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Original Article

Comparison between the effect of immersive virtual reality training versus conventional rehabilitation on limb loading and functional outcomes in patients after anterior cruciate ligament reconstruction: A prospective randomized controlled trial

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A B S T R A C T

Purpose: Anterior cruciate ligament injury (ACL) commonly occurs during sporting events. It causes pain, instability and reduction in range of movement of the knee which results in altered balance, reduced strength as well as loading to the involved knee. The challenge to get the patient back to competitive sports level much depends on the rehabilitation process. Post ACLR rehabilitation is challenging due to the long rehabilitation time as well as boring repetitive exercises. The aim of this study is to compare between the effectiveness of using immersive virtual reality (PlayStation VR) in addition to the conventional rehabilitation as an aid in rehabilitation of patients after ACLR in terms of objective functional assessment and pain and subjective knee function scoring.

Methods: This randomised controlled trial was undertaken in a tertiary hospital in Malaysia from July 2019 until July 2020. Thirty patients were randomised into a group undergoing purely conventional rehabilitation (Group 1) and a group undergoing both conventional rehabilitation and immersive virtual reality assisted rehabilitation (Group 2). The immersive virtual reality assisted rehabilitation was started at 3 months post operatively for 3 months duration. Limb loading, balance, range of motion, functional hop tests of the knee, pain and subjective scoring of the knee with the International Knee Documentation Committee (IKDC) Scores were measured preoperatively and at 6 months.

Results: There were significant differences in terms of improvement of pain scores ($p = 0.012$) as well as IKDC Scores ($p = 0.024$) in Group 2 as compared to Group 1. However, there were no significant differences with regards to limb loading, balance, range of motion and functional hop tests of the knee ($p > 0.05$). No adverse events were observed during the study period.

Conclusion: Immersive virtual reality can be used as an adjunct in rehabilitation of patients after ACL reconstruction in terms of improving their pain as well as their subjective knee evaluation. Large randomised control trial is recommended to further investigate the efficacy.

1. Introduction

Injury to the anterior cruciate ligament (ACL) is a common occurrence during sporting events.[1] The annual incidence of ACL injuries internationally is at 68.6 per 100,000 athletes and,[1,2] in the

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United States of America, approximately 200,000 ACL reconstructions are undertaken in a year.[2,3] It has been reported that 40% of patients who undergo ACL injury fail to attain their pre-injury sports levels.[4,5] The cost of anterior cruciate ligament reconstruction (ACLR) surgeries coupled with the rehabilitation programmes amounts to US$1 billion dollars.[6]

The ACL is commonly injured or torn during non-contact sports which involves pivoting or rotation of the knee.[7] The ACL functions as a primary restraint to anterior tibial translation, which in turn provides stability to the knee.[8] An injury to the ACL results in pain, instability to the affected knee joint as well as reduction in range of movement.[9] These result in altered balance, reduced strength as well as asymmetrical loading to the involved knee, thus compromising the athlete's ability to perform the sporting or recreational activities to their utmost capabilities.[9–11]

A successful ACLR aim to return the patients back to their pre-injury sports activity level, which emphasizes on the importance of the rehabilitation. Rehabilitation protocols which were based on time from surgery has since been replaced by criteria-based protocols, whereby progression of a patient was decided only after selected criteria were met.[12] The programs are more individualised and in an ordered sequence of activities. Yet, the rehabilitation of ACLR is still a long and time-consuming process as the time to return to sport usually takes around 6–9 months from the time of surgery.[13]

Currently there is no standard agreed algorithm on the rehabilitation of patients post ACLR.[14] ACL-reconstructed athletes often express frustration that the rehabilitation process is much slower than expected. This reduces their compliance to the rehabilitation regime, and some have even given up.[15,16] A poor rehabilitation post ACLR surgery often leads to asymmetries in the kinematics of the knee, which is a hurdle in regaining full sporting capabilities.[17] Guy Simoneau et al. states that the current post-operative ACLR regimes may not be optimal in addressing asymmetries of the limb in terms of loading and strength, resulting in failure and reinjury rates as high as 24%.[17]

Virtual Reality (VR) has emerged as a new rehabilitation strategy in many medical fields.[18] The premise of immersive VR is the creation of a virtual environment in which the patient can interact with.[18] Immersive VR is a computer-generated simulation of a 3D image or an environment that can be interacted with.[19] VR has been used in stroke patients to learn basic activities of daily living and in children with cerebral palsy learning to walk.[20–23] Guy Baltaci conducted a randomised controlled trial which compared the effectiveness of rehabilitation using a non-immersive VR setup by using Nintendo Wii Fit board vs conventional rehabilitation and found no significant differences in terms of muscle power and dynamic balance between the two groups.[14]

Another study by Alli Gokeler showed that embedding patients after ACLR into VR changes their movement patterns approximating healthy subjects and that VR may enhance motor learning capabilities and aid in reducing risk factors for second ACL injury.[21] By using this immersive virtual therapy, the clinician can take the patient away from the conventional rehabilitation set-up to a more exciting and invigorating environment. By interacting with the virtual world, the subjects will attain a sense of excitement and motivation even when it comes to boring repetitive tasks.

There is a pertinent need for a newer, much more interesting technique or aid in rehabilitation of patients post ACLR surgery. Development of a more engaging and effective rehabilitation programme will help to address any of the deficiencies and problems encountered during conventional rehabilitation.

The aim of the study was to determine the effectiveness of rehabilitation post ACLR by using immersive VR as an adjunct to conventional rehabilitation in comparison to using conventional rehabilitation alone. The clinical and functional outcomes of the patients in terms of limb loading, balance as well as the knee function were assessed, together with subjective knee function scoring and pain. Despite few studies on using VR in post ACLR rehabilitation, this is the first randomised controlled trial of adding immersive VR using PlayStation-VR as an adjunct to conventional rehabilitation in rehabilitation of patients after post-ACL repair. We hypothesize that there will be improvement in objective functional outcomes, pain score and knee function scoring with the adjunct immersive VR assisted rehabilitation.

2. Materials and methods

This was a single centre randomised controlled trial, carried out in a tertiary hospital in Malaysia from June 1, 2019 until 31st of October 2020 after obtaining ethical approval (PPI.800–1/1/5/JEP-2019-274) from the local ethical board. Patients who had undergone unilateral ACLR who consented were included in the study. Patients with associated posterior cruciate ligament injury to the same knee, patients with significant medical comorbidities such as deaf, epilepsy, underlying surgical site infection, inflammatory arthritis and neuromuscular disorders were excluded from the study.

Sample size calculation was done based on the following equation and software provided by www.openepi.com, based on study by Gokeler et al.,[21] a sample size of 30 patients was required (CI 95%).

The sample size formulae used are as follows:

$$n_1 = \frac{(\sigma_1^2 + \sigma_2^2 / \kappa)(z_{1-\alpha/2} + z_{1-\beta})^2}{\Delta^2}$$

$$n_2 = \frac{(\kappa * \sigma_1^2 + \sigma_2^2)(z_{1-\alpha/2} + z_{1-\beta})^2}{\Delta^2}$$

The notation for the formulae are:
n_1 = sample size of Group 1
n_2 = sample size of Group 2
σ_1 = standard deviation of Group 1
σ_2 = standard deviation of Group 2
Δ = difference in group means
κ = ratio = n_2/n_1
$Z_{1-\alpha/2}$ = two-sided Z value (eg. Z=1.96 for 95% confidence interval).
$Z_{1-\beta}$ = power

Input Data

Confidence Interval (2-sided)	95%		
Power	80%		
Ratio of sample size (Group 2/Group 1)	1		
	Group 1	**Group 2**	**Difference***
Mean	1.5	0.4	1.1
Standard deviation	1.5	0.2	
Variance	2.25	0.04	
Sample size of Group 1	15		
Sample size of Group 2	15		
Total sample size	30		

*Difference between the means

Results from OpenEpi, Version 3, open source calculator--SSMean

The selected patients were divided randomly using a computer-generated randomization (www.randomizer.org) into 2 groups. Patients in group 1 were assigned for conventional rehabilitation, whilst patients in group 2 were assigned for combined VR assisted rehabilitation and conventional rehabilitation (Fig. 1).

2.1. Group 1

For the first 6 weeks after surgery, the aim of the exercises was to regain early motion of the knee.[12] This included active-assisted range of motion exercises of the knee, done during weekly follow up. This was supplemented with closed kinetic chain flexion exercises, prone hanging exercises as well as isometric quadriceps exercises, straight leg raising exercises, and passive leg extension exercises. Two to three sets a day was advised to be done at home after patients were taught the right technique by physiotherapists. These exercises were aimed to achieve a full extension of the knee which was crucial criteria to meet in order to wean the patient off crutches post operatively.[12] Subsequently, patients were allowed as much weight-bearing as tolerated.

Aggressive exercises were avoided in the early periods. At 2–6 weeks, patients were allowed protected weight-bearing with crutches. Passive knee extension exercises were started and supplemented with isometric quadriceps strengthening and straight leg raising exercises. After 6–8 weeks, patients were started on progressive resistive knee flexion and extension exercises. Single leg balance exercises were started once the subject were able to fully weight bear around 4–6 weeks. At the same time, the patients were started on cycling to increase the hamstring and quadriceps contractions and coordination. After 12 weeks, additional jogging activities were allowed. The progression of the patient through each stage was individualised. At 6 months, the clinical and functional outcomes were assessed. (Fig. 2).

2.2. Group 2

The patients who were assigned into this group underwent a combination of conventional rehabilitation and VR rehabilitation. During the first 3 months, the patients underwent a conventional rehabilitation as per protocol similar to group 1. The VR assisted rehabilitation began at 3 months post-operative as this was the cut off time where the patients were expected to achieve normal gait with full range of knee movement and sufficient muscles strength.[24] By this time, the graft would be to withstand the higher loading forces for advancement of the rehabilitation. In the VR rehabilitation session, the patients were fitted with the PlayStation Virtual Reality (PSVR) headgear and were given two handheld motion controllers by which the patients were taken into the virtual world where they were to partake in pre-selected games.

The games were chosen based on discussions with experts in the field of sports rehabilitation to mimic as close as possible to a conventional rehabilitation regime which involved training like jogging, agility, proprioception and perturbation. The games were *i) Headmaster 3.0 ii) Dream Match Tennis iii) Beat Saber for PSVR iv) Knockout League v) Hoops vi) Richie's Plank Experience vii) Pong It VR viii) Egg Time VR ix) Sparc VR.* Each patient underwent a 30-min session once every 2 weeks. Patients in this group continued to do two to three sets a day twice a day exercise regime as in group 1 in addition to VR rehabilitation once in 2 weeks. Outcome measurement were done at pre and 6 months post-surgery.

Compliance of the patients to the conventional rehabilitation program were assessed during their follow up sessions and phone call review. Attendance of the Group 2 patients to the VR session were also recorded.

2.3. Testing procedure

Limb loading, balance of the patient and knee functional tests such as range of motion and hop test for strength were measured pre-operatively and after completion of the training programme at six months. At the end of six months, patient's subjective knee evaluation via the International Knee Documentation Committee Score (IKDC) and pain score were also evaluated.[12,25] Six months is often reported as the time to progress to sports specific drills.[13,26]

2.4. Limb loading

Asymmetrical limb loading may be present post ACLR,[27] which may lead to deleterious consequences in the short-term, such as an increase of the risk for reinjury, and in the long-term, with the development of knee osteoarthritis. Asymmetrical lower limb loading is traditionally measured using the Limb Symmetry Index (LSI), calculated as (LSI = [surgical side/non-surgical side] x 100).[26] A LSI of <90%, i.e. more than 10% difference between limbs following ACL injury and reconstruction, has been regarded as unsatisfactory for both strength and hop performance.[16,28]

In our study however, we used a weighing monitor, the Lower Limb Weighing Device developed by Corstein Technologies Malaysia, that accurately measured the limb loading of the lower extremity. This monitor used a mathematical model, the Modified Symmetry Index, to quantitively measure the limb load asymmetry.[29] The patient stood on the lower limb weighing monitor as one would with any weighing scale. Data from the lower limb weighing device was then recorded via software and presented as percentage of loading. A ten percent difference between both limbs indicates a more asymmetrical lower limb loading.

2.5. Dynamic balance testing

Achieving a balance of both lower limbs is an integral part in post ACLR. Even with a successful surgery, failure to attain proper balance in the knees may result in poor outcomes.[30] In our trial, the modified Star Excursion Balance Test (SEBT) was used to assess the balance between the operated knee and the healthy knee.[25,31]

The patients were to stand on one leg in the center of a grid, with the distal aspect of their great toe at the starting point. While maintaining a single-leg stance, the patient was then asked to reach out with the free leg as far out as possible in three directions which were anterior, posteromedial and posterolateral directions. The furthest reach attained by the limb was recorded in centimeters. This was then repeated with the contralateral leg and average scores calculated. The difference between the operated and non-operated limb was then recorded.

2.6. Range of motion of the knee

Presence of an extension lag resulted in abnormal joint kinematics and leads on abnormal cartilage loading.[12] To measure the range of motion of the knee, the patient was asked to lie supine. A goniometer was placed on the lateral aspect of the knee that was to be measured. The fulcrum was aligned to the lateral epicondyle of the femur.

The proximal arm was kept in line with the greater trochanter of the femur and the distal arm in line with the lateral malleolus. A measurement was then taken in full extension. Next the patient flexed the knee maximally and the goniometer was kept steady along the axis following the flexion. Measurement at full flexion was then taken. This is a recognised method of measuring the range of motion of the knee.[32]

2.7. Functional hop test

Hop tests are routinely used as a measure of the knee function after ACLR.[28] There is a multitude of leg hop test to measure the function of the lower limbs. To improve the accuracy and reliability of the hop tests, Gustavsson et al. proposed a test battery of 3 hop

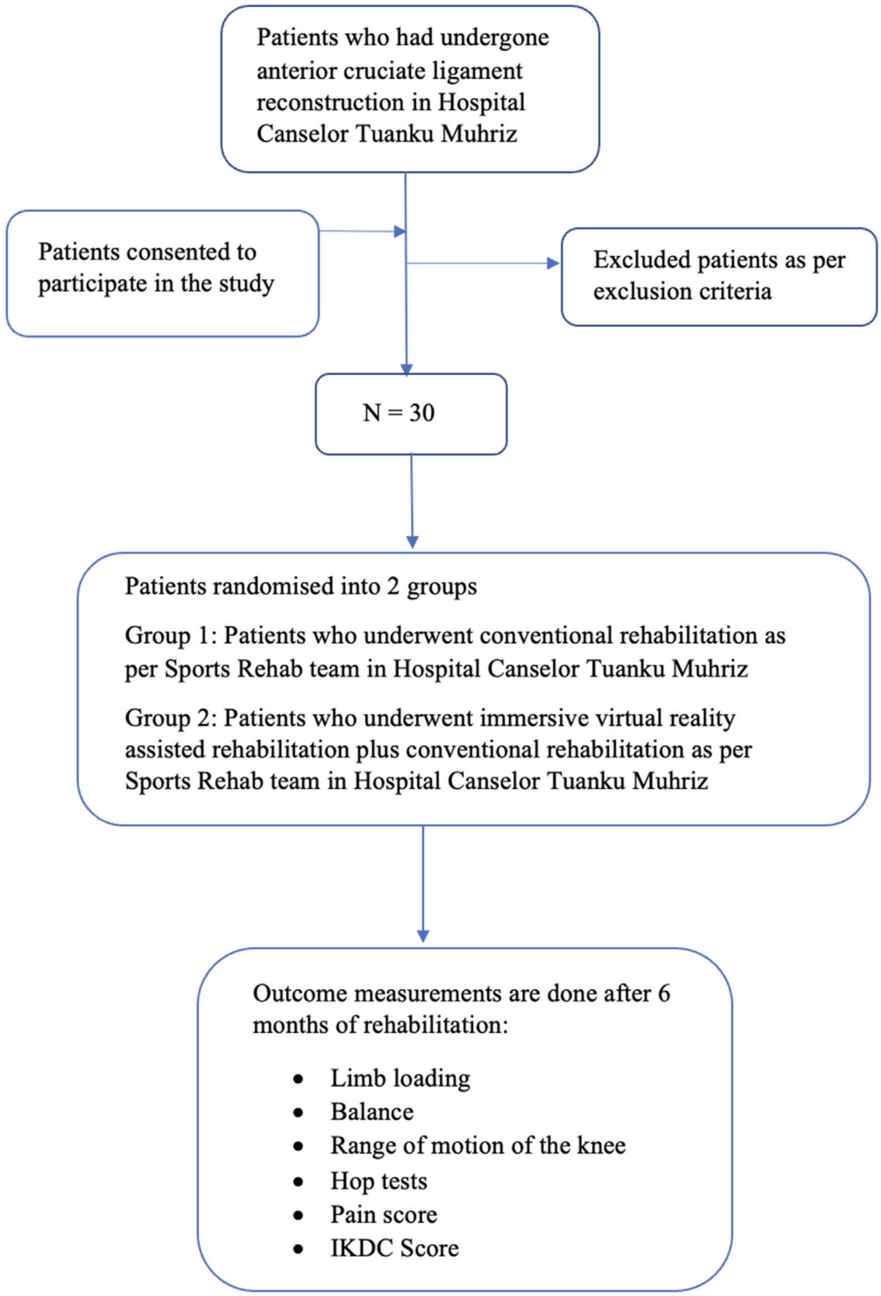

Fig. 1. Flow Chart of patients enrolled in the study.
Detailed legend: Fig. 1 describes the inclusion criteria and grouping of patients enrolled in the study. The inclusion criteria included patients who had undergone unilateral ACLR who consented to enter this study, while the exclusion criteria were patients with any associated posterior cruciate ligament injury to the same knee, patients with significant medical comorbidities or deaf patients, patients with epilepsy, patients having infection to operated knee, patients with inflammatory arthritis, and patients with neuromuscular impairment. As such, thirty consented patients who fulfilled the inclusion and exclusion criteria were included in the study. The selected patients were then divided randomly using a web-based randomization into 2 groups, one group (Group 1) who underwent conventional rehabilitation, whilst the second group (Group 2) underwent VR assisted rehabilitation together with conventional rehabilitation. Outcome measurements in terms of limb loading, dynamic balance, range of motion of the knee, hop tests, pain score, and IKDC score were carried out after 6 months of rehabilitation.

tests, *i) Single leg hop test ii) Vertical jump and iii) Side to side hop.*[28,33]

In the single leg hop test, the patient started by standing on the single leg. The patient was then asked to hop forwards as far as possible, landing on the same limb maintaining for 2 s. The distance of the jump was measured in centimeters.

In performing the vertical jump, the patient was to stand on one knee with their hands placed at the hips against a scaled backdrop. The patient then flexed the knee as much as desired and attempted to jump as high as possible. Measurement was obtained through the scaled backdrop. The height achieved was recorded in centimeters.

In measurement of the side to side hop, the patient stood on one limb, with their hands behind their back. Next, they were required to jump from side to side across two parallel strips of tape on the ground, 40 cm apart. The patient had to jump as many times as possible in a period of 30 s. Number of successful jumps not touching the tape was recorded.

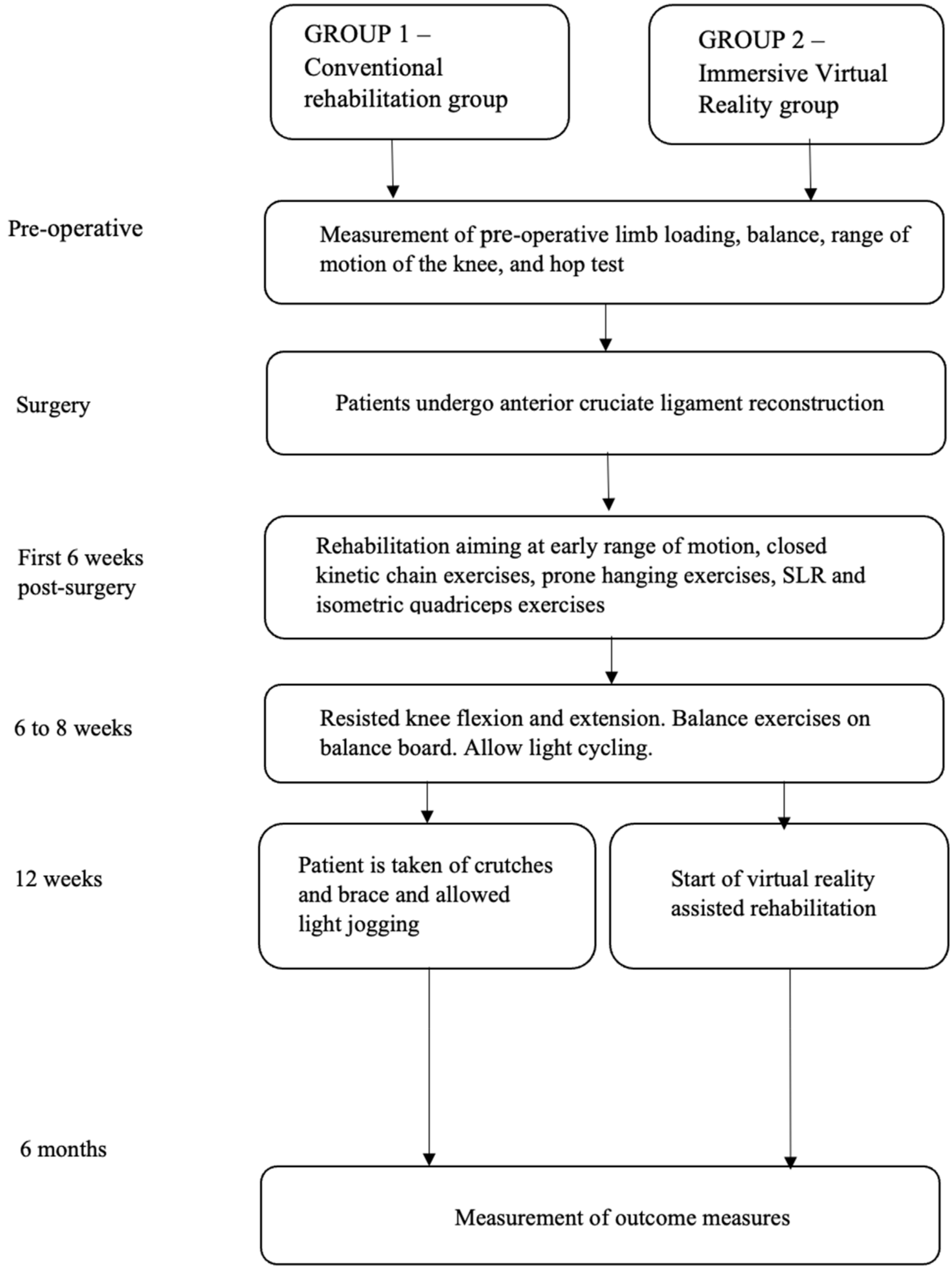

Fig. 2. Timeline of activities for Group 1 and Group 2.
Detailed legend: Fig. 2 describes the timeline of activities for Group 1 and Group 2 in the study. Firstly, limb loading, patient balance, and knee functional tests such as range of motion and hop test for strength were measured pre-operatively. Next, the patients underwent ACLR surgery. For the first 6 weeks after surgery, the aim of the exercises was to regain early motion of the knee. This included active-assisted range of motion exercises of the kneeand supplemented with closed kinetic chain flexion exercises, prone hanging exercises as well as isometric quadriceps exercises and straight leg raising exercises. Patients were also advised to do patellofemoral joint mobilization exercises to encourage extension range of motion. Two to three sets a day was advised to be done at home after patients were taught the right technique by physiotherapists. At 2–6 weeks, patients were allowed protected weight-bearing with crutches. Active knee extension exercises were started and supplemented with resisted straight leg raising exercises. After 6–8 weeks, patients were started on resistive knee flexion, extension exercises, and balance exercises. At the same time, light cycling was allowed to increase the hamstring and quadriceps contractions and coordination. After 12 weeks, Group 1 patients were weaned off crutches and light jogging was allowed. Group 2 patients meanwhile were started on VR assisted rehabilitation. Each patient underwent a 30-min session once every 2 weeks. At 6 months, the measurement for outcomes were done.

2.8. Pain score

Patients after ACLR often reported having pain during the rehabilitation.[34] This led to poor mood as well as anxiety to return to sports.[35] To measure the pain intensity in our patients we used the Numerical Pain Rating Scale.[36–38] Patients were to choose a number between 0 and 10 to describe their pain intensity, 0 being 'no pain' and 10 being 'the worst possible pain ever experienced'.

2.9. Patient subjective knee evaluation

The IKDC 2000 Subjective Knee Form has been used frequently after ACLR to measure knee function.[39] It is a subjective scoring system which looks into three parameters which include experience of pain, the sports activities of the patient and their perception about their knee function. The IKDC score is calculated as (IKDC score = [sum of items/maximum possible score] x 100). The higher the score, the better the functional outcome of the tested knee.[40]

2.10. Statistical analysis

The outcome measures were analysed using Statistical Package for the Social Sciences (SPSS) programme version 26. The results were presented into two sections: the descriptive analysis and the statistical analysis of the objectives in this study. The detection of the outlier in this study was done by using the Box-Plot where the box-plots were categorized by the outcome measures taken from the patients. Extreme outliers were rectified by Winsorization. The data was then analysed using Independent T-Test Analysis. The level of significance was set at $p < 0.05$.

3. Results

Out of the 30 patients who were included in the study, 23 were male and the remaining 7 were females. The age group of the patients involved ranged from 16 to 38, with the mean age 25.1 (Group 1) and 28.6 (Group 2). More than half of the patients had a right ACL tear (n = 19) and the rest had a left ACL tear (n = 11). Majority of the participants in this study (21 out of 30) played sports and their ultimate aim of undergoing the ACL surgery was to return to the sports activities at their pre-injury levels (Table 1). All the ACL reconstruction surgery were performed using ipsilateral hamstring autograft. All the subjects were compliant to the conventional rehabilitation exercises as prescribed. All Group 2 subjects also attended the VR sessions as per the time table.

The difference between both the limbs in terms of loading was expressed as a percentage of loading (Table 2). In both groups, patients put more load on the unaffected limb. In group 1, the mean load on the unaffected limb is 40.44 ± 1.859 as compared to the affected limb (37.14 ± 1.918). For group 2, the load on the unaffected limb (mean 40.57 ± 1.672) was also higher as compared to affected limb (mean 37.68 ± 2.683). On an average, the patients were loading more on the unaffected limb approximately 6% (6.24% in Group 1 and 5.38 in Group 2). However, the Independent T-test showed that there was no significant difference between the groups.

The next assessment was to test the balance of the patients with the modified SEBT. The results (Table 3) showed that the distance recorded in posterolateral direction for the unaffected leg was higher in both groups. Distance in posteromedial direction for the unaffected limbs for both groups were slightly higher with the mean value of (mean = 88.20 ± 8.96 cm) and (mean = 95.87 ± 11.51 cm) in group 1 and 2 respectively. However, there was no significant differences in the distance of excursion in all directions for both the groups.

In both groups, the pre-operative range of knee flexion on the affected knee was less than the unaffected knees (Table 4). The patients who underwent VR assisted rehabilitation (Group 2) on average have improved their range of motion of the operated knee by 19.34° as compared to the conventional rehabilitation group (Group 1) at 16.66°, however this is not a statistically significant finding ($P > 0.05$).

The next outcome measure conducted was the battery hop tests. As an overall, the vertical jump and side to side hop test showed a positive increment in the LSI, however the single leg hop test for distance recorded a decrement of average in Group 1 post operatively as compared to their preoperative values (Table 5). On average, Group 1 patients had a post-operative LSI of 74.87 ± 2.973 for the single leg hop test for distance compared to a pre-operative LSI of 77.93 ± 5.633. Group 2 recorded an improvement in the LSI from 93.07 ± 1.387 to 94.67 ± 1.175. In this study, the single leg hop test for distance showed a significant difference between both groups post-operatively. However, as a battery of tests, the cumulative measurements of all the hop tests showed no significant differences between the groups.

Patients in the study showed an improvement in the pain scores and IKDC 2000 scores post operatively in both groups. In Group 1 the pain score improved from 4.80 ± 0.86 to 0.93 ± 0.70 and in Group 2 the pain score improved from 4.60 ± 0.83 to 0.40 ± 0.51. A significant reduction in pain score was noticed in Group 2 in comparison to Group 1 (Table 6).

Post operatively the IKDC scores were above 90%, as compared to their preoperative score of 85.00% and 82.87% for Group 1 and Group 2 respectively. The IKDC scores are also significantly better ($P = 0.024$) in the group that underwent VR assisted rehabilitation as compared to the group that underwent conventional rehabilitation (Table 6).

4. Discussion

A proper rehabilitation after ACLR returns patients to their pre-injury sports level, prevents reinjury, long-term derangement to the kinematics of the knee and secondary osteoarthritis.[9–11,17] There is often a failure of rehabilitation as the rehab protocols are long, time-consuming procedures that requires high motivation from the patients.[17] In this research, we attempted to compare the effectiveness of immersive VR as an aid to conventional rehabilitation on limb loading, balance, range of motion, knee function, pain scores, and patients' subjective knee evaluation after a successful ACLR. To our knowledge, there has not been any research in ACLR rehabilitation that uses immersive VR with the use of PSVR headgears and motion controllers, in which we are able to render full immersion to the patients.

The important finding in this research was that immersive VR assisted rehabilitation after ACLR have similar outcomes in objective assessment including limb loading, balance, range of motion and knee function in terms of hop tests as compared to the group undergoing conventional rehabilitation. However, in terms of subjective assessment, there was a significant improvement in the pain score as well as the patients' subjective knee evaluation in the VR assisted group as compared to the conventional rehabilitation group. This also showed that the subjects are feeling good about the use to immersive VR assisted rehabilitation.

Our first assessment was a bilateral limb loading, in which asymmetries in both the groups were noted at 6 months, regardless if they underwent combined immersive VR assisted rehabilitation and conventional rehabilitation or conventional rehabilitation alone. The asymmetries were around 6%, in patients who underwent conventional rehabilitation and 5% in patients who underwent combined immersive VR assisted training and conventional

Table 1
Patient's demographic profile between Group 1 (Conventional Rehabilitation) and Group 2 (Immersive Virtual Reality Plus Conventional Rehabilitation).

Demographic profile *(N = 30)*		Group	
		Group 1 *(n = 15)*	Group 2 *(n = 15)*
Gender	Male	10	13
	Female	5	2
Age	<20 years 'old	4	1
	21–30 years' old	8	8
	31–40 years old	3	6
Diagnosis	Left ACL tear	5	6
	Right ACL tear	10	9
Pre-Op Sports Activity	Non-professional Sports Person	7	4
	Non-Sports Person	4	5
	Professional Sports Person	4	6
Occupation	Businessman	1	2
	Government officer	1	0
	Lab assistant	1	0
	Lorry driver	0	2
	Office clerk	2	0
	Police officer	0	3
	Radiographer	0	1
	Sales representative	1	0
	Software Engineer	2	0
	Student	5	3
	Teacher	2	4

Group 1: Patients who underwent conventional post ACLR rehabilitation.
Group 2: Patients who underwent a post ACLR rehabilitation regime involving immersive VR plus conventional rehabilitation.

Table 2
Limb loading test result in total weight (kg), median weight (kg) and percentage loading for all patients at 6 months post operation.

Assessment: Limb Loading *(N = 30)*		Group 1 *(n = 15)*			Group 2 *(n = 15)*			Sig. (P-value)	Mean Difference*
		Min	Max	(Mean ± SD)	Min	Max	(Mean ± SD)		
Total Weight (kg)	Affected leg	33.5	39.4	37.14 ± 1.918	30.9	40.2	37.68 ± 2.683	0.530	−0.541
	Unaffected leg	37.4	43.3	40.44 ± 1.859	36.8	43.2	40.57 ± 1.672	0.836	−0.134
Median Weight (kg)	Affected leg	30.0	38	34.33 ± 2.664	30.0	38.0	36.07 ± 2.017	0.054	−1.733
	Unaffected leg	33.0	39.0	36.73 ± 1.944	33.0	43.0	38.20 ± 2.513	0.085	−1.467
Percentage Loading (%)	Affected leg	−6.47	−6.02	−6.24 ± 0.145	−6.64	6.12	−5.38 ± 3.186	0.306	−0.859
	Unaffected leg	6.02	6.47	6.24 ± 0.145	6.12	6.47	5.38 ± 3.186	0.306	−0.859

Group 1: Patients who underwent conventional post ACLR rehabilitation.
Group 2: Patients who underwent a post ACLR rehabilitation regime involving immersive VR plus conventional rehabilitation.
SD: Standard deviation.
Mean difference*: Between group 1 and 2.

Table 3
Star Excursion Balance test result in Posterolateral (cm), Posteromedial (cm) and Anterior (cm) for all patients at 6 months post operation.

Assessment: Star Excursion Balance *(N = 30)*		Group 1 *(n = 15)*			Group 2 *(n = 15)*			Sig. (P-value)	Mean Difference*
		Min	Max	(Mean ± SD)	Min	Max	(Mean ± SD)		
Distance in Posterolateral (cm)	Affected leg	42.0	60.0	51.20 ± 7.360	42.0	66.0	53.47 ± 6.105	0.366	−2.267
	Unaffected leg	60.0	105.0	74.33 ± 11.836	66.0	110.0	75.00 ± 10.309	0.871	−0.667
Distance in Posteromedial (cm)	Affected leg	66.0	101.0	88.20 ± 8.962	78.0	125.0	95.87 ± 11.513	0.051	−7.667
	Unaffected leg	68.0	94.0	78.47 ± 8.790	63.0	96.0	78.13 ± 9.023	0.919	0.333
Distance in Anterior (cm)	Affected leg	70.0	82.0	77.20 ± 3.688	72.0	86.0	78.93 ± 2.987	0.168	−1.733
	Unaffected leg	70.0	82.0	77.40 ± 4.437	72.0	84.0	78.67 ± 3.904	0.413	−1.267

Group 1: Patients who underwent conventional post ACLR rehabilitation.
Group 2: Patients who underwent a post ACLR rehabilitation regime involving immersive VR plus conventional rehabilitation.
SD: Standard deviation.
Mean difference*: Between group 1 and 2.

rehabilitation. This difference was, however, not statistically significant. This finding was similar to a study done by Labanca L et al., which found the asymmetries in lower limb loading in their patients at both 1 month and 6 months.[27]

Other studies have suggested a worse interlimb asymmetry ranging from 10% to 15% difference between the limbs.[41,42] This was unsatisfactory as 6 months is normally regarded as the time to return to sport[13] and any abnormal loading may cause damage to the cartilages and hasten the progression to secondary osteoarthritis within 10–15 years.[43]

The reasoning behind this abnormal loading is said to be due to adaptation to impaired postural control in an injured/operated knee whereby the central nervous system responds by transferring loads from the injured limb to the uninjured limb. [27,44,45] Current conventional rehabilitation exercises mainly focus on the injured leg which was operated on, and this may not be beneficial in

Table 4
Range of Motion (Flexion) test result in pre and post operation for all patients.

Assessment: Range of Motion *(Degrees) (N = 30)*		Group 1 *(n = 15)*			Group 2 *(n = 15)*			Sig. (P-value)	Mean Difference*
		Min	Max	(Mean ± SD)	Min	Max	(Mean ± SD)		
Pre-Op	Affected leg	90.0	100.0	94.67 ± 5.164	90.0	100	93.33 ± 4.880	0.473	1.333
	Unaffected leg	110.0	125.0	122.67 ± 4.169	120.0	125	123.33 ± 2.440	0.597	−0.667
Post-Op	Affected leg	100.0	120.0	111.33 ± 5.164	100.0	120	112.67 ± 5.936	0.517	−1.333
	Unaffected leg	110.0	125.0	122.67 ± 4.169	120.0	125	123.33 ± 2.440	0.597	−0.667

Group 1: Patients underwent undergo conventional post ACLR rehabilitation.
Group 2: Patients who underwent a post ACLR rehabilitation regime involving immersive VR plus conventional rehabilitation.
SD: Standard deviation.
Mean difference*: Between group 1 and 2.

Table 5
Limb Symmetry Index in pre and post operation for all patients.

Assessment: Limb Symmetry Index *(N = 30)*		Group 1 *(n = 15)*			Group 2 *(n = 15)*			Sig. (P-value)	Mean Difference*
		Min	Max	(Mean ± SD)	Min	Max	(Mean ± SD)		
Vertical Jump	Pre-Op	62.0	80.0	65.93 ± 4.367	50.0	75.0	63.33 ± 7.027	0.234	2.600
	Post-Op	87.0	94.0	90.82 ± 1.931	90.0	97.0	91.93 ± 1.831	0.116	−1.113
Side to Side	Pre-Op	61.0	75.0	66.07 ± 4.891	59.0	71.0	64.00 ± 4.036	0.217	2.067
	Post-Op	90.0	94.0	91.87 ± 1.457	90.0	96.0	92.73 ± 1.668	0.141	−0.867
Single Leg Hop Test	Pre-Op	63.0	83.0	77.93 ± 5.663	91.0	96.0	93.07 ± 1.387	0.074	3.067
	Post-Op	72.0	82.0	74.87 ± 2.973	93.0	97.0	94.67 ± 1.175	0.002**	−1.600

Group 1: Patients who underwent conventional post ACLR rehabilitation.
Group 2: Patients who underwent a post ACLR rehabilitation regime involving immersive VR plus conventional rehabilitation.
SD: Standard deviation.
**Significant at 0.05 (Independent T Test).

Table 6
Pain score and International Knee Documentation Committee score between Group 1 and Group 2.

Outcome Assessments	Pre/Post Operation	Group 1 (n = 15)	Group 2 (n = 15)	P-value (between group)
International Knee Documentation Committee Score	Pre-Op	85.00 ± 3.80	82.87 ± 3.18	0.107
	Post-Op	92.87 ± 1.19	93.93 ± 0.961	0.012*
Pain Score	Pre-Op	4.80 ± 0.86	4.60 ± 0.83	0.522
	Post-Op	0.93 ± 0.70	0.40 ± 0.51	0.024*

Group 1: Patients who underwent conventional post ACLR rehabilitation.
Group 2: Patients who underwent a post ACLR rehabilitation regime involving immersive VR plus conventional rehabilitation.
*Significant at 0.05 (Independent T Test).

correcting asymmetries in limb loading.[27] In immersive VR, the patient is fully immersed in the games or activity and will thus use both limbs. This could explain the slight improvement in lower limb asymmetry in our study.

The SEBT was chosen to evaluate the balance of the patients in our study.[31,46,47] Herrington et al. found statistical difference between balance measured in multiple directions between ACL injured patients and a control group.[48] Our study was in partial agreement to the above study whereby the affected or injured limb has a less excursion in all 3 directions, anterior, posteromedial and posterolateral as compared to the uninjured limb at 6 months of testing. However, there was no significant difference between the group that underwent conventional rehabilitation or combined immersive VR assisted rehabilitation and conventional rehabilitation.

In evaluating the knee function, we divided the testing into objective measurements such as range of motion of the knee and a battery of hop tests ((*i) Single leg hop test ii) Vertical jump and iii) Side to side hop*) and a subjective evaluation of the knee in the form of knee pain as well as IKDC scoring. In this study, a significant difference was found in the pain scores to the knee of patients who did the immersive VR assisted rehabilitation as compared to those who underwent conventional rehabilitation.

Regarding the subjective evaluation of function of the knees using the IKDC score, patients who underwent combined immersive VR training and conventional rehabilitation reported to have better scores than those who underwent conventional rehabilitation alone. Patients who underwent ACL surgery often reported to have pain and low mood post-operatively.[34] Removing this pain, fear, anxiety and low mood is crucial rehabilitation goals after ACL surgery. Immersion in VR allows the patients to interact in the virtual world with virtual objects. The rationale behind the use of immersive VR is the ability to provide an engaging, motivating and enjoyable environment for the patients during the arduous, long-term process of ACL rehabilitation.[49]

This can potentially improve compliance to the rehabilitation process and improve outcomes. Besides that, VR has the potential to improve the central nervous system capability for motor learning.[21] This is due to the fact that immersive VR mimics real life scenarios by programmes and the focus of attention of the patient is shifted from their knees to interaction with the VR.[21] The VR also acts as a distractor [21] and takes the patients' mind off the pain enhances focus on exercises.

There were a few limitations in our study. Firstly, research investigators and the subjects were not blinded in this randomised trial. Limited number (once in 2 weeks) of immersive VR sessions was another major limitation and we were not able to provide VR equipment to each patient due to the cost. We postulated that we would be able to see significant improvement in objective knee functions if the frequency of the rehabilitation with VR was increased and over a longer duration. Moreover, the number of games that are available to completely mimic conventional rehabilitation were limited. The motivational level and fitness levels pre- and post-surgery of the patient were not included in this study. The possibility of other confounding factors such as BMI, severity of injury, type of sport may also affect the results. Assessment of the parameters just prior to commencement of immersive VR rehabilitation will also improve the result analysis and comparison.

Despite these limitations, our study is the first randomised controlled trial of immersive VR using PlayStation-VR which has the potential to be used as an effective adjunct to conventional rehabilitation in rehabilitation of patients after post-ACL repair. It would be truly interesting to expand this study in a larger scale with frequent VR sessions to further determine the clinical and functional outcome of combined use of immersive VR and conventional rehabilitation in ACLR patients.

5. Conclusion

The immersive VR can be used as an adjunct to conventional rehabilitation after ACLR to optimise the clinical and functional outcome especially in reducing pain as well as subjective knee evaluation. The development of newer software may be beneficial in further strengthening the exercise programs to address deficits from the current conventional rehabilitation protocols.

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Declaration of competing interest

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LIST OF ABBREVIATIONS

ACL: Anterior Cruciate Ligament
ACLR: Anterior Cruciate Ligament Reconstruction
IKDC: International Knee Documentation Committee Score
LSI: Limb Symmetry Index
PSVR: PlayStation Virtual Reality
SEBT: Star Excursion Balance Test
SPSS: Statistical Package for the Social Sciences
VR: Virtual Reality