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A randomized trial on transphyseal *vs.* physeal-sparing reconstruction in skeletally immature patients: functional outcomes and safety considerations

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Abstract

Reconstruction of the Anterior Cruciate Ligament (ACL) in Skeletally Immature Patients (SIP) poses challenges due to anatomical and developmental factors. This randomized controlled trial evaluated the Functional Recovery (FR) of pediatric patients undergoing ACL Reconstruction (ACLR), comparing Transphyseal Reconstruction (TPR) and physeal-sparing reconstruction (PSR). Forty-three young athletes (mean age 14.1±2.3 years), including 29 boys and 14 girls, were randomized to TPR (n=23) or PSR (n=20). FR was assessed by using the Pediatric International Knee Documentation Committee (Pedi-IKDC) questionnaire at baseline, 8 months, and 12 months post-surgery. At the 12-month follow-up, the TPR group demonstrated a significantly greater improvement in Pedi-IKDC scores, with a 66.95% increase compared to 56.73% in the PSR group, reflecting notable differences in knee function between the groups at both 8 and 12 months ($p < 0.001$). Additionally, 80% of participants in the TPR group returned to sports, with 56% resuming limited activities, while the PSR group exhibited a slower recovery trajectory. These preliminary findings indicate that TPR provides superior FR and a faster return to sports compared to PSR, underscoring the importance of tailored rehabilitation protocols and long-term follow-up to optimize outcomes in SIP.

Key Words: Skeletally immature patients; anterior cruciate ligament; reconstruction; transphyseal reconstruction; physeal sparing reconstruction; Pediatric International Knee Documentation Committee (Pedi-IKDC)..

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Knee injuries are a prevalent concern among school-aged and adolescent athletes, contributing to approximately 50% to 60% of all sports-related injuries in this group. Anterior Cruciate Ligament (ACL) injuries, in particular, constitute over 25% of these knee injuries, reflecting the significant impact of this pathology on young athletes' health and performance.[1] The incidence of ACL injuries is influenced by various factors, including the type of sport, gender, and the athlete's level of training, with studies indicating an estimated occurrence of 6.5 injuries per 100,000 U.S. high school athletes.[2] Notably, female athletes are at a disproportionately higher risk of ACL Rupture (ACLR), with the likelihood of injury being two to eight times greater compared to their male counterparts. This increased risk is largely attributed to differences in lower limb biomechanics, hormonal fluctuations, and Neuromuscular Control (NC) patterns between the genders.

In pediatric and adolescent populations, ACL injuries typically occur during sports activities, with football (soccer) and basketball being among the sports associated with the highest incidence of these injuries.[3] The Physical Activity (PA) levels in younger athletes are generally higher than in adults, which not only increases their risk of sustaining an initial ACL injury but also heightens the likelihood of re-injury or graft rupture following surgical reconstruction. For instance, individuals under 21 years of age have been reported to have a 7.76-fold increased risk of ACLR compared to older populations.[4]

The management of ACL injuries in Skeletally Immature Patients (SIP) presents unique challenges due to the ongoing growth and development of these patients. Several surgical techniques have been developed to either avoid or minimize the risk of physeal damage during ACLR in SIPs. Two commonly employed surgical methods are Transphyseal Reconstruction (TPR) and physeal-sparing reconstruction (PSR).[5] TPR involves drilling a tunnel through both the tibial and femoral growth plates (physes). Although it has proven effective, it has traditionally been approached with caution due to the potential risk of growth disturbances. On the other hand, PSR techniques aim to protect the growth plates by employing either all-epiphyseal drilling or using an extra-articular "over-the-top" technique on the femoral side, with fixation to the tibial metaphysis

However, in addition to surgical considerations, conservative management remains a key component of the overall treatment strategy for ACLR in SIPs. Conservative management typically involves activity modification, bracing, and structured rehabilitation programs designed to enhance NC and prevent further injury.[6]

Rehabilitation strategies following ACLR in this population are complex and multifaceted, requiring a tailored approach that addresses both the physiological and psychological aspects of recovery. Rehabilitation programs are individualized based on the patient's age, degree of bone maturity, and the specific surgical technique employed.[7] A crucial aspect of successful rehabilitation is the establishment of realistic goals and expectations, which should be aligned with the patient's and their parents' perspectives. Open communication between the healthcare team, the patient, and their family is essential to ensure a shared understanding of the treatment plan and to optimize long-term outcomes.[8]

Typically, rehabilitation programs for pediatric and adolescent patients are designed to facilitate a safe return to sports while promoting proper biomechanical movement patterns.[9] These programs usually progress through four distinct stages, with each stage focusing on specific functional milestones. The progression from one stage to the next is determined by achieving these milestones, which are often evaluated using the International Classification of Functioning, Disability, and Health (ICF) framework. This comprehensive approach ensures that all aspects of the patient's recovery are addressed, from physical function to psychological well-being.[10]

During the initial two stages of rehabilitation, it is crucial to avoid rotational movements to prevent undue stress on the healing structures. Rehabilitation programs for children with ACLR typically span 3 to 6 months. However, the rehabilitation process may extend to approximately 9 months for those who aspire to resume active participation in sports. Active involvement of parents and family members is essential in the daily postoperative rehabilitation process. This involvement includes assisting the child with technical and Functional Exercises (FE), ensuring adherence to the rehabilitation protocol, and providing emotional support throughout the recovery journey.[11]

Early surgical stabilization of the ACL has been shown to reduce the risk of pathological joint instability and significantly decrease the time required for a return to active sports participation.[12] This is particularly important in young athletes, where the demands on knee stability are high. Conversely, conservative treatment is generally reserved for patients with lower activity levels, those willing to modify or limit their physical activities, or in cases of partial ACL injuries where instability is not present, and the knee can still perform functional Activities Of Daily Living (ADL) without significant impairment.[13] Conservative management may also be considered for patients who are not ideal candidates for surgery due to other medical or personal reasons.

The TPR involves the creation of bone tunnels through the growth plates (physes) of both the tibia and femur, is a widely used surgical approach in SIP with ACL injuries. A critical aspect of this technique is the orientation and size of the femoral tunnel, which is designed to be vertical-central with a small diameter to minimize the risk of permanent damage to the growth plate of the distal femur. The use of a soft tissue graft in this technique further reduces the likelihood of bone fusion within the bone tunnel, thus preserving growth potential. One of the primary advantages of the TPR is its similarity to the procedures performed in adult patients, allowing surgeons to leverage their experience and expertise in this area.[14] Therefore, the aim of this study was to assess the Functional Recovery (FR) of pediatric patients following ACLR by comparing the outcomes of two surgical techniques: TPR and PSR. We hypothesized that TPR would result in superior functional outcomes while minimizing the risk of growth disturbances, compared to PSR.

Materials and Methods

Design overview

Our single-center randomized controlled trial was conducted at the Orthopedics and Traumatology Clinic of the Military Medical Academy in Sofia, Bulgaria, from January 2023 to December 2023. Recruitment began in May 2022 and was completed in December 2022. The trial was carried out in compliance with the Helsinki Declaration of Ethical Principles for Medical Research, in which human subjects participate, and was approved by the Ethics Committee of the Military Medical Academy in Sofia, Bulgaria, Prot. No. 36926/2022. Study participants and their parents were informed about

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the objectives of the study and written informed consent was obtained from all the patients before they participated in the study.

Study participants

The study cohort comprised pediatric patients who underwent ACLR using both surgical techniques respectively TPR and PSR at the Clinic of Orthopedics and Traumatology, Military Medical Academy, Sofia, Bulgaria. Participants, of both genders, with a mean age of 14.1±2.3 years. Initially, 60 children with ACLR were enrolled in the study. However, 13 SIPs were excluded for the following reasons: eight (n=8) declined to participate in the group-based rehabilitation sessions, three (n=3) had moved abroad during the study period, and two subjects (n=2) attended fewer than 50% of the GBRI sessions. Four SIPs (n=4) of both study groups were lost of follow-up. Ultimately, 43 eligible participants (29 boys, 78.26%, and 14 girls, 21.74%) with a mean age of 14.1±2.3 years were included in the study. Participants were randomly assigned to either the TPR group (n=23) or the PSR group (n=20) using a 1:1 ratio, generated by the online tool Research Randomizer (Figure 1).[15] The majority of participants were football players (22 participants, 51.16%), followed by basketball players (11 participants, 25.58%), and ski athletes (10 participants, 23.26%). The baseline characteristics of the study participants are presented in Table 1, illustrating the demographic and clinical comparability between the TPR and PSR groups (Table 1).

All study participants consented to participate in a supervised group-based rehabilitation intervention (GBRI) conducted at the Clinic of Physical and Rehabilitation Medicine, Military Medical Academy, Sofia, Bulgaria.

Group-based rehabilitation intervention

To optimize clinical outcomes and enhance cost-efficiency,[16] study subjects performed supervised GBRI.[11] This protocol encompassed a series of neuromuscular, plyometric, and muscle-strengthening exercises, specifically designed to im-

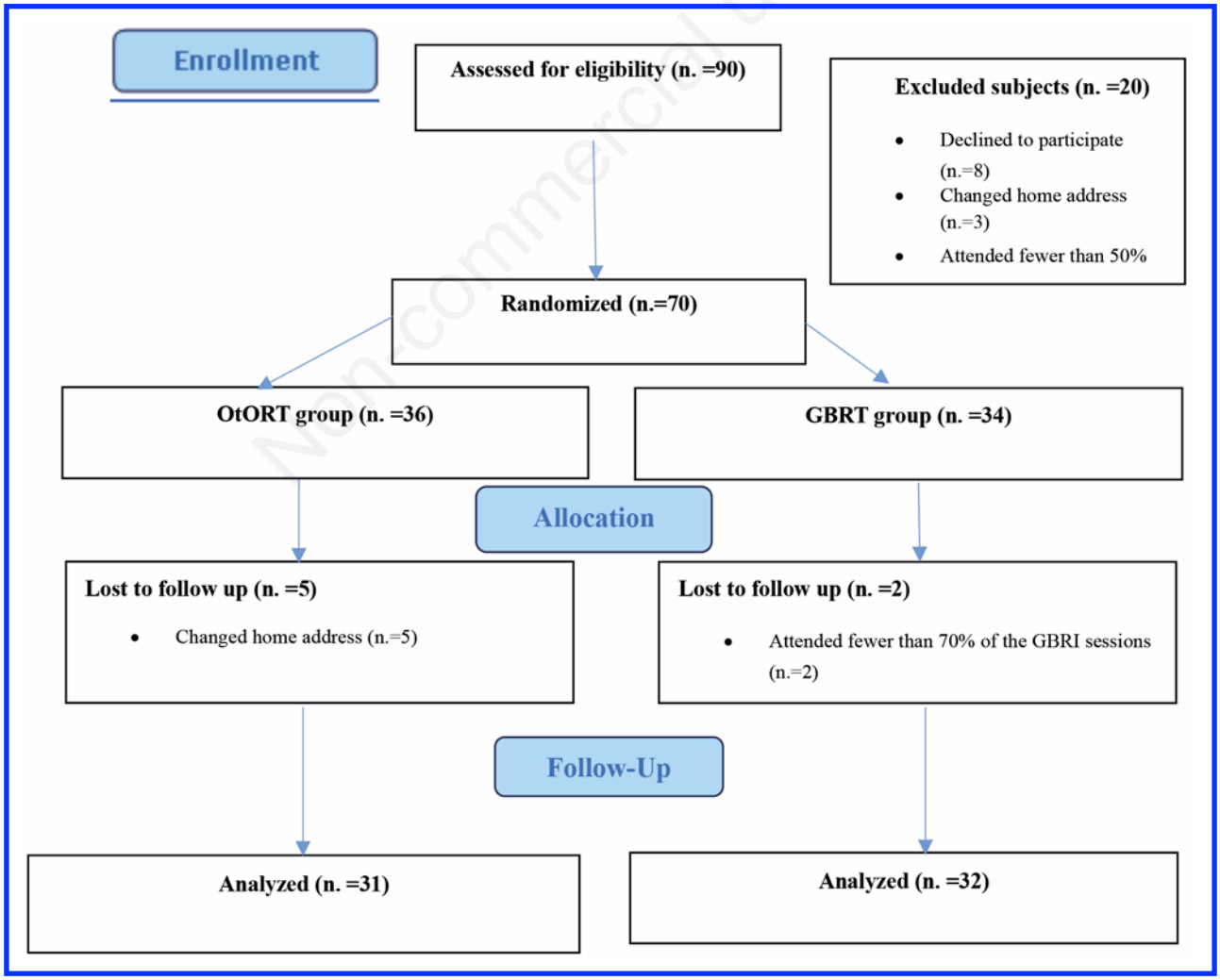

Figure 1. *Flow chart of the study.*

prove muscle strength, NC, and range of motion (ROM). The rehabilitation process was divided into four stages, each focusing on different aspects of FR in SIP's.[17]

The first stage of the supervised GBRI was focused on restoring both active and passive knee extension, reducing intra-articular swelling, and reactivating the quadriceps femoris muscle. During this stage, SIP's implemented dynamic open-chain unloaded knee extension exercises, stationary cycling, prone knee extension hangs, and partial weight-bearing exercises with an emphasis on normalizing the gait cycle.

In the second stage, SIPs performed Neuromuscular Exercises (NE) aimed at enhancing NC of terminal knee extension.[18] These exercises included single-leg stance, step-up, and squatting exercises, which were carefully structured to avoid dynamic valgus, a common biomechanical risk factor for knee injuries. Additionally, low-load, closed-chain quadriceps and hamstring exercises were incorporated to gradually build strength and stability around the knee joint without overloading it.

In the third stage of GBRI, SIPs engaged in double-leg and single-leg hop exercises with a primary focus on safe landing techniques and ensuring optimal trunk, hip, and knee alignment. Hop exercises were progressively intensified, advancing to multihop plyometric movements that incorporated stops and cutting motions. During this stage, the goals were to restore the ability to run without gait deviations and intra-articular swelling, as well as to develop the capability to perform single-leg hops with stable landings, emphasizing adequate NC.[19]

In the fourth and final stage, a comprehensive range of NE was implemented to maintain functional stability as part of a secondary prevention strategy. SIPs were advised to engage in these exercises at least twice a week, as well as to reinforce NC and minimize the risk of recurrent injuries. NE such as proprioception training, strength conditioning, and balance exercises are known to play a crucial role in preventing secondary ACL injuries, particularly in young, active individuals.[20]

Throughout the GBRI, SIPs were closely supervised by a multidisciplinary team, including orthopedic surgeons, PRM physicians, and physiotherapists. Regular assessments were conducted to monitor progress, allowing for timely adjustments to the GBRI based on each participant's recovery trajectory and to address any emerging complications. Monthly consultations with the PRM physician (J.P. and I.M.) provided ongoing evaluation and updates, ensuring continuous oversight. Additionally, SIPs from our study were evaluated by an orthopedic surgeon (V.S.) until they reached skeletal maturity, guaranteeing a comprehensive, long-term approach to rehabilitation and injury prevention.[11]

Table 1. *Demographics and sports participation of study participants.*

Characteristic (%)	Value
Total number of subjects (n)	43
Gender	
Boys	29 (78.26)
Girls	14 (21.74)
Mean age (years)	14.1±2.3
Sports participation	
Football	22 (51.16)
Basketball	11 (25.58)
Skiing	10 (23.26)

Pediatric International Knee Documentation Committee (Pedi-IKDC) Score

The effectiveness of both surgical techniques in restoring knee stability and improving functional outcomes in SIP with ACLR was assessed using the Pediatric International Knee Documentation Committee (Pedi-IKDC) questionnaire. We utilized the Bulgarian-validated version of Pedi-IKDC questionnaire, a specific assessment tool designed to evaluate knee symptoms, functional status, and sports activity levels in adolescents and young athletes aged 9–18 years. It is particularly useful in detecting changes in symptoms, function, and sports activity following knee injuries and subsequent interventions, including surgical reconstruction.[21] The Pedi-IKDC questionnaire comprises two subscales that assess various aspects of knee health, including pain, symptoms, and functional limitations. A higher Pedi-IKDC score corresponds to less pain, fewer complaints, and a higher level of PA, reflecting better overall knee function. The Pedi-IKDC questionnaire was administered by two investigators (K.P. and A.A) blinded to group assignment. SIP's from our study completed the Pedi-IKDC questionnaire at baseline, as well as at 8 and 12 months after GBRI.

Statistical analysis

The Statistical Product and Service Solutions (SPSS) for Windows, version 19.0 (SPSS, Chicago, Illinois) was used to analyze the data. The independent variables included age, gender, and preoperative Pedi-IKDC scores. Participant characteristics were summarized using frequencies, means, Standard Deviations (SD), or medians, as appropriate. The normality of data distribution was assessed with the Kolmogorov-Smirnov test.

Differences in group characteristics were assessed with the chi-square test for nominal data, the Mann-Whitney U-test for ordinal data, and t-tests for interval data. General linear modeling for repeated measures was used to assess the effect of the independent variables over time on the outcomes, including the Pedi-IKDC questionnaire, measured at three-time points: one week before TT, and 8 and 12 months after GBRI. Post-hoc analyses with Bonferroni correction were applied to adjust for multiple comparisons. A mixed-model Analysis Of Variance (ANOVA) was employed to assess differences in Pedi-IKDC scores over time, with measurements taken one week preoperatively, and at 8 and 12

months post-GBRI, with time as the within-subject factor. Linear regression analyzed the association between time (in months) and Pedi-IKDC scores.

For subgroup comparisons, Mann-Whitney U or Kruskal-Wallis tests were performed, and Bonferroni corrections were applied for post-hoc analyses. The Sidak multiple comparisons test was also used where applicable. A significance level of $p < 0.05$ was considered statistically significant.

Results

Of the 60 SIPs eligible for ACLR at the Clinic of Arthroscopic Traumatology, Military Medical Academy, Sofia, Bulgaria, between January 2023 and December 2023, 43 participants completed the study. The participants performed supervised GBRI at the Clinic of Physical and Rehabilitation Medicine, Military Medical Academy, Sofia, Bulgaria. The cohort comprised twenty-nine boys (67.4%) and fourteen girls (32.6%), with a mean age of 14.1±2.3 years. The SIPs were randomly assigned to either the TPR group (n=23) or the PSR group (n=20) in a 1:1 ratio, Table 1.

No significant difference in gender distribution was observed between the two groups ($p = 0.71$). Similarly, there was no significant difference in the type of sports participation across the groups, with p-values ranging from 0.71 to 0.84, indicating comparable baseline involvement in sports activities (Table 2; Figure 2). However, participants in the PSR group exhibited a slightly higher baseline functional status, reflected by a higher mean baseline Pedi-IKDC score compared to the TPR group. Despite this initial difference, the TPR group demonstrated greater improvements in FR throughout the study, as shown in subsequent evaluations.

By the 8th month, both the TPR and PSR groups demonstrated statistically significant improvements in Pedi-

Table 2. *Comparison of groups by gender and sports participation.*

Parameter	TPR Group n=23 (%)	PSR Group n=20 (%)	p-value
Gender distribution			
Boys	15 (65.22)	14 (70.00)	0.71
Girls	8 (34.78)	6 (30.00)	0.71
Sports participation			
Football	12 (52.17)	10 (50.00)	0.84
Basketball	6 (26.09)	5 (25.00)	0.84
Skiing	5 (21.74)	5 (25.00)	0.71

PSR, physeal sparing reconstruction; TPR, transphyseal reconstruction.

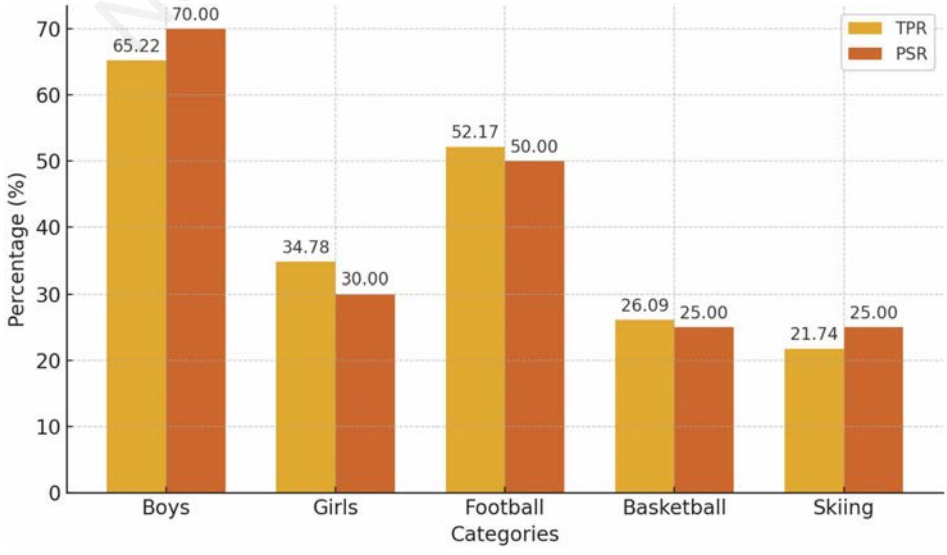

Figure 2. *Comparison of the TPR and PSR groups by gender and sports participation.*

IKDC scores from baseline (p <0.001; Figure 3). The mean Pedi-IKDC score for the TPR group increased to 80.3, reflecting a 37.46% improvement, while the PSR group achieved a mean Pedi-IKDC score of 77.5, corresponding to a 28.92% improvement (Table 3; Figure 3). Figure 4 illustrates the percentage improvement in Pedi scores Pedi-IKDC scores from baseline to the 8th month for both TPR and PSR groups. The improvements in both study groups were statistically significant (p <0.001), in favor of the TPR group, indicating a greater and faster FR in the SIP's at this follow-up.

Both study groups exhibit a steady increase in Pedi-IKDC scores over time, indicating significant improvement in knee function post-surgery. The TPR group shows a steeper incline, particularly after the 8-month follow-up, reflecting a more rapid and substantial recovery compared to the PSR group (Figure 5). Study participants from the TPR group reached a mean Pedi-IKDC score of 97.5±3.8, representing a 66.95% improvement, while those from the PSR group attained a mean score of 94.2±2.6, corresponding to a 56.73% improvement, Table 3.

The TPR group exhibits a broader range of scores, with a higher median (around 97) compared to the PSR group, whose scores are more tightly clustered with a median close to 94. The wider interquartile range in the TPR group suggests greater variability in the outcome, but the overall higher median demonstrates superior FR compared to the PSR group (Figure 6). This result is consistent with the hypothesis that TPR leads to better FR at 12 months, as evidenced by significantly higher Pedi-IKDC scores. The mixed-model ANOVA revealed a significant improvement in Pedi-IKDC scores over time (p <0.001) and highlighted a significant interaction between group and time (p =0.007). The steeper slope observed in the TPR group indicates a faster FR compared to the PSR group. The significant time effect (p <0.001) dem-

Table 3. *Pedi-IKDC scores at baseline, 8 months, and 12 months post-surgery and GBRI.*

Variable	TPR Group (n=23)	Change (%)	PSR Group (n=20)	Change (%)	p-value
Pedi-IKDC score (Baseline)	58.4±7.1	-	60.1±5.1	-	<0.001
Pedi-IKDC score (8th month)	80.3±2.4	37.46%	77.5±1.8	28.92%	<0.001
Pedi-IKDC score (12th month)	97.5±3.8	66.95%	94.2±2.6	56.73%	<0.001

PSR, physeal sparing reconstruction; TPR, transphyseal reconstruction.

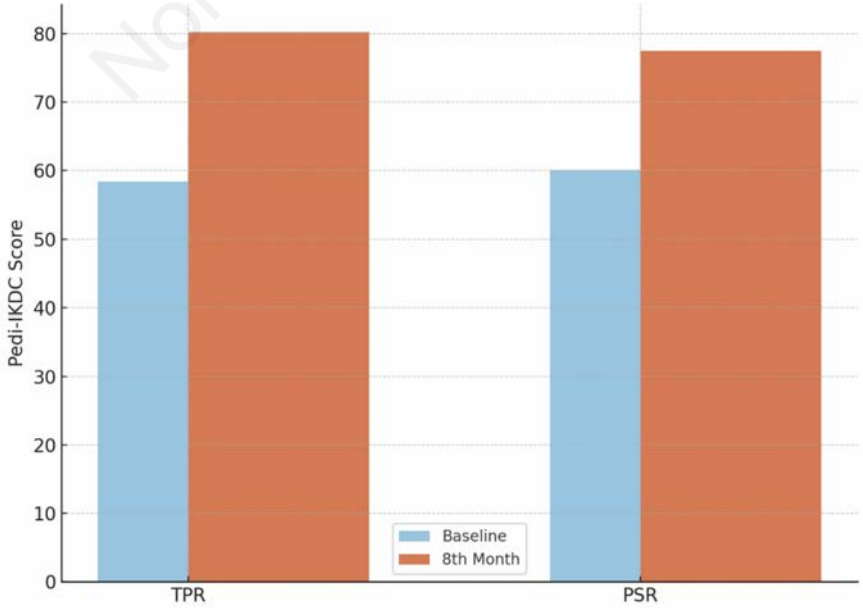

Figure 3. *The Pedi-IKDC scores from baseline vs. 8th month by group (TPR vs. PSR groups).*

onstrates substantial improvement in Pedi-IKDC scores across both study groups over the 12 months. Additionally, significant interaction between group and time (p=0.007) suggests that the TPR group experiences a more pronounced improvement in FR compared to the PSR group (Figure 7).

Regression analysis showed a strong linear association between time and Pedi-IKDC scores, with FR consistently improving in both study groups (Figure 8). The upward trend in the fitted regression line, with a slope of 3.01 points per month, indicates a significant time-dependent improvement in functional outcomes (p <0.001). The R^2=0.967 suggests that time accounts for 96.7% of the variance in scores, confirming steady recovery in both groups, with TPR consistently outperforming PSR.

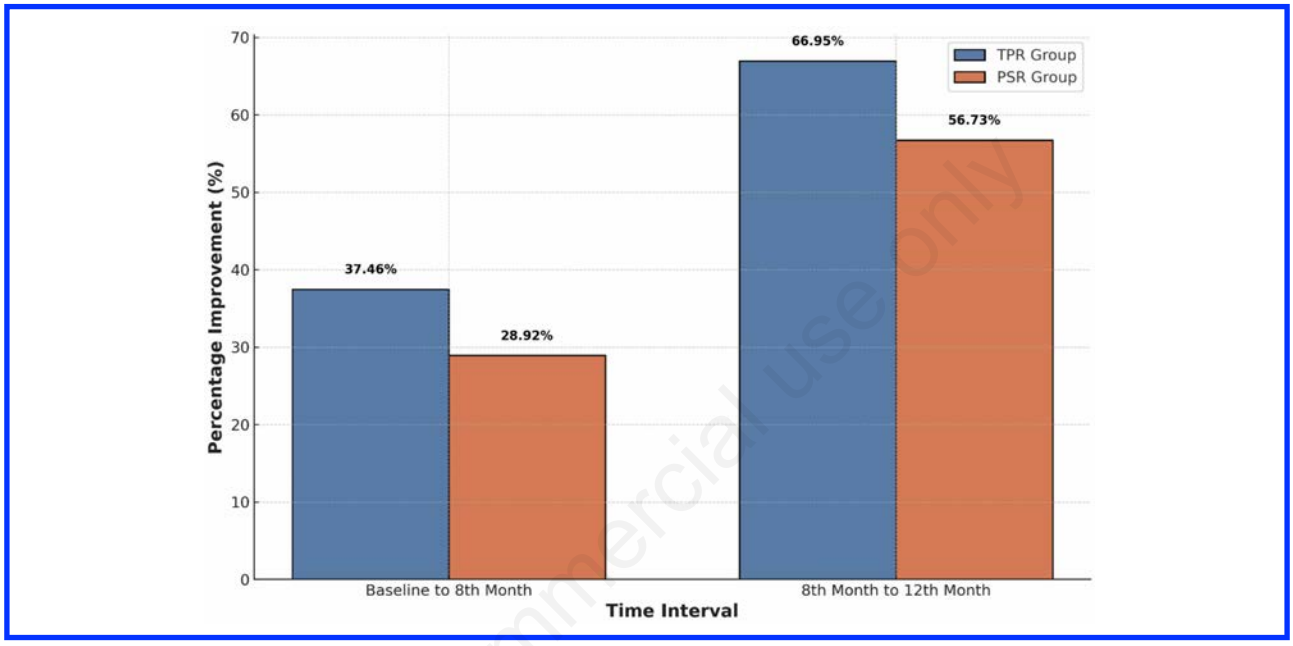

Figure 4. *Percentage improvement in Pedi scores Pedi-IKDC scores from baseline to the 8th month for both TPR and PSR groups.*

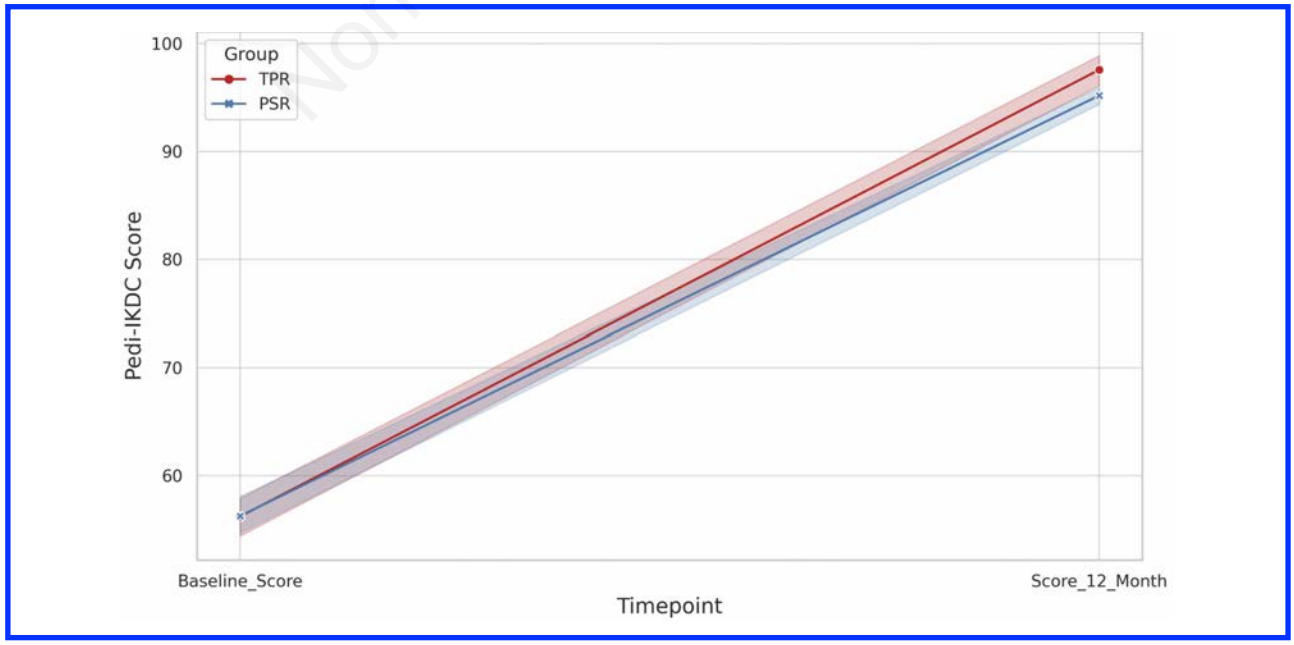

Figure 5. *The Pedi-IKDC scores from baseline to 12th month by group (TPR vs. PSR groups).*

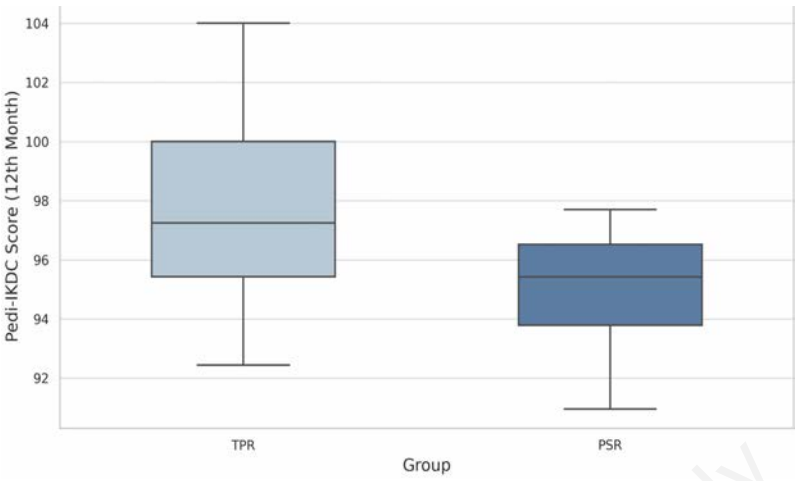

Figure 6. *The Pedi-IKDC scores at 12th month postoperatively by group (TPR vs. PSR groups).*

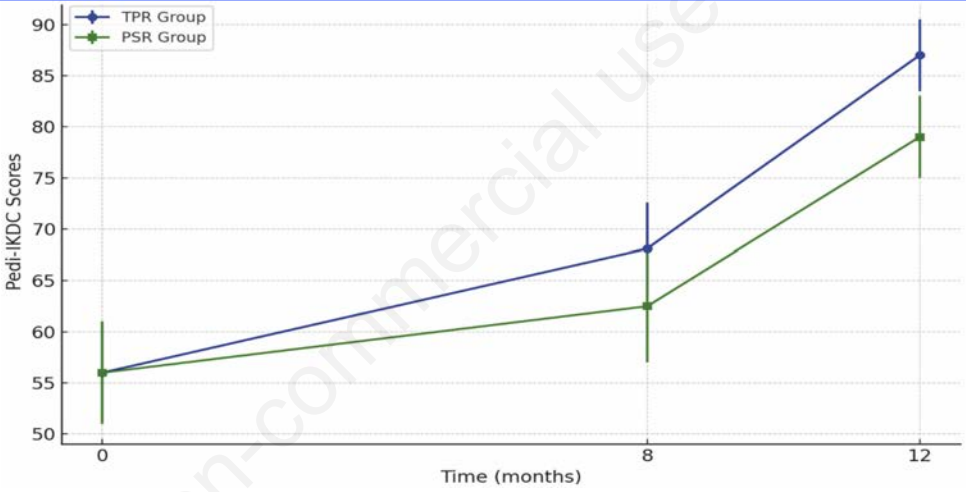

Figure 7. *Changes in Pedi-IKDC over time for TPR and PSR groups.*

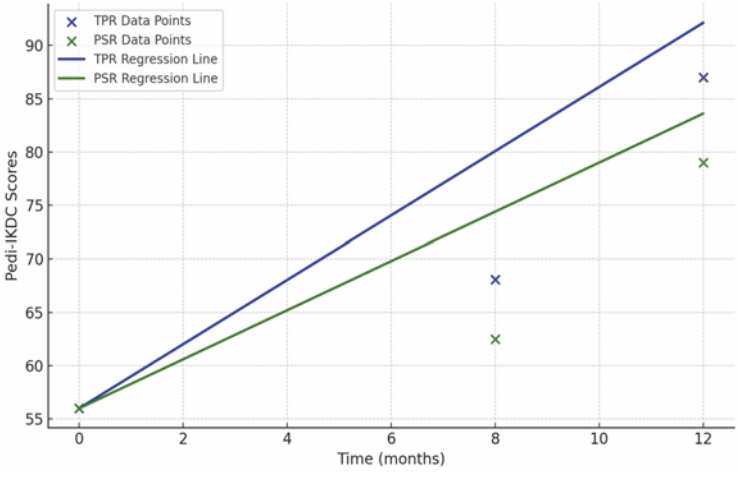

Figure 8. *Regression analysis of Pedi-IKDC over time for TPR and PSR groups.*

Discussion

The preliminary results of our RCT highlighted the significant functional benefits of TPR compared to PSR in SIPs. Both study groups demonstrated notable improvements in functional outcomes over time, as measured by the Pedi-IKDC score, with statistically significant gains observed at the 8- and 12-month follow-ups (Table 3). However, the TPR group consistently exhibited superior outcomes, with greater percentage improvements and faster FR, particularly evident at the 12-month mark where TPR showed a 66.95% improvement versus 56.73% in the PSR group (Figure 5). Frosch et al., demonstrated that both TPR and PSR were effective surgical techniques in restoring knee stability among skeletally immature athletes (SIA).[22] However, their findings, like ours, indicated a trend toward superior functional outcomes and higher patient satisfaction with the transphyseal approach. SIPs underwent TPR in Frosch's study, exhibited a quicker return to sports and a lower incidence of graft failure, similar to the 80% return-to-sports rate observed in our TPR cohort. In contrast, only 56% of the PSR group resumed sports activities, indicating a slower FR. The greater improvement in the TPR group can be attributed to several factors. First, the transphyseal surgical approach provides enhanced knee joint stability, which is crucial for high-functioning young athletes. By crossing the physis, TPR offers more robust biomechanical support during dynamic movements, which could explain the faster attainment of functional milestones and quicker return to sports activities in this group. Previous research corroborates the efficacy of TPR in maintaining joint stability without increasing the risk of growth disturbances, especially when combined with careful surgical techniques and postoperative rehabilitation protocols.

Kocher *et al.*, provided further evidence for better overall knee function and fewer complications in terms of graft failure and re-injury in favor of TPR among SIPs.[23]

In our study, the TPR group demonstrated a 66.95% improvement in Pedi-IKDC scores by the 12th month, while the SIPs from the PSR group achieved a lower but still substantial improvement of 56.73% (Table 3; Figure 6). These findings suggest that while both techniques are viable, the TPR approach may offer a more robust and faster FR. Similarly, Guzzanti *et al.* referred that TPR was associated with less growth disturbance than originally feared when performed with careful surgical planning.[24] The authors emphasized the importance of precise drilling angles and minimal violation of the growth plate to avoid complications. Our study did not observe any significant growth disturbances in the TPR group, supporting the safety of this technique in SIPs. The higher functional gains observed in the TPR group, with faster improvement in Pedi-IKDC scores, underscore the potential advantages of this technique when proper surgical protocols are followed.

Early functional gains as predictors of long-term outcomes

The early gains observed in the TPR group at 8 months are particularly noteworthy, as previous studies have indicated that early function improvements can predict long-term outcomes. Kocher *et al.* found that pediatric patients who showed early functional improvements after ACLR were less likely to experience graft failure or knee instability later on.[25] The TPR group in our study exhibited a 37.46% improvement in Pedi-IKDC scores by the 8th month, compared to 28.92% in the PSR group (Table 3; Figure 3). These findings suggest that TPR may facilitate early FR and contribute to improved long-term knee stability and function, potentially reducing the risk of re-injury in SIA.

Impact of group-based rehabilitation

Another key finding of this study is the significant impact of the GBRI in supporting the FR process. Both study groups received structured rehabilitation tailored to the specific biomechanical demands of pediatric patients, emphasizing neuromuscular control, strength, and ROM. The supervised nature of GBRI ensures adherence to the rehabilitation protocol, which likely contributed to the significant improvements observed in both groups. GBRI also fostered a supportive environment that may have positively influenced motivation and adherence, as has been observed in other rehabilitation settings.[9,11]

Our study's findings align with this perspective, as both groups *i.e.* TPR and PSR, showed substantial improvements in Pedi-IKDC scores over time, likely partly attributable to the consistency and effectiveness of the GBRI.[26] The GBRI protocol applied in our study consisted of exercises targeting ROM, strength, proprioception, and NC, all of which are essential for successful FR post-ACLR.[18] Despite the overall success of both surgical techniques, TPR demonstrated superior outcomes, suggesting that it should be considered the optimal approach for pediatric patients needing rapid and full FR.[27] This suggests that the TPR technique may result in faster and more substantial functional gains during rehabilitation. One possible explanation is that TPR provides greater knee stability, which may facilitate more effective participation in rehabilitation exercises and quicker attainment of key functional milestones.

Enhanced joint stability allows patients to engage in advanced rehabilitation interventions earlier in the FR, thus accelerating functional improvements. Moksnes *et al.*, have highlighted the critical role of early knee stability in optimizing rehabilitation outcomes after ACLR.[28] Previous systematic reviews have demonstrated that improved knee stability post-ACLR is associated with better FR, faster return to sports, and a lower risk of re-injury during rehabilitation.[29]

Supervised rehabilitation interventions incorporating progressive strengthening, proprioception, and functional exercises are essential for promoting long-term knee function and minimizing the risk of complications, particularly in pediatric populations. Furthermore, rehabilitation protocols that emphasize early stability training, combined with a gradual increase in exercise intensity, have been shown to accelerate FR and improve patient outcomes.[30]

In this context, the superior outcomes observed in the TPR

group may reflect the interaction between surgical technique and GBRI, with TPR providing a more stable foundation for early, and effective rehabilitation. Early knee stability offered by TPR may have enabled patients to progress through advanced rehabilitation exercises faster, contributing to superior functional gains compared to the PSR group.

Strengths and limitations

A notable strength of our study is its rigorous design, which includes the randomization of participants to either TPR or PSR, along with the use of a standardized rehabilitation protocol across both groups. This approach ensures that the observed differences in FR can be largely attributed to the surgical technique and the rehabilitation intervention applied. Additionally, the inclusion of a substantial follow-up period of 12 months allows for a comprehensive assessment of FR trajectories in both groups.

However, the study has several limitations that should be acknowledged. The sample size, while sufficient to detect statistically significant differences, remains relatively small, particularly when considering the gender distribution and sports participation subgroups. Further longitudinal studies incorporating quality-of-life instruments and long-term joint health assessments are needed to provide more generalizable results and a more comprehensive understanding of outcomes following pediatric ACLR.

Conclusions

The preliminary findings from this RCT demonstrate that TPR is a superior surgical technique for achieving faster and more robust FR in pediatric ACLR. The significant improvements in Pedi-IKDC scores and the quicker return to sports in the TPR group highlight the benefits of optimizing joint stability through advanced surgical methods. Additionally, the structured GBRI was instrumental in supporting the FR, emphasizing the importance of comprehensive, individualized rehabilitation plans for young athletes. These results suggest that integrating GBRI with TPR can enhance functional outcomes and facilitate a more rapid return to physical activities. Further research is warranted to investigate the long-term outcomes associated with TPR, PSR and to assess the broader applicability of GBRI in pediatric populations across different clinical settings.

List of acronyms

ACL, anterior cruciate ligament
ACLR, anterior cruciate ligament reconstruction
ADL, activities of daily living
FR, functional recovery
GBRI, group-based rehabilitation intervention
NC, neuromuscular control
NE, neuromuscular exercise
PA, physical activity
Pedi-IKDC, Pediatric International Knee Documentation Committee
PSR, physeal-sparing reconstruction
ROM, range of motion
SIA, skeletally immature athletes
SIP, skeletally immature patients
TPR, transphyseal reconstruction

Contributions of Authors

All authors have read and approved the final edited typescript.

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Conflict of interest

The authors declare no financial, personal, or other conflicts of interest.

Ethics approval

The Ethics Committee of the Military Medical Academy in Sofia, Bulgaria approved this study (Prot. No. 36926/2022). The study is conformed with the Helsinki Declaration of 1964, as revised in 2013, concerning human and animal rights.

Informed consent

All patients participating in this study signed a written informed consent form for participating in this study.

Patient consent for publication

Written informed consent was obtained from a legally authorized representative(s) for anonymized patient information to be published in this article.

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

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