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COMPARATIVE EFFECTIVENESS OF SUPERVISED AND HOME-BASED REHABILITATION AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION IN COMPETITIVE ATHLETES

PhD thesis

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Abbreviations

ACL	Anterior Cruciate Ligament
ACLR	Anterior Cruciate Ligament Reconstruction
SVR	Supervised Rehabilitation
HBR	Home-based Rehabilitation
RTS	Return to Sport
TAS	Tegner Activity Scale
IKDC-SKF	International Knee Documentation Committee Subjective Knee Form
ACL-RSI	Anterior Cruciate Ligament Return to Sport after Injury
BTB	Bone - Tendon - Bone
MRI	Magnetic Resonance Imaging
SA	Squat ability
LS	Load symmetry
ROM	Range of motion
COP	Center of pressure

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1. Introduction

Anterior cruciate ligament (ACL) injuries are among the most common and debilitating injuries for athletes, often requiring surgical reconstruction followed by extensive rehabilitation (1,6,10). The increasing incidence of these injuries in sports, coupled with their potentially long-term effects on an athlete's career, caught my attention and inspired my interest in researching this area. My motivation for pursuing a PhD emerged from a personal fascination with sports medicine and a desire to make a meaningful impact on the rehabilitation process for athletes recovering from ACL injuries. Having witnessed the impact of ACL injuries on athletes' careers, I became more determined to find ways to improve recovery and reduce the risk of re-injury. As a sports enthusiast and advocate for athletes' health, I was motivated to study the effectiveness of various rehabilitation approaches and their impact on athletes' return to sport (RTS).

The primary goal of my research was to address a significant question in the field of sports medicine: How can we improve rehabilitation outcomes for athletes following ACL reconstruction (ACLR) surgery? Specifically, I wanted to explore whether supervised rehabilitation (SVR) or home-based rehabilitation (HBR) was more effective in facilitating successful RTS and reducing the risk of re-injury. Additionally, I aimed to understand the psychological factors that might influence an athlete's recovery journey and how these factors could be integrated into a comprehensive rehabilitation program. By focusing on competitive athletes, my research intended to provide valuable insights for sports medicine professionals, physiotherapists, coaches, and athletes themselves. I hoped to contribute to the ongoing discussion on best practices for rehabilitation and to ultimately help athletes regain their pre- injury level of performance with confidence and reduced risk of re-injury.

My thesis outlines a prospective experimental study designed to compare the outcomes of SVR and HBR after ACLR surgery. Through this research, I sought to address key questions regarding rehabilitation effectiveness, RTS rates, and re-injury risk. Ultimately, the findings could inform clinical practices and contribute to the development of improved rehabilitation protocols, with the aim of supporting athletes in achieving a safe and successful return to their sports.

1.1. Background

ACL is one of the four knee stabilizing ligaments that play a significant role in stabilizing the knee joint. ACL injury is one of the most common sports injuries, especially in competitive athletes, including sports that involve cutting, jumping, and twisting movements (1,2). However, the rates of ACL injury vary by sport, gender, and type of participation (3). Injury to ACL can be considered not only as an injury to the musculoskeletal system, but also as a neurophysiological dysfunction, often accompanied by ligament rupture, meniscus injury, articular cartilage surface lesions, possibly intra-articular fractures and knee osteoarthritis over time (4,5). The incidence of ACL tear shows an increasing tendency worldwide. With a yearly incidence of 68.6 per 100,000 persons, isolated ACL injuries remain a most common orthopaedic injury, having more incidences in females as compared to the males (6). In the United States, it increased from 86,687 (32.9/100,000 people/year) to 129,836 (43.5/100,000 people/year) in just 12 years' period (7).

ACLR is considered the best treatment of choice after an ACL injury in athletes, with the aim to restore the stability, strength, and functional ability of the ACL-deficient knee, thus enabling a safe RTS (8,9). It is usually performed through a minimally invasive procedure using an auto graft (usually a bone-tendon-bone (BTB) or hamstrings tendon taken from the athlete's own, same-sided limb), or less commonly using an allograft (a material taken from a cadaver). The surgery is usually performed after the 6th week of injury. In case there is no accompanying injury that requires acute intervention, this period is sufficient for the mental preparation of the patient as well. This pre-operative period is suitable for arranging prerehabilitation to improve movement ranges, condition muscles, and enables the patient to carry out the postoperative rehabilitation afterwards with a well-practiced exercise routine not having to learn them with a recently operated painful knee.

Rehabilitation is considered as an integral component of overall treatment process post ACLR, and its importance is considered to be equally comparable with that of surgery itself, as it can dramatically affect the postoperative course and the final outcomes of the surgical procedure (10).

A rehabilitation program consists of physiotherapy exercise trainings that can be carried out according to patient's interest and benefits, usually chosen depending on their efficiency, resource constraints, time consumption and cost effectiveness. Postoperative rehabilitation can be conducted either at a specialized rehabilitation clinic, referred to as SVR, or in the athlete's home, known as HBR. The rehabilitation strategy is almost the same in both the programs, with unremarkable differences in the clinical performance, resource utilization, and the recovery rate. Patients have complete autonomy to choose a program that better satisfies their needs. SVR is considered to be relatively costly regarding transport and utilization of time and resources; however also have many benefits as the patients are directly supervised by a therapist during the whole rehabilitation process, hence providing them with a confidence that they are in the safe and professional hands. HBR, on the other hand, permits the patient to perform their exercises independently as per the physiotherapist's guidance, and to make them acquainted with their own daily duties related to their rehabilitation in their own home. Additionally, HBR may involve the family members in the patient's rehabilitation process. Mostly these programs are provided by the community health organisations as well as the physiotherapists who provide the patients with the adequate guidance materials post- operatively. HBR is considered to be cost-effective as it may save the transport cost and time for the patient.

Considering the great importance of rehabilitation after ACLR, various previous research studies investigated the effectiveness of comparison between SVR and HBR, but found no statistical differences between the two approaches. These studies included range of motion (ROM), muscle strength, hop tests, and patient-reported questionnaires as the major outcome measures (11–18).

The reported success rate of ACLR has been documented as high (>90%) in the literature (19,20), but regardless of this high rate of successful surgeries, the rate of re-injury is also increasing at a higher level, and thus restricting the re-injured athletes to carry out their pre- injury level or competitive level sports participation. According to a systematic review study, just 63% of the athletes return to their preinjury level of sports participation and only 44% of them return to competitive sports after a primary ACLR (9). Another study showed that less than fifty percent of athletes are able to regain their pre-injury level of functional capabilities
(21). A recent research showed that 65% of athletes returned to pre-injury sports levels within 2 years after ACLR (22). Competitive athletes are at high risk of re-injury in the

first couple of years after a primary reconstruction surgery. A study suggested that in the 5 years following ACLR, 3–22% of athletes have their reconstructed ligament ruptured and 3–24% have the ACL injury of the contralateral knee (23). According to a retrospective study performed on 948 post- ACLR patients, only 69% of them were categorised as normal or close to normal as per the evaluation system (24). The incidence rate of re-injury has been documented to be higher in female athletes (25). According to a study, 29.5% re-injuries occur in the 2nd year with twenty percent underneath contralateral ACL tear (25). This high risk of re-injury sustains up to upcoming five years after a primary injury (26).

Risk factors of an ACL re-injury have been extensively investigated in the literature. Biomechanical attributes, for example asymmetric load distribution patters during the static and dynamic postures, high external knee abduction moment among female gender (27), bilateral differences in lower limbs, abnormal truncal displacement during stance (28), and decreased flexor muscles activation during squat jumping (27) have been documented as some of the major risk factors of re-injury. Muscle strength deficits, especially in quadriceps is a very common persisting risk factor post ACLR (29), the possible reason being asymmetric loading patterns during gait biomechanics. Being an agonist, it also greatly influences the strength of its antagonist i.e., hamstrings, thus creating an abnormal neuromuscular control, leading towards a re-injury. Therefore, in our current study, we measured the strength deficits of both quadriceps and hamstrings muscles, along with other objective and subjective parameters.

According to a cohort study, the unilateral graft rupture is more prevalent in males (30). Another research study reported that there is no difference in gender with respect to the graft tear, although the study showed that the contralateral graft rupture after a primary injury was common in female athletes (31). A study reported the significant increase in the occurrence of re-injury with the early RTS by reconstructed athletes who resumed their sports activity within less than 9.5 months’ post ACLR (32). It is important to consider all these risk factor related to re-injury after a primary ACLR, in order to achieve satisfactory recovery outcomes. Criteria based rehabilitation program focused on eliminating these risk factors may lead to the success of the surgery itself, prevent the chances of a re-injury, and hence promote safe RTS.

Based on the literature findings, it is obvious that despite of the well-developed and accurate ACLR surgical techniques, the increasing rate of re-injury can have multiple other reasons. The reasons can be improper or non-criteria based rehabilitation, too early RTS, or RTS without satisfying a specific biomechanical control examination, inability to achieve the basic criteria to RTS, no or improper test battery to make RTS decision, or any psychological fear in athlete related to RTS. To advocate these causes, it is important to find out the answers to the following questions:

1. How do patient-reported outcomes compare between competitive athletes undergoing SVR and those undergoing HBR after ACLR?
2. Does SVR lead to a higher rate of successful RTS compared to HBR among competitive athletes post-ACLR?
3. Does comprehensive psychological support in a rehabilitation program reduce re-injury rates among competitive athletes following ACLR, compared to rehabilitation programs without such support?

To find out the best possible answers to these research questions, we performed a prospective experimental study, in which we investigated and compared the outcomes of ACLR in terms of RTS and re-injury, including biomechanical aspects like muscle strength, neuromuscular control, and psychological readiness, between two homogenous groups of patients; one group (SVR) undergoing supervised rehabilitation, whereas the other group (HBR) undergoing home-based rehabilitation following a primary ACLR.

1.2. Hypothesis

- SVR will result in significantly better patient-reported outcomes compared to HBR among competitive athletes following ACLR.
- Competitive athletes undergoing SVR will have a higher rate of successful RTS after ACLR compared to those undergoing HBR.
- Rehabilitation programs that include comprehensive psychological support will lead to significantly lower re-injury rates among competitive athletes post- ACLR, compared to programs that do not incorporate psychological support.

1.3. Technical Literature

1.3.1. Rehabilitation

Criteria based rehabilitation after ACLR is essential to enable effective recovery and allow athletes to achieve their goals of returning to sports while extenuating impairments related to re-injury (22,33). The decisions related to activity progression after ACLR should commonly involve both the operating surgeon and the rehabilitation specialist/physiotherapist. It has been observed that surgeons rely profoundly on clinic-based physical examination procedures like knee laxity tests, and range of motion measurements.

However, shared decision making is emphasized by the additional constraint of physical performance tests (for example: strength, squat tests, quality of movement assessment) characteristically performed and inferred by a rehabilitation specialist. These results are mainly evident at the time of RTS, and are insightful of an increased awareness of research demonstrating that the use of objective physical performance measures are mandatory to direct activity progression and identify the risk factors related to re-injury (34).

Rehabilitation process after ACLR consists of 5 distinct phases, (explained in the methodology section). The criteria based rehabilitation has been proved to be much effective as it is based predominantly on the "proprioceptive" or functional exercises (35), in addition to few additional advanced level trainings (36), as being practiced in the SVR. The gradual introduction of sport-specific movement techniques in the late rehabilitation phase can be used to assess the patient's condition (37). Gradually increasing the athletic workout is a key element of athlete’s RTS (38). Swelling and pain in the knee joint can be used as a clinical marker to measure the response to exercise (39) and to monitor progress during rehabilitation.

When resuming sports activity, in addition to the gradual application of the load, the continuous monitoring of the condition of the knee is also an important task. Thus, exacerbation of possible symptoms (pain, swelling, decreased range of motion) and / or injury to the knee or other parts of the body can be avoided (33). The ratio of symmetry and strength between knee flexor and extensor muscles has direct correlation with the integrity of ACL. An ACL is considered to be healthy if the difference between peak torque ratios in both the muscles is less than 10%. A ratio of more than 10% is an indicative of muscular asymmetry, and hence imposes bad impact on the strength and extensibility of ACL (40). Therefore, both Quadriceps and Hamstrings should be considered equally while rehabilitating the muscular strength, power, endurance, and extensibility (41).

There is a debate in literature regarding the most effective rehabilitation method after ACLR. There are studies that reported SVR and HBR as equally beneficial for the patient's recovery after an ACLR surgery. Other studies found significant benefits of one method over the other. A study by Hohmann et al demonstrated no additional benefit in SVR as compared to HBR (11). Beard et al added that the SVR, in combination with HBR, has nominal additional advantages than the HBR alone, for patients who underwent ACLR (12). De Carlo and colleagues in their study found that a structured physical therapy program at home, along with only few supervised rehabilitation sessions, can bring successful outcomes in patient's recovery postoperatively (13).

Recreational athletes undergoing non-acute ACL reconstruction can successfully reach acceptable rehabilitation goals following minimally supervised HBR program, allowing them more flexibility to integrate the necessary postoperative rehabilitation into their ADLs (16). Lim and colleagues conducted a study to investigate the differences in knee strength improvement, endurance, and proprioception between SVR and HBR, which resulted in a conclusion that HBR improved knee strength as effectively as SVR, but the later proved to be more effective for the recovery of proprioception and functional knee movement (42). It shows that the supervision and location does not necessarily equally affect all the biomechanical components related to the final recovery outcomes.

Many other variables, like patient's prior physical fitness, level of sports participation (in athletes), comorbidities, and motivation can also influence the overall results (43). According to a study published in American Journal of Sports Medicine in 2005, HBR has clinical attendance after every 3 months of operation indicating that this program is cost effective and time conserving (16). Contrary to this, a study by Ugutmen et al stated that patients who are rehabilitated by a physiotherapist in supervised mode receive vocational training to learn developing confidence in their state, adding additional benefit, in comparison to those in home settings (44).

Feller et al concluded in a study that HBR with a minimal supervision can result in satisfactory, however not better results than a structured SVR (14). Fischer et al, on the other hand gave priority to the HBR over SVR in terms of feasibility, safety, and effectiveness (15). Grant et al found that a HBR is more effective in the first three months' post ACLR in terms of knee joint mobility than SVR (16). A study by Robert et al stated that both SVR and HBR regimens are equally beneficial for the patient's recovery after an ACLR, except the cost-effectiveness, that is significantly better in HBR (17). Similarly, Treacy and colleagues in a study found no significant difference between the two rehabilitation programs in terms of post-operative recovery (18). The whole debate in literature has been yet unsuccessful to ultimately decide the most beneficial rehabilitation method.

1.3.2. Who is a Competitive Athlete?

An athlete can be classified as a professional or an amateur, however according to PubMed, there are lots of descriptors often added to the term "athlete" such as recreational, amateur, master, competitive, high-level competitive, etc., adding more complexity to the interpretation of the term "athlete". The American College of Cardiology defined the competitive athlete as "one who participates in a systematized team or individual sport activity that requires regular competition against other sportsmen as a fundamental component, highly emphasizing on excellence and achievement, and requires some form of controlled and intense training". On the other side, the European Society of Cardiology, proposed a definition of competitive athletes, as "persons of young and adult age, either amateur or professional, who are involved in exercise trainings on a regular basis and take part in official sports competition (local, regional, national, or international) are recognized as competitive athletes" (45,46,47).

1.3.3. Prevention of Re-injury

Determining safe RTS is a key issue in preventing another injury. However, making the right decision is greatly complicated by not knowing exactly what measurements are needed to prevent re-injury. According to recent high-scientific publications, the decision to return to sport by preventing the re-injury is mostly linked to temporal and quantitative criteria rather than objective clinical criteria (48). To date, it has been demonstrated that quality criteria (e.g., ratio of Hamstrings to quadriceps muscle, i.e., H /Q quotient, knee flexion angle, torso control, stability index, and locomotor technique) play an important role in re-injury prevention and rehabilitation.

Dynamic knee valgus on landing on the ground from a squat jump also greatly increases the risk of ACL re-injury (49). This knowledge must be incorporated into the post- ACLR rehabilitation process. Early RTS that are dangerous for knee twisting (football, handball, skiing) increases the risk of knee re-injury (50,51). Recent evidence suggested that after ACLR, the incidence of knee re-injury is significantly reduced by about 51%, if RTS occur at least 9 months after surgery (50). Based on this, RTS that is dangerous for knee twisting is recommended at least 9 months after ACLR. A prerequisite for a safe and early RTS is to take into account the latest evidence on ACL rupture and to establish ongoing professional communication between the injured athlete, coach, physician, and a physiotherapist (48,52).

1.3.4. Objective Criteria for RTS

The series of tests recommended in the previous studies are the measurement of quadriceps and hamstrings muscle strength (≥90% of the contralateral side), squat and contralateral jump tests (≥90% of the contralateral side), one skill test (≤11 s), and one sport -specific assessment and a functional rating scale (≥90 points, 0 worst and 100 best). It would be desirable for these surveys to be performed in specialized biomechanical laboratories by specially trained professionals. According to the literature, those who meet these criteria before returning to sport are 4–6 times less likely to have ACL re-injury (36,53).

1.3.5. Psychological Readiness

Certain mental factors greatly influence RTS after ACLR. These include lack of intrinsic motivation and self-confidence, as well as fear of re-injury, which may be associated with competence, autonomy and kinship of an athlete (54,55). Psychic responses generally improve during rehabilitation, but in some cases fear may increase and is a serious risk factor when returning to sports (56). The assessment of psychological factors related to RTS can be assessed using a variety of methods (57), theroutine use of which helps to identify the risks of returning to sport and to determine the need for further treatment. Rehabilitation can be successfully complemented by consultation with a sports psychologist and the use of methods that influence mental factors, such as active goal setting and relaxation techniques (55).

2. Objectives

This study was designed to determine whether or not there are any biomechanical differences in knee joint health, in terms of quadriceps, hamstrings, abductors, and adductors muscles strength, Squat analysis (SA), and stance evaluation (SA), as well as psychological readiness for RTS, with respect to the prevention of re-injury post ACLR, between supervised and home- based rehabilitation program in competitive athletes. We aimed to find out the better rehabilitation program in terms of re-injury rate and RTS after a primary ACLR; and what criteria should be used to thoroughly examine the physical, biomechanical, as well as psychological status of the recovering athletes who want to RTS without any risk of re-injury, as we believe that the re-injury prevention is the key element for safe RTS in athletes. In other words, we expected from the study that upon evaluating the results, the preventive strategy with respect to criteria based rehabilitation and the RTS testing battery could be optimized, as most of the athletes with an ACL injury remain symptomatic and could not safely RTS due to re- injury even following structured rehabilitation after a primary ACLR, and later opt for follow-up surgery. So our main aim was to find out the effectiveness of SVR versus HBR after ACLR in competitive athletes. We also aimed to find out the possible reasons that despite the advancements in surgical procedures, why some of the athletes do not completely recover and experience a re-injury after surgery; and to find out that what should be the criteria for rehabilitation program to prevent the re-injury, and enable the athletes to safely return back to their pre-injury level of sports participation, and on what experimental grounds should we decide the RTS. To find out the answers to the above questions, we aimed to assess the physical as well as psychological parameters of the study participants through a set of subjective and objective evaluations.

3. Methods

3.1. Study Design

This clinical study was conducted at Castle Park Surgical Hospital in Tata, Hungary, and the TSO Biomechanics Lab in Budapest, Hungary, over a three-year period from January 2020 to February 2023. It received ethical approval from the Regional and Institutional Science and Research Ethics Committee of Semmelweis University, Budapest (SE RKEB number: 120/2021). All participants provided written informed consent prior to enrollment.

The study was designed as a non-randomized experimental study without blinding. Participants were assigned to groups based on specific criteria, allowing researchers to observe the effects of rehabilitation in a real-world setting. The lack of blinding indicated that both participants and researchers knew which rehabilitation methods were being used, a factor that could influence outcomes due to bias. Despite this limitation, the study design provided insights into the impact of rehabilitation methods following ACLR.

The dual-location approach allowed the study to examine rehabilitation outcomes from both a clinical and a biomechanical perspective. Castle Park Surgical Hospital served as the primary site for surgical procedures and immediate postoperative care, while the TSO Biomechanics Lab provided facilities for in-depth biomechanical analysis. This setup offered a comprehensive view of the rehabilitation process, from surgery through advanced biomechanical testing. The study's timeline encompassed the COVID-19 pandemic, presenting unique challenges to the continuity of research and patient care. The successful completion of the study during this period demonstrated the adaptability of the research team and the robustness of the study design.

3.2. Patient Enrollment

The patient enrollment process for this study was conducted with a specific focus on systematic and transparent selection, utilizing a predetermined methodology to ensure clarity and consistency. The enrollment procedure did not involve random allocation of participants to treatment groups, and neither the participants nor the researchers were blinded to the group assignments.

Sampling Methodology: Participants were selected based on predefined inclusion and exclusion criteria, ensuring a uniform and unbiased approach to recruitment. The sampling strategy targeted competitive athletes engaged in high-risk pivoting sports—such as soccer, rugby, handball, gymnastics, and tennis—who were diagnosed with non-acute isolated anterior cruciate ligament (ACL) injuries. These participants had undergone ACL surgical reconstruction at the Castle Park Surgical Hospital in Tata, Hungary, between January 2020 and March 2021. Notably, all surgeries were performed by a single experienced operating surgeon, providing consistency in the surgical technique and post-operative care.

Inclusion Criteria: The inclusion criteria were designed to align with standards set by the American College of Cardiology, focusing on competitive athletes of both genders, aged between 15 and 50 years, who had been diagnosed with non-acute isolated ACL injuries and required ACL reconstruction surgery. These individuals had no secondary underlying pathologies that could affect the study outcomes. By including athletes from a range of sports, the study aimed to gather a diverse sample that could represent various athletic demands and recovery patterns.

Exclusion Criteria: Exclusion criteria were established to ensure the selection of a homogenous group of participants for the study. Individuals were excluded if they were not competitive athletes, if they were younger than 15 or older than 50 years, or if they had multiple ligamentous or bony injuries, or secondary underlying pathologies. This strict approach to exclusion ensured that the study outcomes would be specific to the targeted population.

Screening and Group Assignment: An initial screening of 74 patients was conducted to identify eligible participants based on the defined criteria. Out of these, 14 patients were excluded due to unresolved medical complications, concurrent injuries, or refusal to provide informed consent. This screening process ultimately led to the recruitment of 60 participants evenly divided into two groups using non-probability convenience sampling. The division resulted in 30 participants in the Single-Versus-Revision (SVR) group, considered the case group, and 30 in the Healthy-Benefit-Received (HBR) group, serving as the control group. Each group comprised an equal distribution of 15 males and 15 females.

Gender-Differentiated Sports Breakdown: To offer a more detailed understanding of the participants' athletic backgrounds, a gender-differentiated breakdown of the types of sports engaged in was provided (Figure 1).

This breakdown allowed for a comprehensive view of the various sports that each gender participated in, contributing to a more nuanced analysis of the study results. Overall, the patient enrollment process was designed to ensure that the selected participants were representative of a specific athletic population, with strict adherence to inclusion and exclusion criteria, resulting in a well-balanced and robust study group.

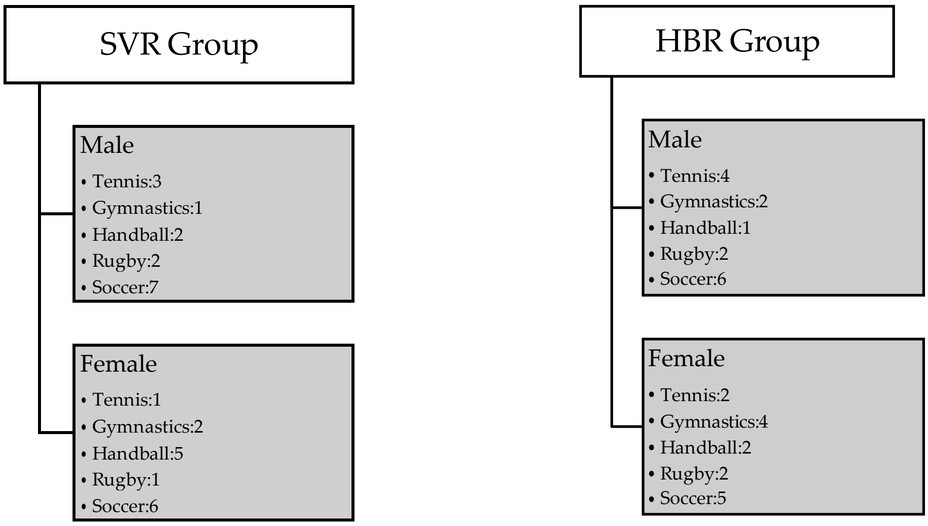

Figure 1. Type of Sports; A gender-differentiated breakdown of sports participation among athletes in SVR and HBR groups.

3.3. Surgical Technique

ACLR was carried out using the arthroscopic transtibial technique, a method known for its precision and reliability in ACL reconstruction. Patients undergoing this procedure were placed in a supine position on the operating table to facilitate the surgical approach. To control bleeding and maintain a clear surgical field, a thigh tourniquet was applied, which constricted blood flow during the operation.

Initial Arthroscopy and Assessment: The procedure began with the creation of a standard anterolateral portal for initial visualization of the knee joint. This allowed the surgical team to conduct a thorough diagnostic arthroscopy, assessing the extent of the ACL injury and identifying any associated pathologies, such as meniscal tears or cartilage damage. This preliminary step ensured that any additional issues could be addressed during the ACL reconstruction procedure.

Graft Harvesting and Preparation: The graft used for the ACLR was harvested from the patient's own hamstring tendons, specifically the semitendinosus and gracilis. This approach, known as a quadruple-bundle hamstring autograft, involved removing these tendons and preparing them for use in the reconstruction. The tendons were meticulously cleaned, measured, and folded to create a strong, robust graft with multiple layers for enhanced strength.

Transtibial Tunnel Creation and Graft Placement: After the graft preparation, the transtibial technique was employed to create the femoral tunnel. A guide pin was inserted through the tibial tunnel to establish the femoral tunnel's correct footprint, ensuring that the graft would be positioned accurately within the joint. This step was followed by careful reaming to create the tunnel, taking care to avoid any damage to the surrounding bone and tissue.

Addressing Meniscus Injuries: During the surgical procedure, particular attention was given to the menisci, which are often injured alongside the ACL. If meniscal tears were detected, the surgical team attempted to repair them using either the inside-out or all-inside technique, depending on the tear's location and severity.

In cases where repair was not feasible, a partial meniscectomy was performed to remove the damaged portion of the meniscus, promoting joint stability and reducing the risk of further complications.

Graft Fixation and Tensioning: Once the tunnels were prepared and any additional issues addressed, the graft was positioned within the knee joint. Graft fixation was achieved using an endobutton on the femoral side, ensuring secure anchoring in the femoral tunnel. On the tibial side, a Milagro® advance interference absorbable screw (DePuy Synthes, Johnson & Johnson) was used to lock the graft in place. This dual-fixation approach provided stability and minimized the risk of graft slippage.

Graft tensioning was meticulously conducted to ensure proper stability and knee function. This involved carefully adjusting the graft's tightness to avoid excessive laxity or stiffness, allowing for a natural range of motion post-surgery. Once the graft was securely fixed and appropriately tensioned, the surgical team closed the incisions, and the patient was moved to recovery for post-operative care and rehabilitation.

3.4. Rehabilitation Protocols

Following ACLR, a comprehensive rehabilitation program was implemented to optimize recovery and ensure a safe RTS. The protocol was structured into five distinct phases, each with specific goals and activities tailored to facilitate a progressive recovery. The early stages of the program emphasized pain management, mobility, and ROM; while the later phases focused on building strength, power, endurance, stability, and extensibility in the knee and associated structures. The type, intensity, and frequency of rehabilitation training were tailored according to the physical and psychological needs of individual patients, as assessed by the rehabilitation specialist and the operating surgeon (58).

Rehabilitation Phases

The rehabilitation program consisted of five phases, as illustrated in Figure 2, which outlined the progression from initial recovery to full athletic activity. Each phase built upon the previous one, allowing for a gradual increase in activity level and complexity.

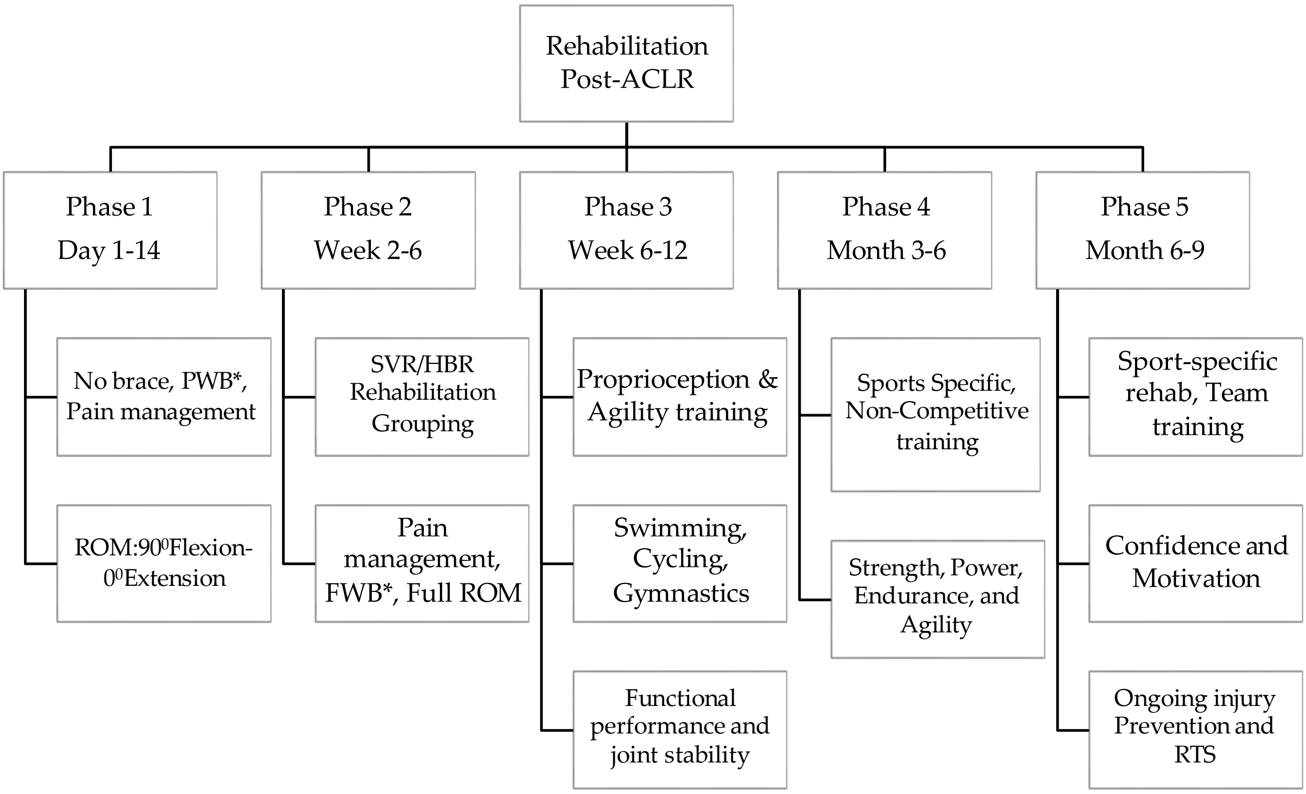

Figure 2. Rehabilitation Flow Chart. The flow chart represents the phase wise division of rehabilitation process post-ACLR in 5 distinct phases. *Partial Weight Bearing (PWB)and Full Weight Bearing (FWB) are indicated.

Phase 1: Initial Recovery (0-2 weeks)

In the first two weeks following surgery, the primary focus was on pain management and reducing inflammation. During Phase 1, both groups followed the same rehabilitation protocol. Non-pharmacological techniques such as cryotherapy, manual therapy, and neuromuscular interventions were used to alleviate discomfort. Early mobilization exercises helped maintain circulation and prevent stiffness. During this phase, patients were instructed on partial weight- bearing (PWB) and were advised to use crutches to avoid placing excessive pressure on the knee.

Phase 2: Early Mobility (2-6 weeks)

As pain subsided, the emphasis shifted to improving ROM and beginning muscle activation exercises. Patients continued with PWB but gradually transitioned to full weight-bearing (FWB) as tolerated. Gentle stretching and strengthening exercises were introduced to promote knee stability. A key component of this phase was educating patients on proper movement patterns to avoid undue stress on the ACL reconstruction.

Phase 3: Strengthening and Stability (6-12 weeks)

This phase focused on building muscle strength and joint stability. Resistance training exercises, both isometric and isotonic, were included to strengthen the quadriceps, hamstrings, and other supportive muscles around the knee. Proprioceptive training, such as balancing exercises and agility drills, helped improve coordination and joint control.

Phase 4: Advanced Strength and Conditioning (12-24 weeks)

With increased muscle strength and stability, patients progressed to more advanced exercises that involved higher intensity and power. Plyometric exercises, running drills, and sport- specific movements were integrated into the program. Endurance training was also introduced to improve cardiovascular fitness.

Phase 5: Return to Sport (24-36 weeks)

The final phase focused on preparing patients for a safe RTS. This phase involved high-intensity training and sport-specific drills to simulate game situations. Functional assessments were conducted to ensure patients had the necessary strength, agility, and stability to safely return to competitive sports. Clearance for RTS was granted based on both subjective and objective evaluations at the Biomechanics Lab.

Differing Approaches for SVR and HBR Groups

During the initial eight months’ post-surgery, participants' rehabilitation experiences differed between the SVR and the HBR. The structure and frequency of physiotherapy sessions in these two groups varied, with the SVR group attending frequent supervised sessions and the HBR group performing exercises independently at home.

SVR Group: Participants in the SVR group attended outpatient physical therapy sessions at a rehabilitation clinic twice a week. The duration of each session ranged from 90 to 120 minutes. Over the course of 8 months’ post-surgery, participants in this group attended between 40 and 64 sessions. These supervised sessions were designed to provide personalized guidance and support to ensure optimal rehabilitation outcomes. The core focus of these classes was on proprioceptive and functional training exercises, which are crucial for rebuilding balance, coordination, and muscle strength after ACLR. Periodic updates to the exercise routines were implemented to align with individual progress and recovery timelines. The structured nature of the supervised sessions allowed physiotherapists to monitor each participant's technique, providing real-time feedback and correcting any issues that could hinder recovery. The exercises encompassed a wide range of activities, from simple mobility exercises to more complex functional movements, preparing participants for a gradual return to daily activities and, eventually, sports and athletic pursuits.

HBR Group: In contrast, the HBR group performed all their exercises at home without direct supervision. To guide them, participants were given detailed written instructions along with pictorial representations to illustrate proper exercise techniques. The recommended minimum frequency was two sessions per week, but participants were encouraged to adjust the frequency based on their recovery progress. This approach provided flexibility, allowing participants to integrate rehabilitation into their daily routines.

Adherence to the treatment plan in the HBR group was monitored through periodic assessments at the rehabilitation clinic. During these visits, therapists evaluated the participants' adherence and progress, making adjustments as needed. These sessions also served as an opportunity to provide additional education and clarify any questions about the exercise protocols. To ensure consistent communication, regular follow-up appointments were scheduled, supplemented by remote consultations via phone or video calls. This hybrid approach helped maintain patient engagement and allowed therapists to guide the rehabilitation process even without direct supervision.

Monitoring and Adherence Tracking

A key aspect of the HBR group was the maintenance of exercise logs to track home-based sessions. Participants were required to document their exercises, including frequency, duration, and any difficulties encountered. These logs were reviewed during clinic visits, enabling therapists to assess adherence and make necessary modifications to the exercise plan. This record-keeping also provided an opportunity to identify trends in recovery and address any issues before they became problematic.

In the SVR group, where exercises were supervised, the focus was on monitoring attendance and active participation in the physical therapy sessions. While there were no prescribed home exercises, the supervised sessions allowed therapists to track participants' progress and ensure that they were meeting rehabilitation milestones. Efforts were made to standardize exercise protocols across both groups, while still allowing for individual adjustments based on each participant's response to therapy.

Technological Opportunities for Future Studies:

Although not utilized in this study, the potential benefits of smartphone applications for monitoring adherence were acknowledged. Such technology could play a significant role in future studies, offering a more streamlined approach to tracking rehabilitation progress and facilitating communication between therapists and patients. This approach could enhance adherence monitoring, providing a more efficient way to manage and adjust rehabilitation protocols.

Overall, the structured and comprehensive nature of the SVR group provided direct supervision and support, ensuring consistent progress throughout the rehabilitation process. On the other hand, the flexibility and autonomy offered to the HBR group allowed participants to integrate rehabilitation into their daily lives, with periodic checks to maintain accountability. By comparing these two approaches, this study aimed to identify the most effective strategies for ACLR rehabilitation, with a focus on long-term recovery and return to normal activities.

Follow-Up Examinations

To ensure effective recovery and progression during the rehabilitation process following ACLR, both the SVR and HBR groups underwent five mandatory follow-up

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examinations at various stages post-surgery. These follow-up sessions served as critical checkpoints to assess the healing process, monitor progress, and make necessary adjustments to the rehabilitation protocol.

First Follow-Up: Postoperative Day 14: The initial follow-up examination occurred 14 days after surgery. This appointment primarily focused on the removal of stitches, a key step in the healing process. During this examination, participants were examined for signs of infection or complications and were evaluated for their readiness to begin more intensive rehabilitation. After this initial check, participants were divided into the SVR and HBR groups. The division was based on predetermined criteria, considering factors such as patient preference, logistics, and individual recovery needs.

Second Follow-Up: Six-Week Activity Assessment: The second mandatory follow-up occurred approximately six weeks after surgery. This examination was crucial in assessing the progression of activity levels. Therapists evaluated the participants' range of motion, muscle strength, and stability. This examination also provided an opportunity to assess adherence to the rehabilitation protocol and to determine whether participants in both groups were on track with their recovery. During this phase, the rehabilitation program began to diverge between the SVR and HBR groups in terms of supervision. While the exercise programs were the same, the SVR group continued with supervised sessions at the rehabilitation clinic, while the HBR group performed exercises at home with periodic clinic visits for monitoring.

Third Follow-Up: Three-Month Evaluation: The third mandatory follow-up examination took place at the three-month mark. This review was designed to assess the participants' ability to perform more complex physical activities. The therapists evaluated balance, coordination, and overall functionality, which are critical for daily activities and sports. The objective was to determine if the participants were ready for more advanced rehabilitation exercises and to identify any areas requiring additional attention.

Fourth Follow-Up: Six-Month Review for Return-to-Sport: At the six-month point, the fourth mandatory follow-up examination assessed progress towards achieving the physical attributes necessary for return-to-sport (RTS). This review focused on strength, agility, and endurance, ensuring that participants were building the foundational skills required for athletic activities. The intensity and frequency of training were standardized for all patients, with supervision being the primary difference between the SVR and HBR groups. This phase also included discussions about the timeline for RTS and safety considerations.

Fifth Follow-Up: Eight-Month Biomechanical Lab Examination: The fifth and final follow-up examination, at the 8-month mark, involved subjective and objective evaluations at the Biomechanics Lab. These evaluations included various assessments, such as gait analysis, strength measurements, and functional tests, to comprehensively evaluate participants' readiness for a gradual return to competitive sports. Based on the results, the treating therapist determined whether participants met the criteria for RTS. These criteria were designed following scientific literature guidelines and incorporated individual recovery trajectories.

Return-to-Sport and Re-Injury Monitoring

The mean time to RTS for both the SVR and HBR groups was approximately nine months after ACLR. Following RTS, re-injury rates were measured and recorded at the 5-6-month mark to monitor for potential complications or setbacks. This data provided valuable insights into the long-term outcomes of the rehabilitation protocol and the effectiveness of the different rehabilitation approaches. The overall rehabilitation protocol was based on "Campbell's Operative Orthopaedics," a comprehensive reference for orthopaedic surgical practices and rehabilitation strategies (59).

3.5. Outcome Measures

In assessing the rehabilitation progress and outcomes of participants following ACLR, three key subjective instruments were employed to measure various aspects of recovery: the Tegner Activity Scale (TAS), the International Knee Documentation Committee subjective knee form (IKDC-SKF), and the ACL Return to Sport after Injury (ACL-RSI) questionnaire. Each of these tools provides a distinct perspective on the functional, physical, and psychological components of rehabilitation.

TAS: The TAS was used to evaluate participants' levels of sports activity and physical performance. This scale is a numerical index ranging from 0 to 10, where 0 indicates a state of knee-related disability, and 10 represents the highest level of competitive sports participation. The TAS helps categorize individuals based on their activity levels, providing a simple yet effective way to assess the extent to which participants have resumed or are able to resume their pre-injury activity levels. It is a useful tool for tracking progress over time, indicating whether participants are achieving their desired activity goals as part of their rehabilitation journey.

IKDC-SKF: The IKDC-SKF is a self-reported questionnaire used to assess the functional outcomes of the knee from the patient's perspective. This form utilizes a scale from 0 to 100, where 0 signifies the lowest level of knee function and 100 denotes the highest level of knee function. The IKDC-SKF is designed to capture the patient's subjective experience of knee function, symptoms, and activity levels. The form is divided into three sections: knee symptoms (7 items), function (2 items), and sports activities (2 items). Each section is designed to evaluate specific aspects of knee performance. A higher score on the IKDC-SKF indicates better knee function and fewer symptoms, providing a comprehensive overview of the patient's subjective recovery and ability to engage in daily activities and sports.

ACL-RSI: Psychological readiness to RTS was assessed using the ACL-RSI questionnaire. This tool, developed by Webster, Feller, and Lambros in 2008 (60), comprises 12 questions aimed at evaluating the athlete's emotional and psychological state after injury. The questions are designed to measure three primary domains: emotional wellbeing (5 questions), confidence in performing the respective sport (5 questions), and risk appraisal (2 questions). Participants respond to the questions based on their subjective experience, and the total score is calculated as a percentage. This score provides insight into the psychological factors that may influence the participant's willingness and readiness to return to competitive sports. A higher score suggests greater psychological readiness, while a lower score may indicate ongoing fears or hesitations about returning to sport. Together, these three outcome measures—TAS, IKDC-SKF, and ACL-RSI—offer a comprehensive view of the participant's rehabilitation progress, encompassing physical, functional, and psychological dimensions. By combining these tools, the study aims to assess not only the physical recovery of participants but also their emotional and mental readiness to resume competitive sports.

3.6. Assessment of Muscle Strength and Neuromuscular Control

An accurate assessment of muscle strength and neuromuscular control is crucial for understanding the functional recovery and risk of re-injury following ACLR. Researchers have found that muscle strength deficits, such as asymmetry between the legs and imbalances between the strength of the hamstrings and quadriceps muscle (H-Q ratio), are important in determining readiness to RTS (61,62,63). To assess these factors, various testing methods were employed to measure the isometric strength of key muscle groups, analyse balance, and evaluate concentric muscle contractions. These assessments provide a detailed comparison between the operated and non-operated sides, offering insights into muscle imbalances and recovery progress, which are instrumental in guiding rehabilitation programs and establishing safe return-to-sport timelines.

Isometric Strength Measurement: Isometric maximum strength tests were conducted to evaluate the strength of the quadriceps and hamstrings muscles (8). This was achieved using Kinvent Isometric Dynamometers (KINVENT, France; K-Pull and K-Push Handheld Dynamometers) at knee flexion angles of 30°, 45°, and 90° (Figure 3). The results were recorded in kilograms, indicating the maximum force generated by the muscles during an isometric contraction. A key outcome of these tests was the percentage of strength deficit in the muscles on the operated side compared to the non-operated side at each specific angle. This allowed researchers to identify any significant imbalances that could affect the rehabilitation process or increase the risk of re-injury.

Furthermore, the ratio between the hamstrings and quadriceps muscles (H/Q ratio) was calculated at each joint angle. This ratio provides a crucial metric for assessing the balance between agonist and antagonist muscles, which is important for knee stability. Discrepancies in the H/Q ratio may indicate a need for targeted interventions to prevent imbalances that could lead to complications during rehabilitation.

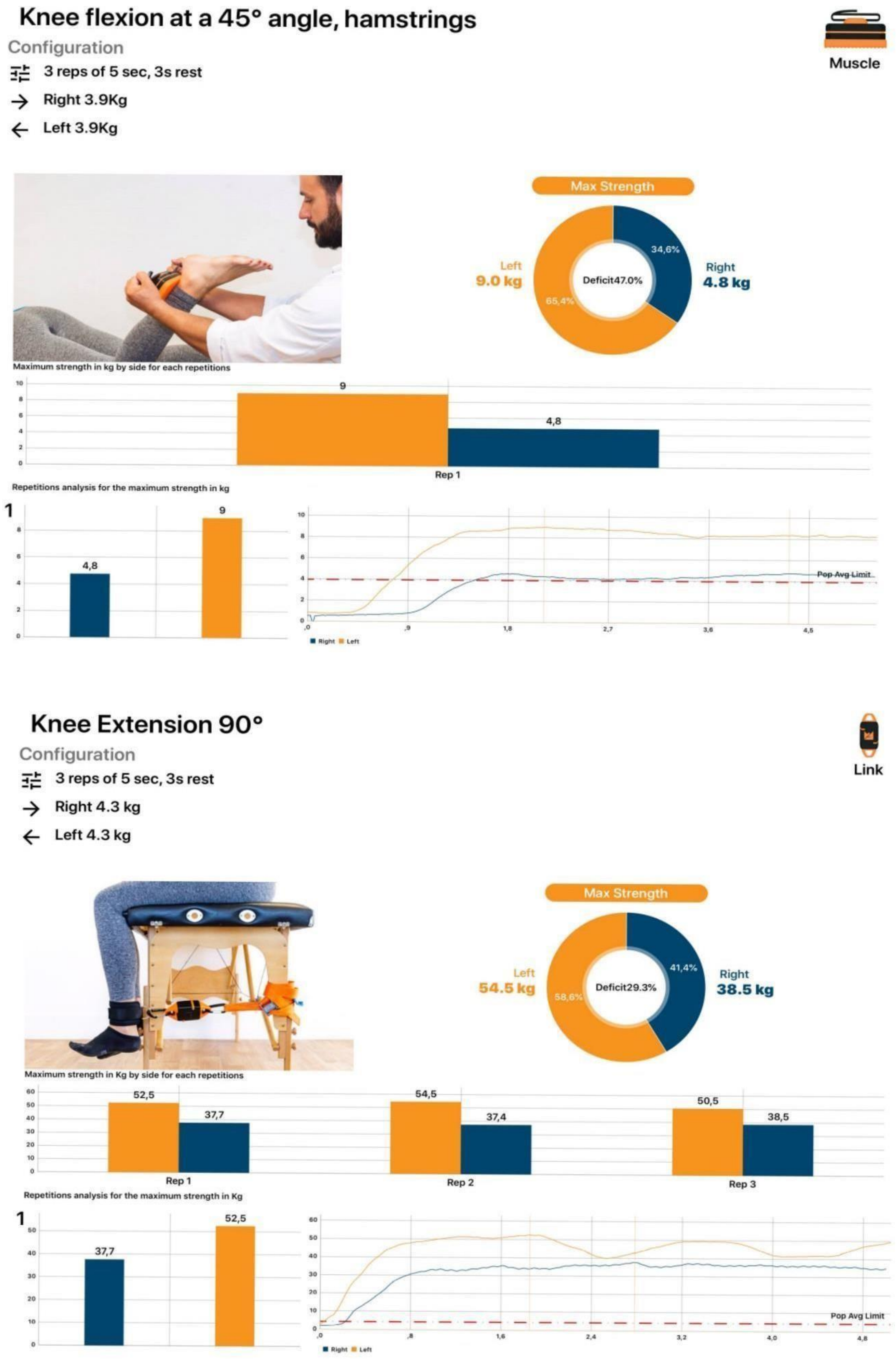

Figure 3. Isometric dynamic muscle strength measurement report of quadriceps and hamstrings using kinvent isometric hand-held and pull dynamometers

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Concentric Contraction Measurement: To assess quadriceps concentric contractions, the Kineoglobus system (Kinetic Systems, USA) was used. This system allowed for the measurement of muscle performance during knee joint extension at two different angular velocities: 120^0 and 240^0. These measurements provided valuable insights into the strength and speed of concentric muscle contractions, which are essential for activities involving dynamic knee movements. By analysing the data from these tests, therapists could determine the progress of rehabilitation and make adjustments to exercise protocols if needed.

Balance Assessment: Balance and stability are critical components of rehabilitation after ACLR. To evaluate both static and dynamic balance, participants underwent a series of tests on KINVENT Force Plates (Figure 4). These tests included standing and unilateral squatting, during which the average Center of Pressure (COP) position was measured (Figure 5). The COP indicates the point of pressure exerted by the foot, providing information about balance and weight distribution. Additionally, the differences in average foot pressures between the operated and non-operated sides were calculated during both measurements. This analysis helped identify any stability issues that could impact recovery or increase the risk of re-injury.

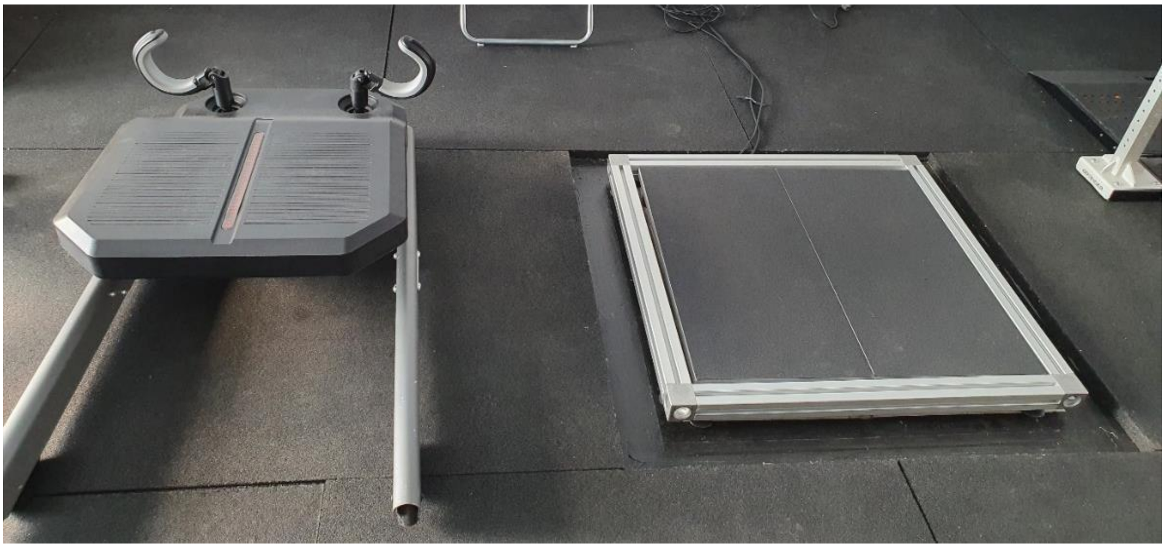

Figure 4. Kinvent Force Plates

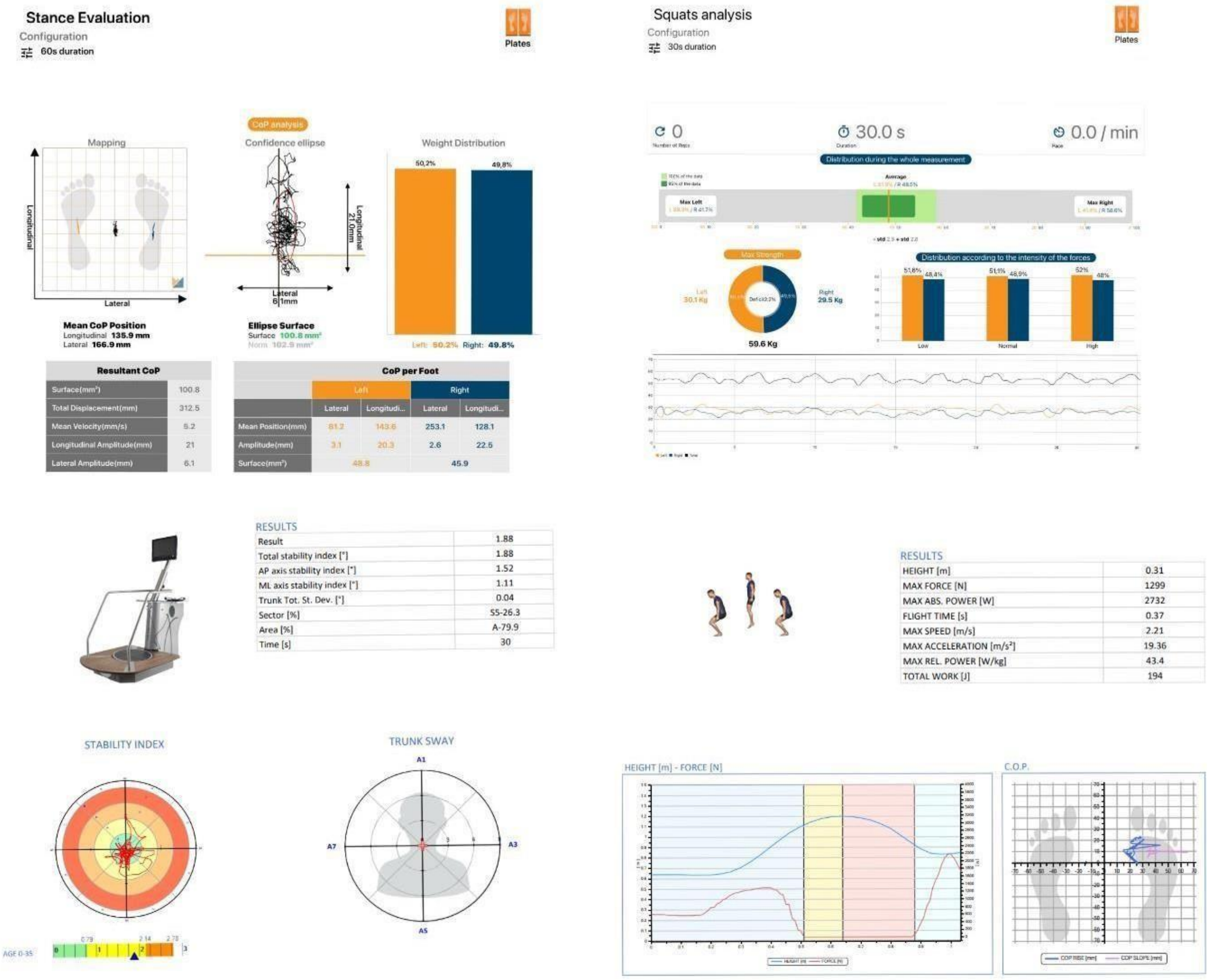

Figure 5. Stance, Balance, and Squat Evaluation Reports

Hip Adductor and Abductor Strength Measurement: The maximum isometric strength of the hip adductors and abductors was measured using Vald Performance's Force Frame at a knee joint angle of 60 degrees. These results were calculated in Newtons, allowing for a quantitative assessment of hip muscle strength. The force deficit between the operated and non-operated sides was also determined, along with the ratio between agonist and antagonist muscles. This information is vital for understanding the contribution of hip muscles to knee stability and identifying areas for further strengthening.

Re-Injury Detection and RTS: Re-injury after ACLR is a significant concern, and its detection requires a combination of clinical evaluation and imaging techniques.

Clinical and MRI examinations were conducted by the operating doctor to identify any signs of re-injury. This comprehensive approach ensured accurate diagnosis and informed any necessary adjustments to the rehabilitation program.

The timeline for RTS was recorded based on the athletes' self-reported sports participation. This data helped track the progression of participants back to their respective sports and provided an indication of the success of the rehabilitation program. By correlating RTS data with strength, balance, and neuromuscular control assessments, researchers could evaluate the overall effectiveness of the rehabilitation process and identify factors contributing to successful recovery or re-injury.

3.7. Statistical Analysis

To ensure the robustness of our results and the reliability of our conclusions, we conducted comprehensive statistical analyses. Given the limitations in prior data for conducting an a priori power calculation, we utilized a post hoc power analysis to assess whether our sample size was sufficient for detecting statistically significant differences in the measured outcomes. The GPower software (version 3.1.9.7) was used for this post hoc analysis, taking into account the observed effect sizes and the sample sizes from our study.

Data Representation and Normality Testing: Data were primarily represented as averages with corresponding standard deviations, providing a clear understanding of the central tendency and dispersion within our dataset. To determine whether the data followed a normal distribution, we applied the Shapiro-Wilk W test. This test is particularly useful for smaller sample sizes and helps guide the choice of appropriate statistical procedures. If the data were found to be normally distributed, parametric tests were employed; otherwise, non-parametric tests were used.

Statistical Tests for Comparisons: We employed a combination of statistical tests to compare datasets within and between groups. For within-group comparisons, which involve analysing changes or effects within the same group over time, we utilized either paired sample t-tests or Wilcoxon tests. The choice between these tests depended on whether the data met the assumptions of normality. Paired sample t-tests were used for normally distributed data, while Wilcoxon tests were chosen for non-parametric data.

For between-group comparisons, we used independent sample t-tests or Mann-Whitney U tests, again depending on the distribution of the data. Independent sample t-tests were applied to compare groups with normally distributed data, while the Mann-Whitney U test was used for non-parametric data. These tests allowed us to assess whether there were significant differences between the groups in terms of the various measured outcomes. For discrete value comparisons, such as categorical data, we employed the Chi- Square test. This test is particularly useful for analysing differences in proportions or frequencies between groups, providing insights into categorical outcomes.

Statistical Software and Significance Level: JASP (version 0.17.1) and Statistica (version 14.0.1) statistical software (TIBCO Statsoft USA) were used for the calculations.

These tools offered a range of statistical methods and visualizations, facilitating comprehensive analysis of the data. To determine statistical significance, we set the significance level at $p < 0.05$, a common threshold in research indicating that the results are statistically significant with less than a 5% chance of error.

Effect Size and Post Hoc Power Values: To provide additional context and insight into the strength of the observed effects, we included Effect Size (Cohen's d) and Post Hoc Power values for instances where significant differences ($p < 0.05$) were detected. Effect size indicates the magnitude of the difference between groups, while post hoc power assesses the likelihood that the study had enough power to detect a true effect. These values were calculated using GPower software, adding an additional layer of robustness to the statistical analysis.

By incorporating these diverse statistical methods, we aimed to ensure the reliability of our findings and provide a thorough evaluation of the study's outcomes. The combination of normality tests, within-group and between-group comparisons, and the inclusion of effect sizes and post hoc power values helped to strengthen the validity of the results and support the conclusions drawn from the data.

3.8. Ethical Considerations

Our study was conducted in accordance with ethical standards, as outlined below:

- *Ethical Approval:* The study received approval from the Regional and Institutional Science and Research Ethics Committee at Semmelweis University (approval number: SE RKEB 120/2021), ensuring that our research methods met the required ethical guidelines.
- *Adherence to Ethical and Moral Values:* During the development of our research plan, we took special care to uphold ethical and moral principles. We aimed to ensure thesafety, dignity, and rights of all participants throughout the study.
- *No Harm to Participants:* The study was designed to avoid causing any physical or emotional harm to participants. We implemented procedures to minimize risks and ensure a safe and respectful environment during all phases of the research.
- *Informed Consent:* We obtained informed consent from all participants prior to their involvement in the study. To ensure clarity and understanding, we translated all questions into Hungarian, with the assistance of a colleague, to accommodate participants' language preferences.

By adhering to these ethical considerations, we ensured that our study maintained high ethical standards, protecting participants' rights and well-being while contributing valuable knowledge to the field.

4. Results

4.1. Baseline Characteristics

A total of 60 participants were enrolled in this study, with a balanced allocation between the SVR) and HBR groups. Each group comprised 15 male and 15 female participants, ensuring an equal distribution of gender. This strategic approach to gender balance was implemented to strengthen the robustness of our analysis, thereby reducing the risk of gender-related biases. While gender representation in ACL injury studies often reflects injury frequency, our study's design aimed at creating a representative cohort for a thorough and unbiased assessment.

Age Distribution: The mean age of participants in the SVR group was 22.43 ± 6.34 years, while in the HBR group, it was slightly higher at 24.96 ± 7.93 years. Despite this difference, a statistical analysis using the t-test revealed that the age disparity between the two groups was not significant (p = 0.1991), indicating that both groups were comparable in terms of age distribution.

Height and Weight: Regarding height, the mean value in the SVR group was 174.78 ± 9.59 cm, compared to 172 ± 9.81 cm in the HBR group. Similarly, the mean weight was 71.11 ± 12.90 kg in the SVR group and 77.23 ± 20.41 kg in the HBR group. Statistical tests showed no significant differences between the groups in terms of height (p = 0.3022) and weight (p = 0.1960), suggesting a homogeneous distribution of these physical characteristics.

Body Mass Index (BMI) and Gender Comparisons: To further examine the comparability of the groups, BMI was calculated separately for men and women. The t-test for BMI found no significant differences among male and female athletes in their respective rehabilitation groups. This result indicates that, aside from height and weight, BMI was also consistent between the SVR and HBR groups, reinforcing the notion that the groups were balanced in terms of key demographic parameters.

Follow-Up Time: The mean follow-up time was 8.62 ± 7.32 months for the SVR group and 8.48 ± 7.68 months for the HBR group, with a non-significant difference (p = 0.9501). This similarity in follow-up times suggests that both groups were monitored over a comparable duration, providing a consistent basis for assessing outcomes across the study.

Overall, the baseline characteristics demonstrate that the SVR and HBR groups were similar in terms of gender distribution, age, height, weight, BMI, and follow-up time. This balance at baseline is crucial for drawing valid conclusions from the results, as it minimizes the influence of confounding factors related to demographic disparities. Table 1 contains detailed demographic data for all participants in the study, providing a comprehensive overview of the characteristics of each group.

Table 1. Demographic data of participants in the SVR and HBR Groups. Values are expressed as mean ± standard deviation. The table describes the uniform distribution of baseline characteristics (gender, age, height, weight, follow-up time, and BMI in male and female participants) among the two rehabilitation groups, along with their significance values.

Baseline Characteristics	**SVR (n = 30)**	**HBR (n = 30)**	**p**
Gender (male/female)	15/15	15/15	
Age (years)	22.43±6.34	24.96±7.93	0.199
Height (cm)	174.78±9.59	172±9.81	0.302
Weight (kg)	71.11±12.90	77.23±20.41	0.196
Follow-up time(months)	8.62±7.32	8.48±7.68	0.950
BMI (Male)	22.19±2.02	23.93±2.75	0.070
BMI (Female)	24.23±2.52	25.53±3.66	0.327

4.2. Patient-Reported Questionnaires

Our study utilized three key patient-reported questionnaires: TAS, IKDC-SKF, and ACL-RSI. The results from these tools provided a comprehensive view of physical function, knee-related symptoms, and psychological readiness for RTS.

TAS: The TAS scores were assessed both preoperatively and at postoperative day (POD) 240, providing insights into changes in activity levels over time. For male participants in the SVR group, the TAS scores decreased from 8 preoperatively to 7 at POD 240. In contrast, the HBR group experienced a greater decline, with scores dropping from 7 preoperatively to 5 at POD 240.

Female participants in the SVR group showed a similar trend, with TAS scores decreasing from 7 preoperatively to 6 at POD 240, while the HBR group decreased from 8 to 6 over the same period. The overall average TAS score in the SVR group was 8 preoperatively, decreasing to 7 at POD 240. The HBR group had an average preoperative TAS score of 8, but it dropped to 6 at POD 240. These findings suggest that both rehabilitation approaches ledto a reduction in TAS scores postoperatively, with the HBR group experiencing a more significant decrease, indicating potentially lower activity levels following surgery compared to the SVR group.

IKDC-SKF: The mean preoperative IKDC-SKF score in the SVR group was 49, compared to 45 in the HBR group, indicating that both groups had similar baseline levels of knee function and symptoms. However, at POD 240, the mean IKDC-SKF score in the SVR group increased to 81.82, while in the HBR group, it was 68.43.

The significant difference between the groups ($p = 0.0021$) suggests that individuals in the SVR group achieved better postoperative knee function compared to those in the HBR group. Despite this, it is worth noting that both groups showed improvement in their IKDC-SKF scores postoperatively, indicating that the rehabilitation process was effective in enhancing knee function for all participants.

ACL-RSI: The mean ACL-RSI score at POD 240 in the HBR group was 55.25 ± 9.72, while in the SVR group, it was 49.46 ± 8.14. The statistically significant difference ($p = 0.0194$) indicates that individuals in the HBR group had higher ACL-RSI scores, suggesting greater psychological readiness to return to sport compared to the SVR group. Unfortunately, preoperative data for ACL-RSI scores was not available, which limits our ability to assess changes in psychological readiness over time.

However, the observed difference at POD 240 suggests that the HBR group felt more confident and emotionally prepared to return to sports activities. This outcome may be attributed to the autonomy and self-reliance inherent in the home-based rehabilitation approach.

Overall, these results indicate that while the SVR group achieved better postoperative knee function as measured by the IKDC-SKF, the HBR group demonstrated greater psychological readiness to RTS as indicated by higher ACL-RSI scores. The differing outcomes underscore the importance of considering both physical and psychological factors in the rehabilitation process after ACLR.

4.3. Comparison of Muscle Strength and Neuromuscular Control Parameters

The comparative evaluation of isometric strength deficits, H/Q (hamstring-to-quadriceps) ratios, isokinetic leg extensions, and hip adductor and abductor force measurements at various knee joint angles provided key insights into the differences between SVR and HBR groups. Additionally, assessments of static and dynamic balance, including stance evaluation and squat analysis, helped identify disparities or similarities between the two groups in terms of neuromuscular control and overall functional stability.

Isometric Quadriceps Strength: At 30 degrees of knee flexion, the isometric strength deficit in the quadriceps between the operated and non-operated limb was 26.1% in the SVR group and 27.9% in the HBR group. While these percentages are close, there was a slightly higher deficit in the HBR group. However, when comparing the actual isometric strength in kilograms, the difference between the operated limbs in the two groups was not statistically significant ($p = 0.077$). The non-operated limbs showed a significant difference in isometric strength ($p = 0.035$), with the SVR group having higher strength (68.957 ± 16.720 kg) compared to the HBR group (57.323 ± 18.257 kg).

At 45 degrees of knee flexion, the quadriceps strength deficit between the operated and non- operated limbs was similar for both groups: 22.3% in the SVR group and 22.1% in the HBR group. Despite this, the actual strength measurements showed no significant differences between the operated limbs ($p = 0.214$), suggesting a consistent level of recovery in both groups.

At 90 degrees of knee flexion, the quadriceps strength deficit was 23.1% in the SVR group and 23.9% in the HBR group, indicating almost identical outcomes in terms of strength deficit.

Overall, these results suggest that the rehabilitation approaches yielded comparable results for quadriceps strength, with minor variations in some specific measurements.

Isometric Hamstrings Strength: For the hamstrings, a different pattern emerged. At 30 degrees of knee flexion, the isometric strength deficit was significantly lower in the SVR group (14.1%) compared to the HBR group (32.2%). This considerable difference indicates that the SVR group's rehabilitation approach might have been more effective in preserving hamstring strength. The actual strength values for the operated limbs also reflected this difference, with the SVR group showing higher strength (21.514 ± 6.237 kg) compared to the HBR group (19.217 ± 6.091 kg), although this was not statistically significant ($p = 0.224$).

At 45 degrees of knee flexion, the hamstrings strength deficit was 12.8% in the SVR group and 47.8% in the HBR group, a marked difference indicating greater hamstrings recovery in the SVR group. This was further corroborated by the significant difference in hamstrings strength between the operated limbs ($p = 0.031$), with the SVR group showing higher strength (20.233 ± 6.684 kg) compared to the HBR group (16.304 ± 4.953 kg). At 90 degrees, the hamstrings strength deficit was 69.7% in the SVR group and 84.9% in the HBR group, indicating that both groups experienced substantial deficits in hamstrings strength, but with the HBR group showing a significantly greater deficit.

H/Q Ratio and Asymmetry: The H/Q ratio, indicating the balance between the hamstrings and quadriceps, showed interesting results. At 30 degrees, the H/Q ratio asymmetry was not statistically significant between the two groups. However, at 45 degrees, the H/Q asymmetry was significantly higher in the HBR group (16.6%) compared to the SVR group (0.8%), suggesting an imbalance in muscle function in the HBR group. At 90 degrees, both groups showed significant H/Q asymmetry (SVR: 37.9%, HBR: 30.5%), indicating that further rehabilitation might be required to correct muscle imbalances.

Isokinetic Leg Extensions and Other Measurements: For isokinetic leg extensions at 240 degrees per second, there were significant differences between the SVR and HBR groups for both operated and non-operated limbs. The SVR group showed significantly higher strength in isokinetic leg extension measurements, indicating that this group achieved better muscle function at this angular velocity, as shown in the Table 2.

Table 2. Comparison of various measured biomechanical data values between SVR and HBR groups. O represents operated, NO non-operated leg. Data is represented by means and standard deviations, asterisk (*) indicates significant difference between SVR and HBR groups ($p<0.05$, independent samples t-test).

Measurement procedure	Group	Mean	SD	p	Effect Size	Power
30.deg Max Isometric Quadriceps Strength (kg) O	SVR	54.614	16.295	0.077		
	HBR	44.810	18.607			
30.deg Max Isometric Quadriceps Strength (kg) NO	SVR	68.957	16.720	0.035*	0.664	0.689
	HBR	57.323	18.257			
30.deg Quadriceps Asymmetry (%)	SVR	21.519	11.708	0.969		
	HBR	21.352	15.479			
30.deg Max Isometric Hamstrings Strength (kg) O	SVR	21.514	6.237	0.224		
	HBR	19.217	6.091			
30.deg Max Isometric Hamstrings Strength (kg) NO	SVR	24.686	6.528	0.730		
	HBR	25.465	8.194			
30.deg Hamstrings Asymmetry (%)	SVR	17.490	10.564	0.042*	0.633	0.662
	HBR	24.970	12.832			
30.deg H/Q Ratio (%) O	SVR	38.462	11.329	0.218		
	HBR	43.979	16.704			
30.deg H/Q Ratio (%) NO	SVR	34.664	7.189	0.018*	0.752	0.782
	HBR	43.412	14.672			

45.deg Max Isometric Quadriceps Strength (kg) O	SVR	58.252	15.364	0.214		
	HBR	51.448	19.344			
45.deg Max Isometric Quadriceps Strength (kg)NO	SVR	71.233	17.792	0.155		
	HBR	62.868	19.986			
45.deg Quadriceps Asymmetry (%)	SVR	21.019	11.199	0.781		
	HBR	19.895	14.650			
45.deg Max Isometric Hamstrings Strength (kg) O	SVR	20.233	6.684	0.031*	0.673	0.691
	HBR	16.304	4.953			
45.deg Max Isometric Hamstrings Strength (kg) NO	SVR	24.233	6.163	0.981		
	HBR	24.183	7.993			
45.deg Hamstrings Asymmetry (%)	SVR	19.967	13.815	0.010*	0.81	0.84
	HBR	31.696	15.057			
45.deg H/Q Ratio (%) O	SVR	34.025	10.749	0.786		
	HBR	33.066	11.922			
45.deg H/Q Ratio (%) NO	SVR	33.790	7.743	0.131		
	HBR	38.528	11.878			
Isokinetic Leg Extension 240./s (Kg) O	SVR	20.850	6.716	0.007*	1.183	0.885
	HBR	13.809	4.781			
Isokinetic Leg Extension 240./s (Kg) NO	SVR	25.114	6.431	0.010*	1.133	0.86
	HBR	17.664	6.763			

Table 3. Comparison of abductor, adductor force, asymmetry, stance and squat weight distribution for the SVR and HBR groups. O represents operated, NO non-operated leg. Data is represented by means and standard deviations, no significant difference was detected between SVR and HBR groups ($p<0.05$, independent samples t-test).

Measurement procedure	Group	Mean	SD	p
Max Isometric Hip Adductors Strength at 60. Knee Flexion (N) O	SVR	379.837	96.169	0.164
	HBR	339.609	89.725	
Max Isometric Hip Adductors Strength at 60. Knee Flexion (N) NO	SVR	387.188	90.290	0.160
	HBR	348.174	88.023	
Hip Adductors Asymmetry (%)	SVR	5.633	3.356	0.956
	HBR	5.694	3.760	
Max Isometric Hip Abductors Strength at 60. Knee Flexion (N) O	SVR	354.967	87.474	0.127
	HBR	315.326	79.593	
Max Isometric Hip Abductors Strength at 60. Knee Flexion (N) NO	SVR	352.650	76.089	0.163
	HBR	318.630	80.340	
Hip Abductors Asymmetry (%)	SVR	7.759	5.368	0.854
	HBR	8.076	5.814	
Hip ABD/ADD Ratio (%) O	SVR	94.480	15.259	0.958
	HBR	94.752	18.359	
Hip ABD/ADD Ratio (%) NO	SVR	92.825	18.038	0.931
	HBR	92.400	13.792	

Stance Evaluation Weight Distribution (%) O	SVR	49.757	3.667	0.408
	HBR	48.870	3.371	
Stance Evaluation Weight Distribution (%) NO	SVR	50.243	3.667	0.408
	HBR	51.130	3.371	
Squat Analysis Average Weight Distribution (%) O	SVR	48.433	2.765	0.961
	HBR	48.395	2.338	
Squat Analysis Average Weight Distribution (%) NO	SVR	51.567	2.765	0.961
	HBR	51.605	2.338	

Table 3 above showed that the static and dynamic balance assessments, including stance evaluation, squat analysis, and hip adductor and abductor force measurements, demonstrated no significant differences between the SVR and HBR groups. These results suggest that both rehabilitation approaches produced similar outcomes in terms of these variables. The power analysis indicated that our study design had achieved satisfactory power levels across the measured endpoints, ensuring that our sample size was adequate to detect meaningful differences if they existed.

4.4. Return to Sport

RTS is a critical outcome measure in assessing the success of ACLR rehabilitation programs. In this study, the rates of RTS varied significantly between SVR and HBR group, as given below:

Return to Same Level of Sport Participation: In the SVR group, 76.6% of participants were able to return to the same level of sport participation they had before their injury. This high percentage suggests that the SVR group's structured and supervised rehabilitation approach may have contributed to a more effective and consistent recovery process, allowing most participants to regain their previous levels of physical performance and competitive ability.

In contrast, the HBR group had a lower rate of RTSat the same level, with only 53.3% of participants achieving this outcome. This lower percentage could indicate that the home-based approach, which relies on less frequent supervision and greater individual discipline, may lead to varied adherence and potentially less consistent rehabilitation outcomes. The reduced rate of returning to the same level of sport in the HBR group suggests that some participants may have faced challenges in reaching their pre-injury performance levels.

Return to a Lower Level of Sport Participation: Regarding participants who returned to a lower level of sport participation, the outcomes differed between the two groups. In the SVR group, 16.6% of individuals returned to a lower level of sport, possibly indicating that they were either unable or chose not to pursue their original sport intensity or competition level. This reduction could be due to factors like ongoing knee issues, personal preference, or a more cautious approach to physical activity. In the HBR group, 30% of participants returned to a lower level of sport, almost double the rate observed in the SVR group. This higher percentage could suggest that individuals in the HBR group might have experienced more significant challenges in rehabilitation, leading to a more conservative return to sport.

No Return to Sport: For those who did not return to any sport activities, the SVR group had a lower rate, with only 6.6% of participants not returning to sports. In contrast, the HBR group had a higher rate, with 16.6% of participants not resuming any sports-related activities. This discrepancy indicates that the lack of supervision and guidance in the HBR group could contribute to lower confidence or increased risk of re-injury, leading some participants to avoid sports altogether.

Statistical Significance: The observed disparities in sport participation levels between the two groups are statistically significant, as confirmed by a Chi-Square test contingency table ($p = 0.036$) as indicated in the Table 4. This result indicates that the differences in RTS outcomes between the SVR and HBR groups are unlikely to be due to random variation, highlighting the potential benefits of supervised rehabilitation.

Table 4. Number of individuals returning to sport for the SVR and HBR groups respectively. The table describes numbers and percentages of RTS to difference levels as reported in both the rehabilitation groups.

RTS	**SVR Group**	**HBR Group**
Same level	23 (76.6 %)	16 (53.3 %)
Lower level	5 (16.6 %)	9 (30 %)
No return	2 (6.6 %)	5 (16.6 %)

Overall, these findings suggest that the structured approach in the SVR group leads to higher rates of returning to the same level of sport, with fewer participants not returning to sports at all. The HBR group, with its greater flexibility and autonomy, may face more challenges in achieving comparable RTS outcomes, with more individuals returning to a lower level of sport or avoiding sports activities altogether.

4.5. ACL Re-Injury

Assessing the re-injury rates after primary ACLR requires a nuanced approach, distinguishing between re-injury to the previously operated knee and new injuries, especially those involving the contralateral knee.

Re-Injury to the Operated Knee: In this study, both the SVR and HBR groups had an overall re-injury rate of 3.3% for the operated knee. This rate indicates that, regardless of the rehabilitation approach, a small percentage of participants experienced complications or setbacks leading to re-injury. Such occurrences could stem from several factors, including inadequate healing, improper rehabilitation techniques, or premature return to high-intensity sports activities.

Contralateral ACL Injury Rate: Contralateral ACL injuries, which refer to injuries occurring on the opposite knee from the operated one, represent another area of concern. While the re- injury rate to the previously operated knee was 3.3% in both groups, the rate of contralateral ACL injury was higher, with the SVR group experiencing a rate of 6.6% compared to 3.3% in the HBR group. This discrepancy raises questions about factors contributing to contralateral injuries, such as altered biomechanics, compensation for the operated knee, or a lack of balanced rehabilitation targeting both legs.

Implications and Considerations: The overall re-injury rate of 3.3% for the operated knee in both the SVR and HBR groups suggests that re-injury is relatively rare but not negligible. It also emphasizes the need for continued monitoring and caution, even after participants are cleared to return to sports activities. The differing rates of contralateral ACL injuries between the SVR and HBR groups indicate that rehabilitation programs should address the potential risks associated with contralateral compensation. Rehabilitation strategies may need to include exercises targeting both knees to reduce the likelihood of contralateral injuries.

5. Discussion

A recent systematic review indicated that prior studies did not demonstrate significant differences in outcomes between SVR and HBR (64). Some studies suggest that HBR offers better recovery outcomes after ACLR compared to SVR (16). However, other studies indicate that there is no significant difference between the two approaches (65). The literature also points out that high compliance with SVR can lead to improved knee function and a greater likelihood of RTS within one year of ACLR (36). A recent study found that SVR offers additional benefits over HBR, such as increased muscle strength, improved neuromuscular control, and higher self- reported knee function scores (66).

These varying outcomes can be attributed to several factors, notably the inadequate assessment of patient-reported outcomes and the limited focus on competitive athletes. Our study aimed to address this gap by comparing outcomes in competitive athletes following ACLR, with a deliberate focus on both biomechanical and psychological measures. By examining these outcomes, we gained key insights into the effectiveness of different rehabilitation approaches.

Gender-Balanced Allocation: A notable aspect of our study was the deliberate gender-balanced allocation, which was designed to enhance robustness and minimize gender-related biases. Although this approach may not directly align with the demographic trends in ACL injury, it supports a more comprehensive assessment by creating a representative cohort (19). The baseline characteristics of age, height, weight, and follow-up time were comparable across both rehabilitation groups, reinforcing the importance of homogeneous cohorts for accurate evaluation (9,19,21).

While our study included both male and female participants, the initial analysis lacked detailed gender-specific insights. Given the importance of understanding gender influences in ACL rehabilitation, future research should delve deeper into the underlying mechanisms to identify targeted interventions that can address any gender-related disparities. By exploring these aspects, researchers can refine rehabilitation strategies to better support both male and female athletes.

Postoperative Activity Levels: Our results showed a reduction in TAS scores postoperatively for both rehabilitation groups, aligning with the literature, which suggests that rehabilitation generally results in lower activity levels after surgery (9,19).

However, the average postoperative TAS score in the HBR group was slightly lower than in the SVR group. This trend supports findings indicating variations in activity scale outcomes based on rehabilitation methods (11), prompting further exploration into factors influencing postoperative activity levels and the need for tailored rehabilitation approaches.

Knee Function and Psychological Readiness: While the improvement in IKDC-SKF scores postoperatively for both rehabilitation groups concurs with previous studies (19), our results revealed that the SVR group exhibited superior outcomes in this regard. This outcome may be due to the structured and closely monitored nature of SVR, likely resulting in better adherence to the rehabilitation protocol and a more consistent recovery trajectory. On the other hand, HBR participants showed greater psychological readiness to RTS, possibly due to differences in patient perceptions, coping mechanisms, resilience, and reduced fear of re-injury. These findings suggest that addressing psychological factors during rehabilitation is crucial for optimizing outcomes (54,60,67).

Incorporating consultations with sports psychologists and using interventions targeting psychological factors could further improve the rehabilitation process and enhance RTS readiness post-ACLR (55,68). Although psychological responses generally improve during rehabilitation, in some cases, fear of re-injury may increase, becoming a significant risk factor when resuming sports activities (56). It's important to note that successful RTS is not solely dependent on postoperative knee function (69). Individuals with lower levels of optimism might particularly benefit from targeted interventions aimed at enhancing psychological readiness for return to sport (70).

Muscle Strength Imbalances: Muscle strength imbalances are of particular concern following ACLR. Our study assessed muscle strength at knee flexion angles of 30°, 45°, and 90°, chosen for their biomechanical relevance during functional activities. This approach aligns with existing literature and provides insights into muscle performance critical for knee stability. Significant differences in dynamometric values favouring the SVR group suggest that supervised programs may be more effective in achieving balanced muscle strength and symmetry (11). Future research should explore the underlying mechanisms contributing to observed imbalances, especially H/Q asymmetry, to optimize rehabilitation strategies for improved muscle balance.

RTS and Re-Injury Rates: The significant divergence in RTS percentages between the rehabilitation groups echoes existing literature emphasizing the impact of rehabilitation methods on these outcomes (9,21). Our study's re-injury rate of 3.3% is consistent with literature that underscores the importance of considering different types of injuries (50).

The observed contralateral ACL injury rates suggest that while the overall re-injury rate is consistent across groups, the distribution of injuries varies, highlighting the need for comprehensive rehabilitation to prevent contralateral injuries. Monitoring re-injury rates 5-6 months after resuming sports activities provided valuable insights into the effectiveness of rehabilitation protocols in preventing further injuries. These time points are crucial in assessing recovery milestones and the associated risks of RTS. Achieving successful ACL restoration involves unrestricted sports participation and a return to pre-injury levels, underscoring the significance of addressing the fear of re-injury (71).

SVR Advantages: SVR offers advantages for athletes, providing more challenging training and promoting the development of sport-specific skills and confidence, especially in the later phases of rehabilitation (36). The selected time periods in this study, with comprehensive assessments at 8 months' post-operation and evaluations for return to sport at 9 months' post-operation, were designed to capture key aspects of recovery.

Future Directions: Optimizing recovery after ACLR requires comprehensive rehabilitation plans that prioritize muscle strength restoration and functional status in both the reconstructed and unaffected limbs (72). Criterion-based rehabilitation programs are essential to enable effective recovery and allow athletes to achieve their RTS goals while mitigating the risk of re- injury (33,39). Furthermore, rehabilitation programs should focus on improving subjective knee function and psychological readiness (22). To ensure safe and effective return to sport, ongoing communication among the injured athlete, coach, physician, and physiotherapist is critical (52). Ultimately, to achieve optimal recovery outcomes for competitive athletes, prioritizing psychological readiness and addressing muscle imbalances are crucial. Future studies should continue to explore the interplay between physical and psychological aspects of rehabilitation to refine strategies that support athletes' successful return to sport.

5.1. Limitations

While our study provides valuable insights into post-ACLR rehabilitation strategies, few limitations could impact the generalizability and robustness of our findings.
Firstly, we chose not to conduct a gender-specific analysis due to the resulting reduction in sample sizes. While an equal gender distribution was desirable, this choice restricts our ability to identify potential differences in rehabilitation outcomes between male and female athletes. As there is evidence suggesting that gender may influence ACL injury recovery, this limitation emphasizes the need for future studies with larger sample sizes, allowing for robust gender- specific analyses.

Secondly, we did not adjust our results for multiple comparisons, such as using Bonferroni correction. This methodological choice, made to aid interpretability, could increase the risk of Type I errors (false positives), potentially affecting the robustness of our conclusions. Recognizing this, we present our study as a pilot, forming the basis for more extensive investigations with larger datasets and a more rigorous approach to statistical analysis, including adjustments for multiple comparisons.

Additionally, our study employed biomechanical measurement tools that are not universally acknowledged as industry standards. While our objective was to compare various samples within our own study framework, the use of simpler equipment could be considered a limitation when aiming for broader comparison with other studies. Given the focus of our study, we believed the equipment used was sufficiently accurate to meet our objectives. However, future research might benefit from using universally recognized devices, like isokinetic dynamometers, to enhance comparability and ensure that results align with broader datasets.

These limitations suggest that future studies should adopt a more extensive approach, involving gender-specific analyses, and rigorous statistical corrections, along with industry-standard measurement tools. By addressing these limitations, subsequent research will be better positioned to validate our findings and contribute to the development of comprehensive post-ACLR rehabilitation strategies.

5.2. Strengths of the Study

The following strengths underscore the quality and rigor of our study:

- *Focus on High-Level Athletes:* The study specifically evaluated competitive athletes, providing insights into rehabilitation outcomes for individuals who must perform at a high level. This focus makes our findings particularly relevant to elite sports and high-performance rehabilitation.
- *Uniform Surgical Approach:* The use of a consistent surgical technique throughout the study is a significant strength. This uniformity reduces variability in surgical outcomes, allowing for a more accurate comparison between different rehabilitation approaches.
- *Advanced Biomechanical Instruments:* Our study employed state-of-the-art biomechanical instruments for patient evaluation, ensuring accurate and reliable measurements. These instruments meet internationally accepted standards, contributing to the validity and credibility of our results.
- *Inclusion of Psychological Evaluation:* By incorporating a psychological component into our evaluation process, we expanded the scope of the study beyond physical recovery. This addition provides a more holistic view of rehabilitation, recognizing the importance of psychological factors in successful recovery and return tosport.

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5.3. New Findings from the Study

Our study offers several new insights and contributions to the field of athletic rehabilitation post-ACLR. The following points highlight these findings:

- *Use of Psychological Readiness Score:* The inclusion of a psychological readiness score in our evaluation is a novel aspect of this study. This metric, which had not been previously used in athletic evaluations in Hungary, provides a new perspective on assessing athletes' mental preparedness for RTS.
- *Importance of Strengthening Hamstring Muscles:* Our study emphasizes the need to strengthen hamstring muscles, in addition to focusing on quadriceps muscle development. Achieving an optimal H/Q ratio is crucial for preventing re-injury and ensuring a successful RTS. This finding suggests that future research should give more attention to hamstring strengthening in rehabilitation protocols.
- *Extended Clinical Assessments:* The study demonstrates that clinical assessments in a hospital setting alone are insufficient to determine an athlete's readiness to return to sports. Instead, objective evaluations in a biomechanics lab are essential, particularly for competitive athletes. This underscores the importance of comprehensive performance-based assessments to ensure a safe and effective RTS.
- *Improved Test Battery and Rehabilitation Protocol:* Our study introduces an enhanced test battery for athletic evaluation post-ACLR, providing a more robust method for assessing recovery and readiness to return to sports. Additionally, the recommended criterion-based rehabilitation protocol, developed as part of this study,can serve as a valuable framework for future rehabilitation programs.

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6. Conclusions

Our study compared two rehabilitation approaches for competitive athletes after ACLR: SVR and HBR. The results showed that both approaches produced comparable outcomes in terms of functional recovery and RTS. However, athletes in the SVR group reported better patient- reported outcomes, suggesting that this approach could offer additional benefits, such as a comparable rate of return to their previous level of sport.

Despite these advantages, the re-injury rates for both SVR and HBR groups were similar. This might be because the SVR group did not show significant progress in psychological recovery, especially around eight months after ACLR. This observation suggests that a lack of comprehensive psychological support might contribute to the comparable re-injury rates, indicating that enhanced psychological support could be essential to reducing re-injury risks.

To ensure a successful RTS and reduce the chances of re-injury in competitive athletes, rehabilitation programs should be criterion-based, focusing on both physical recovery and psychological readiness. Criterion-based programs set clear milestones that athletes must meet to progress in their recovery, ensuring a structured and safe approach. Including ongoing psychological support, supervised by a physiotherapist, can help athletes regain confidence and resilience during the recovery process.

While our study provides insights into the comparative effectiveness of different rehabilitation approaches for competitive athletes post-ACLR, further research is required to validate these findings and determine the best rehabilitation strategies that support both physical and psychological recovery.

Future studies should use larger sample sizes, focus on narrower age ranges, and include long-term follow-up to better evaluate the effectiveness of rehabilitation in preventing re-injury after ACLR. Additionally, more comprehensive psychological assessments, beyond tools like the ACL-RSI, are needed to better understand the psychological factors in rehabilitation.

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7. Summary

This study underscores the importance of post-surgical rehabilitation for competitive athletes with ACL injuries who undergo ACLR. To maximize surgical and post-surgical outcomes, structured pre-surgical rehabilitation is essential. A comprehensive, criteria-based rehabilitation program should be developed to guide athletes through both pre- and post-surgical rehabilitation, ensuring they can safely return to their pre-injury level of sports without complications or re-injuries.

Rehabilitation programs should focus on several key areas. First, they should aim to restore muscle strength and minimize neuromuscular deficits, with the goal of achieving a less than 10% strength deficit in the operated leg compared to the non-operated leg. This involves building muscle strength and squat ability above 90% on the operated side.

Additionally, rehabilitation should work on improving static balance and gait symmetry in dynamic sports activities. It's also important to address psychological readiness for sports participation, as lack of motivation and poor psychological preparedness can negatively affect recovery. Rehabilitation programs should consider individual physical and psychosocial attributes for both male and female participants.

To determine when athletes can safely RTS, objective biomechanical tests and a comprehensive evaluation of physiological and psychological factors should be used. A test battery for athletes recovering from ACLR is recommended, incorporating various assessments. Muscle strength measurements, both isometric and isokinetic, should indicate a maximum strength deficit of less than 10% between the operated and non-operated sides. Balance and stability should be assessed through anteroposterior and mediolateral stability tests, with the dispersion in the results not exceeding 2mm.

Squat analysis, both unilateral and bilateral, using force plates should show a mean squat strength deficit of less than 5% for safe RTS. Gait symmetry should be analysed on a treadmill, with a mean load symmetry difference between 3-5%. Psychological readiness should also be evaluated, with a minimum score of 80% on the ACL-RSI subjective evaluation form at least six months post-ACLR.

A criteria-based rehabilitation program for ACL-injured athletes is divided into several distinct phases, each with specific goals for effective recovery. The first phase, "Prehabilitation," focuses on regaining painless full range of motion, optimizing muscular strength, and preventing episodes of knee instability.

The second phase, "Acute Recovery," starts from the day of surgery and lasts about six weeks, concentrating on wound healing, minimizing swelling, restoring joint mobility, and establishing muscular control. The third phase, "Strength and Coordination," aims to build muscle control, balance, and proprioception, introducing strength work and dynamic exercises. The fourth phase, "Proprioception and Agility," emphasizes running and jumping skills, as well as advanced strength training and agility exercises. The fifth phase, "Sports-Specific Skills," seeks to perfect jumping, landing, and abrupt direction changes, with sports-specific training tailored to different sports.

Return to competitive sports typically begins around nine months' post-op and focuses on achieving over 90% on patient-reported outcome scores, as well as muscle strength, while also meeting all other physical and psychological criteria.

For successful rehabilitation, additional recommendations include focusing on individual needs and sports-specific skills, with equal attention to male and female athletes' attributes. Consistent monitoring by supervising physiotherapists and effective communication among surgeons, physiotherapists, and athletes is crucial. Proper dissemination of information to patients is the key for informed decision-making and adherence to treatment plans. By following these recommendations, athletes can safely navigate the recovery process and return to their sports with confidence and reduced risk of re-injury.

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9. Bibliography of the Candidate's Publications

9.1. List of original publications related to the PhD thesis

1. **Syed Rehan Iftikhar Bukhari**, Hangody László Rudolf, Frischmann Gergely, Kós Petra, Kopper Bence, Berkes István Comparative Effectiveness of Supervised and Home-Based Rehabilitation after Anterior Cruciate Ligament Reconstruction in Competitive Athletes JOURNAL OF CLINICAL MEDICINE 13: 8 Paper: 2245, 14 p. (2024) Article (Journal Article) | Scientific Scopus - Medicine (miscellaneous) Rank: Q1
2. Hangody László Rudolf, Gál Tamás, Vásárhelyi Gábor, Hangody György, **Iftikhar Bukhari Syed Rehan**, Hangody László Results of ultra-fresh osteochondral allograft transplantation for large cartilage defects in the knee joint JOINT DISEASES AND RELATED SURGERY 33: 3 pp. 521-530. (2022) Article (Journal Article) | Scientific Scopus - Rehabilitation Rank: Q2 Scopus - Surgery Rank: Q2 Scopus - Orthopedics and Sports Medicine Rank: Q3

9.2. List of original publications not related to the PhD thesis

1. **Syed Rehan Iftikhar Bukhari**, Syed Shakil-ur-Rehamn, Shakeel Ahmad, Aamer Naeem Comparison between effectiveness of mechanical and manual traction combined with mobilization and exercise therapy in patients with Cervical Radiculopathy PAKISTAN JOURNAL OF MEDICAL SCIENCES 32: 1 pp. 31-34. (2016) Article (Journal Article) | Scientific
2. Aczél Dóra, György Bernadett, Bakonyi Péter, **Bukhari Rehan**, Pinho Ricardo, Boldogh István, Yaodong Gu, Radák Zsolt The Systemic Effects of Exercise on the Systemic Effects of Alzheimer's Disease ANTIOXIDANTS 11: 5 Paper: 1028, 16 p. (2022) Survey paper (Journal Article) | Scientific
3. Torma Ferenc, Bakonyi Péter, Regdon Zsolt, Gombos Zoltán, Jókai Mátyás, Babszki Gergely, Fridvalszki Marcell, Virág László, Naito Hisashi, **Iftikhar Bukhari Syed Rehan**, Radák Zsolt Blood flow restriction during the resting periods of high-intensity resistance training does not alter performance but decreases MIR-1 and MIR-133A levels in human skeletal muscle SPORTS MEDICINE AND HEALTH SCIENCE 3: 1 pp. 40-45. (2021) Article (Journal Article) | Scientific

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