Effectiveness of In-Home, Augmented Reality–Based Telerehabilitation After Anterior Cruciate Ligament Reconstruction

A Randomized Controlled Trial

Ji Young Lim,*† PT, PhD, Hee Ju Yu,‡ PT, MS, Seo Hyun Kim,* PT, Jong In Lee,§ MD, PhD, Jae-Young Lim,‖¶ MD, PhD, Joon Ho Wang,#** MD, PhD, and Ji Hye Hwang,**†† MD, PhD

Investigation performed at Samsung Medical Center, Sungkyunkwan University School of Medicine, Seoul, Republic of Korea, and Bundang Seoul National Hospital, Gyeonggi, Seoul, Republic of Korea

Background: New digital technology–based rehabilitation may be a viable option for patients after anterior cruciate ligament reconstruction (ACLR), with advantages such as easy access to treatment and learning as well as cost-effectiveness.

Purpose: To investigate the effects of an augmented reality (AR)–based, telerehabilitation system in patients after ACLR compared with a brochure-based rehabilitation program in terms of patient-reported outcomes and functional performance measures.

Study Design: Randomized controlled trial; Level of evidence, 2.

Methods: This was a multicenter, assessor-blinded study. Enrolled participants were allocated randomly to either the intervention group, who underwent AR-based telerehabilitation system, or to the control group, who underwent a brochure-based rehabilitation program with a self-log. Both groups performed the same postoperative rehabilitation exercise protocol. Subjective knee function was assessed using the International Knee Documentation Committee (IKDC) as the primary outcome; secondary outcomes were a numeric rating scale for pain, the EuroQol 5-Dimension 5-Level, isometric knee strength, range of motion, and the single-leg hop test. The intervention group also completed a satisfaction survey. Follow-up was conducted at 2, 6, 12, and 24 weeks postoperatively.

Results: A total of 28 patients were enrolled in each group; 1 patient in the control group was lost to follow-up. Patients in both groups demonstrated improvement on all outcomes over time. There were no significant between-group differences in the IKDC score from baseline to 12 weeks postoperatively. The intervention group saw a greater increase in the relative isometric strength of the quadriceps on the involved limb at 6, 12, and 24 weeks postoperatively ($P < .05$ for all). No significant group differences were observed in the remaining secondary outcomes.

Conclusion: Study findings indicated that patients who underwent AR-based telerehabilitation in the early rehabilitation phase after ACLR demonstrated similar improvements as those who followed a brochure-based rehabilitation program and had a quicker recovery of knee extensor strength.

Registration: NCT04513327 (ClinicalTrials.gov identifier).

Keywords: anterior cruciate ligament reconstruction; augmented reality; telerehabilitation; telemedicine

The anterior cruciate ligament (ACL) is one of the most frequent ligament ruptures of the knee joint that occurs during sports activities in relatively young individuals.[18] ACL reconstruction (ACLR) is commonly performed to prevent chronic joint instability and the risk of reinjury in the

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long term.[8,20] After reconstruction, phase-to-phase rehabilitation protocols for early weightbearing, recovery of range of motion (ROM), and muscle strength have been applied to patients.[47] Usually, a combination of hospital-based physical therapy and home-based exercise is recommended after ACLR. However, some patients are unlikely to receive face-to-face rehabilitation services after discharge because of lack of time, mobility, and distance issues. Moreover, conventional home-based rehabilitation using brochures is difficult to manage individually and can negatively affect patient adherence to the exercises.[7,31] Insufficient postoperative rehabilitation can constrain the ROM of the knee joint and cause loss of muscle strength and may also increase joint instability after fibrosis, leading to complications such as knee joint fibrosis and restriction in physical activity.[35]

To address such problems, rehabilitation treatments incorporating new technologies have been suggested in various populations, including patients who have undergone orthopaedic surgery.[5,11,40] In a recent questionnaire study[14] regarding the understanding and acceptance of technology-assisted rehabilitation, 89% of 96 patients surveyed after undergoing ACLR were unfamiliar with technology-based rehabilitation but exhibited positive responses to the new mode of therapy. Moreover, they wanted to use digital rehabilitation at various stages of treatment and expected potential benefits, such as improved access to treatment and learning, as well as saving resources.[14] Given the needs of these patients and the global changes following the COVID-19 pandemic, it has become increasingly important to establish a useful rehabilitation treatment system that can be safely performed at home while reducing costs and increasing compliance.

Previous studies have demonstrated the effects of postoperative rehabilitation using web-based programs, mobile-based applications, exergaming, and virtual reality in patients after ACLR.[3,4,6,10,13,16,17,27,33] However, in most studies, the participant number was limited, and the follow-up period was short. Moreover, virtual reality–based rehabilitation may lead to discomfort from wearing a headset[21] and can also be limited in providing various balance exercise programs.[46] Similarly, virtual reality may be limited in providing adequate environments for the rehabilitation of ACLR patients who may need training for a gradual increase in weightbearing and ROM. Among exergaming, the commercial Wii platform (Nintendo) does not accurately detect the ROM of the knee and may not be suitable if maintaining a specific angle is required in some exercises during the initial rehabilitation stages.[31]

In this study, an augmented reality (AR)–based telerehabilitation system was applied to patients who had undergone ACLR. Compared with other technologies, AR involves the creation of an enhanced reality by integrating virtual objects or environments into the real world and offers users the opportunity to interact with augmented virtual information and immerse themselves in a real-time experience, providing positive evidence of AR in physical rehabilitation.[19] In this system, patients view their movement, number of exercises, and holding time in real time, while simultaneously receiving audiovisual feedback through the use of a 3-dimensional Kinect camera (Xbox One Kinect for Windows; Microsoft) that tracks joint movements. Notably, no prior studies have ascertained the efficacy of rehabilitation for patients after ACLR within a home-based setting while employing AR-based feedback, exercise prescriptions, and monitoring by health care professionals. The aim of this study was to compare the effects of this AR-based telerehabilitation system with a brochure-based rehabilitation program in patients after ACLR.

METHODS

Study Design and Participants

This was a single-blinded (outcome assessors), multicenter, clinical, randomized controlled trial (RCT). The study protocol received ethics committee approval, and all included participants received a full explanation of the research and voluntarily submitted their written consent. Participant eligibility criteria were as follows: patients who were aged $\geq$18 years, underwent isolated ACLR

††Address correspondence to Ji Hye Hwang, MD, PhD, Department of Physical & Rehabilitation Medicine, or Joon Ho Wang, Department of Orthopedic Surgery, Samsung Medical Center, Sungkyunkwan University School of Medicine, #81 Irwon-Ro, Gangnam-Gu, Seoul 06351, Republic of Korea (email: hwanglee@skku.edu).

*Research Institute for Future Medicine, Samsung Medical Center, Seoul, Republic of Korea.

†Department of Physical and Rehabilitation Medicine, Sungkyunkwan University School of Medicine, Seoul, Republic of Korea.

‡Department of Physical Therapy, Graduate School, Sahmyook University, Seoul, Republic of Korea.

§Department of Rehabilitation Medicine, Seoul St. Mary's Hospital, College of Medicine, Catholic University of Korea, Seoul, Republic of Korea.

‖Department of Rehabilitation Medicine, Seoul National University Bundang Hospital, Seongnam-si, Gyeonggi-do, Republic of Korea.

¶Department of Rehabilitation Medicine, Seoul National University College of Medicine, Seoul, Republic of Korea.

#Department of Orthopedic Surgery, Samsung Medical Center, Sungkyunkwan University School of Medicine, Seoul, Republic of Korea.

**Department of Physical and Rehabilitation Medicine, Samsung Medical Center, Sungkyunkwan University School of Medicine, Seoul, Republic of Korea

J.H.W. and J.H.H. contributed equally to this article and are co-corresponding authors.

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Ethical approval for this study was obtained from Samsung Medical Center (ref No. SMC-2019-05-021) and Bundang Seoul National University Bundang Hospital (ref No. B-2005-612-001).

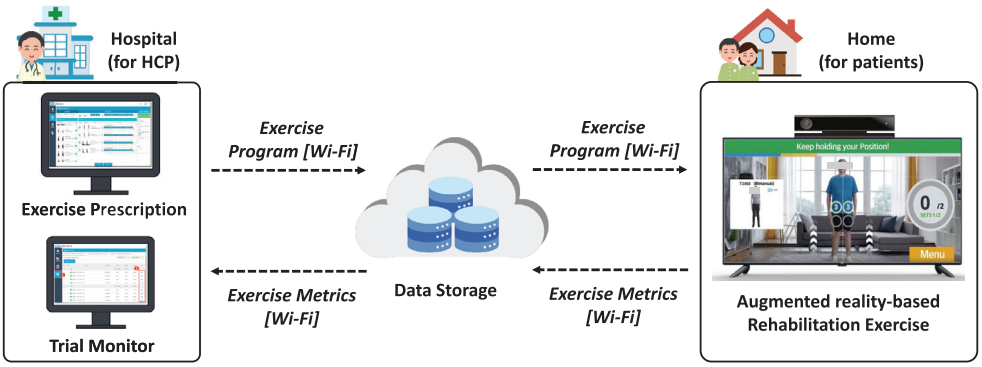

Figure 1. Delivery flow of the augmented reality–based telerehabilitation intervention. HCP, health care professional.

surgery,underwent meniscectomy in conjunction with ACLR, and underwent meniscal repair in conjunction with ACLR. Specific graft types and/or fixation techniques were not considered as selection criteria. Patients who had undergone ACLR in the previous 6 months,underwent bilateral ACLR, had other knee joint disorders (rheumatoid arthritis, osteoarthritis, etc), had neurological deficits or infection in the affected knee joint, and had severe comorbidity that inhibited exercise were excluded. The enrolled participants were divided into an intervention group that underwent AR-based telerehabilitation at home and a control group that performed brochure-based rehabilitation exercises.

Sample Size Calculation

Assuming an attrition rate of 20%, a sample size of 56 participants (28 participants per group) was calculated to have 80% power, $\alpha = .05$, and a well-established minimal clinically important difference of 11.5 points,[26] with a standard deviation on the International Knee Documentation Committee (IKDC) subjective knee evaluation form score of 14.

Randomization, Allocation, and Blinding

A block of size 4 was used to create a randomization table. Participants were assigned to the intervention or control group before their first postoperative evaluation. Randomization was conducted by an independent researcher (Ji.Y.L.) who did not participate in the registration and evaluation processes. To minimize bias, the results of the group assignment were sealed in opaque envelopes and delivered to the patients. The outcome assessors (H.J.Y. and S.H.K.) were blinded until the end of the follow-up.

Interventions

All participants received a brochure containing exercise photographs and explanations during their postoperative hospital stay (approximately 3 to 5 days), along with a Thera-band green elastic band (Hygenic) to generate resistance. They also underwent a single educational session provided by a physical therapist on proper posture, exercise frequency, progressive joint ROM, and weight-bearing improvements on the involved side. The participants were recommended to start exercising at least once a day immediately after discharge. They visited the outpatient clinic at 2, 6, 12, and 24 weeks after surgery in accordance with the treatment procedures.

The rehabilitation exercise programs for the 2 groups were based on the same postoperative exercise schedule. In the 12-week program, different protocols were applied according to surgery type (with vs without meniscal repair). In the intervention group, patients who underwent ACLR alone or ACLR with meniscectomy performed brochure-based exercises for 2 weeks after surgery, followed by 10 weeks of AR-based rehabilitation exercises. For patients who underwent ACLR with meniscal repair, the modified rehabilitation protocol was adapted according to the evidence[1,43] and clinicians' clinical experience: 4 weeks of brochure-based exercises followed by 8 weeks of AR-based rehabilitation exercises. Considering the factors related to meniscal healing and potential damage to the repair—such as tear location, pattern, repaired lesions, age, and concurrent injuries—weightbearing activity exceeding 45° of knee flexion was restricted for the initial 4 weeks after surgery. Patients were allowed toe-touch weightbearing for up to 4 weeks and recommended to have 90° of knee flexion and partial weightbearing from 5 weeks postoperatively.

The control group underwent 12 weeks of brochure-based rehabilitation according to the surgical methods and with the same restrictions as mentioned in the intervention group.

AR-Based Telerehabilitation

As an AR-based rehabilitation exercise program, the UINCARE Home + (UINCARE) was used. The delivery flow of the AR-based telerehabilitation is shown in Figure 1. After randomization and completion of the baseline assessment, an independent researcher (Ji.Y.L.) who did not participate in the outcome assessment prescribed an exercise program (8 or 10 weeks) for each participant using the

UINCARE administrator. The prescribed exercise program was transferred to the UINCARE client, and UINCARE Home + was delivered to the individual's home. The rehabilitation exercise program design per session is presented in Supplementary Table S1 (available separately). Each session lasted approximately 25 minutes, and a total of 3 daily exercise sessions were recommended.

A total of 25 joints for each participant in the intervention group were calibrated using infrared and motion capture technology with a 3-dimensional Kinect camera to track lower-extremity movements in real time. The screen showed the virtual information in the real home environment. During exercises, the participant was able to check visual information such as exercise guide image, joint position, target point for each exercise, holding time counted by voice, number and sets of exercises, and encouraging messages in real time. In addition, performance and accuracy scores (0% to 100%) were provided upon each session's completion. The details of the feedback in the AR-based rehabilitation exercise are presented in Supplementary Table S2. The number of daily exercises performed and their execution and accuracy were sent to the administrator through the server. An independent researcher (Ji.Y.L.) observed participant compliance during the interventions. The researcher simply monitored patients' compliance without additional feedback. If a participant did not perform the prescribed exercise session for 3 consecutive days, the researcher contacted the participant to recommend completing the exercises at least once a day.

Brochure-Based Rehabilitation With Self-Report Logs (Active Comparator)

The control group exercised at home using a brochure that explained the programs each week and included self-reported logs that recorded whether and how many times each patient exercised each day. No additional encouragement messages were delivered to the control group. The control group was provided the same exercise program at the same rate of progression as the intervention group.

Outcome Measures

Patient-reported outcome measures, knee ROM, and quadriceps and hamstring strength were measured at postoperative 2 weeks (baseline), 6 weeks (during the intervention), 12 weeks (immediately after the intervention), and 24 weeks (3 months after the intervention), and a single-leg hop test for distance was conducted at postoperative 12 and 24 weeks. The intervention group completed the survey on satisfaction with the AR-based telerehabilitation system at 12 weeks postoperatively.

The primary outcome, the Korean version of the IKDC, was used to evaluate the subjective knee symptoms, function, and sports activity.[25,28] The IKDC helps to identify symptoms and disorders in patients with ACL or meniscal tears or knee osteoarthritis.[44] The questionnaire consists of 18 items, with scores ranging from 0 to 100. Higher scores indicate greater knee function.

Secondary outcomes included (1) knee pain at rest and during activity as measured on an 11-point numeric rating scale (NRS)[42]; (2) health-related quality of life as measured by the validated Korean translation of the EuroQol 5-Dimension 5-Level (EQ-5D-5L),[29] which evaluates mobility, self-management, daily activities, pain or discomfort, and anxiety or depression (total score ranges from −0.066 to 1.000); (3) active and passive knee ROM in extension (maximum, 0°) and flexion (maximum, 135°) as measured once each in a sitting position by a blinded physical therapist with a goniometer; (4) relative isometric knee strength, reported as peak isometric force (in newtons) of the quadriceps and hamstrings and measured by a portable dynamometer (Nicholas Manual Muscle Tester; Lafayette Instrument), which has demonstrated excellent test-retest reliability and good validity ($r = 0.62$) when compared with a handheld dynamometer.[2] All strength data were normalized to body weight and expressed as relative force considering individual differences. The participant was asked to sit on the edge of a treatment table and flex the knee to 45°.[36] After 1 practice session, the uninvolved side was measured first. Both sides were measured twice for 5 seconds, and the highest value was used for the analysis. (5) The quadriceps index (QI; in %) was calculated using the formula $QI = (\textit{maximal force on the involved side/maximal force on the uninvolved side}) \times 100$.[24] (6) Single-leg hop test for distance, which was converted to a limb symmetry index (LSI; in %); calculated as (*distance on the involved side/distance on the uninvolved side*) × 100. The greatest distance was used in the analysis.[39]

The custom survey on satisfaction with the AR-based telerehabilitation system, given to the intervention group, consisted of 10 items (total score, 100), including 8 multiple-choice items (evaluated on a 4-point scale) and 2 subjective items. For the subjective items, participants were asked to indicate any issues, improvements required, and experience of satisfaction.

Statistical Analysis

Statistical analysis was performed using SPSS Version 29.0 (IBM) with a 5% level of statistical significance (2-tailed). Descriptive statistics were used to summarize the demographics and clinical outcomes of the participants. According to the results of normality tests of variables (using the Shapiro-Wilk test), the independent-samples *t* test was used to assess the change in the primary outcome variable (IKDC score) between the 2 groups with an intention-to-treat analysis. Only participants who completed the baseline (2 weeks) and endpoint (12 weeks) assessment were included in the primary outcome analysis. Additionally, the single-leg hop test LSI values were compared between the 2 groups using independent-samples *t* tests. Generalized estimating equation (GEE) models, with an a first-order autoregressive structure including the covariates of age and sex, were used to evaluate the differential change in the secondary outcomes between the 2 groups

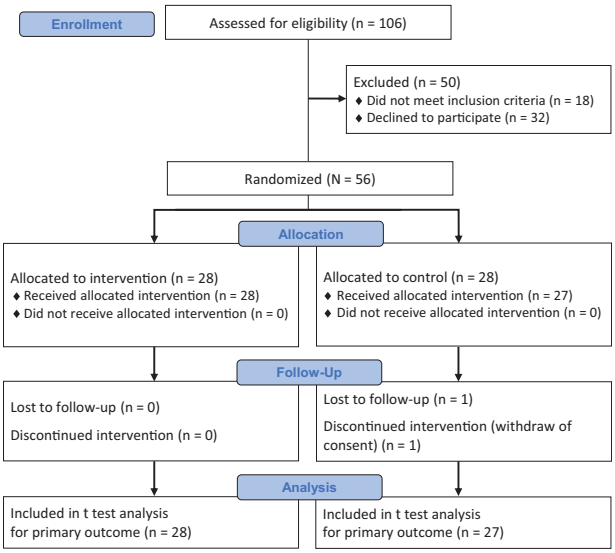

Figure 2. CONSORT (Consolidated Standards of Reporting Trials) flowchart of the participant inclusion process.

at 6, 12, and 24 weeks compared with 2 weeks (baseline) for both outcomes. For the GEE analysis, all participants who had outcomes assessed at baseline were included. To adjust for multiple comparisons between the groups regarding changes in outcome measures (at 3 points), the Bonferroni correction was used (significance level, $P < .016$; otherwise $P < .05$ was considered the threshold for significance).

RESULTS

Between April 2020 and May 2021, a total of 56 participants were enrolled; 28 patients each were randomized to the intervention and control groups. The CONSORT (Consolidated Standards of Reporting Trials) flowchart[41] for screening participants for eligibility, assignment, follow-up, and analysis is shown in Figure 2. Of all included participants, only 1 (1.8%) was dropped from the control group due to consent withdrawal.

Table 1 summarizes the demographic characteristics of the participants. Among the measures collected, no significant differences were detected between the groups. At the baseline of clinical outcomes, there were no significant differences between the groups. During the intervention period, no adverse effects were observed in any participant.

Primary Outcome

Differences in IKDC scores from baseline (2 weeks postoperative) to 12 weeks postoperative were 37.2 ± 15.0 in the intervention group and 31.1 ± 13.3 in the control group. There were no significant between-group differences in the change of IKDC scores from baseline to 12 weeks (mean difference, 5.9 [95% CI, −2.31 to 13.09]; $P = .166$).

Secondary Outcomes

The baseline and follow-up results of secondary outcomes of both groups are presented in Table 2. Both groups showed significant improvement on all secondary outcome variables over time. Compared with the control group, participants in the intervention group had significantly greater improvement in relative isometric strength of the quadriceps on the affected side from baseline to 6, 12, and 24 weeks postoperative (time × group interaction, 6 weeks: β = 0.57 [95% CI, 0.14-0.99; $P = .009$]; 12 weeks: β = 0.97 [95% CI, 0.35-1.59; $P = .002$]; 24 weeks: β = 1.25 [95% CI, 0.62-1.89; $P < .001$]). The number of participants who completed testing of isometric strength of the knee extensor was 28 and 26 participants for the control and intervention groups, respectively, at baseline (2 weeks), and the numbers were reduced to 19 and 22 participants, respectively, at 24 weeks postoperatively.

There were no significant between-group differences in the NRS score, EQ-5D-5L score, active or passive knee ROM, relative isometric strength of the hamstrings on the affected side, or the QI at any time point. In addition, the mean single-leg hop test LSI values were not significantly different between the intervention group (12 weeks: 59.01% ± 28.60%, n = 26; 24 weeks: 73.85% ± 20.66%, n = 24) and control group (12 weeks: 66.91% ± 22.32%, n = 24; 24 weeks: 66.91% ± 22.32%, n = 19), with a mean difference between groups of −0.22% at 12 weeks (95% CI, −15.64% to 15.20%; $P = .997$) and −6.94% at 24 weeks (95% CI, −20.22% to 6.33%; $P = .297$).

Satisfaction With AR-Based Telerehabilitation

Of the 28 participants in the AR group, 26 completed the satisfaction questionnaire after the intervention. The mean satisfaction score was 80.5 ± 11.5 out of 100; a breakdown of scores by item is shown in Supplementary Table S3. Among the subjective responses, most participants reported that they experienced software issues due to internet connection problems. Regarding the AR-based rehabilitation exercises, participants indicated satisfaction in that they could exercise at their desired time at home (6 responses); that time was saved by not needing to visit a rehabilitation hospital (2 responses); that posture correction was through feedback (5 responses); and that they were motivated to perform the exercises and to exercise regularly (5 responses). Regarding other areas of the questionnaire, participants indicated satisfaction in the structured rehabilitation exercise programs (5 responses) and the automated feedback that was provided (4 responses).

DISCUSSION

In this randomized single-blind clinical trial, the clinical effects of AR-based telerehabilitation at home for 8 to 10 weeks was investigated at 2, 6, 12, and 24 weeks after primary ACLR or ACLR with meniscectomy or meniscal repair. The AR telerehabilitation system improved

TABLE 1
Baseline Characteristics of the Participants[a]

Variable	Intervention (AR) Group (n = 28)	Control (Brochure) Group (n = 28)	P^b
Sex			.729
Male	22 (79)	24 (86)	
Female	6 (21)	4 (14)	
Age, y	30.5 ± 11.0	35.7 ± 9.6	.065
Height, cm	172.4 ± 8.3	172.8 ± 7.4	.407
Weight, kg	77.7 ± 13.4	77.9 ± 12.4	.967
Surgery			.673
Isolated ACLR	14 (50)	12 (43)	
ACLR with meniscectomy	3 (11)	6 (21)	
ACLR with meniscal repair	11 (39)	10 (36)	
Graft type[c]			≥.999
Autograft	17 (61)	16 (57)	
Allograft	11 (39)	12 (43)	
Involved limb			.102
Right	20 (71)	13 (46)	
Left	8 (29)	15 (54)	

[a]Data are presented as n (%) or mean ± SD. ACLR, anterior cruciate ligament reconstruction; AR, augmented reality.
[b]To assess homogeneity between the 2 groups, the independent *t* test was used to compare continuous variables, and the chi-square test was used to compare categorical variables.
[c]Autograft was the hamstring (semitendinosus) tendon, and allografts were tibialis anterior tendon, tibialis posterior tendon, and quadriceps bone–patellar tendon–bone.

functional performance, knee function, pain, and quality of life similar to conventional home-based rehabilitation. However, compared with the brochure-based rehabilitation group, the patients who participated in the AR telerehabilitation system had quicker and more significant recovery of quadriceps isometric strength in the involved limb, which is a useful indicator of return to activity[30] and plays an important role in knee stability[34]; however, as there were no significant group differences in the QI, IKDC scores, or single-leg hop test LSI, this finding should be interpreted with caution. In the intervention group, the mean satisfaction score was 80.5 out of 100, indicating that the majority of the participants believed the telerehabilitation system was helpful in the early rehabilitation stages.

Different technology-assisted rehabilitation interventions such as mobile applications, websites, and exergaming have been studied for use in patients after ACLR; however, to the best of our knowledge, none of them examined the effect of postoperative home rehabilitation exercise using an AR-based telerehabilitation system during 6-month follow-up in patients with mixed ACL surgery type. In addition to different technologies, comparisons with relevant studies need to be made carefully due to the different outcome measures, measurement methods, and differences in the time of intervention application after surgery.

The findings of our study align with those of previous studies that used technology-based interventions for postoperative rehabilitation and found a positive improvement in patient-reported outcomes, knee ROM, quadriceps function, and functional performance. In a recent study[10] in which physical therapy and exergaming-based rehabilitation training was provided for 3 weeks to 14 patients immediately after primary ACLR, the experimental group showed significant improvement (from preoperatively to 6 weeks postoperatively) in absolute and relative quadriceps strength compared with a control group that received only physical therapy. Patient-reported knee function in the experimental group was similar to that in the control group. A 2013 study by Baltaci et al[6] demonstrated that the Nintendo Wii Fit system (n = 15) for 12 weeks showed the same effect as conventional rehabilitation (n = 15) in patients after hamstring ACLR on isokinetic knee strength; dynamic balance measured by the star excursion balance test; and coordination, proprioception, and response time through functional squat tests. In 22 male patients who had undergone ACLR, a retrospective study[17] combined physical therapy and a mobile application consisting of rehabilitation exercise videos from 1 to 90 days postoperatively; the evaluation analysis 3 weeks postoperatively revealed that the likelihood of fully straightening the knee while walking on crutches was 3.86 times higher in the group using the application for >11 days than the group using the application for ≤10 days. Moreover, they were 4.2 times more likely to be pain-free. In another RCT,[27] the Nintendo Wii balance games added to an accelerated rehabilitation program in the fourth week for 40 minutes a day (3 sessions per week, for a total of 12 sessions) under physical therapist supervision were performed for 14 patients who had undergone ACLR. However, virtual reality–based rehabilitation in the early stage could not provide additional benefits. Similarly, in a 1-group pretest-posttest study,[4] a virtual reality–based rehabilitation system and conventional physical therapy were used 3 times a week for 8 weeks, which greatly improved proprioception, ROM, pain, and knee edema in 15 patients with ACLR.

TABLE 2
Results of Generalized Estimating Equation Models for the Comparison of Secondary Outcomes Variables[a]

	Estimated Mean ± SE		Group Effect[b]		Time Effect[c]		Group × Time Effect[d]	
Outcome	Intervention	Control	β (95% CI)	*P*	β (95% CI)	*P*	β (95% CI)	*P*
NRS pain at rest								
2 wk postop	1.33 ± 0.23	1.04 ± 0.23	0.30 (–0.33 to 0.93)	.357	—	—	—	—
6 wk postop	0.44 ± 0.13	0.46 ± 0.11			–0.58 (–1.00 to −0.16)	.007	–0.31 (–0.98 to 0.36)	.361
12 wk postop	0.23 ± 0.09	0.36 ± 0.13			–0.68 (–1.13 to −0.22)	.003	–0.43 (–1.10 to 0.24)	.208
24 wk postop	0.10 ± 0.06	0.14 ± 0.09			–0.89 (–1.38 to −0.41)	<.001	–0.34 (–1.04 to 0.36)	.339
NRS pain with activity								
2 wk postop	4.29 ± 0.33	4.01 ± 0.42	0.28 (–0.76 to 1.31)	.602	—	—	—	—
6 wk postop	2.47 ± 0.26	2.62 ± 0.24			–1.39 (–2.28 to −0.50)	.002	–0.43 (–1.43 to 0.56)	.395
12 wk postop	1.72 ± 0.17	2.18 ± 0.31			–1.83 (–2.72 to −0.94)	<.001	–0.74 (–1.81 to 0.33)	.176
24 wk postop	1.57 ± 0.22	1.59 ± 0.24			–2.43 (–3.42 to −1.43)	<.001	–0.30 (–1.48 to 0.89)	.625
EQ-5D-5L								
2 wk postop	0.53 ± 0.03	0.61 ± 0.02	–0.08 (–0.15 to 0.00)	.038	—	—	—	—
6 wk postop	0.74 ± 0.02	0.76 ± 0.01			0.15 (0.11 to 0.19)	<.001	0.06 (0.00 to 0.13)	.058
12 wk postop	0.83 ± 0.01	0.81 ± 0.01			0.20 (0.15 to 0.25)	<.001	0.10 (0.02 to 0.18)	.019
24 wk postop	0.87 ± 0.01	0.86 ± 0.01			0.25 (0.19 to 0.31)	<.001	0.09 (0.00 to 0.18)	.041
Active knee ext, deg								
2 wk postop	13.11 ± 1.79	11.76 ± 1.12	1.34 (–2.80 to 5.48)	.525	—	—	—	—
6 wk postop	6.82 ± 1.12	7.35 ± 1.18			–4.41 (–6.60 to −2.23)	<.001	–1.87 (–5.48 to 1.74)	.310
12 wk postop	2.28 ± 0.66	5.66 ± 0.94			–6.10 (–8.19 to −4.00)	<.001	–4.73 (–8.81 to −0.65)	.023
24 wk postop	0.95 ± 0.62	3.19 ± 0.78			–8.58 (–10.78 to −6.37)	<.001	–3.58 (–7.84 to 0.68)	.100
Passive knee ext, deg								
2 wk postop	5.37 ± 1.02	4.58 ± 0.89	0.79 (–1.86 to 3.44)	.558	—	—	—	—
6 wk postop	0.62 ± 0.40	2.12 ± 0.69			–2.45 (–4.30 to −0.61)	.009	–2.29 (–4.85 to 0.26)	.078
12 wk postop	0.10 ± 0.35	1.31 ± 0.47			–3.27 (–5.19 to −1.34)	.001	–2.00 (–4.75 to 0.74)	.153
24 wk postop	–0.07 ± 0.33	0.95 ± 0.58			–3.63 (–5.38 to −1.88)	<.001	–1.81 (–4.48 to 0.85)	.183
Active knee flex, deg								
2 wk postop	86.49 ± 2.60	79.43 ± 3.16	7.06 (–0.95 to 15.08)	.084	—	—	—	—
6 wk postop	113.62 ± 1.60	110.27 ± 2.68			30.84 (24.69 to 37.00)	<.001	–3.72 (–11.18 to 3.75)	.329
12 wk postop	121.48 ± 1.29	119.23 ± 1.64			39.80 (33.19 to 46.41)	<.001	–4.82 (–13.38 to 3.74)	.270
24 wk postop	125.50 ± 1.44	121.74 ± 1.54			42.31 (35.77 to 48.88)	<.001	–3.30 (–12.07 to 5.46)	.460
Passive knee flex, deg								
2 wk postop	93.91 ± 3.02	88.44 ± 3.50	5.47 (–3.57 to 14.50)	.236	—	—	—	—
6 wk postop	127.84 ± 0.77	123.34 ± 2.73			34.90 (27.33 to 42.46)	<.001	–0.96 (–9.95 to 8.04)	.834
12 wk postop	135.24 ± 1.61	131.77 ± 1.12			43.34 (36.38 to 50.29)	<.001	–2.00 (–11.55 to 7.54)	.681
24 wk postop	135.62 ± 0.90	133.84 ± 0.89			45.40 (38.34 to 52.45)	<.001	–3.68 (–13.29 to 5.93)	.452
QT strength, %BW								
2 wk postop	1.87 ± 0.22	1.99 ± 0.19	–0.12 (–0.69 to 0.46)	.696	—	—	—	—
6 wk postop	3.24 ± 0.19	2.79 ± 0.19			0.81 (0.54 to 1.07)	<.001	0.57 (0.14 to 0.99)	.009[e]
12 wk postop	4.41 ± 0.30	3.55 ± 0.20			1.57 (1.17 to 1.97)	<.001	0.97 (0.35 to 1.59)	.002[e]
24 wk postop	5.21 ± 0.29	4.07 ± 0.26			2.08 (1.64 to 2.52)	<.001	1.25 (0.62 to 1.89)	<.001[e]
HT strength, %BW								
2 wk postop	1.13 ± 0.09	1.04 ± 0.10	0.10 (–0.16 to 0.35)	.472	—	—	—	—
6 wk postop	2.16 ± 0.12	1.86 ± 0.12			0.83 (0.61 to 1.04)	<.001	0.21 (–0.08 to 0.49)	.159
12 wk postop	2.55 ± 0.16	2.32 ± 0.14			1.29 (1.02 to 1.56)	<.001	0.13 (–0.25 to 0.51)	.503
24 wk postop	2.97 ± 0.15	2.79 ± 0.20			1.75 (1.37 to 2.13)	<.001	0.09 (–0.35 to 0.53)	.693
QI, %								
2 wk postop	43.25 ± 4.41	45.94 ± 3.91	–2.69 (–14.25 to 8.88)	.649	—	—	—	—
6 wk postop	65.34 ± 3.69	63.58 ± 3.02			17.65 (10.49 to 24.80)	<.001	4.45 (–5.78 to 14.69)	.394
12 wk postop	80.93 ± 3.34	78.42 ± 3.07			32.48 (24.48 to 40.49)	<.001	5.20 (–6.75 to 17.15)	.393
24 wk postop	92.03 ± 3.36	80.89 ± 3.42			34.95 (26.13 to 43.77)	<.001	13.83 (0.04 to 27.63)	.049

[a]The control group (group = 0) and the baseline (ie, week 2) measurement (time = 0) were the reference categories in the generalized estimating model, adjusting for age and sex. Dashes indicate areas not applicable. BW, body weight; EQ-5D-5L, EuroQol 5-Dimension 5-Level; ext, extension; flex, flexion; HT, hamstrings; NRS, numeric rating scale; postop, postoperative; QI, quadriceps index; QT, quadriceps.

[b]Group effect was defined as group differences at baseline (2 weeks postoperatively) between groups.

[c]Time effect was defined as the change in values for the control group at 6, 12, and 24 weeks compared with 2 weeks (baseline).

[d]Group × time effect at 6, 12, and 24 weeks was defined as the additional change in values for the intervention group compared with the control group at 6, 12, and 24 weeks, respectively.

[e]Statistically significant ($P < .016$).

We observed increased quadriceps isometric strength of the surgical limb at 6 weeks to 24 weeks follow-up in the intervention group compared with the control group, but there were no significant group differences in the QI, IKDC scores, or single-leg hop test LSI. Based on our findings, the strength of the nonsurgical limb in the intervention group significantly improved at all time points from 2 weeks onward. In contrast, the strength in the control group showed a significant change only at 24 weeks compared with 2 weeks. During the early stages after ACLR, the extent of changes in both limbs differed between the groups, although no significant interaction was observed in the strength of the nonsurgical limb. Previous studies have reported variable degrees of associations between isometric strength values of the surgical limb measured in different ways and single-leg hop test results or patient-reported outcomes (such as the IKDC) in the late stages of recovery due to the nature of the measurements, or at long-term, extending beyond the span of 1 to 2 years after ACLR.[9,12,22,23,32,37,38,45] Although the strength of the surgical limb improved in terms of raw data, patients could not perceive the effect of the improvement on their activities of daily living. Considering the timing of the outcome evaluations, the total number of participants assessed for functional performance at 24 weeks had decreased, which potentially affected the study's statistical power. Finally, similar to an exergaming study for strengthening,[10] our intervention was able to induce more accurate exercise performance and muscle strengthening by providing scores on performance and accuracy and a visual target point. Also, we encouraged the patients in the intervention group to exercise regularly during remote monitoring, and as a result, it may have motivated them to exercise more.

Limitations

The limitations of this study and suggestions for future research are as follows. Most of the participants were men and enrolled mainly at a single institution, and it is difficult to generalize the results due to the small number of participants and only 6 months of follow-up. In a study[15] that provided ACLR patients and physical therapists with a web-based program and confirmed their acceptance, the physical therapists suggested functions such as patient-centered goal setting, notifications, and feedback according to goal achievement. They believed that, if added, these functions would help to promote participation in rehabilitation. Moreover, measuring potential factors influencing adherence and participation,[48] including sociodemographic characteristics, preoperative sports activity level, experience with digital health care devices, and self-efficacy, will help identify suitable patients for technology-assisted rehabilitation. Because of the characteristics of the tertiary hospital in which this study was conducted, it was difficult to recruit patients who underwent only ACLR. Most patients had a complex operation or rereconstruction by reinjury. Given the rehabilitation protocol according to the surgical method, we extended the selection criteria and attempted to ensure external validity. Our study is meaningful because it examined the effect in patients who underwent mixed surgery along with primary ACLR. In addition, AR-based rehabilitation exercises did not have any side effects during the period when the graft was believed to be most vulnerable. The development of an exercise program that can be safely performed in a home environment to prevent secondary injuries may have contributed to these results.

CONCLUSION

Taken together, AR-based telerehabilitation at home in the short term was found to yield comparable improvements to brochure-based rehabilitation in terms of patient-reported outcomes and functional performance measures during the early stages after ACLR. In addition, it was associated with a quicker recovery of knee extensor strength in this study.

ORCID iD

Ji Hye Hwang https://orcid.org/0000-0002-8176-3354

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