pISSN:2349-5707 Volume:13,Issue 3, March -2026 eISSN:2349-5715

UDC: 616.728.3 + 615.8

COMPREHENSIVE REHABILITATION FOR KNEE JOINT CONTRACTURES: MODERN TRENDS AND EFFECTIVENESS

Sattarova D.B.
Saidnosirov O.K.
Makhmudov D.E.
Taraleva T.A.
Kimyo International University in Tashkent
Republican Scientific and Practical Center for Sports Medicine

Annotation. Knee joint contractures are among the most common and clinically significant complications following traumatic injuries, surgical interventions, and inflammatory disorders of the musculoskeletal system. This article provides an analytical review of current rehabilitation strategies for patients with this condition. The pathogenetic mechanisms underlying contracture development, the main stages of the recovery process, and the effectiveness of various physiotherapeutic, kinesiotherapeutic, and manual techniques are discussed. Particular emphasis is placed on a comprehensive rehabilitation program that includes early mobilization, individualized exercise prescription, and the use of modern rehabilitation technologies. Publications from both domestic and international sources over the past five years were analyzed. The importance of multidisciplinary collaboration among rehabilitation physicians, orthopedic specialists, and physiotherapists is highlighted.

Keywords: knee joint contracture, rehabilitation, range of motion restoration, mechanotherapy, physiotherapy, therapeutic exercise, massage.

Relevance. Knee joint contractures continue to occupy a leading position among the most common and socially significant medical problems. A decrease in the joint's range of motion (ROM) causes a pronounced limitation in functional activity, impaired walking biomechanics, the formation of chronic pain syndrome, and a deterioration in the patients' quality of life. Against the background of an increase in the number of musculoskeletal injuries, a rise in postoperative complications, and the demographic aging of the population, the issue of optimizing and improving the effectiveness of rehabilitation programs is of particular relevance.

Modern comprehensive rehabilitation includes a wide range of methods: kinesiotherapy, manual techniques, physiotherapeutic procedures, orthotics, mechanotherapy, as well as the introduction of innovative technologies—robotic recovery systems, biofeedback techniques, and high-tech physiotherapeutic solutions. At the same time, information about their comparative effectiveness is fragmented, which complicates the formation of evidence-based and standardized treatment algorithms.

Conducting a review study contributes to the systematization of accumulated scientific data, the determination of the most effective approaches, and the identification of promising directions for the development of comprehensive rehabilitation for knee joint contractures. This highlights the significance of the chosen topic for both the scientific community and practical healthcare.

Purpose of the study. To analyze modern approaches to comprehensive rehabilitation for knee joint contractures, evaluate their effectiveness, and identify the most productive methods used in clinical practice.

Materials and Methods. A literature search was conducted in the PubMed, Scopus, Web of Science, and Google Scholar databases covering the last five years. The review included original

pISSN:2349-5707 Volume:13,Issue 3, March -2026 eISSN:2349-5715

studies, clinical trials, systematic reviews, and meta-analyses dedicated to the rehabilitation of knee joint contractures. The selected works were analyzed to summarize rehabilitation methods, treatment stages, intervention parameters, and clinical outcomes. The final analysis allowed for highlighting modern evidence-based approaches, the effectiveness of multidisciplinary strategies, and identifying gaps requiring further investigation.

Results and Discussion. The knee joint is one of the most heavily loaded and structurally complex joints, providing stability and mobility during walking and running [1]. Its biomechanics are determined not only by the geometry of the articular surfaces but also by the action of stabilizing muscles, the capsuloligamentous apparatus, and neuromuscular regulation [2]. Ligament damage or altered joint anatomy leads to kinematic disturbances and tissue overload, which contributes to the development of contractures and increases the risk of recurrent injuries [3].

The anterior cruciate ligament (ACL) is a key stabilizer of the knee. Alteration of its length or orientation impairs the control of anterior tibial translation and increases the risk of instability [5]. ACL injury causes an increase in anterior displacement and a rise in load on the menisci and cartilage, leading to secondary changes and complications, including contractures [6]. Even with a technically successful reconstruction, a mismatch in the restored anatomy can disrupt biomechanics and increase the risk of complications [8].

Normally, flexion is accompanied by physiological rotation and a shift in the knee's center of rotation, ensuring smooth movement [9]. The center of rotation is more often localized laterally during the stance phase, providing a normal "lateral pivot" [10]. Soft tissue properties—elasticity, stiffness, tension—significantly influence joint kinematics [11], and their impairment can lead to excessive rotation, patellar maltracking, and contracture formation [12; 13; 14].

ACL injury causes a change in the force vector, the axis of motion, and load redistribution. A shift in the center of rotation disrupts meniscal function, increases contact pressures, and promotes microtrauma, which creates preconditions for fibrosis and motion restriction [15; 16; 17].

The pathophysiology of contractures involves myofascial, capsuloligamentous, and neurogenic mechanisms. Within just two weeks of immobilization, a myogenic contracture develops, accompanied by a decrease in muscle fiber volume and fibrosis [18]. Increased expression of TGF-β1, p-Smad2/3, and α-SMA confirms the development of soft tissue fibrosis [19]. In the capsule, the HIF-1α → NLRP3 → caspase-1 → GSDMD-N and TGF-β1/Smad3 pathways are activated, causing fibrosis and decreased elasticity [20; 21]. Neurogenic mechanisms, including Arthrogenic Muscle Inhibition, lead to decreased quadriceps activation and increased flexor tone, reinforcing the contracture [22; 23].

Contracture is one of the most frequent complications following ACL reconstruction, occurring in 2–35% of cases [24]. Its development is associated with biological characteristics, the severity of the inflammatory response, a predisposition to hyperfibrosis, intra-articular hemorrhages, and the formation of Cyclops syndrome [25; 26]. The optimal window for early mobilization is 7–14 days, provided the graft is stable [27]. Rehabilitation errors, lack of quadriceps activation, and chronic pain increase the risk of persistent pathological movement patterns and contractures [28].

To choose the correct treatment strategy, it is important to distinguish between muscular, fibrous, arthrogenic, and mixed contractures. The muscular form is associated with the predominant involvement of myofascial structures. Fibrous contracture arises due to prolonged movement restriction or inflammation; fibrosis can affect the capsule and intra-articular plicae, causing significant limitations in flexion and extension [29]. Arthrogenic contracture is caused by intra-articular changes—adhesions, synovial scarring, posterior capsule thickening, as well as Cyclops syndrome or improper ACL graft placement [30]. The mixed form includes elements of all the listed mechanisms and is encountered most frequently. Modern classifications distinguish

pISSN:2349-5707 Volume:13,Issue 3, March -2026 eISSN:2349-5715

mild, moderate, and severe degrees of mobility restriction based on the extent of flexion and extension loss [31].

Contractures cause a shift in the knee joint's center of rotation (COR) in various directions, which alters the muscle moment arm, increases contact pressures, and disrupts load transmission [32]. Limited mobility leads to compensatory overload of the hip and ankle joints, as well as myofascial disorders and secondary dysfunctions.

Key markers are a decrease in active and passive range of motion, especially the loss of full extension, which is associated with the risk of developing osteoarthritis [34]. Additional diagnostic methods allow for differentiating tissue changes from simple muscle rigidity [35]. Even when the range of motion is restored following an ACL reconstruction, rotational and tibial translation abnormalities may persist, indicating hidden contractures and altered biomechanics [36].

Modern approaches to rehabilitation after ACL reconstruction. The evolution of rehabilitation has led to the introduction of early mobilization, neuromuscular stimulation, isokinetic training, and 3D movement control, which has significantly reduced the incidence of contractures [37].

Main stages of rehabilitation. Modern protocols are based on a phase-driven rather than a calendar-driven principle [38].

Acute phase (0–2 weeks): pain and inflammation control, contracture prevention, restoration of full passive extension [39].

Subacute phase (2–6 weeks): restoration of active movement control, gait normalization, increasing ROM.

Recovery phase (6–12 weeks): muscle strengthening, restoring symmetry; the key criterion is ≥90% flexor and extensor strength compared to the healthy limb, with no asymmetries [40].

Early mobilization is a key factor in preventing contractures; prolonged immobilization leads to structural changes and loss of mobility [41]. Early restoration of full extension reduces the risk of arthrofibrosis and improves long-term functional outcomes [42]. At the same time, weight-bearing should be individualized, taking into account the graft type and tissue condition [43].

Kinesiotherapy, manual therapy, physiotherapy, electrical muscle stimulation, and hydrokinesiotherapy remain the core methods of recovery after ACL reconstruction [44]. Kinesiotherapy is aimed at restoring the range of motion, strength, and neuromuscular control; early dosed exercises, including isometrics and closed kinetic chain exercises, reduce the risk of contractures [45; 46].

Manual therapy reduces soft tissue rigidity and improves fascial glide; its combination with active exercises accelerates the restoration of extension and normalizes the axis of motion [47; 48]. Physiotherapy reduces pain and inflammation (magnetotherapy, ultrasound therapy, laser therapy, cryotherapy) but requires personalization depending on the healing stage [49; 50].

Electrical muscle stimulation prevents quadriceps atrophy in the early stages; parameters of 35–50 Hz and 300–400 μs are considered optimal [51; 52].

Hydrokinesiotherapy provides gentle training, improves gait and blood circulation, and promotes tissue regeneration [53; 54].

Traditional methods do not sufficiently account for biomechanics, including shifts in the center of rotation and axis of motion, which leads to asymmetric loading on the joint [55; 56]. In addition, there is a lack of quantitative control of three-dimensional kinematic parameters [57], and electrical stimulation and hydrotherapy do not provide full proprioceptive activation of the knee extensors and stabilizers [58]. Physiotherapeutic methods act locally and do not always account for the interconnection of the capsule, fasciae, and biomechanics of the entire limb [59]. This underscores the need for integrating 3D movement analysis, robotic therapy, and sensorimotor training [60].

pISSN:2349-5707 Volume:13,Issue 3, March -2026 eISSN:2349-5715

Innovations in contracture rehabilitation: Robotic kinesiotherapy and exoskeletons allow for dosed movement and control over speed and force, ensuring safe loading conditions for the graft and soft tissues [61]. The use of visual and tactile feedback facilitates real-time movement correction and improves functional kinematics [62]. Integrative methods target myofascial, capsular, and neurogenic mechanisms, reducing the risk of contracture chronification [63]. Artificial intelligence-based technologies provide a personalized approach that considers anatomophysiological characteristics, graft status, and the patient's biomechanical parameters [64].

Biomechanical movement analysis: Motion capture systems with optical and inertial sensors enable the quantitative assessment of kinematics, load distribution, and compensatory strategies, which is important for contracture prevention [65; 66; 67]. Integrating gait analysis improves exercise personalization and functional outcomes [68].

Use of feedback sensors: Wearable sensors allow tracking of ROM, gait symmetry, and load parameters, making therapy accessible in the clinic and at home [69]. Training with load or centrifugal feedback improves strength and walking parameters [70]. Modern IMU systems are comparable in accuracy to optical methods for standard movements, although they are less accurate during high-speed maneuvers [71].

The development of telemedicine expands the possibilities for remote monitoring, but hybrid protocols combining sensors and clinical assessment are considered optimal [72].

Conclusion. The literature review shows that knee joint contractures following ACL reconstruction have a multifactorial nature, involving biomechanical, myofascial, capsuloligamentous, and neurogenic mechanisms. Even minor disruptions in the axis of motion and load distribution can lead to secondary tissue changes and persistent mobility restriction.

Traditional rehabilitation methods remain the foundation of recovery; however, their effectiveness is limited by an insufficient consideration of hidden kinematic abnormalities. Modern technologies—robotic therapy, 3D movement analysis, feedback systems, and artificial intelligence tools—allow for more precise movement control, correction of compensatory strategies, and personalized treatment.

Thus, the literature analysis confirms that the most effective strategy for the prevention and treatment of knee joint contractures is multidisciplinary, biomechanically oriented, and personalized rehabilitation, based on early mobilization, movement quality control, and the use of modern kinematic analysis and correction technologies. Future research should be directed towards developing standardized protocols that account for biomechanics, graft type, degree of soft tissue injury, and individual recovery characteristics.

References.

1. Mozheyko, E. Yu. (2021). The use of video motion analysis in the assessment of locomotor functions after arthroscopic reconstruction of the anterior cruciate ligament. Digital Medicine. 1(2), 45–52. https://cyberleninka.ru/article/n/ispolzovanie-videoanaliza-dvizheniy-pri-otsenke-lokomotornyh-funktsiy-posle-artroskopicheskoy-rekonstruktsii-peredney
2. Adams, D., Logerstedt, D., Hunter-Giordano, A., Axe, M. J., & Snyder-Mackler, L. (2012). Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. Journal of Orthopaedic & Sports Physical Therapy, 42(7), 601–614. https://doi.org/10.2519/jospt.2012.3871
3. Adams, D., Logerstedt, D., Hunter-Giordano, A., Axe, M. J., & Snyder-Mackler, L. (2020). Current concepts for anterior cruciate ligament reconstruction: A criterion-based rehabilitation progression. Journal of Orthopaedic & Sports Physical Therapy, 50(12), 647–658. https://doi.org/10.2519/jospt.2020.01020
4. Ageberg, E., & Roos, E. M. (2019). Neuromuscular function and proprioception in ACL-reconstructed knees: implications for rehabilitation. Knee Surgery, Sports Traumatology, Arthroscopy, 27(1), 23–35. https://doi.org/10.1007/s00167-018-5206-7

pISSN:2349-5707 Volume:13,Issue 3, March -2026 eISSN:2349-5715

5. An, J., Cheon, S-J., & Lee, B-H. (2024). The effect of combined balance exercise on knee range of motion, balance, gait, and functional outcomes in the acute phase following total knee arthroplasty: A single-blind randomized controlled trial. Medicina (Kaunas), 60(9), 1389. https://doi.org/10.3390/medicina60091389
6. Arundale, A. J. H., Capin, J. J., Zarzycki, R., & Snyder-Mackler, L. (2018). Biomechanical considerations in ACL rehabilitation: implications for return-to-sport testing. Sports Health, 10(3), 225–231. https://doi.org/10.1177/1941738117743356
7. Arundale, A. J., Cummer, K., Capin, J. J., Zarzycki, R., Snyder-Mackler, L. (2018). Report of the clinical and functional primary outcomes in men of the ACL-SPORTS trial: a randomized clinical trial. The American Journal of Sports Medicine, 46(5), 1061–1070. https://doi.org/10.1177/0363546517751912
8. Asayama, A., Yagi, M., Taniguchi, M., Hirono, T., Kato, T., Hayashi, R., & Ichihashi, N. (2024). Effect of soft tissue tension around the knee joint on medio-lateral patellar position. Journal of Biomechanics, 168, 112137. https://doi.org/10.1016/j.jbiomech.2024.112137
9. Beynnon, B. D., Johnson, R. J., Abate, J. A., Fleming, B. C., & Nichols, C. E. (2011). Treatment of anterior cruciate ligament injuries, part I: Nonoperative and preoperative management. The American Journal of Sports Medicine, 33(10), 1579–1602. https://doi.org/10.1177/0363546505279923
10. Blanco-Coloma, L., García-González, L., Sinovas-Alonso, I., Torio-Álvarez, S., Martos-Hernández, P., González-Expósito, S., Gil-Agudo, Á., & Herrera-Valenzuela, D. (2024). Validation of inertial measurement units based on waveform similarity assessment against a photogrammetry system for gait kinematic analysis. Frontiers in Bioengineering and Biotechnology, 12. Article 1449698. https://doi.org/10.3389/fbioe.2024.1449698
11. Chen, X., Wang, F., & Zhang, Q. (2022). Hypoxia-induced fibroblast activation contributes to knee joint capsule fibrosis after anterior cruciate ligament reconstruction. BMC Musculoskeletal Disorders, 23(1), 813. https://doi.org/10.1186/s12891-022-05892-8
12. Christiansen, C. L., Bade, M. J., Davidson, B. S., Dayton, M. R., & Stevens-Lapsley, J. E. (2015). Effects of Weight-Bearing Biofeedback Training on Functional Movement Patterns Following Total Knee Arthroplasty: A Randomized Controlled Trial. The Journal of orthopaedic and sports physical therapy, 45(9), 647–655. https://doi.org/10.2519/jospt.2015.5593
13.Dauty, M., Collon, S., Dubois, C., & Pichon, C. (2022). Neuromuscular electrical stimulation after ACL reconstruction: efficacy and parameters optimization. Physical Therapy in Sport, 55, 76–83. https://doi.org/10.1016/j.ptsp.2022.01.005
14. Dauty, M., Plong, C., Vançon, A., Beaudreuil, J., & Michel, F. (2023). Arthrofibrosis risk factors after anterior cruciate ligament reconstruction. Frontiers in Sports and Active Living, 5, 1264150. https://doi.org/10.3389/fspor.2023.1264150
15. Donelon, T. A., Edwards, J., Brown, M., Jones, P. A., O'Driscoll, J., & Dos' Santos, T. (2024). Differences in biomechanical determinants of ACL injury risk in change of direction tasks between males and females: A systematic review and meta-analysis. Sports Medicine - Open, 10(1), 1-22. https://doi.org/10.1186/s40798-024-00701-z
16. Early Home Exercises and Formal Physical Therapy After Anterior Cruciate Ligament Reconstruction. (2025). Arthroscopy. https://doi.org/10.1016/j.arthro.2025.000248
17. Ekhtiari, S., Horner, N. S., de Sa, D., Simunovic, N., Hirschmann, M. T., Ogilvie, R., et al. (2019). Recovery of knee extension and incidence of extension loss following ACL reconstruction is associated with radiographic arthritic changes after surgery. Journal of Orthopaedic Surgery and Research, 14(1), 427. https://doi.org/10.1186/s13018-019-1427-8

pISSN:2349-5707 Volume:13,Issue 3, March -2026 eISSN:2349-5715

18. Escamilla, R. F., & Andrews, J. R. (2018). Biomechanics of the knee during motion capture analysis: implications for rehabilitation. Sports Health, 10(4), 305–312. https://doi.org/10.1177/1941738118771983
19. Fahlbusch, H., Krivec, L., Müller, S., Reiter, A., & Krause, M. (2023). Arthrofibrosis is a common but poorly defined complication in multiligament knee injuries: a systematic review. Archives of Orthopaedic and Trauma Surgery, 143, 5117-5132. https://doi.org/10.1007/s00402-022-04730-9
20. Grooms, D. R., Myer, G. D., & Ford, K. R. (2018). Sensorimotor training in ACL rehabilitation: clinical and biomechanical perspectives. Journal of Sport Rehabilitation, 27(3), 205–214. https://doi.org/10.1123/jsr.2017-0163
21. Grooms, D. R., Page, S. J., & Onate, J. A. (2020). Integration of sensorimotor and biomechanical feedback in ACL rehabilitation: emerging perspectives. Journal of Orthopaedic Research, 38(7), 1538–1547. https://doi.org/10.1002/jor.24577
22. Gupton M, Imonugo O, Black AC, et al. Anatomy, Bony Pelvis and Lower Limb, Knee. [Updated 2023 Nov 5]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2025 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK500017/
23. Guo, N., Smith, C. R., Schütz, P., Trepczynski, A., Moewis, P., Damm, P., Maas, A., Grupp, T. M., Taylor, W. R., & Hosseini Nasab, S. H. (2024). Posterior tibial slope influences joint mechanics and soft tissue loading after total knee arthroplasty. Frontiers in Bioengineering and Biotechnology, 12, 1352794. https://doi.org/10.3389/fbioe.2024.1352794
24. Hart, J. M., & Kuenze, C. M. (2022). Artificial intelligence and movement analysis in ACL rehabilitation: future directions. Sports Health, 14(5), 601–609. https://doi.org/10.1177/19417381211060974
25. Hart, J. M., Kuenze, C. M., & Diduch, D. R. (2016). Rehabilitation considerations for allograft ACL reconstruction. Sports Health, 8(6), 518–523. https://doi.org/10.1177/1941738116665054
26. Hart, J. M., Pietrosimone, B., Hertel, J., & Ingersoll, C. D. (2023). Quadriceps activation failure after anterior cruciate ligament reconstruction: Current perspectives. Journal of Orthopaedic Research, 41(4), 899-908. https://doi.org/10.1002/jor.25621
27. Hewett, T. E., Myer, G. D., & Ford, K. R. (2019). Understanding and preventing ACL injuries: current biomechanical and neuromuscular considerations. NCAA Sports Science Review, 1(2), 12–23. [Open Access]
28. Huguenin, L. K., & Vicenzino, B. (2019). Aquatic therapy following anterior cruciate ligament reconstruction: A systematic review. Physical Therapy Reviews, 24(1–2), 67–75. https://doi.org/10.1080/10833196.2018.1564657
29. Hwang, C. E., Kim, D. H., & Lee, Y. S. (2020). Effectiveness of joint mobilization combined with exercise therapy in patients with post-ACL reconstruction stiffness. Journal of Physical Therapy Science, 32(3), 158–164. https://doi.org/10.1589/jpts.32.158
30. Kim, D. K., Seo, H. S., & Park, S. J. (2020). Early full extension after anterior cruciate ligament reconstruction reduces arthrofibrosis and improves outcomes. Knee Surgery & Related Research, 32(1), 56. https://doi.org/10.1186/s43019-020-00073-y
31. Kim, J. G., & Park, J. H. (2022). Timing of early rehabilitation after anterior cruciate ligament reconstruction: Balancing graft protection and prevention of arthrofibrosis. Knee Surgery, Sports Traumatology, Arthroscopy, 30(11), 3689-3697. https://doi.org/10.1007/s00167-022-07166-8
32. Konda, S., Ishibashi, T., & Arakawa, T. (2022). Influence of axial rotation between the femoral neck and ankle joint (total rotation [TR]) on normal knees. JAAOS Global Research & Reviews.

pISSN:2349-5707 Volume:13,Issue 3, March -2026 eISSN:2349-5715

33. Kong, L., et al. (2025). The evolution of three-dimensional knee kinematics after anterior cruciate ligament reconstruction: a 6DOF assessment. Journal of Orthopaedic Research. https://doi.org/10.1002/jor.26012
34. Kordzadeh, A., & Khorsandi, M. (2021). Robotic-assisted rehabilitation after ACL reconstruction: a systematic review. Journal of Knee Surgery, 34(12), 1359–1370. https://doi.org/10.1055/s-0040-1716452
35. Kuenze, C. M., & Hart, J. M. (2021). Physical therapy after ACL reconstruction: limitations of conventional approaches. Current Reviews in Musculoskeletal Medicine, 14(3), 237–247. https://doi.org/10.1007/s12178-021-09731-2
36. Kumar, P. (2017). Gait analysis of a patient recovering from knee injuries. University of Waterloo.Retrieved from https://uwaterloo.ca/scholar/sites/ca.scholar/files/p43kumar/files/knee_rehab.pdf
37. Lepley, L. K., Wojtys, E. M., & Palmieri-Smith, R. M. (2021). Combination of cryotherapy and neuromuscular electrical stimulation to improve quadriceps function after ACL reconstruction. Knee Surgery, Sports Traumatology, Arthroscopy, 29(6), 1881–1889. https://doi.org/10.1007/s00167-020-06232-8
38. Lepley, L. K., Wojtys, E. M., & Palmieri-Smith, R. M. (2021). Combination of conventional and technology-assisted rehabilitation to enhance functional outcomes after ACL reconstruction. Knee Surgery, Sports Traumatology, Arthroscopy, 29(6), 1881–1889. https://doi.org/10.1007/s00167-020-06232-8
39. Li, G., Zhou, C., Li, S., Yu, J., Foster, T., & Bedair, H. (2024). Tibiofemoral articulation and axial tibial rotation of the knee after a cruciate retaining total knee arthroplasty. Knee Surgery & Related Research, 36(20). https://doi.org/10.1186/s43019-024-00224-7
40. Li, H., Hu, S., Zhao, R., Zhang, Y., Huang, L., Shi, J., Li, P., & Wei, X. (2022). Gait analysis of bilateral knee osteoarthritis and its correlation with Western Ontario and McMaster University Osteoarthritis Index assessment. Medicina, 58(10), 1419. https://doi.org/10.3390/medicina58101419
41. Li, J., Xu, H., Wang, H., & Chen, S. (2022). Manual therapy for knee joint contracture after anterior cruciate ligament reconstruction: a randomized controlled trial. Clinical Rehabilitation, 36(9), 1068–1078. https://doi.org/10.1177/02692155221094513
42. Lin, J., Zeng, Y., Zhang, X., et al. (2025). Biomechanical alterations during gait following partial anterior cruciate ligament injury and the effectiveness of anatomical reconstruction: An in-vitro robotic investigation. Frontiers in Bioengineering and Biotechnology, 1546180. https://doi.org/10.3389/fbioe.2025.1546180
43. Mao, Z., Yang, Q., Meng, X., et al. (2025). Dynamic biomechanical effects of medial meniscus tears on the knee joint: a finite element analysis. Journal of Orthopaedic Surgery and Research, 20, 26. https://doi.org/10.1186/s13018-024-05401-8
44. MedRxiv. (2020, November 26). Knee stiffness after surgical reconstruction of the ACL: incidence and risk factors [Preprint]. medRxiv. https://doi.org/10.1101/2020.11.26.20239046
45. Morales-Avalos, R., Torres-González, E. M., Padilla-Medina, J. R., & Monllau, J. C. (2024). ACL anatomy: Is there still something to learn? Revista Española de Cirugía Ortopédica y Traumatología, 68(4), 422–427. https://doi.org/10.1016/j.recot.2023.02.005
46. Nagai, T., et al. (2022). Graft remodeling and mechanical property changes following ACL reconstruction: A systematic review. Knee Surgery, Sports Traumatology, Arthroscopy, 30(5), 1675-1688. https://doi.org/10.1007/s00167-022-06943-5
47. ord, K. R., Taylor, J. B., Westbrook, A. E., Paterno, M. V., Huang, B., Nguyen, A.-D., … (2025). Outcomes of a randomized controlled trial of neuromuscular training with real-time biofeedback in young female athletes. BMC Musculoskeletal Disorders, 26, Article 366. https://doi.org/10.1186/s12891-025-08647-3

pISSN:2349-5707 Volume:13,Issue 3, March -2026 eISSN:2349-5715

48. Palmieri-Smith, R. M., & Lepley, L. K. (2020). Quadriceps strength and knee biomechanics after ACL reconstruction: implications for rehabilitation. Journal of Orthopaedic & Sports Physical Therapy, 50(9), 487–495. https://doi.org/10.2519/jospt.2020.9360
49. Paschos, N. K. (2022). Editorial Commentary: Major Technical Advances in Knee Anterior Cruciate Ligament Reconstruction Address Anatomy, Biomechanics, and Healing. Arthroscopy, 38(6), 1978-1979. https://doi.org/10.1016/j.arthro.2022.01.028
50. Ptaszyk, O., Boutefnouchet, T., Cummins, G., Kim, J. M., & Ding, Z. (2025). Wearable devices for the quantitative assessment of knee joint function after anterior cruciate ligament injury or reconstruction: A scoping review. Sensors, 25(18), 5837. https://doi.org/10.3390/s25185837
51. Qu, H., Zhen, Q., Li, H., Jiang, Q., Cao, X., Zhang, L., Huang, L., & Dou, H. (2025). Effects of Balance and Proprioceptive Training on Rehabilitation After Total Knee and Total Hip Replacement: A Systematic Review and Meta-Analysis. Journal of aging and physical activity, 1–9. Advance online publication. https://doi.org/10.1123/japa.2024-0390
52. Ramachandran, A. K., Pedley, J. S., Moeskops, S., Oliver, J. L., Myer, G. D., & Lloyd, R. S. (2024). Changes in lower limb biomechanics across various stages of maturation and implications for ACL injury risk in female athletes: A systematic review. Sports Medicine, 54, 1851-1876. https://doi.org/10.1007/s40279-024-02022-3
53. Reinke, E. K., Spindler, K. P., Lorring, D. K., Jones, M. H., & Schmitz, L. (2020). Use of physical therapy modalities following anterior cruciate ligament reconstruction: a systematic review. Sports Health, 12(2), 136–144. https://doi.org/10.1177/1941738119893055
54. Savage, M., Kobayashi, S., & Smith, J. R. (2025). Are altered knee joint biomechanics associated with future post-traumatic osteoarthritis outcomes? A systematic review and meta-analysis. Sports Medicine, 55, 2595-2612. https://doi.org/10.1007/s40279-025-02288-1
55. Saxby, D. J., Catelli, D. S., Lloyd, D. G., & Sawacha, Z. (2023). Editorial: The role of biomechanics in anterior cruciate ligament injuries prevention. Frontiers in Sports and Active Living, 5. https://doi.org/10.3389/fspor.2023.1134969
56. Schnittjer, A. J., Simon, J. E., Whittier, T. T., & Grooms, D. R. (2025). The Neuroplastic Outcomes from Impaired Sensory Expectations (NOISE) hypothesis: How ACL dysfunction impacts sensory perception and knee stability. Musculoskeletal Science and Practice, 75, 103222. https://doi.org/10.1016/j.msksp.2024.103222
57. Shelbourne, K. D., & Nitz, P. (1990). Accelerated rehabilitation after anterior cruciate ligament reconstruction. The American Journal of Sports Medicine, 18(3), 292–299. https://doi.org/10.1177/036354659001800314
58. Shelbourne, K. D., & Urch, S. E. (2020). Cyclops lesion: A cause of loss of extension after ACL reconstruction. Sports Health, 12(4), 342-348. https://doi.org/10.1177/1941738119896014
59. Sonnery-Cottet, B., Conteduca, J., Thaunat, M., et al. (2021). Technical errors and complications in ACL reconstruction: How to avoid loss of motion. Orthopaedics & Traumatology: Surgery & Research, 107(6), 102984. https://doi.org/10.1016/j.otsr.2021.102984
60. Sun, J-N., Shan, Y-Z., Wu, L-X., Li, N., Xu, F-H., Kong, X-R., & Zhang, B. (2023). Preoperative high-intensity strength training combined with balance training can improve early outcomes after total knee arthroplasty. Journal of Orthopaedic Surgery and Research, 18, 692. https://doi.org/10.1186/s13018-023-04197-3
61. Tang, Y., Zhao, Y., & Zhou, C. (2023). The role of TGF-β/Smad signaling in postoperative arthrofibrosis: From molecular mechanisms to therapeutic perspectives.

pISSN:2349-5707 Volume:13,Issue 3, March -2026 eISSN:2349-5715

Frontiers in Bioengineering and Biotechnology, 11, 1229456. https://doi.org/10.3389/fbioe.2023.1229456

62. Tedesco, S., Manzano Torre, O., Belcastro, M., Torchia, P., Alfieri, D., Khokhlova, L., Komaris, D. S., & O'Flynn, B. (2022). Design of a multi-sensors wearable platform for remote monitoring of knee rehabilitation. IEEE Access, 10, 98309-98328. https://doi.org/10.1109/ACCESS.2022.3204969
63. Tok, F., & Özgül, B. (2023). Prevention of knee stiffness following ligament reconstruction: Understanding the role of arthrogenic muscle inhibition (AMI). Joint Diseases and Related Surgery, 34(3), 503–510. https://pubmed.ncbi.nlm.nih.gov/38056774/
64. Usher, K. M., et al. (2019). Pathological mechanisms and therapeutic outlooks for arthrofibrosis of the knee. Bone Research, 7, 39. https://doi.org/10.1038/s41413-019-0047-x
65. van Melick, N., et al. (2023). Evidence-based clinical practice update: Rehabilitation after anterior cruciate ligament reconstruction. British Journal of Sports Medicine, 57(14), 912-920. https://doi.org/10.1136/bjsports-2022-106815
66. Wada, O., Hirano, K., & Takahashi, H. (2023). Optimal NMES parameters for quadriceps recovery after ACL reconstruction: A randomized crossover trial. BMC Musculoskeletal Disorders, 24(1), 72. https://doi.org/10.1186/s12891-023-06075-4
67. Weiner, T. R., Shah, R. P., Neuwirth, A. L., et al. (2024). Soft tissue laxity is highly variable in patients undergoing total knee arthroplasty. Arthroplasty, 6, 45. https://doi.org/10.1186/s42836-024-00268-w
68. Wellsandt, E., & Snyder-Mackler, L. (2024). Return-to-sport criteria and biomechanical readiness following ACL reconstruction. Sports Health, 16(2), 123-132. https://doi.org/10.1177/19417381231210988
69. Wu, D., Zhao, X., Wu, B., Zhou, L., Luo, Y., Huang, X., Xu, W., & Wang, S. (2023). Subregional analysis of joint stiffness facilitates insight into ligamentous laxity after ACL injury. Frontiers in Bioengineering and Biotechnology, 11. https://doi.org/10.3389/fbioe.2023.1298402
70. Yang, S., et al. (2023). Computational study of extrinsic factors affecting ACL strain during single-leg jump landing. BMC Musculoskeletal Disorders, 25, 318. https://doi.org/10.1186/s12891-024-07372-7
71. Yoo H, Marappa-Ganeshan R. Anatomy, Bony Pelvis and Lower Limb, Knee Anterior Cruciate Ligament. [Updated 2023 Jul 24]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2025 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK559233/
72. Yoon, H. S., Park, S. J., & Kim, D. K. (2021). Effects of hydrotherapy on knee proprioception and balance after ACL reconstruction. Journal of Back and Musculoskeletal Rehabilitation, 34(5), 857–865. https://doi.org/10.3233/BMR-200138