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Knee Injuries in Childhood and their Long-term Effects on Motor Development: An Integrative Review

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Abstract

Objective

This integrative literature review explores the relationship between knee injuries in children and their motor development.

Methodology

A comprehensive search of peer-reviewed articles published between 2014 and 2024 was conducted in databases such as PubMed. Inclusion criteria encompassed studies addressing knee injuries and motor development in children, published in English or Portuguese, and freely accessible. A total of 43 studies were included and analyzed thematically.

Results

The findings indicate that knee injuries significantly impact motor development in children, with effects on gait, muscle strength, and joint stability. Factors such as hypermobility, surgical interventions, and rehabilitation strategies are critical in mitigating long-term developmental delays.

Conclusion

Proper diagnosis, early intervention, and targeted rehabilitation are essential to prevent long-term impairments in motor development. Future research should focus on optimizing intervention strategies.

Keywords: Knee Injuries, Children, Motor Development, Rehabilitation, Integrative Review

1. Introduction

Knee injuries are an increasingly prevalent concern in pediatric populations, particularly among children who actively participate in sports and recreational activities. These injuries can extend their impact beyond immediate physical impairments, often disrupting motor development and diminishing overall quality of life. The spectrum of knee injuries in children is diverse, encompassing patellar dislocations, ligament tears, and cartilage damage—each contributing uniquely to functional limitations and developmental challenges.

Gornick *et al*. (2024) [19] highlighted the efficacy of medial patellofemoral ligament augmentation repairs in addressing primary patellar dislocations, showcasing the importance of surgical precision in restoring knee stability. Similarly, Sasaki and Nagano (2024) [34] identified growth-related knee pain as a critical issue among Japanese footballers aged 12-15 years, emphasizing the need for timely interventions to prevent long-term complications. Ursei *et al*. (2024) [38] provided valuable insights into altered gait patterns following anterior cruciate ligament (ACL) reconstruction in children, underlining the biomechanical repercussions of such injuries.

Negru *et al*. (2024) [27] examined the relationship between stabilometry and muscle force in children with surgically treated slipped capital femoral epiphysis, revealing the intricate interplay between hip and knee dynamics. Tsagkaris *et al*. (2024) [37] explored walking and running mechanics in children with decreased femoral torsion, shedding light on adaptive biomechanical responses. The extent and risk of knee injuries in hypermobile children aged 9-14 years were thoroughly investigated by Junge *et al*. (2015) [22], adding to the understanding of vulnerability factors in this population.

Innovative preventive measures have also been explored. Emery *et al*. (2022) [13] introduced the "SHRed Injuries Basketball" program, which successfully reduced knee injury rates by 36% among youth basketball players through neuromuscular training. Similarly, Kocher *et al*. (2018) [24] demonstrated the advantages of physeal-sparing ACL reconstruction techniques in skeletally immature children, offering a promising approach to preserving growth potential. Dietvorst *et al*. (2019) [10] underscored the need for pediatric-specific Patient-Reported Outcome Measures (PROMs) in evaluating knee ligament injuries, highlighting the limitations of adult-oriented assessment tools.

Biomechanical factors such as fatigue and sex differences have also been implicated in injury risk. Briem *et al*. (2017) [5] reported that these variables significantly influence movement patterns during physical activities, which may predispose children to injuries. Additionally, Toomey *et al.* (2017) [36] identified a link between higher fat mass and an increased history of knee injuries in youth sports, pointing to modifiable risk factors. Salzmann *et al*. (2018) [33] provided critical insights into cartilage repair techniques, emphasizing their role in preserving joint function in pediatric populations.

Reconstruction outcomes have been another focal point of research. Christino *et al*. (2018) investigated revision ACL reconstruction, providing evidence on the challenges and success rates of these procedures. Jacobsen *et al*. (2015) validated the reproducibility and responsiveness of the Danish Pedi-IKDC subjective knee form, a tool specifically designed for children with knee disorders. Meanwhile, Browne and Barnett (2016) [6] documented common sports-related musculoskeletal injuries, including knee injuries, presenting in emergency departments, emphasizing the need for improved prevention strategies.

Neuromuscular training and rehabilitation protocols have proven instrumental in mitigating the impact of knee injuries. Junge *et al*. (2016) [23] emphasized the importance of structured interventions in reducing injury recurrence. Duart, *et al*. (2023) [11] provided an epidemiological overview of pediatric ACL tears, highlighting diagnostic challenges and the need for comprehensive management strategies.

This integrative review synthesizes findings from these 43 studies to provide a nuanced understanding of how knee injuries influence motor development in children. By consolidating evidence, the review seeks to bridge the gap between injury management and developmental outcomes, offering actionable insights for clinicians, researchers, and educators.

The objective of this study is to comprehensively investigate the multifaceted impact of knee injuries on motor development in children. This includes identifying key risk factors, assessing the effectiveness of various treatment approaches, and proposing evidence-based rehabilitation strategies aimed at minimizing developmental impairments and enhancing long-term functional outcomes.

2. Methodology

This integrative literature review was conducted following a systematic and rigorous framework to ensure the reliability and relevance of findings. The methodology is detailed as follows:

The research process began with the identification of the problem, focusing on understanding how knee injuries impact motor development in children. The scope was defined to highlight the importance of prevention, diagnosis, and rehabilitation strategies tailored to pediatric populations.

A comprehensive search was conducted in the PubMed database using Boolean descriptors such as "AND," "OR," and "NOT" to refine the query. The primary search terms included "knee injuries," "children," "motor development," and "rehabilitation." Filters were applied to include studies published between 2014 and 2024, written in English or Portuguese, and available as open-access full-text articles. This ensured that the selected studies were current, relevant, and accessible.

The inclusion criteria encompassed peer-reviewed articles focusing on knee injuries and their relationship with motor development in children. Studies were excluded if they were review articles, conference abstracts, theses, or not freely accessible. After applying these criteria, a total of 43 articles were selected for further analysis.

Each article underwent a meticulous evaluation to assess its relevance, methodological quality, and key findings. This process involved reviewing the study design, sample size, intervention protocols, and outcome measures. Articles with robust methodologies and significant contributions to the topic were prioritized.

The selected studies were subjected to thematic analysis to identify patterns, trends, and gaps in the literature. Data were categorized based on risk factors, treatment outcomes, and rehabilitation strategies. This categorization facilitated a structured synthesis of the evidence, ensuring a comprehensive understanding of the subject matter.

The results were presented narratively, supported by tables to enhance clarity and accessibility. The tables summarized key aspects of the included studies, such as objectives, methodologies, and main findings, providing an organized and visual representation of the evidence.

Finally, the findings were synthesized to draw meaningful conclusions. The integration of evidence aimed to identify effective strategies for managing knee injuries and mitigating their impact on motor development in children. This step also highlighted areas requiring further research to address existing gaps in literature.

3. Results

The integrative review aimed to consolidate findings from 43 studies to assess the impact of knee injuries on motor development in children. However, a critical evaluation of the references based on inclusion criteria revealed that only 24 studies met the necessary methodological rigor and relevance for inclusion in the analysis. The discrepancy between the initial and final count of studies can be attributed to several factors.

First, duplication of studies was a primary reason for exclusion. Some references appeared more than once, presenting identical findings and involving the same study populations. These redundancies were removed to maintain the integrity of the dataset.

Second, exclusion criteria played a significant role in narrowing the selection. Articles that did not fully meet the predefined requirements—such as those focusing on adult populations, providing incomplete data, or lacking a direct connection to motor development in children—were excluded. Additionally, studies that were review articles, theses, or abstracts without sufficient methodological detail were omitted to ensure the analysis was grounded in robust

and reliable evidence.

Lastly, limited access to full data contributed to the reduction. Despite being initially identified, some articles lacked essential methodological details or were inaccessible in full text, preventing a comprehensive evaluation of their findings. These were excluded to uphold the reliability and transparency of the review.

The final selection of 24 studies provides a focused and high-quality dataset, which is presented in Table 1. The table summarizes critical aspects of the studies, including authors, populations studied, types of knee injuries, and key findings. These studies collectively offer insights into various dimensions of knee injuries, from risk factors to rehabilitation strategies, and their profound impact on motor development in pediatric populations. By refining the dataset to include only the most relevant and rigorous studies, this review ensures a robust foundation for understanding and addressing the challenges associated with knee injuries in children.

Table 1: Summary of Studies on Knee Injuries, Motor Alterations, and Rehabilitation Outcomes

Authors	Population Studied	Type of Knee Injury	Key Findings	Motor Alterations
Gornick *et al.* (2024) [19]	Children and adolescents with patellar dislocation	Patellar dislocation	Medial patellofemoral ligament augmentation improves stability and function.	Reduced balance and increased compensatory gait patterns.
Sasaki & Nagano (2024) [34]	Japanese footballers aged 12-15	Growth-related knee pain	Early intervention critical to prevent chronic impairment.	Altered motor control during sports activities.
Ursei *et al.* (2024) [38]	Post-ACL reconstruction children	ACL injury	Altered gait biomechanics highlight rehabilitation needs.	Limited knee flexion and abnormal walking patterns.
Negru *et al.* (2024) [27]	Children with slipped femoral epiphysis	Slipped capital femoral epiphysis	Improved stabilometry correlates with enhanced muscle force.	Reduced stability and delayed coordination development.
Maneekhiew *et al.* (2024) [26]	Children with bleeding disorders	Joint instability	Natural rubber knee supports provide superior protection.	Difficulty maintaining dynamic balance.
Emery *et al.* (2022) [13]	Youth basketball players	Knee ligament injuries	Neuromuscular training reduces injury rates by 36%.	Improved agility and prevention of motor deficits.
Kocher *et al.* (2018) [24]	Skeletally immature prepubescent children	ACL tear	Physeal-sparing ACL reconstruction preserves growth.	Enhanced post-operative motor performance.
Beatty *et al.* (2024) [3]	Children and adolescents	Patella fractures	Favorable outcomes with intensive rehabilitation.	Recovery of full knee range of motion.
Salzmann *et al.* (2018) [33]	Pediatric patients undergoing cartilage repair	Cartilage damage	Enhanced joint function post-cartilage repair.	Improved movement efficiency during walking and running.
Junge *et al.* (2015) [22]	Children aged 9-14 with joint hypermobility	Knee ligament injuries	Generalized hypermobility increases injury risk.	Decreased joint stability and control.
Dietvorst *et al.* (2019) [10]	Pediatric patients	Ligament injuries	Pediatric PROMs improve assessment accuracy.	Enhanced rehabilitation focus on specific motor impairments.
Browne & Barnett (2016) [6]	Sports-injured children in emergency settings	Various knee injuries	Highlighted need for specialized care in emergency cases.	Temporary motor deficits affecting mobility.
Christino *et al.* (2018)	Adolescents with revision ACL reconstruction	ACL revision	Successful outcomes with structured rehabilitation.	Gradual improvement in dynamic movements.
Jacobsen *et al.* (2015)	Pediatric patients in Denmark	ACL and other knee injuries	Danish Pedi-IKDC tool validated for children.	Identified specific deficits in motor development.

Legend: ACL: Anterior Cruciate Ligament; PROMs: Patient-Reported Outcome Measures; Pedi-IKDC: Pediatric International Knee Documentation Committee

Table 1: Summary of Studies on Knee Injuries, Motor Alterations, and Rehabilitation Outcomes

Authors	Population Studied	Type of Knee Injury	Key Findings	Motor Alterations
Toomey *et al.* (2017) [36]	Youth athletes	Knee injuries linked to higher fat mass	Fat mass management reduces injury risk.	Limited motor coordination and increased fatigue.
Duart *et al.* (2023) [11]	Pediatric ACL patients	ACL and associated lesions	Accurate imaging improves diagnosis.	Altered motor strategies post-injury.
Briem *et al.* (2017) [5]	Children in drop-jump tasks	Biomechanical stress	Fatigue and sex influence injury risk.	Reduced jump height and stability under fatigue.
Ekås *et al.* (2018)	ACL patients followed over 8 years	ACL injuries from childhood to adulthood	Rehabilitation improves coping strategies.	Improved motor planning and endurance.
Iversen *et al.* (2016) [20]	Children with sports-related injuries	Knee injuries	Validated physical activity scales for pediatric use.	Facilitated better assessment of motor outcomes.
Junge *et al.* (2016) [23]	Children aged 8-15	Knee ligament injuries	Neuromuscular risk factors linked to injury prevention.	Enhanced motor learning in prevention programs.
Tsagkaris *et al.* (2024) [37]	Children with decreased femoral torsion	Femoral torsion-related knee dysfunction	Adaptive gait mechanics developed over time.	Persistent compensatory gait patterns.
Junge *et al.* (2016)	Children aged 8-15	Risk factors for knee injuries	Generalized joint hypermobility	Impaired dynamic movement

[23]			is a significant risk.	and increased instability.
Christino *et al*. (2018)	Adolescents undergoing ACL revisions	ACL injury	Structured rehabilitation enhances surgical success.	Improved coordination and functional return to sports.
Junge *et al*. (2015) [22]	Pediatric cohort	ACL & cartilage issues	Broader analyses tied to late-stage return mechanisms.	Optimized return-to-play protocols enhancing motor recovery.

Legend: ACL: Anterior Cruciate Ligament; PROMs: Patient-Reported Outcome Measures; Pedi-IKDC: Pediatric International Knee Documentation Committee

The studies reveal a broad spectrum of knee injuries affecting children, including patellar dislocations, ACL tears, growth-related knee pain, cartilage damage, and joint instability. Despite differences in etiology and clinical presentation, these injuries uniformly disrupt motor development. For instance, Gornick *et al*. (2024) [19] demonstrate how patellar dislocations lead to balance impairments, while Salzmann *et al*. (2018) [33] highlight the long-term functional limitations associated with cartilage damage. This diversity underscores the need for tailored interventions that address specific injury types and their motor implications.

Several studies emphasize the critical role of rehabilitation and targeted interventions in mitigating the effects of knee injuries. Emery *et al*. (2022) [13] show that neuromuscular training programs can significantly reduce injury rates, improving motor outcomes and preventing recurrences. Similarly, Kocher *et al*. (2018) [24] underline the success of physeal-sparing surgical techniques in skeletally immature children, preserving both motor development and growth potential. These findings demonstrate that evidence-based interventions can effectively bridge the gap between injury management and functional recovery.

Certain risk factors predispose children to knee injuries and subsequent motor deficits. Junge *et al*. (201identifies identify generalized joint hypermobility as a significant contributor to knee ligament injuries, while Toomey *et al*. (2017) [36] link higher fat mass to increased injury risk. These studies highlight the importance of early screening and preventive strategies, such as promoting healthy weight management and implementing conditioning programs to enhance joint stability and reduce injury susceptibility.

The necessity of comprehensive rehabilitation programs tailored to pediatric needs is evident from the studies. Ursei *et al*. (2024) [38] highlight how ACL injuries alter gait biomechanics, requiring focused rehabilitation to restore natural walking patterns. Similarly, Briem *et al*. (2017) [5] emphasize the impact of fatigue on motor control, particularly during dynamic tasks like jumping, indicating the need for endurance-focused training. These findings emphasize the importance of addressing motor deficits as part of the recovery process to optimize long-term functional outcomes.

Accurate diagnosis and monitoring are essential for managing knee injuries and their motor consequences. Jacobsen *et al*. (2015) validate the Danish Pedi-IKDC tool as a reliable instrument for assessing knee disorders in children, while Dietvorst *et al*. (2019) [10] advocate for pediatric-specific PROMs to improve injury evaluations. These tools facilitate better understanding and tracking of motor impairments, ensuring more effective treatment plans.

4. Discussion

The complexity of knee injuries in pediatric populations demands a multifaceted approach to understanding their impact on biomechanics, motor development, and recovery processes. These injuries, ranging from patellar dislocations to anterior cruciate ligament (ACL) tears and cartilage damage, often result in profound functional limitations and long-term developmental challenges. As highlighted in the studies by Gornick *et al*. (2024) [19] and Ursei *et al*. (2024) [38], the biomechanical disruptions caused by such injuries extend beyond the knee joint, affecting overall motor performance and stability. Exploring these disruptions and their implications is critical for developing targeted prevention and rehabilitation strategies.

Motor development and control are intricately linked to the health of the musculoskeletal system, particularly in growing children. Knee injuries not only compromise immediate physical function but also interfere with the natural progression of motor skills, as evidenced by Sasaki and Nagano (2024) [34]. These interruptions in motor development can lead to compensatory movement patterns and secondary injuries, creating a cycle of dysfunction. Addressing these challenges requires an in-depth understanding of the mechanisms of injury, diagnostic tools, and evidence-based interventions tailored to pediatric populations.

This discussion synthesizes findings from 24 studies, examining the biomechanical, developmental, and clinical aspects of pediatric knee injuries. The focus is on identifying injury mechanisms, evaluating diagnostic advancements, and analyzing treatment strategies that support motor recovery and re-adaptation. By integrating biomechanical insights with practical applications, this section aims to provide a comprehensive framework for addressing the multifaceted impact of knee injuries on children.

Knee injuries profoundly disrupt the biomechanical stability of pediatric joints, influencing both static and dynamic movements. Patellar dislocations, for instance, alter medial patellofemoral ligament integrity, leading to joint instability and lateral sway. Gornick *et al*. (2024) [19] demonstrated that medial patellofemoral ligament augmentation can restore some level of stability. However, residual biomechanical deficits, such as reduced stride length and impaired proprioception, persist and exacerbate the risk of subsequent injuries.

Altered gait patterns are prevalent among children recovering from knee injuries. Ursei *et al*. (2024) [38] identified significant asymmetries in stance time and load distribution following ACL reconstruction, emphasizing the necessity of targeted interventions to correct these deficits. Similarly, Tsagkaris *et al*. (2024) [37] explored how decreased femoral torsion in children affects walking and running mechanics, further highlighting the interplay between hip and knee biomechanics.

Fatigue is another biomechanical challenge that exacerbates injury risks. Briem *et al*. (2017) [5] noted that fatigue impairs dynamic stability and increases valgus collapse during high-impact activities. These findings underscore the importance of endurance training and proprioceptive exercises to restore

balance and coordination in pediatric populations. Incorporating rest intervals into training regimens also mitigates the biomechanical effects of fatigue.

Children with cartilage damage face unique biomechanical challenges. Salzmann *et al.* (2018) [33] observed that such injuries disrupt joint congruency, leading to increased energy expenditure during movement. Rehabilitation protocols for these children should include non-weight-bearing activities, such as swimming or cycling, to promote recovery without adding stress to the injured joint.

Neuromuscular control plays a critical role in biomechanical recovery. Delayed muscle activation and reduced proprioceptive feedback are common among children with knee injuries (Ursei *et al*., 2024) [38]. Kocher *et al*. (2018) [24] emphasized the importance of restoring quadriceps-hamstring co-contraction to stabilize the joint and improve functional outcomes.

Additionally, the compensatory adaptations in adjacent joints are a significant concern. Children recovering from knee injuries often shift stress to the hip or ankle to protect the injured knee (Negru *et al*., 2024) [27]. These compensations can lead to secondary injuries, underscoring the need for comprehensive rehabilitation programs targeting the entire kinetic chain.

Biomechanical assessments using advanced tools such as force plates and motion capture systems enable clinicians to monitor recovery and fine-tune rehabilitation protocols. These technologies, as highlighted by Duart *et al*. (2023) [11], provide valuable insights into movement patterns and joint load distribution, facilitating more precise interventions.

Knee injuries disrupt motor development in children by altering neuromuscular control and coordination. Rapid growth during adolescence, coupled with insufficient muscle-tendon adaptation, exacerbates joint instability (Sasaki & Nagano, 2024) [34]. These biomechanical imbalances hinder the natural progression of motor skills, such as agility and balance.

Growth-related knee pain, such as Osgood-Schlatter disease, further complicates motor development. Sasaki and Nagano (2024) [34] observed that children with this condition often adopt compensatory strategies to minimize pain, such as avoiding full knee flexion. While these adaptations provide short-term relief, they lead to long-term muscle imbalances and asymmetrical motor patterns.

Psychological factors also influence motor control. Fear of re-injury is common among children recovering from knee injuries (Ekås *et al*., 2018). This fear often results in guarded movements and reduced participation in physical activities, delaying motor recovery. Psychological interventions, including confidence-building exercises, are essential to restore normal motor patterns.

Neuromuscular deficits are a critical aspect of impaired motor control. Delayed activation of the quadriceps and hamstrings, as highlighted by Ursei *et al.* (2024) [38], compromises joint stability and increases the risk of re-injury. Rehabilitation programs should emphasize neuromuscular re-education through exercises such as single-leg squats and dynamic balance drills.

Compensatory motor behaviors also extend to the upper body. Children recovering from knee injuries often rely on increased trunk and arm movements to stabilize their gait (Negru *et al*., 2024) [27]. Addressing these compensations through core stabilization exercises can improve overall motor coordination and prevent secondary issues.

Proprioception deficits further hinder motor control. Jacobsen *et al*. (2015) validated the Danish Pedi-IKDC tool, which emphasizes proprioceptive feedback as a critical component of pediatric knee injury assessment. Rehabilitation programs that incorporate balance boards and dynamic stability exercises can significantly improve proprioceptive awareness. Personalized motor control strategies are essential for effective recovery. Tailoring rehabilitation protocols to the child's age, injury severity, and activity level ensures optimal outcomes. Real-time feedback tools, such as motion capture systems, enable children to correct movement patterns and enhance motor learning (Duart *et al*., 2023) [11].

Understanding the mechanisms of knee injuries is crucial for developing effective prevention and treatment strategies. Patellar dislocations are often caused by direct trauma or abrupt directional changes during physical activities, as described by Gornick *et al*. (2024) [19]. Identifying risk factors such as joint hypermobility can help clinicians implement preventative measures (Junge *et al*., 2015) [22].

ACL injuries are commonly associated with non-contact mechanisms, such as rapid deceleration or improper landing from a jump. Ursei *et al*. (2024) [38] emphasized the importance of addressing these mechanisms through neuromuscular training programs, which reduce the risk of ACL tears by improving dynamic stability and landing mechanics.

Repetitive stress injuries, such as growth-related knee pain, are another significant concern. Sasaki and Nagano (2024) [34] highlighted the role of high-impact activities, such as jumping or running, in exacerbating these conditions. Preventative strategies should focus on modifying training regimens to reduce repetitive stress on the knee joint.

Cartilage injuries often result from a combination of acute trauma and repetitive microtrauma. Salzmann *et al*. (2018) [33] noted that these injuries disrupt joint congruency and load distribution, increasing the risk of secondary injuries. Early diagnosis and activity modification are critical to preventing long-term complications.

Finally, fatigue-induced mechanisms, as discussed by Briem *et al*. (2017) [5], highlight the role of muscle endurance in injury prevention. Fatigue impairs coordination and dynamic stability, increasing the likelihood of improper movements and subsequent injuries. Endurance-focused training programs can mitigate these risks and enhance overall joint resilience.

Accurate diagnosis is the cornerstone of effective knee injury management. Advanced imaging techniques, such as MRI, provide detailed assessments of soft tissue and cartilage damage (Duart *et al*., 2023) [11]. These tools enable clinicians to identify specific injury patterns and tailor interventions accordingly.

Validated assessment tools, such as the Danish Pedi-IKDC, play a vital role in diagnosing pediatric knee injuries (Jacobsen *et al*., 2015). These tools account for the unique anatomical and developmental characteristics of children, ensuring more accurate evaluations and treatment planning.

Surgical and non-surgical treatments are essential for managing pediatric knee injuries. Physeal-sparing techniques, as highlighted by Kocher *et al*. (2018) [24], are critical for preserving growth potential while addressing ligament injuries. Non-surgical options, such as bracing and activity modification, are also effective for certain injury types (Maneekhiew *et al*., 2024) [26].

Re-adaptation to physical activity post-injury requires a multidisciplinary approach. Neuromuscular training programs that include balance, proprioception, and agility exercises are vital for restoring motor competence (Emery *et al*., 2022) [13]. Advanced tools like motion capture systems facilitate precise motor re-education, enabling children to optimize movement patterns and prevent re-injury.

Psychological support is equally critical. Fear of re-injury often hinders motor re-adaptation, emphasizing the need for confidence-building exercises and gradual exposure to dynamic activities (Ekås *et al*., 2018).

5. Conclusion

This study provides a comprehensive exploration of the multifaceted impact of knee injuries on motor development in children, addressing key risk factors, evaluating treatment effectiveness, and proposing evidence-based rehabilitation strategies. The findings underscore that knee injuries such as patellar dislocations, ACL tears, and cartilage damage disrupt not only the structural integrity of the joint but also the biomechanical and motor development processes. These injuries lead to compensatory movement patterns, altered gait mechanics, and long-term functional impairments, emphasizing the need for targeted intervention.

Key risk factors identified include joint hypermobility, higher fat mass, rapid growth phases, and biomechanical imbalances. Early recognition of these risks, as highlighted by Junge *et al*. (2015, 2016) [22, 23] and Toomey *et al*. (2017) [36], is critical for prevention. Additionally, neuromuscular training and individualized rehabilitation programs, such as those described by Emery *et al*. (2022) [13] and Kocher *et al*. (2018) [24], have been shown to improve outcomes by addressing muscle imbalances, proprioceptive deficits, and psychological barriers like fear of re-injury.

This study highlights the importance of a multidisciplinary approach that integrates advanced diagnostic tools, personalized treatment plans, and comprehensive rehabilitation strategies. Interventions should focus on restoring biomechanical efficiency, enhancing motor control, and preventing re-injury through education, psychological support, and long-term follow-up. By addressing these aspects holistically, clinicians can optimize motor development, minimize impairments, and enhance the overall quality of life for children recovering from knee injuries. Further research is needed to refine these strategies and explore innovative technologies that can support pediatric rehabilitation.

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