was obtained, and the participant signed a consent agreement. Lower limb imaging was performed using computed tomography (CT) and magnetic resonance imaging (MRI) to capture detailed anatomical data. The CT scan was conducted with a GE DISCOVERY CT 750 HD scanner (Tianjin Hospital) using a scan voltage of 120 kV, a current of 300 mA, and a slice thickness of 0.625 mm. Additionally, sagittal MRI imaging of the knee joint was obtained using a 3.0 T MRI scanner (GE DISCOVERY MR 750, Tianjin Hospital) with a slice thickness of 1 mm and an interslice gap of 0 mm.

2.2. Experimental setup and motion capture

The flow chart is shown in **Figure 1**. The experiment was conducted on indoor artificial turf, with the ball placed at a fixed distance of 6 m from a small indoor goal (2 m wide and 1.5 m high). Before the trials, participants performed a warm-up routine that included 10 min of jogging followed by 5 min of dynamic stretching specific to soccer. After warming up, participants performed two maximal instep kicks to familiarize themselves with the kicking force required for the test. The participant used the size 5 soccer ball, with the ball pressure maintained at 10 psi using a pressure testing device. Participants kicked with their preferred leg, adjusting their approach angle (between 30° and 45°) and distance (up to 2 m) based on their comfort. Participants were instructed to perform instep kicks "with maximum effort, aiming to hit the center of the target" [17,18]. A 30-s interval was provided between each kick, and the participant continued until he completed five "successful" trials (where the ball speed was within ± 5% of the target speed and the shot accurately aimed at the center of the goal). Three successful trials were selected for subsequent analysis.

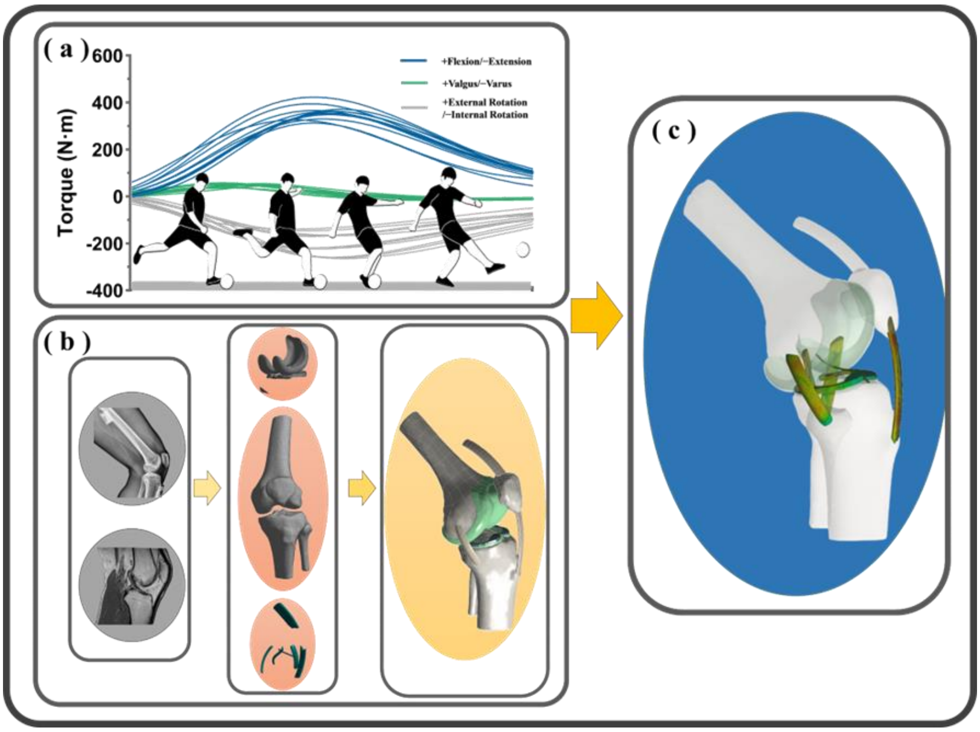

Figure 1. Experimental flowchart. **(a)** motion capture; **(b)** knee joint model development; **(c)** finite element simulation results.

For each successful trial, participants placed their supporting foot on a force platform. By previous protocols, 38 reflective markers were affixed to the participants. Motion capture was conducted using a 10-camera Vicon system at a sampling rate of 200 Hz (Oxford Metrics Ltd., Oxford, UK), and ground reaction force (GRF) data were recorded with two embedded force plates at a frequency of 2000 Hz (Kistler Instruments AG, Winterthur, Switzerland). Following storage in C3D format collected forces and motions were filtered and processed with standard inverse dynamics software (Visual3D, C-Motion, Germantown, MD, USA). The three-dimensional knee joint moments derived from the processed motion capture data were used as loading conditions for subsequent FE simulations of the knee joint.

2.3. Finite element model construction

We obtained an initial model of the knee joint bones from CT data and an initial model of the menisci from MRI data. Characteristic points from the CT and MRI images were then aligned, and the insertion points of various ligaments were identified. Based on the knee joint moments obtained from Visual3D analysis, the knee joint angles were adjusted in SolidWorks 2021 (SolidWorks Corporation, MA, United States) to correspond to the moment when the peak resultant knee joint torque was observed during the motion. The model includes the distal femur, proximal tibia, proximal fibula, medial and lateral menisci (MM and LM), femoral and tibial cartilages, anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL), and lateral collateral ligament (LCL). All components were modeled as isotropic linear elastic materials, with specific material properties assigned as shown in **Table 1** [19,20]. Mesh generation was performed in Ansys Workbench 2021 R1 (developed by ANSYS, Inc., located in Canonsburg, Pennsylvania, USA). All bones and soft tissues were meshed using 4-node linear tetrahedral elements (C3D4). The ligaments were also meshed with C3D4 as they effectively captured the detailed geometry and specific insertion sites, as well as the internal stress and strain states. The element sizes were set to 3 mm for bones, 1 mm for the menisci and cartilage, and 1.5 mm for the ligaments [21].

Table 1. Material parameters of the model components.

	Young's Modulus E (MPa)	Poisson's ratio (ν)	Mesh Size (mm)
Bone	12,000	0.3	3
Cartilage	5	0.46	1
Meniscus	59	0.45	1
ACL	116	0.3	1.5
PCL	87	0.3	1.5
MCL	48	0.3	1.5
LCL	48	0.3	1.5
PT	87	0.3	1.5

2.4. Model validation

To validate the effectiveness of the FE model, a 134 N anterior force was applied to the tibial plateau along the anterior-posterior axis. The femur was fully constrained in all six degrees of freedom, while the tibia was allowed to move only in the anterior-posterior direction. Frictionless contact was assumed between the tibial and femoral cartilage. These loading conditions were selected to match the experimental setup reported in previous studies. The resulting anterior tibial displacement was then compared to findings from similar experiments conducted by other researchers.

2.5. Boundary conditions and loading

The FE model incorporated boundary conditions derived from motion capture data obtained during the support phase of a soccer instep kick. An isothermal condition was assumed to focus exclusively on the biomechanical response of the knee joint under dynamic loading, as supported by recent studies. Frictionless contact was defined between the menisci and the tibial and femoral cartilages to simplify the modeling of contact interactions. The six degrees of freedom of the distal tibia and fibula were constrained, and the loading conditions were derived from three-dimensional knee joint moments averaged over three successful trials of a soccer instep kick performed by a single participant. The time point for analysis was selected based on the peak magnitude of the resultant knee joint moment. At this moment, the supporting leg was in a flexed (64.69°), externally rotated (4.23°), and varus-aligned (2.07°) position. The corresponding joint moments were 3.81 N·m in the flexion-extension direction, 0.53 N·m in the internal-external rotation direction, and 0.26 N·m in the varus-valgus direction.

3. Results

3.1. Knee joint model validation

The FE model was validated by measuring the anterior displacement of the tibia upon the application of the 134 N anterior force, resulting in a displacement of 4.83 mm. This measured tibial displacement was then compared to previous studies under similar loading conditions, which reported displacement of 4.30 mm and 4.91 mm under an anterior load of 134 N [2,15]. The alignment of the model's predicted results with those from previous research confirms the accuracy and reliability of this model for simulating knee joint mechanics.

3.2. Peak stress and stress distribution in the meniscus

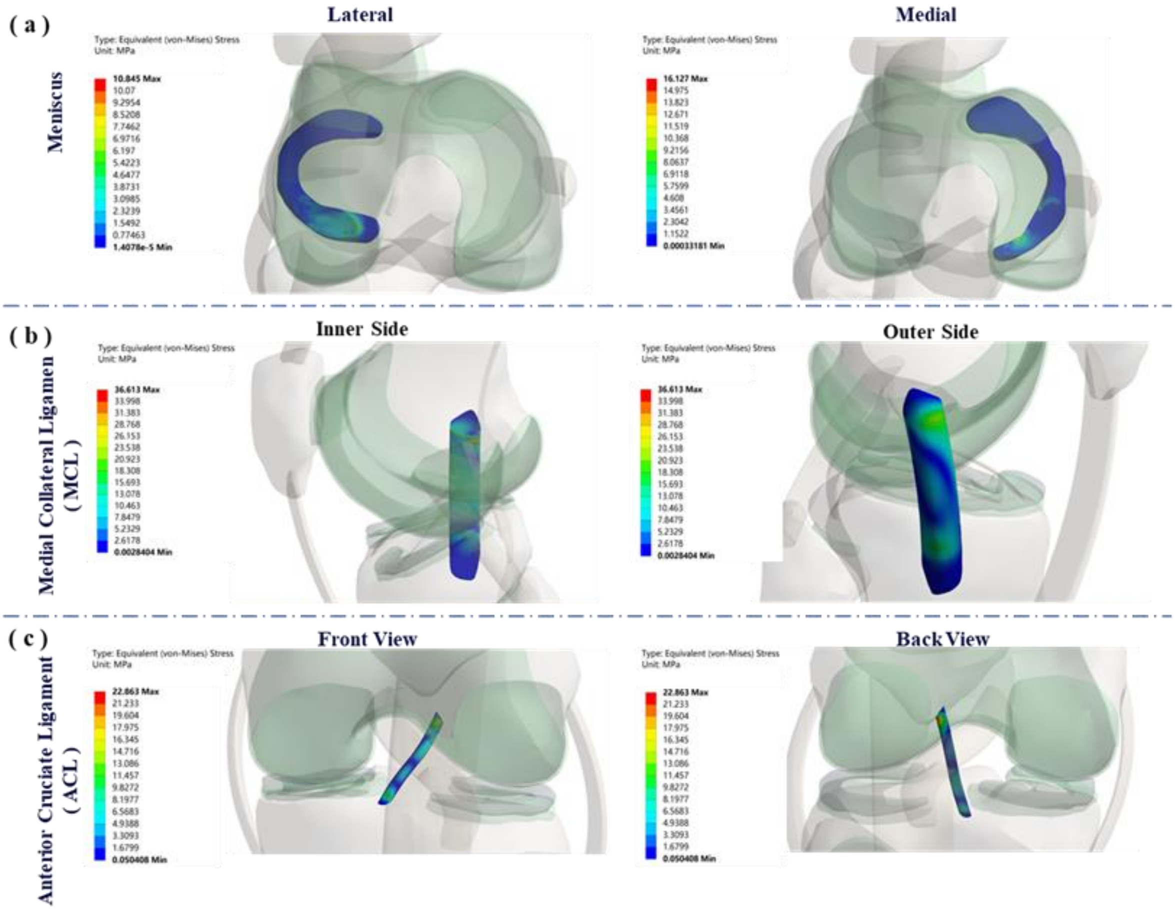

Figure 2. Equivalent (von Mises) stress distribution in knee joint structures during a support moment in soccer kicking. **(a)** equivalent (von Mises) stress results in the meniscus; **(b)** equivalent (von Mises) stress results in the medial collateral ligament (MCL); **(c)** equivalent (von Mises) stress results in the anterior cruciate ligament (ACL).

The FE simulation results are shown in **Figure 2**. The FE analysis of the meniscus under load conditions revealed stress distribution patterns across both the lateral and medial menisci. The peak von Mises stress observed in the lateral meniscus was 16.127 MPa, while the medial meniscus experienced a maximum stress of 10.845 MPa. Stress concentration areas were primarily located along the outer regions, aligning with the typical load distribution in the menisci during weight-bearing activities. The presence of these high-stress regions suggests the menisci's significant role in absorbing and distributing load during dynamic actions such as kicking.

3.3. Peak stress and stress distribution in the medial collateral ligament (MCL)

The MCL experienced substantial stress during the support phase of kicking. The maximum von Mises stress in the MCL reached 36.613 MPa on the medial side, indicating the high tensile forces the ligament undergoes to stabilize the knee against valgus forces. The stress distribution shows a gradient from the proximal to distal regions, with the highest stress values located near the femoral insertion point. These results emphasize the MCL's critical function in resisting medial knee opening, particularly under the dynamic loading conditions seen in soccer

3.4. Peak stress and stress distribution in the anterior cruciate ligament (ACL)

Analysis of the ACL stress revealed a maximum von Mises stress value of 22.863 MPa on the anterior side. The ACL's stress concentration was observed predominantly in the proximal portion near its femoral attachment, highlighting its involvement in stabilizing the knee joint during the rotational and shear forces experienced in kicking. This stress pattern aligns with the ACL's role in controlling anterior tibial translation and rotational stability, which are essential in dynamic lower limb movements.

4. Discussion

The FE analysis of the knee joint during the support phase of the soccer instep kick revealed significant stress concentrations in the MCL, ACL, and meniscus. These structures are crucial for knee stability and are frequently injured in high-intensity sports. The maximum von Mises stress observed in the MCL (36.613 MPa) suggests that this ligament bears a considerable load as it counters valgus forces during the support phase. This finding aligns with prior research indicating that the MCL is heavily loaded during side-to-side movements and serves as a primary stabilizer against lateral knee forces [22]. Given the dynamic, rapid deceleration forces involved in soccer kicks, the MCL's role in stabilizing against valgus stress becomes essential, highlighting the importance of conditioning protocols that focus on MCL resilience to minimize injury risk [23].

The observed peak stress in the ACL (22.863 MPa) predominantly near the femoral attachment underscores the ACL's role in limiting anterior tibial translation and rotational stability during soccer movements. Prior studies have shown similar stress patterns in the ACL during high-intensity athletic actions, noting that the ligament is highly susceptible to stress during rapid deceleration, cutting, and pivoting movements [24,25]. This study's findings support these observations, indicating that ACL loading during soccer-specific actions, such as kicking, should be considered in injury prevention programs. Strengthening surrounding musculature and incorporating neuromuscular training to enhance dynamic knee stability could reduce ACL strain and prevent injuries.

The meniscus, with peak stress values observed at 16.127 MPa in the lateral and 10.845 MPa in the medial regions, experienced substantial compressive forces, especially in the outer regions where load distribution is typically highest. These stress values highlight the menisci's essential role in load distribution and shock absorption, supporting previous research on meniscal mechanics during weight-bearing and dynamic tasks [26,27]. Injury risk in the meniscus could be mitigated through strategies such as strengthening exercises targeting muscles that aid in shock absorption, including the quadriceps and hamstrings [28]. Additionally, incorporating agility and balance drills may enhance the body's ability to manage ground reaction forces effectively during soccer movements [29].

This study has practical implications for both training and rehabilitation. For instance, soccer training protocols could benefit from the inclusion of targeted exercises that strengthen the knee ligaments and surrounding musculature to improve resilience against the forces encountered during the support phase of kicking. Rehabilitation protocols for players recovering from ACL or MCL injuries may also consider the specific loading conditions of soccer actions, emphasizing the importance of replicating sport-specific movements in recovery exercises to ensure that athletes regain functional stability. Future studies may expand on these findings by incorporating more complex multibody dynamics to capture the interplay between knee joint components and by analyzing diverse athletic populations to better generalize the results [28].

Furthermore, this study underscores the potential of FEA in sports biomechanics to simulate complex, high-load movements and offers a foundation for further research on sport-specific injury mechanisms and preventive measures in elite soccer players. While the present study provides valuable insights into knee joint mechanics, it is essential to acknowledge its limitations. This study has several limitations that should be acknowledged. First, the analysis was conducted using data from a single elite-level soccer player, which restricts the generalizability of the findings to athletes with different skill levels, ages, body types, or playing styles; second, the FE model used in this study, although anatomically detailed, includes simplifications such as assuming isotropic and linear elastic material properties for ligaments, cartilage, and bone. These assumptions, while standard in FE studies, do not fully capture the complex non-linear, time-dependent, and heterogeneous behavior of biological tissues [30–32]; Finally, the study focused exclusively on the support phase of an instep kick, a specific soccer action, which may limit the applicability of the findings to other soccer-related movements that impose different mechanical demands on the knee joint, such as cutting, pivoting, or landing. Future studies should aim to address these limitations by including a larger, more diverse sample size to enhance the generalizability of the results and provide a comprehensive understanding of knee joint mechanics across varied athletic populations. Incorporating advanced material models that reflect the non-linear and viscoelastic properties of ligaments, cartilage, and bone could improve the accuracy and reliability of FE simulations. Additionally, expanding the scope of analysis to include various high-risk soccer movements would provide broader insights into the biomechanical challenges faced by players and contribute to more effective injury prevention strategies. In a word, the FE analysis of an elite soccer player's knee during the support phase of instep kicking reveals critical stress patterns in the meniscus, MCL, and ACL. The observed peak stress concentrations correlate with the load-bearing and stabilizing functions of these structures, highlighting the MCL's role in resisting valgus forces and the ACL's role in anterior stabilization. The menisci's ability to absorb considerable forces, particularly in the lateral region, is vital for load distribution and joint stabilization. This study underscores the necessity for targeted interventions, such as proprioceptive and strength training, to enhance knee stability and potentially mitigate injury risks. Future research may build on these findings by analyzing knee joint stress in varied kicking scenarios and comparing stress responses among players of different skill levels and playing positions, ultimately contributing to the development of effective injury-prevention strategies in elite soccer.

5. Conclusion

The FE analysis of an elite soccer player's knee during the support phase of instep kicking reveals critical stress patterns in the meniscus, MCL, and ACL. These structures exhibit peak stress concentrations in alignment with their load-bearing and stabilizing functions, underscoring the MCL's role in resisting valgus forces and the ACL's role in anterior stabilization. The menisci absorb considerable force, especially in the lateral region, which is essential in load distribution and joint stabilization. This study highlights the need for targeted interventions, such as proprioceptive and strength training, to enhance knee stability and potentially reduce injury risk. Future studies may expand on these findings by analyzing knee joint stress in varied kicking scenarios or comparing stress responses between players of different skill levels and playing positions.

Author contributions: Conceptualization, FL and DS; methodology, YS; software, FL and YG; validation, DS, FL and YS; formal analysis, FL and ZG; investigation, DS; resources, ZG and YG; data curation, FL; writing—original draft preparation, FL; writing—review and editing, FL and YS; visualization, FL, MJ and LX; supervision, MJ and LX; project administration, DS; funding acquisition, DS and YG. All authors have read and agreed to the published version of the manuscript.

Funding: This study was sponsored by Zhejiang Province Science Fund for Distinguished Young Scholars (Grant number: LR22A020002), Ningbo Key Research and Development Program (Grant number: 2022Z196), Zhejiang Rehabilitation Medical Association Scientific Research Special Fund (ZKKY2023001), Research Academy of Medicine Combining Sports, Ningbo (No.2023001), the Project of Ningbo Leading Medical & Health Discipline (No.2022-F15, No.2022-F22), Ningbo Natural Science Foundation (Grant number: 2022J065) and K. C. Wong Magna Fund in Ningbo University.

Ethical approval: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of the Research Academy of Grand Health, Ningbo University (RAGH20241013, 2024.10.13).

Conflict of interest: The authors declare no conflict of interest.

References

1. Shan G, Zhang X, Wan B, et al. Biomechanics of coaching maximal instep soccer kick for practitioners. Interdisciplinary Science Reviews. 2018; 44(1): 12–20. doi: 10.1080/03080188.2018.1534359
2. Ren S, Shi H, Liu Z, et al. Finite element analysis and experimental validation of the anterior cruciate ligament and implications for the injury mechanism. Bioengineering. 2022; 9(10): 590. doi: 10.3390/bioengineering9100590
3. Tamura A, Shimura K, Inoue Y. Relationship Between Supporting Leg Stiffness and Trunk Kinematics of the Kicking Leg During Soccer Kicking. Journal of Applied Biomechanics. 2024; 40(6): 512–517. doi: 10.1123/jab.2023-0301
4. Inoue K, Nunome H, Sterzing T, et al. Dynamics of the support leg in soccer instep kicking. Journal of Sports Sciences. 2014; 32(11): 1023–1032. doi: 10.1080/02640414.2014.886126
5. Yao J, Yang B, Fan Y. Biomechanical Study on Injury and Treatment of Human Knee Joint. In: Biomechanics of Injury and Prevention. Springer; 2022. pp. 285–304.
6. Kuhn AW, Brophy RH. Meniscus Injuries in Soccer. Sports Medicine and Arthroscopy Review. 2024; 32(3): 156–162. doi: 10.1097/jsa.0000000000000389
7. Buckthorpe M, Pisoni D, Tosarelli F, et al. Three Main Mechanisms Characterize Medial Collateral Ligament Injuries in Professional Male Soccer—Blow to the Knee, Contact to the Leg or Foot, and Sliding: Video Analysis of 37 Consecutive Injuries. Journal of Orthopaedic & Sports Physical Therapy. 2021; 51(12): 611–618. doi: 10.2519/jospt.2021.10529
8. Della Villa F, Buckthorpe M, Grassi A, et al. Systematic video analysis of ACL injuries in professional male football (soccer): Injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases. British Journal of Sports Medicine. 2020; 54(23): 1423–1432. doi: 10.1136/bjsports-2019-101247
9. Sakamoto KJ, Fujii A, Hong S, et al. Knee joint kinematics of support leg during maximal instep kicking in female soccer players. In: Proceedings of the 38th International Society of Biomechanics in Sport Conference; 20–24 July 2020.
10. Zago M, Esposito F, Stillavato S, et al. 3-Dimensional Biomechanics of Noncontact Anterior Cruciate Ligament Injuries in Male Professional Soccer Players. The American Journal of Sports Medicine. 2024; 52(7): 1794–1803. doi: 10.1177/03635465241248071
11. Ponce E, Ponce D, Andresen M. Modeling Heading in Adult Soccer Players. IEEE Computer Graphics and Applications. 2014; 34(5): 8–13. doi: 10.1109/mcg.2014.96
12. Ying J, Liu J, Wang H, et al. Biomechanical insights into ankle instability: A finite element analysis of posterior malleolus fractures. Journal of Orthopaedic Surgery and Research. 2023; 18(1): 957. doi: 10.1186/s13018-023-04432-x
13. Lu Z, Sun D, Kovács B, et al. Case study: The influence of Achilles tendon rupture on knee joint stress during counter-movement jump—Combining musculoskeletal modeling and finite element analysis. Heliyon. 2023; 9(8): e18410. doi: 10.1016/j.heliyon.2023.e18410
14. Phan PK, Vo ATN, Bakhtiarydavijani A, et al. In silico finite element analysis of the foot ankle complex biomechanics: A literature review. Journal of Biomechanical Engineering. 2021; 143(9). doi: 10.1115/1.4050667
15. Li J, Liu H, Song M, et al. Biomechanical characteristics of ligament injuries in the knee joint during impact in the upright position: A finite element analysis. Journal of Orthopaedic Surgery and Research. 2024; 19(1): 630. doi: 10.1186/s13018-024-05064-5
16. Kothurkar R, Lekurwale R, Gad M, Rathod CM. Finite element analysis of a healthy knee joint at deep squatting for the study of tibiofemoral and patellofemoral contact. Journal of Orthopaedics. 2023; 40: 7–16. doi: 10.1016/j.jor.2023.04.016
17. Apriantono T, Nunome H, Ikegami Y, Sano S. The effect of muscle fatigue on instep kicking kinetics and kinematics in association football. Journal of Sports Sciences. 2006; 24(9): 951–960. doi: 10.1080/02640410500386050
18. Cerrah AO, Şimsek D, Soylu AR, et al. Developmental differences of kinematic and muscular activation patterns in instep soccer kick. Sports Biomechanics. 2024; 23(1): 28–43. doi: 10.1080/14763141.2020.1815827
19. Bao HRC, Zhu D, Gu GS, Gong H. The effect of complete radial lateral meniscus posterior root tear on the knee contact mechanics: A finite element analysis. Journal of Orthopaedic Science. 2013; 18(2): 256–263. doi: 10.1007/s00776-012-0334-5
20. Yang S, Liu Y, Ma S, et al. Stress and strain changes of the anterior cruciate ligament at different knee flexion angles: A three-dimensional finite element study. Journal of Orthopaedic Science. 2024; 29(4): 995–1002. doi: 10.1016/j.jos.2023.05.015

21. Edwards WB, Schnitzer TJ, Troy KL. Torsional stiffness and strength of the proximal tibia are better predicted by finite element models than DXA or QCT. Journal of Biomechanics. 2013; 46(10): 1655–1662. doi: 10.1016/j.jbiomech.2013.04.016
22. Marchant MH, Tibor LM, Sekiya JK, et al. Management of Medial-Sided Knee Injuries, Part 1. The American Journal of Sports Medicine. 2011; 39(5): 1102–1113. doi: 10.1177/0363546510385999
23. Haden M, Onsen L, Lam J, et al. Soccer/Football: Sport-Specific Injuries and Unique Mechanisms in Soccer/Football. In: Specific Sports-Related Injuries. Springer; 2022. pp. 147–162.
24. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. Knee Surgery, Sports Traumatology, Arthroscopy. 2009; 17(7): 705–729. doi: 10.1007/s00167-009-0813-1
25. Zago M, David S, Bertozzi F, et al. Fatigue induced by repeated changes of direction in élite female football (soccer) players: Impact on lower limb biomechanics and implications for acl injury prevention. Frontiers in Bioengineering and Biotechnology. 2021; 9. doi: 10.3389/fbioe.2021.666841
26. Rodeo SA, Monibi F, Dehghani B, Maher S. Biological and mechanical predictors of meniscus function: Basic science to clinical translation. Journal of Orthopaedic Research. 2020; 38(5): 937–945. doi: 10.1002/jor.24552
27. Sukopp M, Schwab N, Schwer J, et al. Partial weight-bearing and range of motion limitation significantly reduce the loads at medial meniscus posterior root repair sutures in a cadaveric biomechanical model. Knee Surgery, Sports Traumatology, Arthroscopy. 2024. doi: 10.1002/ksa.12465
28. Gastaldo M, Gokeler A, Della Villa F. High quality rehabilitation to optimize return to sport following lateral meniscus surgery in football players. Annals of Joint. 2022; 7: 36–36. doi: 10.21037/aoj-21-32
29. Rodrigues G, Dias A, Ribeiro D, Bertoncello D. Relationship between isometric hip torque with three kinematic tests in soccer players. Physical Activity and Health. 2020; 4(1): 142–149. doi: 10.5334/paah.65
30. Song Y, Cen X, Wang M, et al. The influence of simulated worn shoe and foot inversion on heel internal biomechanics during running impact: A subject-specific finite element analysis. Journal of Biomechanics. 2025; 180: 112517. doi: 10.1016/j.jbiomech.2025.112517
31. Cen X, Song Y, Yu P, et al. Effects of plantar fascia stiffness on the internal mechanics of idiopathic pes cavus by finite element analysis: Implications for metatarsalgia. Computer Methods in Biomechanics and Biomedical Engineering. 2024; 27(14): 1961–1969. doi: 10.1080/10255842.2023.2268231
32. Sun D, Song Y, Cen X, et al. Workflow assessing the effect of Achilles tendon rupture on gait function and metatarsal stress: Combined musculoskeletal modeling and finite element analysis. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine. 2022; 236(5): 676–685. doi: 10.1177/09544119221085795