Journal of Physical Education and Sport ® (JPES), Vol. 25 (issue 11), Art 247, pp. 2230-2248, November 2025
online ISSN: 2247 - 806X; p-ISSN: 2247 – 8051; ISSN - L = 2247 - 8051 © JPES

Original Article

Biomechanical research on ACL: A narrative bibliometric review

ZHAOBO ZHOU[1,*], MOHD TAIB HARUN[2], HUICHUN PENG[3], WEIFENG YE[4]
[1]School of Physical Education, Jiangxi Institute of Technology, Nanchang 330098, CHINA
[1]Faculty of Education and Liberal Arts, INTI International University, Negeri Sembilan, MALAYSIA;
[2]Faculty of Education and Liberal Arts, INTI International University, Negeri Sembilan, MALAYSIA
[3]School of Physical Education, Jiangxi Institute of Technology, Nanchang 330098, CHINA
[4]School of Hydraulic and Ecological Engineering, Nanchang Institute of Technology, Nanchang 330099, CHINA

Published online: November 30, 2025
Accepted for publication: November 15, 2025
DOI:10.7752/jpes.2025.11247

Abstract
This study employs a mechanism-oriented bibliometric approach to investigate the biomechanical mechanisms of anterior cruciate ligament (ACL) injury, aiming to address the lack of systematic integration among structural loading, neuromuscular regulation, and long-term degeneration in existing research. The objective is to clarify research trends, mechanistic orientations, and interdisciplinary evolution within the field. A total of 3,285 original articles published between 1996 and 2025 were retrieved from the Web of Science Core Collection. Co-occurrence and network analyses were conducted using VOSviewer to identify research hotspots, thematic clusters, and temporal evolution trajectories. In addition, author, institutional, and journal indicators were analyzed to characterize patterns of knowledge production and academic influence, while keyword clustering was applied to reveal structural relationships among core mechanistic themes.The results identified five major clusters: (1) shear-induced injury pathways and load–control coupling mechanisms; (2) preventive training strategies and neuromuscular modulation frameworks; (3) ACL reconstruction techniques and biomechanical stabilization mechanisms; (4) post-reconstruction rehabilitation pathways and return-to-sport assessment mechanisms; and (5) long-term degenerative processes and osteoarthritis (OA) risk modeling. Since 1996, research output in this field has grown steadily, reaching a stage of maturity after 2018. Highly cited studies have collectively constructed a continuous mechanistic chain from injury initiation to degeneration.The findings indicate significant advances in elucidating shear amplification mechanisms, neuromuscular coordination deficits, and optimization of structural reconstruction consistency. However, limited model dynamism and weak ecological adaptability continue to restrict clinical translation. Future research should focus on dynamic data fusion, multi-domain mechanism modeling, and AI-based predictive systems to realize individualized, closed-loop control of ACL injury prevention and rehabilitation. This study provides a structured and quantitative panorama of ACL biomechanics research and proposes a mechanism-oriented framework that offers theoretical support for interdisciplinary integration and clinical application in sports medicine.
Keywords: Mechanism Integration; Shear Load Dynamics; Neuromuscular Modulation; Structural Reconstruction; Rehabilitation Assessment; Osteoarthritis Risk Modeling

Introduction

ACL injury is a common and highly disabling structural injury that frequently occurs during high-intensity movements such as jump landings and sudden cutting, particularly among youth and female athletes [Ford, K, 2005]. Characterized by high rates of reinjury, prolonged rehabilitation, and increased risk of long-term degeneration, ACL injury is strongly associated with the development of post-traumatic osteoarthritis (PTOA) [Georgoulis, A, 2003; Paterno, M, 2010]. Because the injury process is often not triggered by direct external forces but rather by abnormal postural control and inadequate neuromuscular responses, clinical prediction remains limited [Ford, K, 2003]. Although various screening tools and risk models have been developed, accurately identifying individual injury risk during dynamic tasks remains challenging [Schweizer, N, 2022; Myer, G, 2010], prompting research interest toward multi-mechanism modeling involving shear load pathways, neuromuscular control deficits, and injury cascade dynamics [Tsarbou, C, 2024].

ACL injuries typically exhibit consistent kinetic and neuromuscular features [Krosshaug, T, 2007; Malinzak, R, 2001], most notably insufficient knee flexion, knee valgus, and internal tibial rotation. These high-risk movement patterns often lead to premature peaks in anterior shear forces during landing or directional changes, resulting in anterior tibial translation and localized ligament stress that substantially increase rupture risk [Olsen, O,2004; Fleming, B. C,2001]. Simultaneously, delayed hamstring recruitment and quadriceps-dominant activation patterns—particularly under fatigue—intensify asymmetrical muscle responses between the hamstrings and quadriceps, further diminishing the joint's ability to buffer sudden shear loads [Chappell, J. D,

Corresponding Author: ZHAOBO ZHOU, E-mail: i25031316@student.newinti.edu.my

2005; Chappell, J. D, 2002]. Inadequate feedforward control during the pre-landing phase causes delayed muscular responses after impact, creating a "load-first, control-lag" vulnerability in the injury sequence [Norcross, M. F, 2013].

Although surgical reconstruction can anatomically restore ACL continuity, the recovery of joint function varies considerably. Clinically, both single-bundle and anatomical double-bundle reconstruction techniques are widely used, differing in their ability to control anterior tibial translation and rotational stability [Yagi, M, 2007]. Some studies have attempted to enhance postoperative rotational control by augmenting the reconstruction with anterolateral structures; however, clinical outcomes remain constrained by factors such as graft tension regulation, tunnel positioning accuracy, and integration timing [Sonnery-Cottet, B, 2015; Tashman, S, 2004]. Even after successful anatomical reconstruction, individuals frequently exhibit aberrant joint kinematics and inconsistent mechanical responses during high-load activities [Beynnon, B, 2005].

More critically, the restoration of neuromuscular control often lags behind structural recovery. Postoperative individuals frequently display persistent deficits in hamstring activation, muscle synergy, and inter-limb strength symmetry [Schmitt, L. C, 2012; Rudolph, K, 2000]. Although rehabilitation assessment tools based on three-dimensional motion capture, ground reaction force characteristics, and electromyography have been developed, standardized protocols for return-to-sport decisions, individualized risk assessment, and intervention design remain lacking—particularly in terms of psychological–control coordination, which continues to be an unresolved dimension of recovery planning [Paterno, M, 2010; Mueske, N, 2020; Ardern, C. L, 2011]. Under an incomplete control chain, postoperative movements often exhibit abnormal load path shifts, such as anteriorly displaced ground reaction forces or off-axis load orientations. These deviations expose periarticular cartilage, menisci, and osteochondral interfaces to chronic stress concentrations [Scanlan, S. F, 2010; Andriacchi, T. P, 2004]. Over time, such microdamage–reconstruction cycles accumulate, forming the structural basis for PTOA onset [Ajuied, A, 2014]. Evidence indicates that even after structural reconstruction, patients often demonstrate persistent kinematic abnormalities, altered joint contact patterns, and degenerative signs—suggesting that across the entire injury-to-degeneration continuum, disconnections and regulatory delays persist among structural repair, neuromuscular control, and load transmission [Andriacchi, T. P, 2009]. Therefore, future research must aim to reconstruct an integrated mechanistic pathway from anatomical repair to load protection to mitigate reinjury risk and long-term degeneration.

In summary, ACL injury arises from the combined effects of postural deviation, neuromuscular delay, and shear load imbalance, while the postoperative recovery process is characterized by multi-level disjunctions between structural restoration and neuromuscular control. These unresolved mechanisms not only elevate reinjury risk but also constitute major drivers of long-term joint degeneration. However, current studies often focus on isolated mechanistic variables, lacking an integrative framework that links structural, neuromuscular, and loading factors. Similarly, existing reviews primarily emphasize localized aspects such as injury detection, surgical techniques, or training interventions, while overlooking the entire multi-stage pathway from injury to degeneration, resulting in fragmented theoretical models and limited guidance for comprehensive functional protection strategies.

These persistent structural–control–loading disconnections indicate that current ACL research has yet to establish a comprehensive mechanistic framework. Although numerous studies have explored injury mechanisms and rehabilitation processes from different perspectives, research in this field still lacks a systematic view that integrates the entire continuum of injury occurrence, structural reconstruction, and functional recovery. The absence of such cross-phase integration limits the translation of research findings into effective rehabilitation practices and injury prevention strategies. Given the profound impact of ACL injury on athletic performance and long-term joint health, this study seeks to address this academic gap and clarify its theoretical and practical implications. Specifically, the study aims to (1) systematically map the evolution of ACL research and reveal the intellectual structure of the field, and (2) provide theoretical evidence to support rehabilitation assessment, training intervention, and risk management, facilitating coordinated development among structural restoration, neuromuscular control, and load regulation.

To address these gaps, this study employs a bibliometric approach to systematically synthesize the key mechanistic themes within current ACL research. Research data were obtained from the Web of Science Core Collection. Bibliometric analysis and knowledge visualization techniques were applied to evaluate research productivity, academic influence, and thematic evolution, thereby constructing a knowledge framework for the ACL research domain. Centered on the triad of structural, neuromuscular, and loading factors, the study identifies critical disjunctions across stages and explores opportunities for cross-phase integration and reconstruction of protective mechanisms. Accordingly, the following core research questions are proposed:

RQ1: How has research productivity in the field of ACL injury evolved? What are the distribution characteristics of prolific authors, institutions, and journals?

RQ2: How has the academic influence of ACL injury research developed? How is citation impact distributed across authors, institutions, and journals?

RQ3: What are the core thematic focuses in ACL injury research, and how are these themes distributed and interconnected across semantic and hierarchical dimensions?

Methods

Search string

The literature for this study was retrieved from the Web of Science Core Collection database using the Topic Search (TS) function, with the search scope limited to the title, abstract, and author keywords fields to ensure comprehensive and relevant coverage. The search string was set as: ("anterior cruciate ligament" OR ACL) AND (injur* OR tear* OR ruptur*) AND (biomechanics OR kinematics OR kinetics OR electromyography OR "motion analysis"), aiming to systematically capture mechanistic explorations involving biomechanical variables, kinematic characteristics, and neuromuscular responses in studies related to non-contact ACL injuries. The search was completed on May 12, 2025, which was also designated as the cut-off date for data collection. An initial total of 4,167 records was retrieved. To enhance the scientific rigor and comparability of the dataset, only original research articles were included, while conference abstracts, review articles, and other non-peer-reviewed publications were excluded to ensure academic validity and sample completeness. Additionally, only English-language articles were retained to maintain consistency and enable international comparability of results. Regarding index coverage, only documents indexed in the Science Citation Index Expanded (SCIE) and the Social Science Citation Index (SSCI) were considered, ensuring the authority and academic quality of the data sources. Prior to conducting bibliometric and visualization analyses, all included articles underwent an initial screening process to remove duplicates and check for consistency, thereby guaranteeing data standardization and integrity. Based on the inclusion and exclusion criteria outlined in

Table 1, a total of 3,285 articles were ultimately selected, providing a systematic, standardized, and reproducible dataset for the subsequent bibliometric analyses.

Table 1. Literature retrieval and filtering criteria.

Filtering criteria	Accept	Reject
Search date: 15th May 2025		
Search engine: Web of Science(WOS)		
Search Field: TS(Title, Abstract, keywords)		
Search string: TS = ("anterior cruciate ligament" OR ACL) AND (injur* OR tear* OR ruptur*) AND (biomechanics OR kinematics OR kinetics OR electromyography OR "motion analysis")	4167	
Date range: All years to 2025 included		
Document types: Article	3648	519
Languages: English	3605	43
Web Of Science Index: Social Sciences Citation Index(SSCI) and Science Citation Index Expanded(SCIE)	3285	320

Procedures of bibliometric analysis

Bibliometric analysis, as a data-driven method, reveals the structural patterns and thematic evolution of academic literature through co-citation and keyword co-occurrence networks[Linnenluecke, M. K, 2020]. In this study, VOSviewer version 1.6.20 was used to construct the bibliometric network. For the co-occurrence analysis, author keywords were selected, with a minimum occurrence threshold set at 8, resulting in the inclusion of 156 keywords. The Louvain algorithm was applied to extract five thematic clusters. All other parameters were maintained at default settings to ensure methodological consistency and result reproducibility. This analysis systematically delineates the knowledge structure and mechanistic pathways of research on non-contact ACL injury, providing a robust foundation for identifying critical mechanistic breakpoints, constructing cross-phase research loops, and advancing theoretical integration.

Results and Discussion

Evolution of Research Productivity and Contributor Distribution in ACL Injury Studies

The first research question (RQ1) of this study aims to examine the evolution of research productivity in the field of ACL injury, with a particular focus on elucidating the structural patterns of knowledge generation and the mechanistic roles of core contributing entities. As a key indicator for evaluating the vitality and maturity of a discipline, research productivity helps reveal the pace of expansion and the characteristics of knowledge accumulation, while also clarifying the leading roles of authors, institutions, and journals in the process of knowledge formation [Donthu, N, 2021]. As shown in Figure 1, the volume of ACL-related publications has steadily increased since 1996, entering a phase of accelerated growth after 2005, reflecting a clustering expansion of topics such as injury mechanisms, surgical innovations, and rehabilitation pathways. After 2018, the annual number of publications stabilized at over 200, indicating a transition from early mechanistic exploration to a more integrated stage of intervention validation and model consolidation. The publication volume peaked in 2021, followed by slight fluctuations. This trend may have been influenced by the global pandemic's temporary impact on research progress and data collection, or it may signify an ongoing structural shift from quantitative expansion toward qualitative optimization. As of May 2025, a total of 3,285 publications have been indexed in the Web of Science Core Collection, with an H-index of 145. These metrics indicate not only a substantial research output but also the emergence of a stable and semantically coherent knowledge

ecosystem in this domain. Such intensive knowledge accumulation provides a solid foundation for advancing shear mechanism modeling, optimizing reconstruction strategies, and predicting long-term joint degeneration.

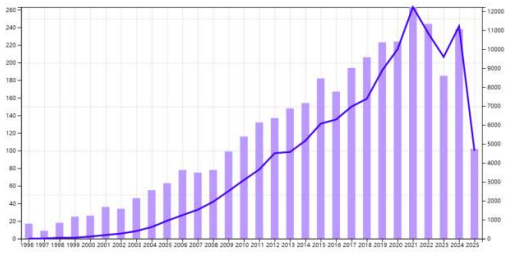

Fig.1 Publications and Citations from 1996 to 2025.

At the author level, the research landscape exhibits a highly concentrated productivity distribution (see Table 2), with a small group of prolific scholars serving as the core driving force for mechanism development and knowledge generation. Hewett (99 publications) proposed the "neuromuscular control deficit–knee valgus shear pathway" framework, significantly advancing theoretical understanding of high-risk profiles in female athletes and initiating some of the earliest dynamic screening tools. Myer (80 publications) and Ford (56 publications) jointly contributed to the design of intervention protocols and standardization of assessment methods, co-constructing a "training–evaluation–feedback" feedback loop that promoted the translation of mechanistic insights into practical applications. Padua (50 publications) led the standardization of the LESS (Landing Error Scoring System), facilitating the transition from qualitative observation to vector-based quantification in postural risk identification. Shultz (46 publications) systematically introduced sex and hormonal variables into neuromuscular regulation models, expanding the theoretical dimensions of control mechanisms. Blackburn (43 publications) further enriched the field by elucidating the coupling between knee joint dynamic stability and muscle activation patterns. Beyond their high publication output, these authors have collectively shaped the intellectual core of the field through frequent collaborations and cross-citations, driving the construction of an integrated mechanism chain centered on "shear–control–intervention–rehabilitation," thereby facilitating a transition from fragmented identification to pathway-level integration.

Table 2. Top productive authors in ACL injury research: publication output and citation network indicators.

Rank	Authors	Documents	Citations	Total Link Strength
1	hewett, timothy e.	99	8687	4521
2	myer, gregory d.	80	6794	3059
3	ford, kevin r.	56	5297	2338
4	fu, freddie h.	52	2499	477
5	padua, darin a.	50	4366	1334
6	shultz, sandra j.	46	1754	1002
7	blackburn, j. troy	43	2127	826
8	zaffagnini, stefano	40	1201	879
9	musahl, volker	39	1349	386
10	pietrosimone, brian	36	781	613

At the institutional level, ACL research exhibits a concentrated productivity pattern dominated by comprehensive universities and clinical centers in North America (see Table 3). UNC(173 publications) has focused on neuromuscular control deficits and movement-based interventions, establishing an integrated pathway encompassing movement recognition, training modulation, and return-to-sport evaluation. PITT(143 publications) has centered its research on a "structural reconstruction–functional recovery–degeneration prevention" continuum, advancing both surgical techniques and rehabilitation mechanisms. UC(102 publications) occupies a central position in the collaboration network (TLS = 6110), having proposed female-specific injury risk models and led the development of the LESS system, facilitating the translation of mechanism-based findings into practical applications. OSU(101 publications) and UM(82 publications) have contributed to kinematic modeling and personalized surgical matching, respectively, strengthening the precision linkage between structural evaluation and therapeutic decision-making. UW-Madison(70 publications) and UD(68 publications) have developed stable research lines focused on sex-specific mechanisms and youth injury risk management.

Duke and the Mayo Clinic have advanced the quantification of postoperative function, reshaping assessment paradigms through the integration of subjective scoring and multimodal evaluation. CCHMC(57 publications) has made notable contributions in youth screening and risk prediction modeling, combining mechanistic depth with translational value. Overall, these leading institutions have co-constructed a synergistic ecosystem across mechanism identification, platform integration, and clinical application, driving ACL research from fragmented mechanisms toward a closed-loop system evolution, and establishing an organizational foundation that balances integration with translational orientation.

Table 3. Top contributing institutions in ACL injury research: publication output and citation network indicators.

Rank	Organisation	Documents	Citations	Total Link Strength
1	univ n carolina	173	10260	4867
2	univ pittsburgh	143	6805	1622
3	univ cincinnati	102	12421	6110
4	ohio state univ	101	6414	4175
5	univ michigan	82	3870	2091
6	univ wisconsin	70	2276	1631
7	univ delaware	68	3518	1228
8	duke univ	66	5472	2404
9	mayo clin	60	1878	2401
10	cincinnati childrens hosp med ctr	57	3019	2821

At the journal level, core findings in ACL research are highly concentrated in high-impact journals within sports medicine, biomechanics, and orthopedics (see Table 4). AJSM leads with 358 publications and a TLS of 8384, serving as the field's most prominent knowledge dissemination platform. It has long focused on injury mechanisms, surgical treatment outcomes, and rehabilitation intervention pathways. KSSTA(257 publications, TLS = 2888) emphasizes surgical interventions and rehabilitation assessment for knee injuries, while Clinical Biomechanics (170 publications, TLS = 3948) provides a critical foundation for biomechanical modeling of loading mechanisms and structural response analysis. The Journal of Biomechanics (144 publications) and Knee (109 publications) continue to advance in movement modeling and soft tissue analysis, offering essential theoretical support for multimodal evaluation and postoperative structural tracking. Additionally, OJSM(101 publications), JOR(100 publications) and JAT(98 publications) contribute significantly to injury surveillance, reconstruction strategy development, and intervention efficacy, playing key roles in evaluation and rehabilitation feedback systems. Although JSR(72 publications) and RTS(64 publications) have relatively fewer publications, they provide valuable insights into postoperative recovery mechanisms and functional restoration. Overall, the journal distribution in ACL research reveals a dissemination structure centered around sports medicine journals, with strong support from biomechanics and orthopedic publications. This ecosystem has effectively facilitated the deepening of mechanisms, the expansion of intervention pathways, and the evolution of research paradigms, establishing a dual-track platform for both theoretical innovation and clinical translation.

Table 4. Core journals in ACL injury research: publication output and citation network indicators.

Rank	Journals	Documents	Citations	Total Link Strength
1	american journal of sports medicine	358	31956	8884
2	knee surgery sports traumatology arthroscopy	257	8139	2888
3	clinical biomechanics	170	8242	3948
4	journal of biomechanics	144	5356	2531
5	knee	109	1802	1474
6	orthopaedic journal of sports medicine	101	1098	1363
7	journal of orthopaedic research	100	3511	1410
8	journal of athletic training	98	4167	1883
9	journal of sport rehabilitation	72	1170	806
10	physical therapy in sport	64	825	943

The Landscape of Academic Influence and Knowledge Dissemination in ACL Injury Research

The second research question (RQ2) aims to explore the evolving academic influence of major knowledge contributors and publication sources in ACL injury research. As a core indicator for evaluating research value and knowledge dissemination, academic influence helps clarify the structural backbone of knowledge construction and its embedded network. As of May 15, 2025, ACL-related publications have accumulated 114,278 citations, with an average of 34.79 citations per article, indicating a well-established foundation for scholarly accumulation and diffusion in this field.

The top ten most-cited publications (see Table 5) collectively account for 11,532 citations and serve as the core pillars of mechanism development in ACL research. Hewett (2005), with 2,429 citations, ranks first and proposed the widely cited "neuromuscular deficit–valgus collapse" model, which laid the theoretical foundation for non-contact injury mechanisms and significantly influenced subsequent studies on movement screening and training interventions. Boden (2000) and Paterno (2010) focused respectively on high-risk posture identification and secondary injury prediction, jointly contributing to a mechanism loop of "early identification–strategic response–outcome evaluation." Notably, six of the top ten publications address posture regulation and muscle coordination, with a combined citation count exceeding 6,500. These works have become theoretical anchors for training system design and injury modeling. Most of these foundational studies were published before 2010, marking a paradigm shift in ACL research from descriptive observation to mechanism-driven inquiry, with their theoretical frameworks still actively inherited and extended. Overall, these highly cited publications not only represent concentrated citation clusters but also provide enduring structural support in mechanism theory,

pathway modeling, and methodological innovation, thereby forming a central force driving the structural integration and knowledge convergence of ACL research.

Table 5. Most cited publications in ACL injury research and their citation impact.

Rank	Title	Citations
1	[Hewett, T. E, 2005]	2429
2	[Boden, B. P, 2000]	1094
3	[Paterno, M. V, 2010]	950
4	[Olsen, O. E, 2004]	905
5	[Krosshaug, T, 2007]	850
6	[Powers C. M, 2010]	749
7	[Ford, K. R, 2003]	667
8	[Koga, H, 2010]	630
9	[Malinzak, R. A, 2001]	530
10	[Myer, G. D, 2005]	519

In the academic evolution of ACL injury mechanism research, a small group of highly cited authors has constructed a cross-stage knowledge chain spanning shear-related injury identification, neuromuscular regulation, training interventions, and rehabilitation assessment (see Table 6), thereby driving the field from fragmented mechanism exploration toward integrated system development. Hewett, with 8,687 citations and a TLS of 4,521, occupies a central position. His "valgus collapse–muscle imbalance–shear coupling" model laid the theoretical foundation for non-contact ACL injury mechanisms, emphasizing the pivotal role of neuromuscular deficits and steering the research paradigm toward proactive risk identification and intervention strategies. Building on this foundation, Myer and Ford empirically validated the regulatory effect of neuromuscular training on high-risk postures, establishing a quantifiable pathway from mechanism recognition to applied intervention.

Padua developed the LESS (Landing Error Scoring System), transforming risk assessment from subjective judgment to standardized indicators, which has been widely adopted in screening, feedback, and personalized training prescriptions. Krosshaug and Bahr, using video-based reconstruction, identified a tri-planar injury mechanism involving insufficient knee flexion, internal tibial rotation, and trunk displacement, thereby extending laboratory biomechanics research into real-world sport-specific contexts. In the domain of surgical technique and postoperative recovery, Fu standardized the anatomical double-bundle reconstruction protocol; Blackburn revealed delayed hamstring activation and disrupted neuromuscular timing, filling a critical gap in the re-injury control pathway; and Andriacchi proposed the "load redistribution–cartilage degeneration" model, elucidating the coupling between altered postoperative kinematics and long-term osteoarthritis risk. Collectively, these leading authors have established a highly integrated knowledge network across key domains such as shear modeling, motor control, intervention optimization, and long-term risk prediction. Their work has built a structural framework for ACL mechanism research and continues to propel the field toward theoretical closure and clinical translation.

Table 6. Highly cited authors in ACL injury research: citation performance and citation network indicators.

Rank	Authors	Documents	Citations	Total Link Strength
1	hewett, timothy e.	99	8687	4521
2	myer, gregory d.	80	6794	3059
3	ford, kevin r.	56	5297	2338
4	padua, darin a.	50	4366	1334
5	krosshaug, tron	23	3237	1142
6	bahr, roald	21	2959	1051
7	fu, freddie h.	52	2499	477
8	blackburn, j. troy	43	2127	826
9	andriacchi, thomas p.	21	1984	498
10	garrett, william e.	31	1900	1050

The academic influence of ACL injury research exhibits a highly centralized pattern dominated by a few core institutions (see Table 7). These institutions not only lead in the production of highly cited literature but also serve as organizational hubs for knowledge integration and theoretical dissemination through their dominant roles in mechanism pathway development and embedded positions within co-citation structures. UC and its affiliate CCH form a dual-core hub, with 12,421 and 7,543 citations respectively, and a combined TLS exceeding 13,000. Their collaborative output centers on neuromuscular control, shear mechanisms, and posture modeling, establishing a theoretical framework that spans from injury identification to high-risk screening. Their work is frequently cited across studies involving motion capture, dynamic assessment, and intervention design, serving as a reference point for multiple thematic domains. UNC has long played a leading role in the "rehabilitation–functional evaluation–individualized regulation" continuum, with 10,260 citations and a TLS of 7,282, demonstrating strong knowledge diffusion in post-surgical recovery and standardized outcome

assessment. OSU and UD have focused on shear-related posture modeling and muscular coordination regulation, contributing frequently to screening systems and intervention frameworks, and forming high-frequency nodes in mechanism linkage. Meanwhile, institutions such as PITT, Duke and CCF provide critical reinforcement in areas such as kinematic deviation analysis, surgical optimization, and geometric parameter modeling, enhancing the structural robustness of pathway dissemination. Collectively, these institutions have established a tightly coupled, functionally segmented collaboration network along key ACL research pathways, including shear identification, control modeling, structural reconstruction, and functional evaluation. Through sustained output and cross-institutional co-citation embedding, they have contributed to the formation of a coordinated knowledge dissemination framework that drives the field from fragmented investigation toward structural integration and translational application.

Table 7. Most cited institutions in ACL injury research: citation impact and network embedding features.

Rank	Organisation	Documents	Citations	Total Link Strength
1	univ cincinnati	102	12421	8375
2	univ n carolina	173	10260	7282
3	cincinnati childrens hosp	28	7543	4696
4	univ pittsburgh	143	6805	2593
5	ohio state univ	101	6414	5681
6	duke univ	66	5472	3503
7	cleveland clin fdn	13	4741	2968
8	human performance lab	19	3945	2412
9	univ michigan	82	3870	3047
10	univ delaware	68	3518	1839

The dissemination of knowledge in ACL injury research is highly reliant on a small group of core journals that continuously contribute to mechanism construction, methodological dissemination, and pathway integration (see Table 8). These journals not only accumulate a substantial volume of highly cited literature but also, through their specialized focus, have established a comprehensive knowledge support network spanning from shear mechanism identification to rehabilitation strategy formulation. AJSM leads with 31,956 citations and a TLS of 8,884, consistently driving core research on non-contact injury mechanisms, neuromuscular regulation, and risk prediction models. Its dense co-citation structure underpins the main research axis of "shear posture – control deficits – intervention strategies," positioning the journal as a theoretical nexus for multi-pathway integration. Clinical Biomechanics (8242 citations) and KSSTA(8,139 citations) offer methodological frameworks in stress transmission analysis, graft design, and postoperative stability modeling, forming a coherent knowledge chain linking structural biomechanics, surgical technique, and functional recovery. Although MSSE and the Journal of Biomechanics have relatively lower publication volumes, they serve as methodological anchors in 3D modeling, dynamic simulation, and movement deviation analysis, reinforcing the "kinematics–mechanics–modeling" cross-pathway infrastructure. In the domain of intervention research, BJSM and JAT focus on high-risk population screening and training feedback, forming knowledge dissemination hubs along the "assessment–modulation–prevention" continuum, with particular relevance to injury risk management in youth and female athletes. JOR and JOSPT continue to deliver high-quality research in tissue reconstruction, rehabilitation metrics, and physiotherapy optimization, thereby establishing a closed-loop framework of "evaluation–intervention–re-evaluation" for post-surgical recovery. Overall, through functional specialization in shear modeling, neuromuscular regulation, surgical integration, and rehabilitation prediction, these core journals have collectively constructed a tightly organized academic dissemination network that is guiding the field of ACL research from isolated mechanism exploration toward systemic integration and theoretical closure.

Table 8. Most cited journals in ACL injury research: citation impact and structural network characteristics.

Rank	Journals	Documents	Citations	Total Link Strength
1	american journal of sports medicine	358	31956	8884
2	clinical biomechanics	170	8242	3948
3	knee surgery sports traumatology arthroscopy	257	8139	2888
4	medicine and science in sports and exercise	63	5864	2385
5	journal of biomechanics	144	5356	2531
6	journal of athletic training	98	4167	1883
7	journal of orthopaedic research	100	3511	1410
8	british journal of sports medicine	26	3121	1320
9	journal of orthopaedic & sports physical therapy	43	2930	927
10	journal of strength and conditioning research	60	2388	1009

Thematic Clustering and Mechanism-Oriented Focus in ACL Injury Research

The third research question (RQ3) of this study aims to identify the core mechanistic themes in biomechanical research on ACL injury and to analyze their organizational patterns and cross-evolutionary trends

in terms of semantic focus, hierarchical structure, and relational connectivity. To address this, the current section employs a co-occurrence analysis approach and extracts five mechanism-oriented research clusters from the keyword network: shear injury pathways and structure–control coupling mechanisms; injury prevention training and risk modulation mechanisms; ACL reconstruction strategies and structural stabilization mechanisms; postoperative rehabilitation pathways and return-to-sport evaluation mechanisms; and postoperative joint degeneration mechanisms and OA risk modeling pathways. Figure 2 illustrates the structure of the co-word network and the distribution of clusters, while Table 9 summarizes the cluster labels and the number of keywords associated with each. The following subsections (3.3.1–3.3.5) will provide a detailed analysis of the research progress and structural characteristics of each mechanistic theme.

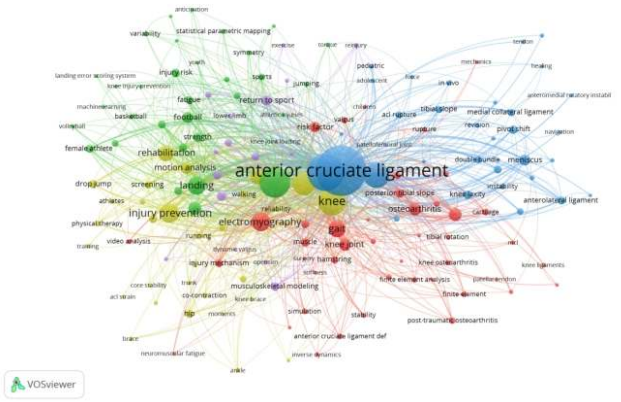

Fig.2 Co-occurrence network of keywords and clustering structure in ACL injury research..

Table 9. Cluster structure and keyword distribution based on co-occurrence analysis.

Cluster No and Colour	Number of Keywords
1 (Red)	44
2 (Green)	32
3 (Blue)	32
4 (Yellow)	30
5 (Purple)	18

Figure 3. Mechanism Chain of Non-contact ACL Injury: From Shear-Induced Loading to Control–Repair Disintegration.

Shear Injury Pathways and Structure–Control Coupling Mechanisms in Non-Contact ACL Rupture

Cluster 1 comprises 44 keywords and is thematically labeled "Shear Injury Pathways and Structure–Control Coupling Mechanisms in Non-Contact ACL Rupture." This cluster focuses on the formation of shear load pathways in non-contact ACL injuries, integrating four key mechanistic components: high-risk postural induction, structural stress amplification, neuromuscular regulation, and coupling imbalance modeling. Collectively, these mechanisms delineate a dynamic chain of failure progressing from load initiation to control

collapse. Such injuries commonly occur during single-leg landing, where the imbalance between structural load transmission and neuromuscular control emerges as the core mechanism[Olsen, O. E, 2004]. A hazardous posture characterized by limited knee flexion, knee valgus, and tibial internal rotation increases anterior shear loads, while accompanying hip adduction and restricted ankle dorsiflexion further elevate peak shear force[Koga, H., 2010]. Under these conditions, the interaction between ground reaction force (GRF) direction and knee flexion–extension triggers stress concentration, forming a high-sensitivity risk profile marked by flexion limitation, valgus collapse, and muscular activation imbalance[Chappell, J. D, 2002].

During dynamic landing, postural deviations and control variability further facilitate shear path convergence[Ishida, T, 2010]. In particular, toe-in foot positioning enhances tibial internal rotation and valgus coupling, resulting in combined shear–rotational–lateral multi-axial stress superposition[Markolf, K. L, 1995]. Concurrently, rapid GRF rise amplifies anterior shear, internal rotation, and valgus components, with steeper rates inducing more severe focal stress[Yeow, C. H, 2011]. Posterior tibial slope, as a key anatomical modulator, contributes to nonlinear amplification of shear force under high load conditions[Marouane, H, 2015; Alentorn-Geli, E, 2014]. Moreover, patellar maltracking or aberrant femoral axis alignment may shift the GRF vector away from the knee joint axis, creating shear–torque coupling imbalance and undermining joint stability[Hsu, W. H, 2006].

Under high-load perturbations, joint stability becomes increasingly reliant on active muscular regulation[Sharifi, M, 2021]. Late-phase gastrocnemius activation is often associated with anterior tibial translation and posterior shift of contact points, indicating a downregulation of stabilizing mechanisms[Sharifi, M, 2020]. In fatigued states, this regulation is further impaired, characterized by disrupted muscle coordination and delayed responses; however, some individuals may compensate by increasing knee flexion and reducing impact at initial contact[Bourne, M. N, 2019].

Decline in control function not only compromises immediate stability but also escalates the regulatory burden on the structural system after injury[Koo, Y. J, 2023]. ACL rupture or elongation leads to increased anterior tibial translation and uneven ligament tension distribution, manifesting as nonlinear instability and raising the precision demands on neural control[Moglo, K. E, 2003]. Rotational axis deviations frequently induce persistent tibial internal rotation, resulting in asymmetric loading and accelerated cartilage degeneration[Bates, N. A, 2018]. In the absence of the ACL, medial meniscus load may double, serving as a critical node in the initiation of osteoarthritic changes[Allen, C. R, 2000]. If internal rotation persists throughout the gait cycle, repeated compressive stress ensues, acting as a central driver of structural degeneration[Boden, B. P, 2010]. Nevertheless, current structural models remain highly sensitive to parameter perturbations and lack the capacity to integrate multi-joint force–timing coupling under dynamic tasks, thus limiting the predictability of structure–control interactions[Song, Y, 2004].

The pathway of active muscle-induced shear offers a crucial supplement to the traditional “external force-dominant model”[DeMorat, G, 2004]. Even in the absence of external impact, sudden quadriceps contraction can trigger ACL rupture, indicating an intrinsic drive–structural instability mechanism that deviates from classical models[Yu, B, 2007]. The injurious potential of this pathway is modulated by the knee flexion angle, which determines the location and intensity of shear stress concentration[Hashemi, J, 2011]. Although the relative priority of shear force, flexion angle, and internal rotation remains debated, the combined shear–internal rotation mechanism is widely regarded as the critical initiation node in non-contact injury chains[Krosshaug, T, 2007].

This cluster corresponds to the three mechanistic modules shown in Figure 3: “High-Risk Posture Activation – Shear Load Amplification – Non-Contact Rupture Trigger,” representing the core trajectory of ACL shear injury. It comprehensively outlines the dynamic process by which structural load input progresses to rupture threshold under non-contact conditions.

Preventive Training Strategies and Risk-Modulating Mechanisms for Non-Contact ACL Injuries

Cluster 2 comprises 32 keywords and is thematically labeled "Preventive Training and Risk Modulation Mechanisms for ACL Injuries." It focuses on the early identification and intervention strategies for non-contact ACL injuries, encompassing four critical stages: high-risk movement pattern recognition, intervention strategy design, mechanism validation, and individualized response adjustment. Kinematic precursors such as knee valgus, insufficient knee flexion, and abnormal muscle activation have been identified as key risk indicators, with early quadriceps activation coupled with hamstring inhibition forming a typical synergistic imbalance that amplifies shear loading[Hewett, T. E, 2005]. Accordingly, the accurate identification of postural configurations is considered the essential starting point for designing effective intervention protocols. Neuromuscular training (NMT), as the core intervention modality, integrates strength, posture, balance, and flexibility training components and has been shown to significantly reduce ACL injury risk[Sadoghi, P, 2012], as evidenced by reductions in knee valgus angles and ground reaction force peaks[Zebis, M. K, 2008]. Programs lasting more than six weeks have demonstrated the most robust preventive effects, especially in adolescent female populations[Myer, G. D, 2013].

To enhance the precision of interventions, current research increasingly emphasizes early detection of risky postures and individualized modulation of adaptive capacity. The Landing Error Scoring System (LESS), as a standardized screening tool with demonstrated reliability and validity, quantifies key technical variables

such as knee valgus, trunk lean, and stance time[Padua, D. A, 2015]. Building upon this, three-dimensional motion analysis and computational modeling have markedly improved the efficiency of identifying high-risk individuals, particularly among adolescent females[DiStefano, L. J, 2011]. Furthermore, factors such as age and neuromuscular maturation significantly influence training effectiveness[Myer, G. D, 2005], and individuals with greater posterior tibial slope often exhibit delayed reductions in shear load during landing, suggesting that structural features also affect training adaptability[Ueno, R, 2020].

Despite ongoing advancements in risk recognition and intervention strategy design, the effectiveness of training still exhibits considerable inter-individual variability and mechanistic debate. Prospective studies highlight knee valgus as the primary injurious movement pattern[Hewett, T. E, 2005], whereas retrospective analyses and modeling studies emphasize the synergistic effect of shear force and tibial internal rotation[Shimokochi, Y, 2013]. Such cognitive divergence has led to polarized intervention outcomes[Gilchrist, J, 2008; LaBella, C. R, 2011], while training quality and participant compliance have also been identified as key confounding factors[Petersen, W, 2005]. To further elucidate the mechanistic linkage between high-risk movements and load pathways, interpretable machine learning has been applied to gait variable analysis, revealing that insufficient hip abductor strength combined with elevated ground reaction force peaks are strong predictors of increased knee valgus torque[Kokkotis, C, 2022].

This cluster corresponds to the "neuromuscular control degradation" and "high-risk posture activation" modules in Figure 3, systematically illustrating the pre-injury mechanisms triggered by neural modulation imbalance. It also demonstrates how standardized screening, targeted training, and individualized adjustments can effectively control the front-end of the injury pathway. This triadic framework of intervention–modulation–validation constitutes a critical upstream mechanism in the ACL injury prevention continuum.

Surgical Reconstruction Strategies and Structural Consistency Optimization for ACL Injuries

Cluster 3 comprises 32 keywords and is thematically labeled “ACL Reconstruction Strategies and Structural Stabilization Mechanisms.” This cluster focuses on the mechanistic design of surgical reconstruction techniques, encompassing four interrelated components: surgical configuration optimization, biomechanical parameter adjustment, tissue integration, and re-injury risk control. Together, these elements form a synergistic mechanism chain linking structural restoration, graft–joint compatibility, and long-term stability.

In terms of surgical configuration, double-bundle reconstruction has demonstrated superior rotational stability in pivot-shift tests, yet shows no significant differences in KT-1000 or IKDC scores compared to single-bundle techniques, suggesting that improved rotational control may not directly translate into comprehensive functional recovery[Suomalainen, P, 2012]. Additionally, some double-bundle patients still exhibit delayed tibial rotation postoperatively, reflecting how individual anatomical variability and intraoperative tunnel placement inaccuracies constrain the reproducibility of surgical outcomes[Tashman, S, 2004; Desai, N, 2017]. In response, combined reconstruction of the ACL and anterolateral ligament (ALL) has been proposed as an enhanced approach to improve rotational stability, particularly in high-risk populations[Smith, J. O, 2015].

Graft parameters are central to mechanical regulation. Optimal graft stiffness and pre-tension help restore physiological knee load responses during gait and reduce cartilage shear stress[Halonen, K. S, 2016]. Conversely, grafts with diameters smaller than the native ACL can induce elevated anterior shear force peaks and rotational instability, highlighting the critical role of geometric compatibility in maintaining structural integrity[Wang, H, 2022]. Regarding graft materials, patellar tendon and hamstring tendon grafts each have distinct advantages—greater stability in the former, reduced postoperative pain in the latter—emphasizing the importance of structure–function coupling in graft selection[Pinczewski, L. A, 2002]. Although autografts and allografts show no significant difference in failure rates, functional recovery after revision surgery remains widely constrained[Mohan, R, 2018].

Tissue healing capacity is a major bottleneck for long-term stability. After ACL rupture, limited synovial cell migration and insufficient vascularization impair endogenous healing at the reconstruction site[Fu, F. H, 1999]. However, transgenic ECM scaffolds have been shown to promote continuous tissue regeneration and significantly enhance tensile load transmission at the bone–ligament interface[Fisher, M. B, 2012]. Hydrogel-integrated scaffolds have also demonstrated promising results in restoring mechanical strength in complex injuries involving the ACL, MCL, and meniscus[Fisher, M. B, 2011]. Additionally, the bridge-enhanced ACL repair (BEAR) technique provides a non-graft alternative, particularly suitable for low-demand individuals[Murray, M. M, 2019]. Nonetheless, most biological repairs remain constrained by time-sensitive healing windows and inflammatory conditions, indicating that biological enhancement strategies should be dynamically tailored to the patient’s immune microenvironment[Papageorgiou, C. D, 2001].

Re-injury risk is largely shaped by the interaction of individual characteristics and surgical variables. Young males and competitive athletes have significantly higher re-injury rates, with femoral tunnel malalignment and graft type identified as high-risk factors. These conditions often result in disorganized collagen architecture and reduced bioactivity, compromising the regenerative load-bearing capacity[Desai, N, 2017; Halinen, J, 2006]. To address this, three-dimensional preoperative planning and intraoperative navigation systems have been introduced to improve surgical accuracy and reconstructive consistency[Robinson, J, 2020]. Yet, even following anatomically precise reconstruction, some patients continue to exhibit delayed external tibial

rotation and abnormal joint contact mechanics during high-speed movements, indicating that full restoration of the neuromechanical control chain may remain incomplete[Gadikota, H. R, 2010].

This cluster corresponds to the “Surgical Reconstruction and Structural Control Mechanisms” module in Figure 3, and comprehensively delineates the mechanistic pathway of ACL surgery, from graft design and parameter matching to tissue integration and risk modulation. It serves as a pivotal control hub for restoring post-shear rupture structural alignment and functional coherence.

Post-Reconstruction Rehabilitation and Return-to-Sport Readiness: A Multidimensional Recovery Framework

Cluster 4 comprises 30 keywords and is thematically labeled “Postoperative Rehabilitation Pathways and Return-to-Sport Assessment Mechanisms for ACL Injuries.” This cluster focuses on the mechanisms underlying functional recovery after ACL reconstruction, covering four critical components: identification of movement control deficits, optimization of neuromuscular interventions, development of return-to-sport (RTS) assessment frameworks, and integration of psychological readiness with risk prediction. Together, these elements delineate a mechanistic pathway linking functional restoration, risk mitigation, and multidimensional decision-making.

Post-ACL reconstruction individuals often exhibit significant asymmetries in joint mechanics during key motor tasks—particularly during single-leg landing—characterized by reduced knee flexion angles and uneven distribution of ground reaction forces on the surgical limb[Schmitt, L. C, 2015]. These deficits are closely associated with quadriceps strength asymmetries, leading to diminished extensor moments at the surgical knee[Palmieri-Smith, R. M, 2015]. While improvements in hip–knee range of motion and energy absorption capacity have been observed within 6–10 months postoperatively, persistent delays in motor patterns and load modulation suggest that recovery does not follow a linear trajectory[Ithurburn, M. P, 2019].

To address these deficits, neuromuscular training (NMT) has emerged as a critical pathway for advanced postoperative intervention. NMT enhances muscle synergy and neuromotor control under high-demand tasks, reduces bilateral discrepancies, and significantly lowers the risk of secondary injuries[Nagelli, C. V, 2021]. Perturbation training, in particular, activates active surgical limb responses and proprioceptive regulation, yielding functional improvements even in early rehabilitation stages[Chmielewski, T. L, 2005]. Closed-chain exercises and gait retraining contribute to improved joint load control and enhance postural stability and transition efficiency under multitask conditions[Risberg, M. A, 2009]. Moreover, the concept of "copers" expands intervention boundaries by enabling non-operative functional stabilization through individualized training strategies[Hudgens, J. L, 2012].

In RTS evaluation, a battery of tests—including isokinetic strength symmetry, single-leg hop performance, and functional scoring—is commonly employed to quantify rehabilitation status and determine return eligibility[Grindem, H, 2016]. Extending rehabilitation duration to over 9 months and implementing stringent criteria have been shown to markedly reduce the incidence of graft re-rupture, establishing a dynamic recovery–risk equilibrium[Myer, G. D, 2012]. Nevertheless, inconsistencies remain across institutions regarding RTS criteria, and some individuals may pass conventional tests while still harboring latent neuromotor deficits that predispose them to re-injury[Ardern, C. L, 2014].

Psychological readiness is a pivotal supplemental mechanism influencing successful RTS outcomes. Postoperative individuals frequently experience fear of re-injury and diminished confidence, which, despite meeting physiological benchmarks, may delay or prevent return to play[McPherson, A. L, 2019]. This psychological state is also closely related to the recovery of neuromotor control capabilities[Kvist, J, 2005]. In response, the ACL-RSI scale has been widely adopted to quantify psychological status, facilitating the construction of models that support synchronous physical and psychological recovery[Ardern, C. L, 2014].

Regarding secondary injury risk, high-risk profiles are characterized by younger age, high athletic load, and incomplete quadriceps strength recovery[Paterno, M. V, 2010]. Even among those who have successfully returned to sport, approximately 30% continue to exhibit tibial rotation delays and dynamic postural control deficits, indicating incomplete reconstruction of the movement control chain[Ardern, C. L, 2011]. Consequently, the integration of psychological, biomechanical, and behavioral markers into multidimensional models is emerging as a critical approach for developing reliable risk identification systems[Ardern, C. L, 2015].

This cluster corresponds to the "Rehabilitation Pathway and RTS Assessment Mechanism" module in Figure 3, with its concluding segment extending into the “Degenerative Risk and Re-injury Prediction” module. It represents a critical transitional pathway in the non-contact injury continuum, bridging functional recovery with risk re-identification.

Long-Term Degenerative Trajectories and Osteoarthritis Risk Pathways Following ACL Reconstruction

Cluster 5 comprises 18 keywords and is thematically labeled "Post-ACL Reconstruction Joint Degeneration Mechanisms and OA Risk Modeling Pathways." This cluster focuses on the challenges in identifying and intervening in long-term degenerative changes of the knee joint, delineating three major mechanistic pathways: abnormal cartilage–bone interface loading, individual structural susceptibility, and delayed imaging/modeling responsiveness. A significant increase in osteoarthritis (OA) incidence is observed 10–20 years post-ACL injury, especially among those with concomitant cartilage or meniscal damage[Lohmander, L. S, 2007], primarily due to the interaction between traumatic structural disruption and postoperative load imbalance. Tibial rotational offset and anterior tibial translation are particularly prominent during late stance phase in gait cycles[Chaudhari, A. M, 2008; ,Andriacchi, T. P, 2005]. Within 2–3 years post-

surgery, the decoupling of cartilage volume and contact force indicates that early load imbalance has already led to localized degeneration[Saxby, D. J, 2017].

Although functional improvements may enhance subjective recovery metrics, no significant differences in five-year outcomes have been found between early and delayed ACL reconstructions[Frobell, R. B, 2013]. Even with increased quadriceps output during rehabilitation, peak torque in the 60–40° flexion range negatively correlates with cartilage volume, suggesting a non-linear mechanical adaptation response[Hipsley, A, 2022]. Minute changes in cartilage thickness can substantially alter stress distribution, rendering OA models highly sensitive to geometric precision[Li, G, 2001]. Additionally, deterioration in the microstructural–mechanical properties of subchondral bone provides a structural foundation for early OA development[Andriacchi, T. P, 2009].

Individual structural features are critical determinants of OA risk. Increased posterior tibial slope reduces joint stability and alters shear load transmission[Napier, R. J, 2019]; deficits in hip muscle control amplify tibial rotation and knee varus, promoting dynamic knee valgus[Powers C. M, 2010]; and abnormalities in trochlear groove angle have been identified as quantifiable early indicators of patellofemoral OA[Macri, E. M, 2018]. However, such risk factors are often obscured by neuromuscular compensation and delayed structural identification. Under fatigue, temporary bilateral load symmetry may mask strength asymmetries and flexion-extension deviations, interfering with postoperative assessments[Webster, K. E, 2015; Hart, J. M, 2010]. Moreover, although cartilage degeneration signals may emerge in early postoperative imaging, delays in identification often result in diagnostic latency[Riordan, E. A, 2013].

In terms of intervention, intraoperative repair of meniscal and cartilage structures combined with low-impact exercise guidance has shown potential in delaying degeneration[Barenius, B, 2014]. Tailored interventions based on postoperative gait patterns and anatomical characteristics have also been proposed to enhance control efficacy[Wellsandt, E, 2017]. However, the long-term effect of ACL reconstruction on delaying OA progression remains controversial[Ajuied, A, 2014], and there is currently no established pathophysiological model specific to post-traumatic OA[Filardo, G, 2016].

This cluster corresponds to the “Degeneration Module” in Figure 3, revealing the long-term deterioration of the knee joint under structural–neuromuscular–loading imbalance after ACL reconstruction. It highlights three key challenges in identification, intervention, and modeling, forming the risk regulation segment at the terminal end of the shear–control–repair mechanism chain.

Taken together, the shear–control–repair–degeneration mechanism chain illustrated in Figure 3 integrates the critical mechanisms across all five clusters, delineating a comprehensive pathway of non-contact ACL injury from initial shear induction to postoperative joint degeneration.

Conclusions

This study provides the first comprehensive quantitative review of ACL biomechanics over the past three decades, revealing a paradigm shift from early descriptive and single-factor investigations toward an integrated, mechanism-driven research framework. By synthesizing publication output, citation networks, and keyword co-occurrence analyses, the study delineates a continuous mechanistic chain encompassing shear-induced injury, neuromuscular control, structural reconstruction, and long-term degeneration. This framework clarifies the intrinsic relationships among academic influence, thematic clustering, and clinical translation, thereby establishing a systematic bridge between theoretical modeling and practical application in sports medicine. Overall, the study defines the knowledge architecture of ACL biomechanics and identifies multi-mechanism integration as the key driver of sustained advancement in the field.

Over time, both annual publication volume and citation density have shown steady growth, reflecting the maturation of ACL research. Foundational models addressing shear loading, neuromuscular coordination, and feedback-based intervention loops have formed the theoretical core of the discipline, while leading institutions have advanced the continuum from risk identification and surgical optimization to rehabilitation evaluation. Thematic clustering revealed five dominant research directions—shear-mechanism modeling, neuromuscular preventive training, structural reconstruction optimization, postoperative rehabilitation assessment, and long-term degeneration prediction. Collectively, these themes outline a complete mechanistic pathway from injury onset to degeneration monitoring, indicating that ACL research is progressing toward mechanistic closure, structural integration, and precision intervention.

Based on these evolutionary trends, the present study proposes a six-stage closed-loop mechanistic model that systematically characterizes the full process from pre-injury risk identification to post-injury functional recovery. The model integrates four essential components—shear-force generation, neuromuscular regulation, structural repair, and long-term degeneration—while elucidating the synergistic interactions among neural drive attenuation, impaired muscle coordination, and abnormal shear loading throughout the injury continuum. Importantly, this model possesses clear operational applicability and can serve as a validated framework for developing evidence-based rehabilitation protocols and individualized preventive training programs, providing a scientific foundation for clinical implementation and functional restoration.

Extensive empirical evidence confirms that hazardous movement patterns—limited knee flexion, knee valgus, and internal tibial rotation—are primary triggers of non-contact ACL injuries. Standardized screening

tools (e.g., the Landing Error Scoring System, LESS) and integrated neuromuscular training (NMT) programs have been proven effective in reducing injury risk, particularly among female and adolescent athletes. Clinically, while ACL reconstruction restores anatomic continuity, delayed recovery of the neuromuscular control chain remains a critical factor for secondary injury. Guided by the six-stage closed-loop model, interventions such as dynamic rehabilitation, gait retraining, and load-modulation therapy are identified as key strategies to enhance functional recovery and delay the progression of PTOA.

Future research should further enhance dynamic modeling of the load–control–response chain through the integration of wearable sensors, motion-capture technologies, and artificial intelligence algorithms to enable real-time monitoring and risk prediction. Establishing a closed-loop feedback system that integrates ecological motion data, neuromuscular signals, and biomechanical models will substantially improve the precision of both preventive screening and personalized rehabilitation. Practically, extending postoperative follow-up, promoting individualized neuromuscular training, and strengthening interdisciplinary collaboration among biomechanics, data science, and clinical rehabilitation will be crucial for developing a systematic and sustainable ACL injury prevention framework.

In summary, this study consolidates fragmented findings into an integrative, mechanism-oriented framework that unifies biomechanics, neuromuscular science, and rehabilitation research. It establishes a reproducible foundation for predictive injury modeling, precision rehabilitation, and long-term joint protection. The proposed approach advances ACL injury research from descriptive observation to predictive and intervention-oriented practice, offering both theoretical insight and actionable guidance for clinical rehabilitation and athletic injury prevention.

Nevertheless, two limitations should be acknowledged. First, the dataset was limited to the Web of Science Core Collection, potentially excluding non-English and interdisciplinary studies. Second, a degree of subjectivity was inherent in the keyword merging and semantic classification processes during co-word clustering. Future work should incorporate additional databases such as Scopus and PubMed and adopt a dual approach combining algorithmic clustering with expert validation to enhance the accuracy, coverage, and generalizability of mechanistic identification across diverse application contexts.

Author Contributions: Author Contributions: The overall conceptualization and design of this study were completed by Zhaobo Zhou. Literature data collection, processing, and visualization analysis were primarily conducted by Zhaobo Zhou, with Huichun Peng providing assistance in data organization and technical support for co-citation and co-word clustering. Mohd Taib Harun contributed to result interpretation and refinement of the English logic, while Weifeng Ye supported figure construction and revision of cluster interpretations. The original draft was written by Zhaobo Zhou, and reviewed and linguistically edited by Mohd Taib Harun. The entire research process was supervised and coordinated by Zhaobo Zhou. All authors have read and agreed to the final version of the manuscript.

Data Availability Statement: The data supporting the findings of this study are derived from the Web of Science Core Collection, covering publications from 1996 to 2025. Access to the Web of Science database requires a subscription, and data retrieval was conducted in accordance with institutional access rights. No new data were created or collected in this study. Derived data supporting the visualizations and analyses are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest that could have influenced the work reported in this paper.

Abbreviations: The following abbreviations are used in this manuscript

ACL	Anterior cruciate ligament
OA	osteoarthritis
POTA	post-traumatic osteoarthritis
LD	Linear dichroism
UNC	univ n carolina
PITT	univ pittsburgh
UC	univ cincinnati
OSU	ohio state univ
UM	univ michigan
UW-Madison	univ wisconsin
UD	univ delaware
Duke	duke univ
CCHMC	cincinnati childrens hosp med ctr
AJSM	american journal of sports medicine
KSSTA	knee surgery sports traumatology arthroscopy
MSSE	medicine and science in sports and exercise
JAT	journal of athletic training
JOR	journal of orthopaedic research
BJSM	british journal of sports medicine

JOSPT	journal of orthopaedic & sports physical therapy
JSCR	journal of strength and conditioning research
CCH	cincinnati childrens hosp
CCF	cleveland clin fdn
UPL	human performance lab
IMUS	inertial measurement units
GNNs	graph neural networks
CNN	Convolutional Neural Network
LSTM	Long Short-Term Memory
MRI	Magnetic Resonance Imaging

References:

Ford, K. R., Myer, G. D., Toms, H. E., & Hewett, T. E. (2005). Gender differences in the kinematics of unanticipated cutting in young athletes. Medicine and science in sports and exercise, 37(1), 124–129. https://doi.org/01.MSS.0000150087.95953.C3

Georgoulis, A. D., Papadonikolakis, A., Papageorgiou, C. D., Mitsou, A., & Stergiou, N. (2003). Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament-deficient and reconstructed knee during walking. The American journal of sports medicine, 31(1), 75–79. https://doi.org/10.1177/03635465030310012401

Paterno, M. V., Schmitt, L. C., Ford, K. R., Rauh, M. J., Myer, G. D., Huang, B., & Hewett, T. E. (2010). Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. The American journal of sports medicine, 38(10), 1968–1978. https://doi.org/10.1177/0363546510376053

Ford, K. R., Myer, G. D., & Hewett, T. E. (2003). Valgus knee motion during landing in high school female and male basketball players. Medicine and science in sports and exercise, 35(10), 1745–1750. https://doi.org/10.1249/01.MSS.0000089346.85744.D9

Schweizer, N., Strutzenberger, G., Franchi, M. V., Farshad, M., Scherr, J., & Spörri, J. (2022). Screening Tests for Assessing Athletes at Risk of ACL Injury or Reinjury-A Scoping Review. International journal of environmental research and public health, 19(5), 2864. https://doi.org/10.3390/ijerph19052864

Myer, G. D., Ford, K. R., Khoury, J., Succop, P., & Hewett, T. E. (2010). Development and validation of a clinic-based prediction tool to identify female athletes at high risk for anterior cruciate ligament injury. The American journal of sports medicine, 38(10), 2025-2033. https://doi.org/10.1177/0363546510370933

Tsarbou, C., Liveris, N. I., Xergia, S. A., Papageorgiou, G., Kvist, J., & Tsepis, E. (2024). ACL Injury Etiology in Its Context: A Systems Thinking, Group Model Building Approach. Journal of clinical medicine, 13(16), 4928. https://doi.org/10.3390/jcm13164928

Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., Hewett, T. E., & Bahr, R. (2007). Mechanisms of anterior cruciate ligament injury in basketball: Video analysis of 39 cases. American Journal of Sports Medicine, 35(3), 359–367. https://doi.org/10.1177/0363546506293899

Malinzak, R. A., Colby, S. M., Kirkendall, D. T., Yu, B., & Garrett, W. E. (2001). A comparison of knee joint motion patterns between men and women in selected athletic tasks. Clinical Biomechanics, 16(5), 438–445. https://doi.org/10.1016/S0268-0033(01)00019-5

Olsen, O. E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. The American journal of sports medicine, 32(4), 1002–1012. https://doi.org/10.1177/0363546503261724

Fleming, B. C., Renstrom, P. A., Beynnon, B. D., Engstrom, B., Peura, G. D., Badger, G. J., & Johnson, R. J. (2001). The effect of weightbearing and external loading on anterior cruciate ligament strain. Journal of biomechanics, 34(2), 163–170. https://doi.org/10.1016/s0021-9290(00)00154-8

Chappell, J. D., Herman, D. C., Knight, B. S., Kirkendall, D. T., Garrett, W. E., & Yu, B. (2005). Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. The American journal of sports medicine, 33(7), 1022–1029. https://doi.org/10.1177/0363546504273047

Chappell, J. D., Yu, B., Kirkendall, D. T., & Garrett, W. E. (2002). A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. The American journal of sports medicine, 30(2), 261–267. https://doi.org/10.1177/03635465020300021901

Norcross, M. F., Lewek, M. D., Padua, D. A., Shultz, S. J., Weinhold, P. S., & Blackburn, J. T. (2013). Lower extremity energy absorption and biomechanics during landing, part I: sagittal-plane energy absorption analyses. Journal of athletic training, 48(6), 748-756. https://doi.org/10.4085/1062-6050-48.4.09

Yagi, M., Kuroda, R., Nagamune, K., Yoshiya, S., & Kurosaka, M. (2007). Double-bundle ACL reconstruction can improve rotational stability. Clinical orthopaedics and related research, 454, 100–107. https://doi.org/10.1097/BLO.0b013e31802ba45c

Sonnery-Cottet, B., Thaunat, M., Freychet, B., Pupim, B. H., Murphy, C. G., & Claes, S. (2015). Outcome of a Combined Anterior Cruciate Ligament and Anterolateral Ligament Reconstruction Technique With a

Minimum 2-Year Follow-up. The American journal of sports medicine, 43(7), 1598–1605. https://doi.org/10.1177/0363546515571571

Tashman, S., Collon, D., Anderson, K., Kolowich, P., & Anderst, W. (2004). Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. The American journal of sports medicine, 32(4), 975–983. https://doi.org/10.1177/0363546503261709

Beynnon, B. D., Johnson, R. J., Abate, J. A., Fleming, B. C., & Nichols, C. E. (2005). Treatment of anterior cruciate ligament injuries, part 2. The American journal of sports medicine, 33(11), 1751–1767. https://doi.org/10.1177/0363546505279922

Schmitt, L. C., Paterno, M. V., & Hewett, T. E. (2012). The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. The Journal of orthopaedic and sports physical therapy, 42(9), 750–759. https://doi.org/10.2519/jospt.2012.4194

Rudolph, K. S., Axe, M. J., & Snyder-Mackler, L. (2000). Dynamic stability after ACL injury: who can hop?. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA, 8(5), 262–269. https://doi.org/10.1007/s001670000130

Mueske, N. M., Patel, A. R., Pace, J. L., Zaslow, T. L., VandenBerg, C. D., Katzel, M. J., Edison, B. R., & Wren, T. A. L. (2020). Improvements in landing biomechanics following anterior cruciate ligament reconstruction in adolescent athletes. Sports biomechanics, 19(6), 738–749. https://doi.org/10.1080/14763141.2018.1510539

Ardern, C. L., Webster, K. E., Taylor, N. F., & Feller, J. A. (2011). Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. British journal of sports medicine, 45(7), 596–606. https://doi.org/10.1136/bjsm.2010.076364

Scanlan, S. F., Chaudhari, A. M., Dyrby, C. O., & Andriacchi, T. P. (2010). Differences in tibial rotation during walking in ACL reconstructed and healthy contralateral knees. Journal of biomechanics, 43(9), 1817–1822. https://doi.org/10.1016/j.jbiomech.2010.02.010

Andriacchi, T. P., Mündermann, A., Smith, R. L., Alexander, E. J., Dyrby, C. O., & Koo, S. (2004). A framework for the in vivo pathomechanics of osteoarthritis at the knee. Annals of biomedical engineering, 32(3), 447–457. https://doi.org/10.1023/b:abme.0000017541.82498.37

Ajuied, A., Wong, F., Smith, C., Norris, M., Earnshaw, P., Back, D., & Davies, A. (2014). Anterior cruciate ligament injury and radiologic progression of knee osteoarthritis: a systematic review and meta-analysis. The American journal of sports medicine, 42(9), 2242–2252. https://doi.org/10.1177/0363546513508376

Andriacchi, T. P., Koo, S., & Scanlan, S. F. (2009). Gait mechanics influence healthy cartilage morphology and osteoarthritis of the knee. The Journal of bone and joint surgery. American volume, 91 Suppl 1(Suppl 1), 95–101. https://doi.org/10.2106/JBJS.H.01408

Linnenluecke, M. K., Marrone, M., & Singh, A. K. (2020). Conducting systematic literature reviews and bibliometric analyses. Australian Journal of Management, 45(2), 175–194. https://doi.org/10.1177/0312896219877678

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. Journal of business research, 133, 285-296. https://doi.org/10.1016/j.jbusres.2021.04.070

Boden, B. P., Dean, G. S., Feagin, J. A., Jr, & Garrett, W. E., Jr (2000). Mechanisms of anterior cruciate ligament injury. Orthopedics, 23(6), 573–578. https://doi.org/10.3928/0147-7447-20000601-15

Olsen, O. E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. The American journal of sports medicine, 32(4), 1002–1012. https://doi.org/10.1177/0363546503261724

Powers C. M. (2010). The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. The Journal of orthopaedic and sports physical therapy, 40(2), 42–51. https://doi.org/10.2519/jospt.2010.3337

Koga, H., Nakamae, A., Shima, Y., Iwasa, J., Myklebust, G., Engebretsen, L., Bahr, R., & Krosshaug, T. (2010). Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. The American journal of sports medicine, 38(11), 2218–2225. https://doi.org/10.1177/0363546510373570

Myer, G. D., Ford, K. R., Palumbo, J. P., & Hewett, T. E. (2005). Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. Journal of strength and conditioning research, 19(1), 51–60. https://doi.org/10.1519/13643.1

Ishida, T., Yamanaka, M., Takeda, N., Homan, K., Koshino, Y., Kobayashi, T., ... & Aoki, Y. (2015). The effect of changing toe direction on knee kinematics during drop vertical jump: a possible risk factor for anterior cruciate ligament injury. Knee Surgery, Sports Traumatology, Arthroscopy, 23, 1004-1009. https://doi.org/10.1007/s00167-013-2815-2

Markolf, K. L., Burchfield, D. M., Shapiro, M. M., Shepard, M. F., Finerman, G. A., & Slauterbeck, J. L. (1995). Combined knee loading states that generate high anterior cruciate ligament forces. Journal of orthopaedic research, 13(6), 930-935. https://doi.org/10.1002/jor.1100130618

Yeow, C. H., Kong, C. Y., Lee, P. V. S., & Goh, J. C. H. (2011). Correlation of axial impact forces with knee joint forces and kinematics during simulated ski-landing. Journal of sports sciences, 29(11), 1143-1151. https://doi.org/10.1080/02640414.2011.578146

Marouane, H., Shirazi-Adl, A., & Hashemi, J. (2015). Quantification of the role of tibial posterior slope in knee joint mechanics and ACL force in simulated gait. Journal of biomechanics, 48(10), 1899–1905. https://doi.org/10.1016/j.jbiomech.2015.04.017

Alentorn-Geli, E., Mendiguchía, J., Samuelsson, K., Musahl, V., Karlsson, J., Cugat, R., & Myer, G. D. (2014). Prevention of anterior cruciate ligament injuries in sports. Part I: systematic review of risk factors in male athletes. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA, 22(1), 3–15. https://doi.org/10.1007/s00167-013-2725-3

Hsu, W. H., Fisk, J. A., Yamamoto, Y., Debski, R. E., & Woo, S. L. (2006). Differences in torsional joint stiffness of the knee between genders: a human cadaveric study. The American journal of sports medicine, 34(5), 765–770. https://doi.org/10.1177/0363546505282623

Sharifi, M., & Shirazi-Adl, A. (2021). Changes in gastrocnemii activation at mid-to-late stance markedly affects the intact and anterior cruciate ligament deficient knee biomechanics and stability in gait. The Knee, 29, 530-540. https://doi.org/10.1016/j.knee.2021.03.004

Bourne, M. N., Webster, K. E., & Hewett, T. E. (2019). Is fatigue a risk factor for anterior cruciate ligament rupture?. Sports medicine, 49(11), 1629-1635. https://doi.org/10.1007/s40279-019-01134-5

Koo, Y. J., Seon, J. K., Lee, G., & Koo, S. (2023). Influences of partial anterior cruciate ligament injury on anterior cruciate ligament tensional force and kinematic stability during walking. Journal of biomechanical engineering, 145(1), 011003. https://doi.org/10.1115/1.4054982

Moglo, K. E., & Shirazi-Adl, A. (2003). On the coupling between anterior and posterior cruciate ligaments, and knee joint response under anterior femoral drawer in flexion: a finite element study. Clinical Biomechanics, 18(8), 751-759. https://doi.org/10.1016/S0268-0033(03)00140-2

Bates, N. A., Nesbitt, R. J., Shearn, J. T., Myer, G. D., & Hewett, T. E. (2018). The influence of internal and external tibial rotation offsets on knee joint and ligament biomechanics during simulated athletic tasks. Clinical biomechanics (Bristol, Avon), 52, 109–116. https://doi.org/10.1016/j.clinbiomech.2018.01.019

Allen, C. R., Wong, E. K., Livesay, G. A., Sakane, M., Fu, F. H., & Woo, S. L. Y. (2000). Importance of the medial meniscus in the anterior cruciate ligament-deficient knee. Journal of Orthopaedic Research, 18(1), 109-115. https://doi.org/10.1002/jor.1100180116

Boden, B. P., Sheehan, F. T., Torg, J. S., & Hewett, T. E. (2010). Noncontact anterior cruciate ligament injuries: mechanisms and risk factors. The Journal of the American Academy of Orthopaedic Surgeons, 18(9), 520–527. https://doi.org/10.5435/00124635-201009000-00003

Song, Y., Debski, R. E., Musahl, V., Thomas, M., & Woo, S. L. Y. (2004). A three-dimensional finite element model of the human anterior cruciate ligament: a computational analysis with experimental validation. Journal of biomechanics, 37(3), 383-390. https://doi.org/10.1016/S0021-9290(03)00261-6

DeMorat, G., Weinhold, P., Blackburn, T., Chudik, S., & Garrett, W. (2004). Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. The American journal of sports medicine, 32(2), 477–483. https://doi.org/10.1177/0363546503258928

Yu, B., & Garrett, W. E. (2007). Mechanisms of non-contact ACL injuries. British journal of sports medicine, 41 Suppl 1(Suppl 1), i47–i51. https://doi.org/10.1136/bjsm.2007.037192

Hashemi, J., Breighner, R., Chandrashekar, N., Hardy, D. M., Chaudhari, A. M., Shultz, S. J., Slauterbeck, J. R., & Beynnon, B. D. (2011). Hip extension, knee flexion paradox: a new mechanism for non-contact ACL injury. Journal of biomechanics, 44(4), 577–585. https://doi.org/10.1016/j.jbiomech.2010.11.013

Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., Hewett, T. E., & Bahr, R. (2007). Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. The American journal of sports medicine, 35(3), 359–367. https://doi.org/10.1177/0363546506293899

Sadoghi, P., von Keudell, A., & Vavken, P. (2012). Effectiveness of anterior cruciate ligament injury prevention training programs. The Journal of bone and joint surgery. American volume, 94(9), 769–776. https://doi.org/10.2106/JBJS.K.00467

Zebis, M. K., Bencke, J., Andersen, L. L., Døssing, S., Alkjaer, T., Magnusson, S. P., Kjaer, M., & Aagaard, P. (2008). The effects of neuromuscular training on knee joint motor control during sidecutting in female elite soccer and handball players. Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine, 18(4), 329–337. https://doi.org/10.1097/JSM.0b013e31817f3e35

Myer, G. D., Sugimoto, D., Thomas, S., & Hewett, T. E. (2013). The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a meta-analysis. The American journal of sports medicine, 41(1), 203–215. https://doi.org/10.1177/0363546512460637

Padua, D. A., DiStefano, L. J., Beutler, A. I., de la Motte, S. J., DiStefano, M. J., & Marshall, S. W. (2015). The Landing Error Scoring System as a Screening Tool for an Anterior Cruciate Ligament Injury-Prevention Program in Elite-Youth Soccer Athletes. Journal of athletic training, 50(6), 589–595. https://doi.org/10.4085/1062-6050-50.1.10

DiStefano, L. J., Blackburn, J. T., Marshall, S. W., Guskiewicz, K. M., Garrett, W. E., & Padua, D. A. (2011). Effects of an age-specific anterior cruciate ligament injury prevention program on lower extremity biomechanics in children. The American journal of sports medicine, 39(5), 949–957. https://doi.org/10.1177/0363546510392015

Ueno, R., Navacchia, A., DiCesare, C. A., Ford, K. R., Myer, G. D., Ishida, T., Tohyama, H., & Hewett, T. E. (2020). 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. Journal of biomechanics, 103, 109669. https://doi.org/10.1016/j.jbiomech.2020.109669

Shimokochi, Y., Ambegaonkar, J. P., Meyer, E. G., Lee, S. Y., & Shultz, S. J. (2013). Changing sagittal plane body position during single-leg landings influences the risk of non-contact anterior cruciate ligament injury. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA, 21(4), 888–897. https://doi.org/10.1007/s00167-012-2011-9

Gilchrist, J., Mandelbaum, B. R., Melancon, H., Ryan, G. W., Silvers, H. J., Griffin, L. Y., Watanabe, D. S., Dick, R. W., & Dvorak, J. (2008). A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. The American journal of sports medicine, 36(8), 1476–1483. https://doi.org/10.1177/0363546508318188

LaBella, C. R., Huxford, M. R., Grissom, J., Kim, K. Y., Peng, J., & Christoffel, K. K. (2011). Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high schools: cluster randomized controlled trial. Archives of pediatrics & adolescent medicine, 165(11), 1033–1040. https://doi.org/10.1001/archpediatrics.2011.168

Petersen, W., Braun, C., Bock, W., Schmidt, K., Weimann, A., Drescher, W., Eiling, E., Stange, R., Fuchs, T., Hedderich, J., & Zantop, T. (2005). A controlled prospective case control study of a prevention training program in female team handball players: the German experience. Archives of orthopaedic and trauma surgery, 125(9), 614–621. https://doi.org/10.1007/s00402-005-0793-7

Kokkotis, C., Moustakidis, S., Tsatalas, T., Ntakolia, C., Chalatsis, G., Konstadakos, S., Hantes, M. E., Giakas, G., & Tsaopoulos, D. (2022). Leveraging explainable machine learning to identify gait biomechanical parameters associated with anterior cruciate ligament injury. Scientific reports, 12(1), 6647. https://doi.org/10.1038/s41598-022-10666-2

Suomalainen, P., Järvelä, T., Paakkala, A., Kannus, P., & Järvinen, M. (2012). Double-bundle versus single-bundle anterior cruciate ligament reconstruction: a prospective randomized study with 5-year results. The American journal of sports medicine, 40(7), 1511-1518. https://doi.org/10.1177/0363546512448177

Desai, N., Andernord, D., Sundemo, D., Alentorn-Geli, E., Musahl, V., Fu, F., Forssblad, M., & Samuelsson, K. (2017). Revision surgery in anterior cruciate ligament reconstruction: a cohort study of 17,682 patients from the Swedish National Knee Ligament Register. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA, 25(5), 1542–1554. https://doi.org/10.1007/s00167-016-4399-0

Smith, J. O., Yasen, S. K., Lord, B., & Wilson, A. J. (2015). Combined anterolateral ligament and anatomic anterior cruciate ligament reconstruction of the knee. Knee Surgery, Sports Traumatology, Arthroscopy, 23, 3151-3156. https://doi.org/10.1007/s00167-015-3783-5https://www.sci-hub.ru/10.1007/s00167-015-3783-5

Halonen, K. S., Mononen, M. E., Töyräs, J., Kröger, H., Joukainen, A., & Korhonen, R. K. (2016). Optimal graft stiffness and pre-strain restore normal joint motion and cartilage responses in ACL reconstructed knee. Journal of biomechanics, 49(13), 2566-2576. https://doi.org/10.1016/j.jbiomech.2016.05.002

Wang, H., Tao, M., Shi, Q., He, K., & Cheng, C. K. (2022). Graft diameter should reflect the size of the native anterior cruciate ligament (ACL) to improve the outcome of ACL reconstruction: a finite element analysis. Bioengineering, 9(10), 507. https://doi.org/10.3390/bioengineering9100507

Pinczewski, L. A., Deehan, D. J., Salmon, L. J., Russell, V. J., & Clingeleffer, A. (2002). A five-year comparison of patellar tendon versus four-strand hamstring tendon autograft for arthroscopic reconstruction of the anterior cruciate ligament. The American journal of sports medicine, 30(4), 523–536. https://doi.org/10.1177/03635465020300041201

Mohan, R., Webster, K. E., Johnson, N. R., Stuart, M. J., Hewett, T. E., & Krych, A. J. (2018). Clinical Outcomes in Revision Anterior Cruciate Ligament Reconstruction: A Meta-analysis. Arthroscopy : the journal of arthroscopic & related surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association, 34(1), 289–300. https://doi.org/10.1016/j.arthro.2017.06.029

Fu, F. H., Bennett, C. H., Lattermann, C., & Ma, C. B. (1999). Current trends in anterior cruciate ligament reconstruction. The American journal of sports medicine, 27(6), 821-830. https://doi.org/10.1177/03635465990270062501

Fisher, M. B., Liang, R., Jung, H. J., Kim, K. E., Zamarra, G., Almarza, A. J., McMahon, P. J., & Woo, S. L. (2012). Potential of healing a transected anterior cruciate ligament with genetically modified extracellular matrix bioscaffolds in a goat model. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA, 20(7), 1357–1365. https://doi.org/10.1007/s00167-011-1800-x

Fisher, M. B., Jung, H. J., McMahon, P. J., & Woo, S. L. (2011). Suture augmentation following ACL injury to restore the function of the ACL, MCL, and medial meniscus in the goat stifle joint. Journal of biomechanics, 44(8), 1530-1535. https://doi.org/10.1016/j.jbiomech.2011.02.141

Murray, M. M., Kalish, L. A., Fleming, B. C., BEAR Trial Team, Flutie, B., Freiberger, C., Henderson, R. N., Perrone, G. S., Thurber, L. G., Proffen, B. L., Ecklund, K., Kramer, D. E., Yen, Y. M., & Micheli, L. J. (2019). Bridge-Enhanced Anterior Cruciate Ligament Repair: Two-Year Results of a First-in-Human Study. Orthopaedic journal of sports medicine, 7(3), 2325967118824356. https://doi.org/10.1177/2325967118824356

Papageorgiou, C. D., Ma, C. B., Abramowitch, S. D., Clineff, T. D., & Woo, S. L. (2001). A multidisciplinary study of the healing of an intraarticular anterior cruciate ligament graft in a goat model. The American journal of sports medicine, 29(5), 620–626. https://doi.org/10.1177/03635465010290051501

Halinen, J., Lindahl, J., Hirvensalo, E., & Santavirta, S. (2006). Operative and nonoperative treatments of medial collateral ligament rupture with early anterior cruciate ligament reconstruction: a prospective randomized study. The American journal of sports medicine, 34(7), 1134–1140. https://doi.org/10.1177/0363546505284889

Robinson, J., Inderhaug, E., Harlem, T., Spalding, T., & Brown, C. H., Jr (2020). Anterior Cruciate Ligament Femoral Tunnel Placement: An Analysis of the Intended Versus Achieved Position for 221 International High-Volume ACL Surgeons. The American journal of sports medicine, 48(5), 1088–1099. https://doi.org/10.1177/0363546520906158

Gadikota, H. R., Wu, J. L., Seon, J. K., Sutton, K., Gill, T. J., & Li, G. (2010). Single-tunnel double-bundle anterior cruciate ligament reconstruction with anatomical placement of hamstring tendon graft: can it restore normal knee joint kinematics?. The American journal of sports medicine, 38(4), 713–720. https://doi.org/10.1177/0363546509353406

Schmitt, L. C., Paterno, M. V., Ford, K. R., Myer, G. D., & Hewett, T. E. (2015). Strength Asymmetry and Landing Mechanics at Return to Sport after Anterior Cruciate Ligament Reconstruction. Medicine and science in sports and exercise, 47(7), 1426–1434. https://doi.org/10.1249/MSS.0000000000000560

Palmieri-Smith, R. M., & Lepley, L. K. (2015). Quadriceps Strength Asymmetry After Anterior Cruciate Ligament Reconstruction Alters Knee Joint Biomechanics and Functional Performance at Time of Return to Activity. The American journal of sports medicine, 43(7), 1662–1669. https://doi.org/10.1177/0363546515578252

Ithurburn, M. P., Paterno, M. V., Thomas, S., Pennell, M. L., Evans, K. D., Magnussen, R. A., & Schmitt, L. C. (2019). Change in Drop-Landing Mechanics Over 2 Years in Young Athletes After Anterior Cruciate Ligament Reconstruction. The American journal of sports medicine, 47(11), 2608–2616. https://doi.org/10.1177/0363546519864688

Chmielewski, T. L., Hurd, W. J., Rudolph, K. S., Axe, M. J., & Snyder-Mackler, L. (2005). Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. Physical therapy, 85(8), 740–754.https://doi.org/10.1093/ptj/85.8.740

Risberg, M. A., Moksnes, H., Storevold, A., Holm, I., & Snyder-Mackler, L. (2009). Rehabilitation after anterior cruciate ligament injury influences joint loading during walking but not hopping. British journal of sports medicine, 43(6), 423–428. https://doi.org/10.1136/bjsm.2008.056846

Hudgens, J. L., & Dahm, D. L. (2012). Treatment of anterior cruciate ligament injury in skeletally immature patients. International journal of pediatrics, 2012, 932702. https://doi.org/10.1155/2012/932702

Grindem, H., Snyder-Mackler, L., Moksnes, H., Engebretsen, L., & Risberg, M. A. (2016). Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. British journal of sports medicine, 50(13), 804–808. https://doi.org/10.1136/bjsports-2016-096031

Myer, G. D., Martin, L., Jr, Ford, K. R., Paterno, M. V., Schmitt, L. C., Heidt, R. S., Jr, Colosimo, A., & Hewett, T. E. (2012). No association of time from surgery with functional deficits in athletes after anterior cruciate ligament reconstruction: evidence for objective return-to-sport criteria. The American journal of sports medicine, 40(10), 2256–2263. https://doi.org/10.1177/0363546512454656

Ardern, C. L., Taylor, N. F., Feller, J. A., & Webster, K. E. (2014). Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. British journal of sports medicine, 48(21), 1543–1552. https://doi.org/10.1136/bjsports-2013-093398

McPherson, A. L., Feller, J. A., Hewett, T. E., & Webster, K. E. (2019). Psychological Readiness to Return to Sport Is Associated With Second Anterior Cruciate Ligament Injuries. The American journal of sports medicine, 47(4), 857–862. https://doi.org/10.1177/0363546518825258

Kvist, J., Ek, A., Sporrstedt, K., & Good, L. (2005). Fear of re-injury: a hindrance for returning to sports after anterior cruciate ligament reconstruction. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA, 13(5), 393–397. https://doi.org/10.1007/s00167-004-0591-8

Ardern, C. L., Österberg, A., Tagesson, S., Gauffin, H., Webster, K. E., & Kvist, J. (2014). The impact of psychological readiness to return to sport and recreational activities after anterior cruciate ligament

reconstruction. British journal of sports medicine, 48(22), 1613–1619. https://doi.org/10.1136/bjsports-2014-093842

Ardern, C. L., Taylor, N. F., Feller, J. A., Whitehead, T. S., & Webster, K. E. (2015). Sports participation 2 years after anterior cruciate ligament reconstruction in athletes who had not returned to sport at 1 year: a prospective follow-up of physical function and psychological factors in 122 athletes. The American journal of sports medicine, 43(4), 848–856. https://doi.org/10.1177/0363546514563282

Lohmander, L. S., Englund, P. M., Dahl, L. L., & Roos, E. M. (2007). The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. The American journal of sports medicine, 35(10), 1756–1769. https://doi.org/10.1177/0363546507307396

Chaudhari, A. M., Briant, P. L., Bevill, S. L., Koo, S., & Andriacchi, T. P. (2008). Knee kinematics, cartilage morphology, and osteoarthritis after ACL injury. Medicine and science in sports and exercise, 40(2), 215–222. https://doi.org/10.1249/mss.0b013e31815cbb0e

Andriacchi, T. P., & Dyrby, C. O. (2005). Interactions between kinematics and loading during walking for the normal and ACL deficient knee. Journal of biomechanics, 38(2), 293–298. https://doi.org/10.1016/j.jbiomech.2004.02.010

Young People With Old Knees Research Team, Saxby, D. J., Bryant, A. L., Wang, X., Modenese, L., Gerus, P., Konrath, J. M., Bennell, K. L., Fortin, K., Wrigley, T., Cicuttini, F. M., Vertullo, C. J., Feller, J. A., Whitehead, T., Gallie, P., & Lloyd, D. G. (2017). Relationships Between Tibiofemoral Contact Forces and Cartilage Morphology at 2 to 3 Years After Single-Bundle Hamstring Anterior Cruciate Ligament Reconstruction and in Healthy Knees. Orthopaedic journal of sports medicine, 5(8), 2325967117722506. https://doi.org/10.1177/2325967117722506

Frobell, R. B., Roos, H. P., Roos, E. M., Roemer, F. W., Ranstam, J., & Lohmander, L. S. (2013). Treatment for acute anterior cruciate ligament tear: five year outcome of randomised trial. BMJ (Clinical research ed.), 346, f232. https://doi.org/10.1136/bmj.f232

Hipsley, A., Hall, M., Saxby, D. J., Bennell, K. L., Wang, X., & Bryant, A. L. (2022). Quadriceps muscle strength at 2 years following anterior cruciate ligament reconstruction is associated with tibiofemoral joint cartilage volume. Knee Surgery, Sports Traumatology, Arthroscopy, 30(6), 1949-1957. https://doi.org/10.1007/s00167-021-06853-9

Li, G., Lopez, O., & Rubash, H. (2001). Variability of a three-dimensional finite element model constructed using magnetic resonance images of a knee for joint contact stress analysis. Journal of biomechanical engineering, 123(4), 341–346. https://doi.org/10.1115/1.1385841

Napier, R. J., Garcia, E., Devitt, B. M., Feller, J. A., & Webster, K. E. (2019). Increased Radiographic Posterior Tibial Slope Is Associated With Subsequent Injury Following Revision Anterior Cruciate Ligament Reconstruction. Orthopaedic journal of sports medicine, 7(11), 2325967119879373. https://doi.org/10.1177/2325967119879373

Macri, E. M., Culvenor, A. G., Morris, H. G., Whitehead, T. S., Russell, T. G., Khan, K. M., & Crossley, K. M. (2018). Lateral displacement, sulcus angle and trochlear angle are associated with early patellofemoral osteoarthritis following anterior cruciate ligament reconstruction. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA, 26(9), 2622–2629. https://doi.org/10.1007/s00167-017-4571-1

Webster, K. E., Austin, D. C., Feller, J. A., Clark, R. A., & McClelland, J. A. (2015). Symmetry of squatting and the effect of fatigue following anterior cruciate ligament reconstruction. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA, 23(11), 3208–3213. https://doi.org/10.1007/s00167-014-31213

Hart, J. M., Ko, J. W., Konold, T., & Pietrosimone, B. (2010). Sagittal plane knee joint moments following anterior cruciate ligament injury and reconstruction: a systematic review. Clinical biomechanics (Bristol, Avon), 25(4), 277–283. https://doi.org/10.1016/j.clinbiomech.2009.12.004

Riordan, E. A., Frobell, R. B., Roemer, F. W., & Hunter, D. J. (2013). The health and structural consequences of acute knee injuries involving rupture of the anterior cruciate ligament. Rheumatic diseases clinics of North America, 39(1), 107–122. https://doi.org/10.1016/j.rdc.2012.10.002

Barenius, B., Ponzer, S., Shalabi, A., Bujak, R., Norlén, L., & Eriksson, K. (2014). Increased risk of osteoarthritis after anterior cruciate ligament reconstruction: a 14-year follow-up study of a randomized controlled trial. The American journal of sports medicine, 42(5), 1049–1057. https://doi.org/10.1177/0363546514526139

Wellsandt, E., Zeni, J. A., Axe, M. J., & Snyder-Mackler, L. (2017). Hip joint biomechanics in those with and without post-traumatic knee osteoarthritis after anterior cruciate ligament injury. Clinical Biomechanics, 50, 63-69. https://doi.org/10.1016/j.clinbiomech.2017.10.001

Filardo, G., Kon, E., Longo, U. G., Madry, H., Marchettini, P., Marmotti, A., Van Assche, D., Zanon, G., & Peretti, G. M. (2016). Non-surgical treatments for the management of early osteoarthritis. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA, 24(6), 1775–1785. https://doi.org/10.1007/s00167-016-4089-y