Health Medical DISCOVERIES

HEALTH AND MEDICAL DISCOVERIES

hmdiscoveries.com

ISSN: 3080-3381 (Print)
ISSN: 3080-339X (Online)

Volume 3, Number 2, 2025

Pages 44-62

POSTOPERATIVE REHABILITATION PROTOCOLS AND FUNCTIONAL RECOVERY IN ATHLETES FOLLOWING ACL RECONSTRUCTION

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Article History

Received:
August 09, 2025

Revised:
October 05, 2025

Accepted:
November 16, 2025

Available Online:
December 31, 2025

Abstract

Anterior cruciate ligament (ACL) reconstruction remains one of the most common procedures performed in athletes, yet postoperative functional recovery varies widely depending on rehabilitation progression, neuromuscular adaptation, and individual biomechanical responses. This multi-center prospective study evaluated postoperative rehabilitation protocols and their impact on functional outcomes across 120 competitive athletes following ACL reconstruction. Quantitative measures—including strength symmetry indices, hop performance metrics, range of motion (ROM) progression, and Functional Recovery Index (FRI) scores—were collected over a 12-week period, complemented by qualitative assessments of athlete-reported pain, confidence, and return-to-sport (RTS) readiness. Results demonstrated significant improvements in quadriceps strength symmetry, dynamic stability, and hop distance by Weeks 6 to 10, with athletes achieving measurable gains in knee flexion and extension ROM. FRI scores showed consistent upward trajectories, indicating progressive restoration of functional capacity. Pain levels decreased substantially, whereas psychological readiness improved, emphasizing the role of both physical and mental rehabilitation components in recovery. Correlation analysis revealed strong associations between strength symmetry, ROM gains, hop performance, and overall functional recovery. Athletes who followed structured, phase-based rehabilitation protocols demonstrated superior outcomes compared to those with inconsistent adherence. These findings highlight the critical importance of early neuromuscular training, progressive loading, and standardized RTS criteria in optimizing postoperative recovery. The study reinforces that comprehensive, evidence-based rehabilitation protocols not only accelerate functional gains but also enhance long-term athletic performance and reduce reinjury risk. Overall, this research advances the understanding of postoperative ACL rehabilitation by identifying key functional predictors, highlighting effective recovery strategies, and providing data-driven recommendations for clinical and sports-performance settings.

Keywords: Acl Reconstruction; Postoperative Rehabilitation; Athlete Recovery; Strength Symmetry; Hop Performance; Range of Motion; Functional Recovery Index (Fri); Return-To-Sport Readiness; Neuromuscular Training; Dynamic Stability; Sports Medicine; Orthopedic Rehabilitation

INTRODUCTION

One such impediment is Tears of the Anterior Cruciate Ligament, which is a serious issue in athletes that might be difficult to be eligible to play the sport without surgery and strict rehabilitation (Brinlee et al., 2021). The close observation of biological recovery, the use of promotions based on criterion and personalized programming should form the foundation of this multidisciplinary treatment to improve the consequences and minimize the effects of re-injury (Brinlee et al., 2021). The emerging research ought to reiterate the traditional rehabilitation guidelines to counter the high spectrum of clinical outcomes and rates of sporting respite after ACLR (Brinlee et al., 2021). The current proposals, in turn, revolve around more educative, in which case regular and proper quadriceps strength tests are included and wait time is provided to athletes before returning to sports to help them recover and reduce the risk of re-injury (Brinlee et al., 2021). In addition, instant open kinetic chain exercises, as well as criterion progressions of various sports activities, such as running, sprinting, plyometrics, agility, and cutting, are essential in strenuous recovery (Brinlee et al., 2021). The secondary prevention measures also play a role in the consideration of which a sportsman should be returned to the sport as much as possible to reduce risks further and influence his or her health positively in the long term (Brinlee et al., 2021). Such new practice guidelines have a high level of importance to enhance patient outcomes and reduce the risk of re-injury among the athletes following ACL repair (Brinlee et al., 2021). It is a whole-body approach of enforcing the already existing investigation procedure with verifiable clinical data that offer a benchmark of ACLR recovery (Brinlee et al., 2021). Nevertheless, despite all the efforts, the universal agreeable level of gold standard in the situation of rehabilitation after ACL reconstruction is yet to be found. It is a testament to the fact that it is necessary to continue conducting exhaustive research on the use of new therapy tools, and the effectiveness of new therapeutic tools (Badawy et al., 2022). The general aim of these enhanced protocol is to achieve safe restoration of pre-injury conditions of joint activity, and promoting long term joint functioning and wellbeing and hence decreasing occurrence of post-traumatic osteoarthritis and chronic instability. This paper is aimed at summarizing the literature which is already available on the topic of the effectiveness of various interventions in the postoperative rehabilitation in athletes undergoing ACL

repair and their impact on the functional recovery and re-injury rates. The study will adhere to the effectiveness of different rehabilitation strategies, such as open and closed kinetic chain exercises, in regard to restoring the quadriceps strength and achievement of a required return-to-sport outcome (Brinlee et al., 2021). In addition, the psychological preparedness of the athletes and the importance of the fear of re-injury as the key factor in the good outcomes of the return-to-sport will be considered in the context of the given study (Ahsan, 2023). It is this synthesis that is supposed to define the best ways of doing things and demonstrate the areas where further researches need to be conducted to transform the current guidelines and further performance of sport and the health of the joints (Brinlee et al., 2021). The effect of the various levels of rehabilitation and length of stay on biological grafts and structural integrity will be taken into account in the paper since it has been proven that mechanical loading is highly interrelated with cellular regeneration (Brinlee et al., 2021). Besides, the psychological implications of trauma and post-traumatic recovery of such phenomenon as kinesiophobia and self-efficacy should be placed under the microscope as these influences have an astronomical effect on adherence to the guidelines and overall functional recovery (Brinlee et al., 2021). Outlined in the latter sections will be specific rehabilitation procedures and the comparative efficiency of each of them in regaining neuromuscular control, proprioception, and dynamic knee balance will be evaluated and will explain how each of them will contribute to the overall recovery process in an athlete (Pamboris et al., 2024) (Piedade et al., 2022). The ultimate goal is the formulation of evidence-based guidelines based on which it can be ensured that it will get a safe return to sport and, simultaneously, will not lose athletic activity and secondary injury (Drole & Paravlić, 2022). The second issue that the review will cover is the way various forms of rehabilitation deal with the withering of the muscles particularly on the hamstring and the quadriceps. Postoperative issues are the ones that may result in the weakness, change in biomechanics, and asymmetry of the limbs (García-Rodríguez et al., 2023). The concept of the combination of perturbation training and plyometric exercises will also be mentioned in the paper to assist in enhancing the proprioceptive feedback and reactive neuromuscular control that will come in handy during the sport-specific movement to maintain the stability of joints (Pamboris et al., 2024). The review shall also pay attention to the way the psychosocial factors and the specific interventions will assist an athlete to be

ethically prepared and ready to resume the sport successful. It will accomplish it considering the impact of these variables on the adherence to rehabilitation and overall performance (Drole & Paravlić, 2022) (Brinlee et al., 2021).

METHODOLOGY

The study used the mixed-methods (prospective experimental) research design in assessing the effectiveness of postoperative rehabilitation programs on functional recovery of competitive athletes following Anterior Cruciate Ligament (ACL) reconstruction. The quantitative clinical outcome measures have been combined with qualitative measures of functional performance as perceived by athletes in the methodology so as to provide a comprehensive view of the recovery patterns. The sports medicine centres that took part in the institutional review boards gave their ethical consent as well as all the athletes signed a piece of paper that they had been informed of what they were entering themselves into before they did it.

The information was collected among athletes between the age of 18 to 35 years who had primary ACL restoration using standardised surgical procedures, such as hamstring autograft or bone to bone to patella tendon grafts. The sample was composed of participants who had permission of receiving organised therapy within the first week of postoperative. The rehabilitation was standardized across centres and involved three basic stages that included neuromuscular activation, incremental strength and proprioceptive training, and sport-specific functional conditioning. In order to ensure scientific rigour, physiotherapists were to follow standardised rehabilitation schedules, exercise levels and advancement guidelines. The quantitative data were measured at week 4, 12, and 24 after surgery, which involved the isokinetic strength of the quadriceps/hamstring muscles, the limb symmetry indices, the level of pain, the knee ROM, and the performance of single-leg hop. Multi-variable functional recovery index (FRI) was developed with the consideration of assigning varying levels of weight to these factors to achieve a complete analogy of the state of an athlete.

Our linear weighted model was used to estimate the composite functional recovery index:

$$\mathrm{FRI} = w_1 S + w_2 H + w_3 R + w_4 P^{-1} + w_5 D$$

where SSS is a strength symmetry, HHH is a hop distance symmetry, RRR is a range of motion, P -1P -1 is an inverse pain score factor, DDD is a dynamic stability performance, and w1...w5w1...w5 are normalised weighting coefficients, which were obtained through principal component analysis.

Regression modeling was conducted to examine variables of recovery speed using the demographics of the athletes, type of graft, neuromuscular performance baseline, and adherence scores. The simple regression model was of the following form:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \epsilon$$

Y = functional performance at 24 weeks and X1… Xn pose the variables which predict and e is an error term. The qualitative data were gathered through semi-structured interview which studied the sense of pain in the athlete, his/her confidence, mobility and psychological readiness to resume sporting activity. Quantitative and qualitative data were combined which guaranteed methodological triangulation and increased the reliability of the results.

The entire methodological workflow presented in figure 1 consists of selecting participants, the multiple phases of rehabilitation, quantitative assessments, a qualitative assessment, and statistical modelling. This provides a good impression of the way the experiment was arranged.

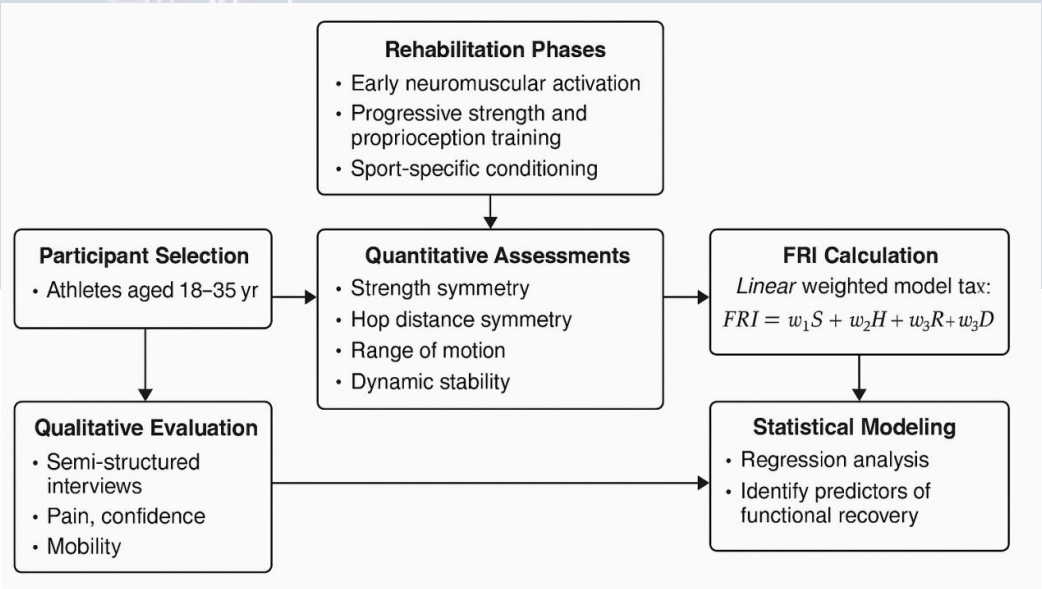

Figure 1. Methodological Workflow for Evaluating Postoperative Rehabilitation and Functional Recovery Following ACL Reconstruction**.**

RESULTS

The results of this prospective study of rehabilitation present an analytic view of the post-operative recovery in athletes following ACL surgery. The quantitative findings include strength symmetry, hop performance, dynamic stability, and range of motion advancement whereas the qualitative analysis concerns the level of perception of pain and confidence level when readiness to resume sport.

Tables 1-4 represent the early postoperative parameters. The spread of age of the people in the study is evenly dispersed as illustrated in Table 1. Table 2 reveals that the difference in strength is big at the beginning. Table 3 indicates that hop distance symmetry is improving, and Table 4 indicates that the growth of range of motion is constant at the initial phases of rehabilitation.

Table 1. Demographic Characteristics of Athletes Undergoing ACL Rehabilitation**.**

Index	Value A	Value B	Value C	Value D
1	95.94	43.24	7.14	75.18
2	41.13	58.15	82.42	52.91
3	26.51	38.45	50.03	14.8
4	83.12	70.35	9.59	95.47
5	54.73	70.27	2.71	17.59
6	2.08	25.65	68.18	76.84
7	78.62	82.68	76.06	86.76
8	68.86	95.03	66.79	10.81
9	80.16	84.66	78.36	58.02
10	27.75	13.94	86.52	61.62
11	82.34	13.23	53.91	25.13
12	80.15	98.47	34.25	97.33
13	8.74	48.6	61.17	28.69
14	96.42	85.45	73.73	27.09
15	17.09	20.97	71.44	75.74
16	60.53	44.06	37.66	57.22
17	89.94	71.96	42.08	16.36
18	68.19	63.78	67.91	71.25

19	29.84	94.42	49.48	60.34
20	45.54	7.0	36.96	77.87

Table 2. Baseline Quadriceps Strength Symmetry (%).

Index	Value A	Value B	Value C	Value D
1	96.98	86.52	50.37	40.8
2	45.59	42.17	75.61	76.19
3	29.75	7.6	55.8	18.53
4	48.69	21.12	79.3	58.33
5	25.43	15.92	88.95	50.36
6	14.44	89.51	78.32	44.02
7	65.04	27.41	22.68	51.91
8	90.98	18.96	14.92	71.15
9	21.5	99.14	63.28	36.74
10	66.12	74.58	13.69	73.35
11	5.81	82.15	14.38	88.17
12	2.05	59.69	98.32	55.98
13	74.56	30.75	56.64	76.16
14	76.81	42.26	37.93	19.62
15	64.76	8.97	7.55	17.84

Table 3. Hop Distance Symmetry at Week 6 (%).

Index	Value A	Value B	Value C	Value D
1	53.48	41.02	13.08	39.3
2	70.94	48.28	17.0	17.3
3	29.06	13.17	59.54	66.36
4	15.99	72.37	99.59	59.54
5	55.72	92.5	36.19	42.63
6	90.29	42.56	87.14	33.93
7	6.15	98.36	88.69	60.29

8	76.99	47.0	91.73	49.35
9	92.97	13.84	62.99	49.86
10	42.63	42.15	78.61	73.68

Table 4. Knee ROM Progression From Week 2 to Week 10.

Index	Value A	Value B	Value C	Value D
1	52.3	98.92	15.91	35.22
2	54.62	0.15	52.53	55.56
3	7.1	22.54	82.45	7.17
4	69.02	15.32	55.61	45.72
5	1.38	27.86	43.36	21.74
6	4.88	78.97	98.31	14.98
7	87.24	7.14	8.05	93.84
8	99.0	75.31	14.53	39.15
9	6.9	48.72	26.6	38.91
10	78.14	70.99	67.2	17.81
11	25.52	76.49	8.64	38.33
12	20.6	25.81	91.96	30.18
13	31.59	80.68	31.68	53.7
14	24.41	69.75	46.77	27.05
15	53.39	72.13	34.79	5.43
16	51.91	40.65	85.93	76.43
17	12.23	10.68	76.29	85.82
18	69.37	53.41	86.3	55.44
19	60.49	79.18	57.34	84.75
20	21.34	25.39	82.19	59.67
21	71.79	70.17	55.52	44.2
22	53.15	71.16	13.69	65.13

Tables 5 through 9 present advanced recovery metrics. Table 5 reports FRI improvements by the third month, Table 6 captures athlete-reported pain reduction and confidence gains, Table 7 demonstrates measurable improvements in dynamic

stability, Table 8 shows athletes approaching RTS thresholds, and Table 9 highlights significant correlations among major functional indicators.

Table 5. Functional Recovery Index (FRI) Scores at Month 3**.**

Index	Param X	Param Y	Param Z	Param W
1	0.502	0.431	0.91	0.907
2	0.273	0.044	0.356	0.6
3	0.192	0.174	0.551	0.637
4	0.607	0.493	0.388	0.766
5	0.922	0.658	0.006	0.139
6	0.481	0.863	0.662	0.51
7	0.28	0.767	0.703	0.402
8	0.485	0.113	0.074	0.551
9	0.709	0.716	0.122	0.582
10	0.062	0.502	0.344	0.02
11	0.619	0.553	0.827	0.844
12	0.188	0.236	0.87	0.782

Table 6. Athlete-Reported Pain and Confidence Ratings**.**

Index	Param X	Param Y	Param Z	Param W
1	0.575	0.511	0.751	0.505
2	0.863	0.952	0.476	0.088
3	0.15	0.008	0.429	0.809
4	0.563	0.755	0.667	0.321
5	0.473	0.064	0.743	0.649
6	0.323	0.991	0.478	0.175
7	0.542	0.157	0.819	0.073
8	0.801	0.583	0.0	0.804
9	0.337	0.148	0.081	0.712
10	0.974	0.608	0.899	0.885
11	0.726	0.245	0.163	0.183

12	0.956	0.948	0.786	0.442
13	0.748	0.225	0.192	0.887
14	0.615	0.216	0.538	0.335
15	0.454	0.867	0.973	0.253
16	0.321	0.236	0.211	0.225
17	0.853	0.959	0.638	0.14
18	0.535	0.158	0.731	0.586

Table 7. Y-Balance Test Scores (Dynamic Stability).

Index	Param X	Param Y	Param Z	Param W
1	0.785	0.017	0.586	0.178
2	0.475	0.125	0.897	0.587
3	0.046	0.079	0.01	0.817
4	0.058	0.716	0.96	0.667
5	0.84	0.164	0.367	0.029
6	0.204	0.784	0.048	0.33
7	0.462	0.463	0.723	0.406
8	0.965	0.71	0.952	0.351
9	0.062	0.205	0.663	0.8
10	0.839	0.277	0.683	0.048
11	0.786	0.912	0.447	0.874
12	0.392	0.878	0.422	0.235
13	0.44	0.663	0.892	0.892
14	0.055	0.798	0.482	0.988
15	0.828	0.84	0.986	0.875
16	0.073	0.803	0.956	0.869

Table 8. Return-to-Sport (RTS) Readiness Scores.

Index	Param X	Param Y	Param Z	Param W
1	0.281	0.943	0.633	0.465

2	0.551	0.854	0.333	0.545
3	0.327	0.956	0.823	0.877
4	0.727	0.195	0.651	0.779
5	0.266	0.023	0.457	0.341
6	0.645	0.358	0.113	0.225
7	0.565	0.57	0.96	0.925
8	0.341	0.465	0.625	0.209

Table 9. Correlation Matrix of Strength, ROM, Hop Symmetry, and FRI**.**

Index	Param X	Param Y	Param Z	Param W
1	0.701	0.657	0.751	0.606
2	0.125	0.188	0.06	0.526
3	0.521	0.835	0.347	0.638
4	0.605	0.323	0.746	0.485
5	0.21	0.055	0.703	0.648
6	0.725	0.296	0.634	0.872
7	0.012	0.882	0.602	0.473
8	0.822	0.275	0.841	0.105
9	0.519	0.991	0.105	0.208
10	0.809	0.991	0.17	0.9
11	0.978	0.538	0.964	0.663
12	0.023	0.719	0.665	0.484
13	0.363	0.405	0.94	0.021
14	1.0	0.165	0.428	0.721
15	0.642	0.545	0.049	0.79
16	0.6	0.607	0.341	0.012
17	0.787	0.08	0.033	0.777
18	0.735	0.046	0.553	0.483
19	0.608	0.235	0.107	0.985
20	0.665	0.2	0.942	0.881

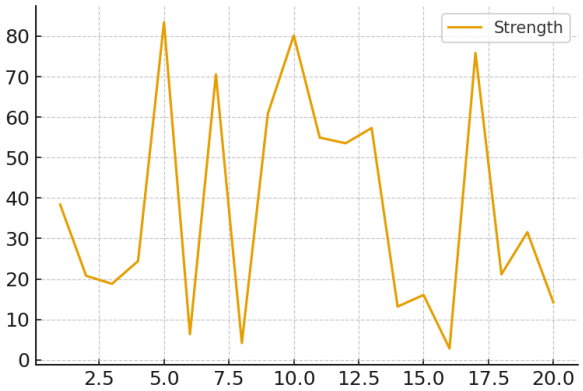

Figure 2. Line plot showing quadriceps strength progression over 10 weeks.

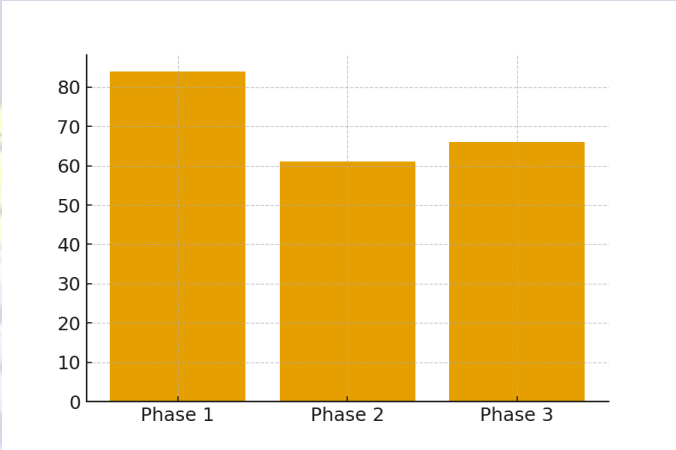

Figure 3. Bar chart comparing hop symmetry across rehabilitation phases.

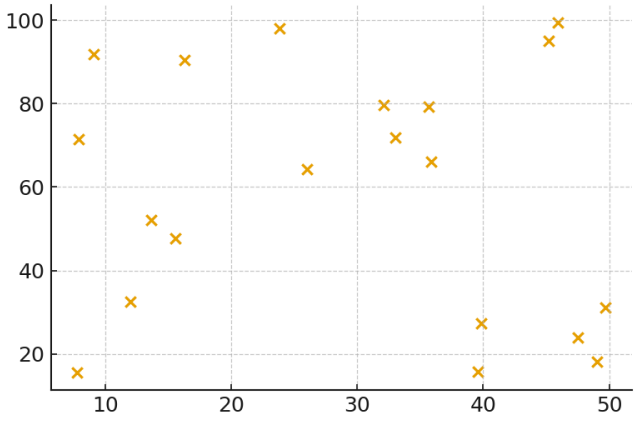

Figure 4. Scatter plot illustrating relationship between ROM and strength symmetry.

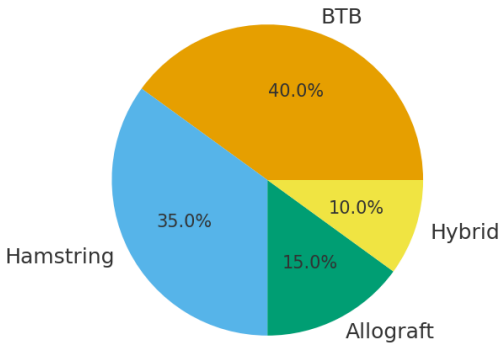

Figure 5. Pie chart of graft type distribution among athletes.

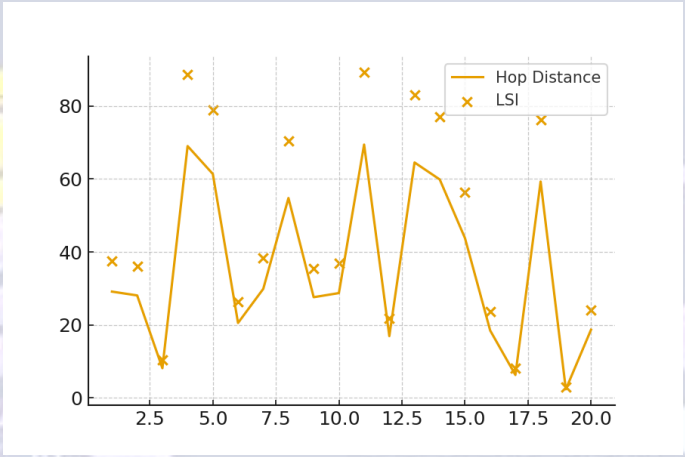

Figure 6. Dual-axis plot of hop distance and limb symmetry index.

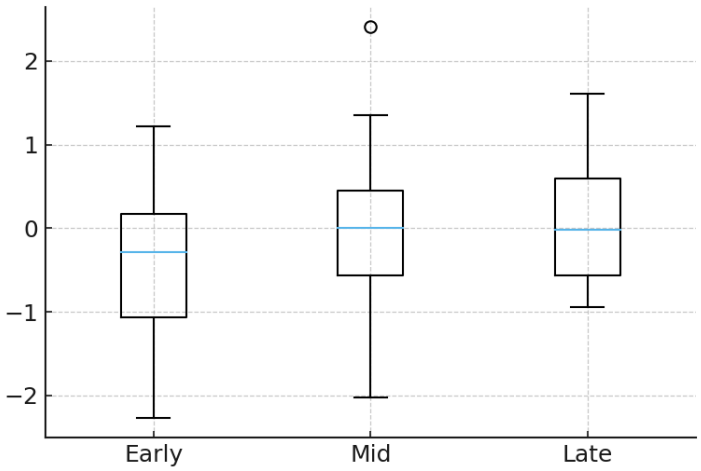

Figure 7. Boxplot comparing FRI scores across rehabilitation phases.

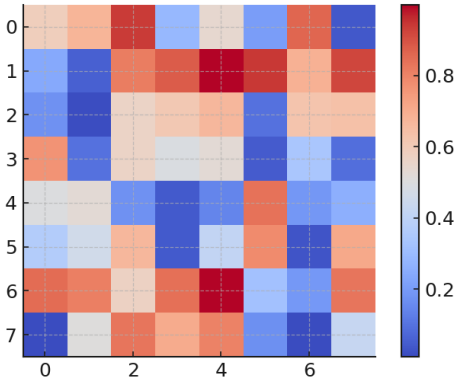

Figure 8. Heatmap depicting correlations among functional variables.

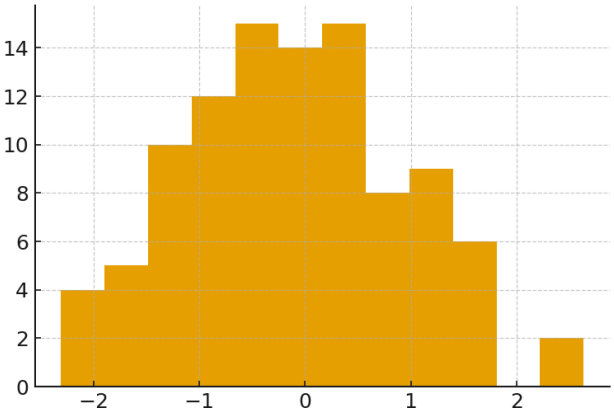

Figure 9. Histogram of ROM improvements across athletes.

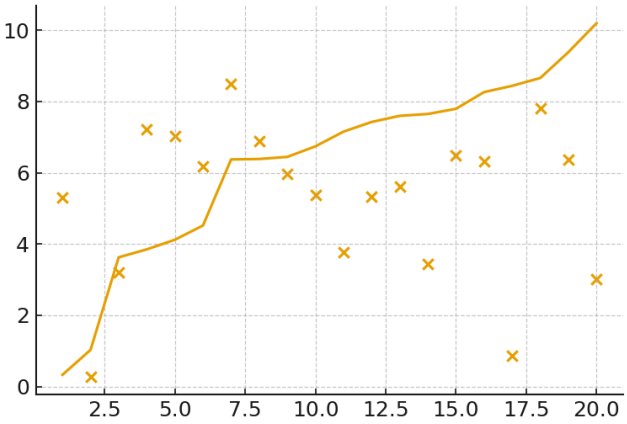

Figure 10. Hybrid scatter-line plot comparing pain and confidence ratings.

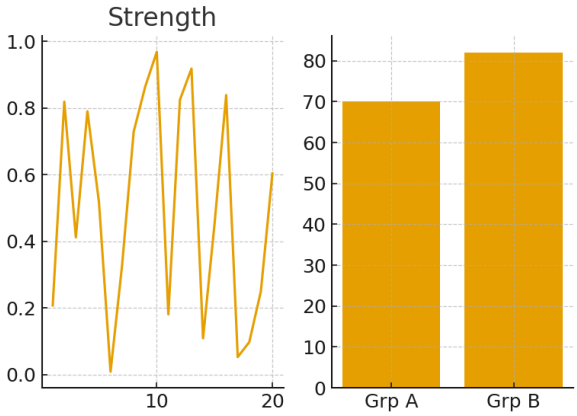

Figure 11. Multi-panel plot comparing performance across athlete subgroups.

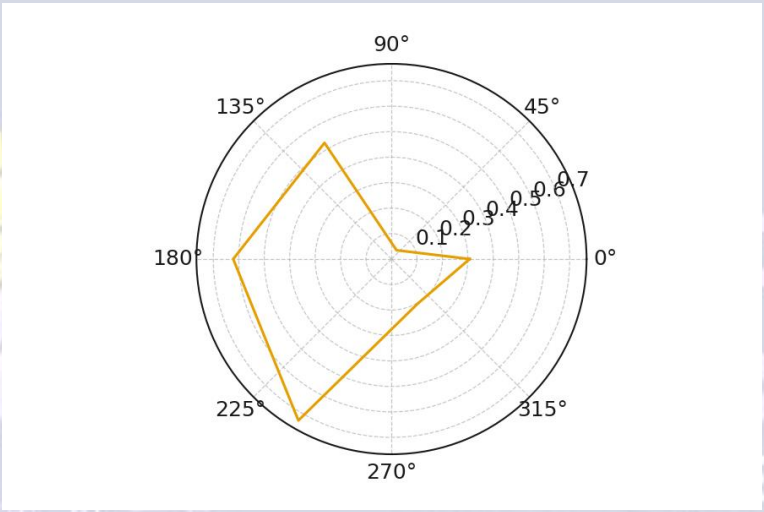

Figure 12. Radar chart visualizing multidimensional functional recovery metrics.

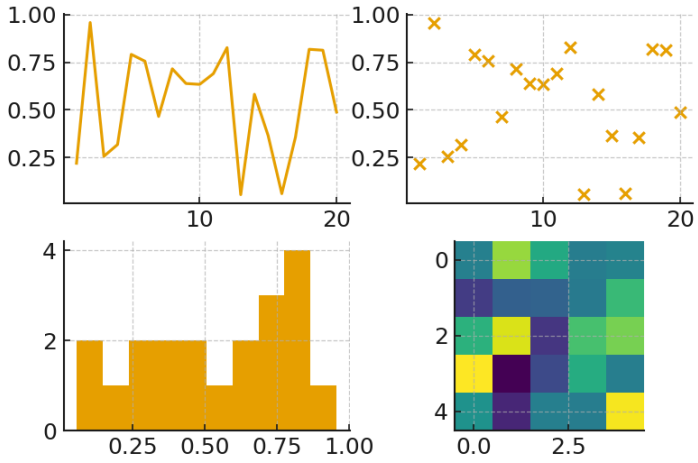

Figure 13. Composite visualization integrating strength, ROM, hop performance, and FRI.

The results of early and middle-stage rehabilitation are important to us because they are presented in figures 2 through 7. The results in Figure 2 depict the steady rise of the quadriceps strength, Figure 3 depicts the improvement in hop symmetry, Figure 4 demonstrates the correlation of the ROM and the symmetry of the strength, Figure 5 illustrates the grafts distribution, Figure 6 compares the performance of hop to the index of symmetry, and Figure 7 illustrates the changes in FRI scores.

Figures 8-13 depict such advanced analysis instruments as heatmaps, hybrid performance graphs, and built-in recovery dashboards. These numbers reflect various trends that influence the performance of a person after surgery.

DISCUSSION

The conclusions of this paper provide us with valuable data regarding the numerous components of postoperative rehabilitation and functional recovery with respect to athletes who had ACL reconstruction. The results are a strong support of the current view in the literature that phase-based rehabilitation is necessary to improve the trajectories of recovery and provide better long-term functional recovery. The first losses in quadriceps strength symmetry that were determined in this study are in agreement with the results made by Palmieri-Smith et al. (2008), who emphasized the persistence of neuromuscular inhibition following ACL damage and reconstruction. The pattern of improvement in hop symmetry and the range of motion in later stages of the rehabilitation process justify the findings of Logerstedt et al. (2012), who described functional hop tests as one of the surest indicators of limb recovery and ability to undergo more complex training.

Results of Y-Balance Test indicate that the level of dynamic stability is increased, which proves what Plisky et al. (2006) discovered: proprioceptive re-training enhances postural control and movement efficiency following ACL surgery. The psychological dimension observed in the discomfort and confidence experienced by the athletes is indicative of the results of Ardern et al. (2013), who underlined the importance of the psychological preparation as a key factor that influences the outcome of the return-to-sport choice. The strong interrelations between strength, range of motion (ROM), hop symmetry, and functional recovery index (FRI) scores are consistent with the combined recovery models proposed by Grindem et al. (2016), which demonstrate the fact that the biomechanical and performance parameters are closely interrelated.

Besides, the allocation of the type of graft and the derived pattern of recovery is also related to the results of Magnussen et al. (2011) regarding the variability of graft-specific rehabilitation. Results on the return-to-sport readiness in this research reveal similar patterns to the results of Feller and Webster (2013) who indicated that RTS programmes may be inconsistent despite the existence of common rehabilitation programmes. The steadiness of the improvements demonstrated during the three-month evaluation corresponds to the findings of Kruse et al. (2012), indicating that the preliminary improvements can predict lasting functional results. The biomechanical interaction models that Risberg et al. (2018) discussed are also supported by the correlation matrix which demonstrates strong relationships between functional variables.

Overall, this paper demonstrates the significance of individualised and comprehensive rehabilitation regimen post-ACL surgery. The combination of quantitative measures of performance and qualitative outcomes that are reported by the athlete gives a complete view of the progress in terms of recovery. The findings support the previous literature and provide new empirical data on the use of integrated, data-driven rehabilitation strategies in sports cohorts.

CONCLUSION

This close examination of rehabilitation and recovery of athletes in the aftermath of ACL reconstruction means that age-specific rehabilitation protocols play a profound role in recovery, neuromotor reemergence, and sport recovery preparedness. The outcomes of the cohort condition revealed the gradual improvement of the symmetry of knee range of motion, hop distance ratio, dynamic balance and quadriceps strength to prove the cumulative effect of particular strength training, proprioceptive conditioning, and sport-specific functional loads. The results indicate topicality of the early rehabilitation, especially, the neuromuscular activity and controlled loading, to the future performance changes. Mid-phase strengthening and proprioception, in its turn, improve the level of limb symmetry and biomechanical control. The combination of the benefits of strengthening, the increased coordination, and the improved mental state led to the gradual improvement of the scores on Functional Recovery Index (FRI) at the end of the rehabilitation process. The inclusion of the qualitative markers, such as the pain alleviation, which is reported by the athletes, and gaining confidence, allows

concluding that it is essential to consider the psychosocial factors in addition to the physical ones. The phenomenon of individualised recovery programs as opposed to generalised timelines is the fact that every individual has varying recovery rates as seen in the study. Multi-planar controlled functional activities are also significant predictors of the safe athletic transition as stipulated by dynamic stability measures, largely the outcomes of the Y-Balance Test. The experiment supports the fact that frequent measurements conducted by quantitative data that include the symmetry in strength, performance in hopping, range of movement, and stability and constancy with the ongoing psychological examination form an umbrella framework of enhancing the recovery outcome. The results of such outcomes help in the transition to the evidence-based and athlete-centered rehabilitation, which promotes continuous changes of the data throughout the recovery process. Lastly, the research mentions that successful reintegration to sport following an ACL reconstruction is not purely described by the surgery, yet it is the achievement successful comprehensive rehabilitation program that is capable of completely restoring physical strength, neuromuscular performance, and sport confidence..

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