INTRODUCTION

One of the most important goals of the rehabilitation process after anterior cruciate ligament (ACL) reconstruction is to reduce the risk of a second ACL injury. Numerous factors affect the likelihood of a second ACL injury, including surgical technique, choice of graft, and the effectiveness of postoperative rehabilitation and patient education. One study also reported that age and sports activity level are key factors in the occurrence of a second ACL injury after ACL reconstruction. Physical therapists can use several treatment...
modalities during postoperative rehabilitation. Some studies have suggested that postoperative rehabilitation should include neuromuscular training to improve outcomes after surgery. Research on the prevention of ACL re-injury has focused on identifying the relevant risk factors, including neuromuscular and biomechanical factors. Modifiable neuromuscular and biomechanical risk factors have been found to contribute to increased risk of a second ACL injury. Addressing these factors in athletes after ACL reconstruction using targeted rehabilitation may significantly reduce the incidence of second ACL injury and subsequent functional disability.

The hybrid assistive limb (HAL) is a wearable exoskeleton robot suit that provides real-time assistance to an individual for walking and limb movements through actuators mounted on the hip and knee joints bilaterally. A single-joint hybrid assistive limb (HAL-SJ) has been developed for use in rehabilitation training. Studies have shown that knee rehabilitation training using an HAL-SJ improves functional outcomes in patients after total knee arthroplasty or opening wedge high tibial osteotomy. In a case report of a patient who had undergone ACL reconstruction, HAL was applied to the knee and showed efficacy improvement in some of the most commonly used clinical scores, in particular, the limb symmetry index (LSI) for peak extension and flexion torque.

HAL training has the potential to be effective in patients with neuromuscular impairment. The HAL-SJ has a bioelectric signal-balancing capability that can adjust the balance of the detected flexion and extension signals by means of computer processing. Knee rehabilitation training using the HAL-SJ could provide useful biofeedback to avoid erroneous motor learning. Therefore, we hypothesized that knee rehabilitation training using the HAL-SJ could be a novel rehabilitation treatment modality for patients after ACL reconstruction. To our knowledge, there has been no clinical trial on the application of the HAL-SJ in patients who have undergone ACL reconstruction. In this study, we investigated the feasibility and safety of knee training with the HAL-SJ after ACL reconstruction and whether use of this device can improve functional outcomes.

MATERIALS AND METHODS

Patients

We performed an open-label prospective trial in our institution between April 2019 and October 2020 with a postoperative follow-up period of 6 months. Within that time period, all patients who had undergone arthroscopic ACL reconstruction were assessed for eligibility. The inclusion criteria for the current study were as follows: a primary ACL injury, unilateral ACL reconstruction, ability to understand an explanation of the study and provide informed consent, and availability for observation throughout the study. Patients with multiple knee ligament injuries, those for whom wearing and training using the HAL-SJ was expected to be difficult because of underlying disease, and those with perioperative complications were excluded. During the study period, a total of 38 patients underwent arthroscopic ACL reconstruction and 27 of these were excluded. Consequently, this study included 11 patients (six men, five women; mean age, 25 ± 8.4 years; height, 167.6 ± 8.4 cm; weight, 68.4 ± 11.0 kg) who had undergone arthroscopic ACL reconstruction with soft tissue graft materials (anatomic single-bundle, n=9; anatomic double-bundle, n=2). The semitendinosus tendon alone or both the semitendinosus and gracilis tendons were harvested and used as multi-stranded grafts. The tendon graft was hooked to the Ultrabutton adjustable-loop device (Smith & Nephew Endoscopy, Andover, MA, USA) on the femoral side. The tibial end of the graft was sutured using a double-spike plate and screw (Smith & Nephew Endoscopy) with an initial tension of 20 N or 30 N using a tension meter at 20° or 30° of knee flexion. The femoral and tibial bone tunnels were anatomically created at the tibial and femoral insertions of the ACL using the outside-in tunnel technique. Three of the 11 patients had a concomitant meniscus injury that was partially removed or repaired; consequently, ACL reconstruction only was performed in eight patients, and lateral meniscus repair, medial meniscus repair, and partial lateral meniscectomy were performed in one patient each. Three patients played soccer, two played handball, one played basketball, one was a skier, one played tennis, one was a javelin thrower, and two played only recreational sports. After surgery, all patients underwent rehabilitation training by a physical therapist starting on postoperative day 1. Range of motion (ROM) and weight-bearing exercises were started on postoperative day 5. If patients had partially repaired menisci, ROM and weight-bearing exercises were not started until 1 week after surgery. Post-discharge, a physical therapist or an athletic trainer administered the rehabilitation program once a week, comprising closed and open kinetic chain exercises, hip and knee muscle strength training, neuromuscular training, neuromuscular electrical stimulation, and cryotherapy for the ACL-reconstructed leg. After 3 months follow-up postoperatively, patients who participated in competitive sports continued to receive the rehabilitation program two or three times per month. In contrast,
patients who participated in recreational sports received the rehabilitation program once a month. In an effort to increase the external validity of the findings, we did not control the rehabilitation program. Table 1 summarizes the patients’ clinical characteristics.

The study was conducted with the approval of the ethics committees of Tsukuba University Faculty of Medicine (approval number TCRB18-077) and Ibaraki Prefectural University of Health Sciences (approval code: e119) and was performed in accordance with the Declaration of Helsinki. All patients provided written informed consent before enrollment in the study.

Knee HAL-SJ Training

The HAL-SJ is a wearable exoskeleton-type robot that provides voluntary assistive training using an actuator on the lateral side of the knee joint and using muscle action potentials detected from the middle fibers of the quadriceps and hamstrings.\(^8,9\) Surface electrodes were attached to the quadriceps and hamstring muscles (vastus medialis [VM], rectus femoris, vastus lateralis [VL], and biceps femoris [BF], and the medial hamstrings) to evaluate the bioelectrical activity from the long axis (along the belly) of each muscle. Knee HAL-SJ training commenced 18 weeks after ACL reconstruction to avoid the risk of laxity of graft tension, partial graft tear, and poor synovial coverage.\(^1,12\) HAL-SJ training was performed once a week for a total of three sessions. Prior to setup, the physical therapist measured the patient’s femoral and lower limb length, hip and ankle width, and ACL-reconstructed leg maximum active flexion and extension ROM. With the patient seated, the therapist fitted the leg attachments and ankle support (fitting time, 3–5 min). After measuring maximum active flexion and extension angles prior to the intervention, the physical therapist set the knee HAL-SJ assist angle to prevent over-assisting. During knee extension training, the patient was seated at the end of a bed. For knee flexion training, the patient remained in the prone position on the bed (Fig. 1). Five sets of HAL-training-assisted knee extension and flexion exercises were performed (10 exercises/set, a total of 50 exercises).\(^10\) Each weekly session lasted approximately 50 min, including fitting and evaluation. Patients underwent conventional knee rehabilitation on the non-HAL training days. Details of the knee HAL-SJ training setup are shown in Fig. 1.

Adverse Events

Adverse events were defined as any undesirable symptom after ACL reconstruction, such as severe pain, fracture, infection, arthritis, skin problems, and a tear or sprain of the ACL graft that was not specifically related to knee HAL training.

Measurements

Physical evaluations were conducted at postoperative week 17 (pre-HAL) and at postoperative week 21 (post-HAL).\(^10\) Isokinetic assessment was performed at 60°/s, 180°/s, and 300°/s using an isokinetic dynamometer (Biodex System III; Biodex Medical Systems, Sakai, Tokyo, Japan), and strength during knee extension and flexion was measured bilaterally. The LSI was calculated to determine whether the side-to-side difference could be classified as normal or abnormal.\(^13\) The LSI was defined as the ratio of the injured side to the

| Patient no. | Age (years) | Sex | Height (cm) | Weight (kg) | Surgical procedure | Sports level |
|-------------|-------------|-----|-------------|-------------|-------------------|--------------|
| 1           | 33          | Male| 177         | 81.1        | ACLR + MMR        | Recreational |
| 2           | 21          | Male| 165.6       | 74.9        | ACLR              | Recreational |
| 3           | 23          | Male| 172         | 82          | ACLR              | Competitive  |
| 4           | 21          | Female| 157.5      | 55          | ACLR              | Recreational |
| 5           | 19          | Female| 160.6      | 54.6        | ACLR              | Recreational |
| 6           | 26          | Male| 175.2       | 79          | ACLR              | Competitive  |
| 7           | 20          | Female| 162        | 56.6        | ACLR              | Competitive  |
| 8           | 25          | Male| 176.3       | 77.4        | ACLR + PLM        | Competitive  |
| 9           | 21          | Male| 178.3       | 68          | ACLR              | Recreational |
| 10          | 47          | Female| 164.5      | 65          | ACLR + LMR        | Recreational |
| 11          | 19          | Female| 155        | 58.4        | ACLR              | Competitive  |

ACLR, anterior cruciate ligament reconstruction; MMR, medial meniscus repair; LMR, lateral meniscus repair; PLM, partial lateral meniscectomy.
non-injured side and expressed as a percentage (injured/non-injured×100%).

ACL graft tears and anterior knee laxity were assessed using the pivot shift and Lachman’s test. The active and passive ROM, the Tegner Activity Scale score (where work and sport activities are graded numerically), the Lysholm Knee Questionnaire score (a 100-point scoring system for examining a patient’s knee-specific symptoms), and the International Knee Documentation Committee subjective knee form score (a scoring system to quantify the disability caused by ACL injury) were also measured. All patients were observed for adverse events during the study period.

Collection and Analysis of Surface Electromyography Signals

We measured the surface electromyography (EMG) signals from the quadriceps and hamstring muscle groups to evaluate neuromuscular impairment and whether it was affected by HAL. Surface EMG measurements were obtained for patients 7, 8, 9, and 11. The measuring system comprised a four-channel MyoSystem EMG unit (Noraxon, Scottsdale, AZ, USA) and bipolar Ag–AgCl surface electrodes, each measuring 1 cm in diameter with a center-to-center distance of 2.5 cm.

The skin was wiped with alcohol before applying the surface electrodes to reduce skin impedance. Pairs of surface electrodes with a diameter of 1 cm and center-to-center spacing of 2.5 cm were applied to the dominant limb. The EMG electrodes were placed on the VL and VM muscles of the quadriceps femoris and the BF and semitendinosus (ST) muscles representing the lateral and medial hamstring muscle groups, respectively. Electrode placement on the examined muscles was based on the SENIAM recommendations.

Evaluations were conducted during each weekly knee HAL training session. During each session, ten repetitions of open-chain knee extension and flexion with EMG evaluations were conducted and recorded before and after knee HAL training. All EMG signals were filtered with a band-pass filter (50–500 Hz) and then rectified and smoothed using a symmetrical moving root mean square (RMS) filter of 100 ms. The RMS EMG amplitude was normalized to the peak EMG signal from the isometric maximal voluntary contraction (MVC). All contractions were completed while seated in the Biodex System III according to the MVC protocol. Before data analysis, all results were normalized by calculating them as percentages of their MVC, after which the EMG of each evaluation was time-normalized to...
100 points. The normalized open-chain knee extension and flexion EMGs were analyzed at each point. The muscle co-contraction index (CCI) was calculated using the average muscle amplitude and the following formula:

\[
CCI = \frac{LEMG}{HEMG} \left( \frac{LEMG + HEMG}{2} \right)
\]

where LEMG is the normalized magnitude of the RMS EMG amplitude for the less active muscle and HEMG is the normalized magnitude of the RMS EMG amplitude for the more active muscle. The CCI was calculated at each point of the evaluation, and the mean CCI was calculated for the lateral hamstring and quadriceps muscles (ST–VM) and for the lateral hamstring and quadriceps muscles (BF–VL) during each trial.

**Statistical Analysis**

The normality of the data was tested using the Shapiro–Wilk test. The t-test or Wilcoxon signed-rank test was then used to evaluate differences between pre-HAL and post-HAL physical evaluations and CCI. The ROM, Tegner Activity Scale and Lysholm Knee Questionnaire scores, and CCI values were calculated as effect sizes in terms of Cohen’s d. Statistical analyses were performed using IBM SPSS Statistics 24 software (IBM, Armonk, NY, USA). The alpha level was set at 5%.

**RESULTS**

All patients completed the three weekly sessions of knee HAL training without adverse events. None of the patients developed pain, clinical signs of inflammation, or functional instability.

The Shapiro–Wilk test confirmed that the measurements followed a normal statistical distribution, except for the LSI at a peak flexion torque of 300°/s, the active ROM, the Tegner Activity Scale and Lysholm Knee Questionnaire scores, and CCI values were calculated as effect sizes in terms of Cohen’s d. Statistical analyses were performed using IBM SPSS Statistics 24 software (IBM, Armonk, NY, USA). The alpha level was set at 5%.

**DISCUSSION**

All patients successfully underwent knee HAL-SJ training during the study period with no serious adverse events. None of the patients had pain, clinical signs of inflammation, or functional instability.

Although the LSI for peak torque at 180°/s and 300°/s showed no significant difference post-HAL and pre-HAL, the LSI for peak torque at 60°/s was significantly improved after the HAL training. For strength testing, the application of knee HAL training in patients who have undergone ACL reconstruction is different from that in patients who have undergone total knee arthroplasty or high tibial osteotomy. However, the absence of serious adverse events in this study supports the notion that knee HAL-SJ training is potentially a safe rehabilitation tool for patients with ACL injury.
Significantly improved in this study. However, these improvements may have resulted from conventional training or the normal recovery from ACL reconstruction, and not from the effect of knee HAL training alone. Regarding neuromuscular function, HAL-SJ has a bioelectric signal-balancing capability that can adjust the balance of detected flexion and extension signals by means of computer processing. In the current study, the CCI for ST-VM and BF-VL in extension was not significantly different post-HAL and pre-HAL; nonetheless, these CCI results showed small or medium Cohen’s d effect sizes, which possibly reflect a change in neuromuscular function as a result of HAL-SJ training. Knee HAL-SJ training may have contributed to the results from a neurophysiological perspective by lowering co-contraction of the hamstring and quadriceps muscles, which would correct impairment of the antagonistic or synergistic muscles and help to optimize the efficiency of muscle activity and ROM during movement. Altered neuromuscular function and biomechanics are likely risk factors for a second ACL injury after ACL reconstruction. Moreover, failure of activation of the quadriceps after ACL reconstruction is not simply an isolated local phenomenon related to atrophy caused by neural inhibition. Therefore, it is important to focus on neuromuscular function after ACL reconstruction to prevent a second ACL injury and to improve the efficiency of muscle function.

In an earlier study, a gradual increase in recovery of muscle strength after ACL reconstruction was identified during the

Fig. 2. Limb symmetry index of (A) peak extension torque and (B) peak flexion torque for three angular velocities. Pre-HAL, before HAL-SJ training; Post-HAL, after HAL-SJ training.
This study had several limitations. Although one of its aims was to determine whether knee HAL-SJ training improved functional outcomes after ACL reconstruction, it was difficult to distinguish recovery as a result of ACL reconstruction itself from the effect of knee HAL training. Therefore, future studies of the efficacy of knee HAL training should include a control group. Furthermore, surface EMG measurements were obtained for only four subjects. Therefore, the mechanism underlying the response in terms of muscle function after knee HAL training from a neurophysiological perspective is unclear, and further investigations are required in a greater number of patients. Another limitation is that assessments of ACL graft tears and anterior knee laxity used only the pivot shift and Lachman’s test. However, those assessments depend on subjective factors. Therefore, objective assessment of ACL graft tears and anterior knee laxity such as KT-1000 is desirable. However, the present study is the first to demonstrate that the use of the knee HAL-SJ could be an effective training tool for patients who have undergone ACL reconstruction.

CONCLUSION

We investigated the feasibility and safety of knee HAL-SJ training.
training and whether it can improve functional outcomes after ACL reconstruction. The absence of serious adverse events in this study indicates that knee HAL-SJ training is potentially a safe rehabilitation tool for patients with an ACL injury. Knee HAL-SJ training may have contributed to the efficiency of muscle activity due to lower co-contraction of the knee muscles, which would correct impairment of the antagonistic or synergistic muscles. Our findings show that knee HAL training is a safe and feasible rehabilitation tool after ACL reconstruction.

ACKNOWLEDGMENTS

The authors thank Ms. Mayuko Sakamaki from the Center for Innovative Medicine and Engineering at the University of Tsukuba Hospital for her excellent technical assistance. This work was supported by a Grant-in-Aid for Encouragement of Scientists from the Japan Society for the Promotion of Science (grant number 20H01124) and Grants-in-Aid for Scientific Research of the Japan Society for the Promotion of Science (grant number 20K19303).

CONFLICTS OF INTEREST

The authors report that there are no conflicts of interest.

REFERENCES

1. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD: Risk of Secondary Injury in Younger Athletes After Anterior Cruciate Ligament Reconstruction: a Systematic Review and Meta-analysis. Am J Sports Med 2016;44:1861–1876. DOI:10.1177/0363546515621554, PMID:26772611
2. van Melick N, van Cingel RE, Brooijmans F, Neeter C, van Tienen T, Hullegie W, Nijhuis-van der Sanden MW: Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. Br J Sports Med 2016;50:1506–1515. DOI:10.1136/bjsports-2015-095898, PMID:27539507
3. Hewett TE, Di Stasi SL, Myer GD: Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. Am J Sports Med 2013;41:216–224. DOI:10.1177/0363546512459638, PMID:23041233
4. Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lázaro-Haro C, Cugat R: Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: A review of prevention programs aimed to modify risk factors and to reduce injury rates. Knee Surg Sports Traumatol Arthrosc 2009;17:859–879. DOI:10.1007/s00167-009-0823-z, PMID:19506834
5. Adams D, Logerstedt D, Hunter-Giordano A, Axe MJ, Snyder-Mackler L: Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. J Orthop Sports Phys Ther 2012;42:601–614. DOI:10.2519/jospt.2012.3871, PMID:22402434
6. Spindler KP, Huston LJ, Wright RW, Kaeding CC, Marx RG, Amendola A, Parker RD, Andrich JT, Reinke EK, Harrell FE Jr, Dunn WR, Pedroza A, An AQ, Schmitz L, McCarty EC, Wolf BR, Jones MH, Matava MJ, Flanigan DC, Brophy RH, Vidal AF, MOON Group: The prognosis and predictors of sports function and activity at minimum 6 years after anterior cruciate ligament reconstruction: a population cohort study. Am J Sports Med 2011;39:348–359. DOI:10.1177/0363546510383481, PMID:21084660
7. Kawamoto H, Sankai Y: Power assist method based on Phase Sequence and muscle force condition for HAL. Adv Robot 2005;19:717–734. DOI:10.1163/1568553054455103
8. Yoshioka T, Kubota S, Sugaya H, Hyodo K, Ogawa K, Taniguchi Y, Kanamori A, Sankai Y, Yamazaki M: Robotic device-assisted knee extension training during the early postoperative period after opening wedge high tibial osteotomy: a case report. J Med Case Reports 2017;11:213. DOI:10.1186/s13256-017-1367-3, PMID:28778214
9. Yoshioka T, Sugaya H, Kubota S, Onishi M, Kanamori A, Sankai Y, Yamazaki M: Knee-extension training with a single-joint hybrid assistive limb during the early postoperative period after total knee arthroplasty in a patient with osteoarthritis: a case report. J Med Case Reports 2017;11:213. DOI:10.1186/s13256-017-1367-3, PMID:28778214
10. Soma Y, Mutsuzaki H, Yoshioka T, Kubota S, Shimizu Y, Kanamori A, Yamazaki M: Rehabilitation training using a single-joint type hybrid assistive limb for the knee after anterior cruciate ligament reconstruction: an initial case report indicating safety and feasibility. J Phys Ther Sci 2021;33:84–88. DOI:10.1589/jpts.33.84, PMID:33519080
11. Aglietti P, Giron F, Losco M, Cuomo P, Ciardullo A, Mondanelli N: Comparison between single-and double-bundle anterior cruciate ligament reconstruction: a prospective, randomized, single-blinded clinical trial. Am J Sports Med 2010;38:25–34. DOI:10.1177/036354509347096, PMID:19793927

12. Goradia VK, Rochat MC, Kida M, Grana WA: Natural history of a hamstring tendon autograft used for anterior cruciate ligament reconstruction in a sheep model. Am J Sports Med 2000;28:40–46. DOI:10.1177/03635465000280011901, PMID:10653542

13. Thomeé R, Neeter C, Gustavsson A, Thomeé P, Ågustsson J, Eriksson B, Karlsson J: Variability in leg muscle power and hop performance after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 2012;20:1143–1151. DOI:10.1007/s00167-012-1912-y, PMID:22314862

14. Tegner Y, Lysholm J: Rating systems in the evaluation of knee ligament injuries. Clin Orthop Relat Res 1985;198:42–49. DOI:10.1097/00003086-198509000-00007, PMID:11018445

15. Albertus-Kajee Y, Tucker R, Derman W, Lamberts RP, Lambert MI: Alternative methods of normalising EMG during normal gait. J Electromyogr Kinesiol 2011;21:579–586. DOI:10.1016/j.jelekin.2011.03.009, PMID:21531148

16. Lubowitz JH, Bernardini BJ, Reid JB III: Current concepts review: comprehensive physical examination for instability of the knee. Am J Sports Med 2008;36:577–594. DOI:10.1177/0363546507312641, PMID:18219052