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Electromyographic examination of knee training using a hybrid assistive limb after anterior cruciate ligament reconstruction: A case report

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A B S T R A C T

Muscle co-contraction can result in higher joint contact forces, compromising knee joint mobility for stability, thus leading to impaired lower extremity neuromuscular control, delayed return to sports, and increased incidence of secondary anterior cruciate ligament (ACL) injury post-ACL reconstruction. Hybrid assistive limb (HAL) training has the potential to correct impairment of antagonistic or synergistic muscle movement of the knee joint through bioelectric signal feedback from muscle signals with computer processing. We considered that HAL training would contribute to improve peak muscle torque through coordinating or decreasing higher levels of muscle co-contractions and reducing differences between hamstring and quadriceps muscle activity on electromyography (EMG). While playing handball, a 20-year-old female injured her ACL upon landing on one leg. Two months post-injury, she underwent arthroscopic, anatomic single-bundle ACL reconstruction with a semitendinosus tendon autograft. At a 4-month follow-up, she underwent knee HAL training, which was performed once a week for three sessions. EMG data were collected during the evaluations of pre- and post-HAL training. The average muscle amplitude was used to calculate the difference between vastus lateralis (VL) and semitendinosus (ST) muscles, and the muscle co-contraction index (CCI). The CCI reflects the simultaneous activation of antagonistic muscles, which is determined for knee extensor-flexor muscle pairs. Post-knee HAL training, the CCI of the lateral hamstring and quadriceps muscles during extension was lower than that during pre-HAL training in all sessions. However, no differences were found in the CCI for the medial hamstring and quadriceps muscles during extension and flexion pre- and post-knee HAL training. For post-knee HAL training, the difference between VL and ST EMG data during a closed-chain squat was lower than that during pre-HAL training in all sessions. Knee HAL training contributed to improved peak muscle torque through coordinating or decreasing higher levels of muscle co-contractions, and it reduced differences between hamstring and quadriceps muscle activity in the ACL reconstructed leg as depicted by EMG.

1. Introduction

Anterior cruciate ligament (ACL) reconstruction is a common treatment for athletes following ACL injury,[1] and the need for evidence-based rehabilitation has increasingly been emphasized.[2] One study reported alterations in lower extremity biomechanics,

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with increased knee abduction angles in patients up to 2 years post-ACL reconstruction compared with healthy controls.[3] Another study reported that excessive knee joint valgus angles were primary predictors of non-contact ACL injury risk.[4] Deficits in neuromuscular control during dynamic movements are the principal cause of secondary ACL injuries.[5] Two studies reported that individuals with ACL deficiency utilised higher levels of muscle co-contraction than did healthy controls.[6,7] After ACL reconstruction, heightened muscle co-contraction, such as excessive quadriceps-hamstring muscle co-contraction, can result in higher joint contact forces, a tendency to decrease knee joint motion when the foot hits the ground, and knee stiffening, thereby compromising mobility for stability.[8] These adaptations may result in impaired neuromuscular control of lower extremities, delayed return to sports activities, and increased incidence of secondary ACL injury post-ACL reconstruction; therefore, neuromuscular training should be included with strength training.[9,10] However, prevention training programmes for interventions in terms of biomechanical risk factors such as lower-extremity alignment and heightened muscle co-contraction are limited.

The hybrid assistive limb (HAL) is a wearable robot exoskeleton that provides real-time assistance for walking and limb movement via actuators mounted laterally on knee joints. The single-joint HAL device is designed to facilitate voluntary knee joint motion control. Movement of the single-joint HAL is triggered through action potentials from the muscles. The power unit on the knee joint comprises angular sensors, actuators, and a control system. Several types of HALs designed specifically for the lower limbs, single joints, and lumbar support exist.[11–16] A study that investigated the efficacy of HAL applied to the knee joint in a patient who underwent ACL reconstruction reported improvements in some clinically relevant scores, including the limb symmetry index (LSI) of extension and flexion peak torque.[17] However, the contribution of knee HAL training to the outcomes remains unknown. Knee HAL training has the potential to correct impairment of antagonistic or synergistic knee joint muscle movement through feedback from muscle signals received using computer processing.[18] To our knowledge, there have been no reports on the application of HAL to the knee joint in combination with surface electromyography (EMG) use in patients who underwent ACL reconstruction. We considered that HAL training would contribute to improved peak muscle torque through coordinating or decreasing higher levels of muscle co-contractions and reducing the difference between hamstring and quadriceps muscle activity. In this case report, knee HAL training was used for a patient who underwent ACL reconstruction to report on movement behaviours and asymmetrical movement strategies, including muscle co-contraction or hamstring-quadriceps muscle coordination, using surface EMG.

2. Case presentation

A 20-year-old university student (height, 162 cm; weight, 56.6 kg) who played handball at a competitive level injured her ACL upon landing on one leg during a game, and subsequently underwent arthroscopic, anatomic single-bundle ACL reconstruction with a semitendinosus (ST) tendon autograft 2 months post-injury.

Postoperatively, she received conventional rehabilitation for 2 weeks from a physical therapist every weekday for 60 min, comprising passive range of motion (ROM), patella mobilization, isometric knee extension, neuromuscular electrical stimulation, weight bearing, and cryotherapy for the ACL reconstructed leg. Post-discharge, an athletic trainer administered the rehabilitation programme once a week for 120 min, comprising closed and open kinetic chain exercises, hip and knee muscle strengthening training, neuromuscular training, neuromuscular electrical stimulation, and cryotherapy for the ACL reconstructed leg. No major issues on rehabilitation progress were noted. At 4 months follow-up, she underwent knee HAL training.

3. Knee HAL training

The knee HAL system comprises an actuator, leg attachments, surface electrode sensor, manual controller, battery, ankle support, and control device (Fig. 1A). It is a wearable exoskeleton-type robot that provides voluntary assistive training using an actuator on the lateral side of the knee joint and muscle action potentials detected from the middle fibres of the quadriceps and hamstring muscles. Prior to setup, the physical therapist measured our patient's femoral and lower limb length, hip and ankle width, and ACL reconstructed leg maximum active flexion and extension ROM. While the patient was seated, the therapist fitted each leg attachment and ankle support (fitting time, 3–5 min). After measuring maximum active flexion and extension angles, the knee HAL assist angle was set to prevent over-assisting prior to intervention. The knee electrodes were attached to the quadriceps and hamstring muscles [vastus medialis (VM), rectus femoris, VL, and biceps femoris (BF), or the medial hamstring muscles] to detect bioelectric signals from the long axis of each muscle. Our patient was instructed to perform knee extension and flexion, thereby contracting the quadriceps and hamstring muscles.

Knee HAL training was performed once a week for a total of three sessions and commenced 18 weeks postoperatively.[17] During knee extension training, the patient was seated at the end of a bed (Fig. 1B, Video 1). For knee flexion training, she remained in a prone position on the bed (Fig. 1C, Video 1). Five sets of knee HAL training-assisted knee extension and flexion exercises were performed (10 exercises/set, a total of 50 exercises).[17] Each session lasted approximately 50 min, including fitting and evaluation. Our patient received conventional rehabilitation on the non-knee HAL training days.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.asmart.2021.12.002

4. Physical evaluations

Evaluations were conducted at postoperative week 17 (pre-HAL) and postoperative week 21 (post-HAL).[17] Isokinetic evaluation was performed at 60, 180, and 300°/s using an isokinetic dynamometer (Biodex System III; BIODEX Medical Systems, Sakai Inc., Japan). Bilateral knee extension and flexion strength were recorded, and peak values were used to calculate the LSI—defined as the ratio of the ACL reconstructed leg side to the normal leg side and expressed as a percentage (Normal leg/ACL reconstructed leg × 100% = LSI)—to determine whether side-to-side differences could be classified as normal or abnormal. An LSI of <90%, that is, >10% difference between legs following ACL injury, has been reported to be unsatisfactory in terms of muscle strength.[19] ACL tears or anterior knee laxity were assessed using the anterior drawer test, pivot shift test, Lachman's test, and KT-2000 test at manual maximum anterior tibial load. Active ROM was measured using a goniometer. Scores for the Tegner activity scale (to grade work and sport activities),[20] Lysholm knee questionnaire (to examine knee-specific symptoms),[20] and International Knee Documentation Committee subjective knee form (to quantify disability due to ACL injury)[21] were determined.

5. Surface EMG

The measuring system comprised a four-channel myosystem EMG unit (Noraxon, Inc., Scottsdale, AZ, USA) and bipolar Ag-AgCl

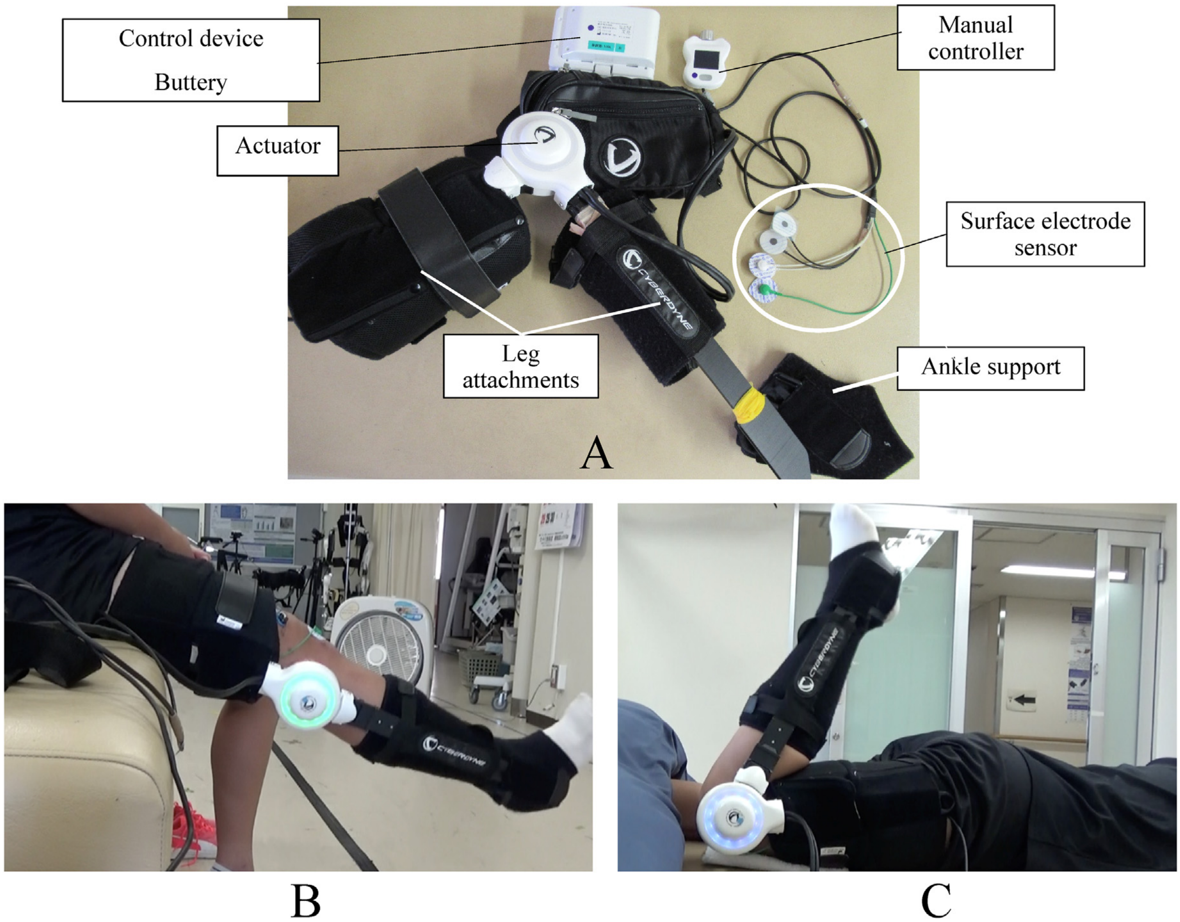

Fig. 1. **(A)** Knee hybrid assistive limb (HAL) structure. The knee HAL system comprises the following: actuator, leg attachments, surface electrode sensor, manual controller, battery, ankle support, and control device. **(B)** Extension training using the knee HAL **(C)** Flexion training using the knee HAL.

surface electrodes. To reduce impedance, the skin was wiped with alcohol before electrode application. Pairs of surface electrodes (1-cm diameter, 2.5-cm centre-to-centre spacing) were applied to the dominant limb on the VL and VM muscles of the quadriceps femoris muscle, and the BF and ST muscles, representing the lateral and medial hamstring muscle groups, respectively, based on the SENIAM recommendations.[22]

Evaluations were conducted during each knee HAL training session, where 10 repetitions of open-chain knee extension and flexion and a closed-chain squat, with EMG evaluations, were conducted and recorded pre- and post-knee HAL training. To enable EMG data normalization, maximal voluntary contraction (MVC) was performed. All contractions were completed while seated in a Biodex System III isokinetic dynamometer (BIODEX Medical Systems, Sakai Inc., Japan) according to the MVC protocol.[23,24] The patient was seated and firmly strapped at the thigh, pelvis, and torso with the hip and knee joints flexed to 80° and 60°, respectively. After familiarization with the testing procedures, our patient performed one maximal contraction for 10 s in extension and flexion directions, respectively. All EMG signals were filtered with a band-pass filter (50–500 Hz), then rectified and smoothed using a symmetrical moving root mean square (RMS) filter of 100 ms. The RMS EMG amplitude was normalised to the peak EMG signal from the isometric MVC. Prior to data analysis, all results were normalised by calculating them as percentages of their MVC (%MVC). Average %MVC value for each knee extension and flexion and the squat exercise was calculated as the arithmetic mean of 10 repetitions. EMG profiles of each exercise were time-normalised to 101 points, with 0% representing initial movement and 100% representing initial position.[25] Previous studies have indicated that reduced pre-activity of the ST in combination with elevated pre-activity of the VL during side-step cutting predisposes female handball players to noncontact ACL injury. Standardized screening of neuromuscular agonist-antagonist activity may be a promising assessment tool in preventive sports science.[26] Another study suggested that when lateral hamstring-quadriceps activation exceeds medial hamstring-quadriceps activation, ACL elongation might follow.[27] Therefore, we measured and calculated the difference between the VL and ST during a squat in terms of risk assessment and injury prevention. We also calculated the coactivation ratio of the hamstrings and quadriceps (H:Q ratio) muscles. The lateral thigh muscles were represented as BF:VL, and the medial thigh muscles were represented as ST:VM. A ratio closer to 1.0 indicates more balanced coactivation; <1.0, more quadriceps muscle activation; and >1.0, hamstrings muscle dominance. To assess whether knee HAL training improved smooth joint motion without simultaneous heightened activation of antagonistic muscles during knee extension and flexion, the muscle co-contraction index (CCI) was measured and calculated during knee extension and flexion. The average muscle amplitude was used to calculate the difference between the VL and ST muscles during a closed-chain squat, and the muscle CCI in open-chain knee extension and flexion pre- and post-knee HAL training, respectively. VL-ST difference represented a combination of EMG data from the medial hamstring muscle (ST) along with EMG data from the quadriceps muscle (VL) during a squat, indicating the magnitude of differential VL-ST EMG.

The CCI was calculated as follows:[28]

$$CCI = \frac{LEMG}{HEMG}(LEMG + HEMG)$$

where LEMG and HEMG are the normalised magnitudes of the RMS EMG amplitude for the less and more active muscles, respectively. The CCI was calculated at each point of the evaluation, and the mean CCI was calculated for the medial hamstring and quadriceps muscles (ST:VM) and lateral hamstring and quadriceps muscles (BF:VL) during each trial.

6. Results

Table 1 shows the medial and lateral hamstring and quadriceps muscle CCI during open-chain knee extension and flexion, H-Q ratio, and difference between VL and ST EMG during a closed-chain squat. The pre-HAL training CCIs of the lateral hamstring and quadriceps muscles (BF:VL) during extension were higher that the post-HAL ones (Fig. 2D). In contrast, the medial hamstring and quadriceps muscles (ST:VM) during extension and flexion and the lateral hamstring and quadriceps muscles (BF:VL) during flexion showed no differences pre- and post-knee HAL training. In all sessions, the VL EMG was lower than that in pre-knee HAL training, whereas the ST EMG increased compared to that in pre-knee HAL training. Therefore, in post-knee HAL training, the difference between the VL and ST EMG during a closed-chain squat was lower than that during pre-knee HAL training in all sessions (Fig. 2B and C), especially in session 3 (Fig. 2C). In all post-HAL training sessions, the medial thigh muscle (ST:VM) H:Q ratios were greater than those of pre-knee HAL training. However, no differences were observed for the lateral thigh muscles (BF:VL) pre- and post-knee HAL training. Table 2 shows the physical evaluation results. The peak extension and flexion torques at 180°/s and 300°/s of the LSI were both higher post-HAL training. Flexion ROM slightly improved from 132° pre-HAL training to 133° post-training. Pre- and post-HAL intervention, the anterior drawer, Pivot shift, and Lachman's test results were negative. Tegner activity scale score increased from 5 pre-HAL training to 6 post-training, Lysholm score increased from 74 pre-HAL training to 87 post-training, and KT-2000 score increased from 0 pre-HAL training to 1 post-training. The International Knee Documentation Committee subjective knee form score was A both pre- and post-training.

7. Discussion

In this case report, reductions were noted in the CCI of the lateral hamstring and quadriceps muscles during extension (post-knee HAL training) and in the difference between VL and ST EMG data during a closed-chain squat. EMG measurement of antagonistic muscle co-contraction is a common method to infer muscle and subsequent joint forces.[28] The CCI represents the weighted ratio of EMG signal intensities obtained from two antagonistic or synergistic muscles, and is usually determined for knee extensor-flexor or medial-lateral muscle pairs and then compared between post-knee injury and control patient groups.[29] Therefore, a reduction in the CCI for the hamstring and quadriceps muscles aids in optimising the efficiency of muscle activities during movement, because knee HAL training has been shown to provide useful biofeedback to avoid erroneous motor learning.[18] Our findings supported our consideration that knee HAL training would contribute to improved peak muscle torque through coordinating or decreasing higher levels of muscle co-contractions and reducing the difference between hamstring and quadriceps muscle activity surface EMG data of an injured knee with ACL reconstruction.

A previous study found that knee HAL training in a patient who underwent ACL reconstruction improved the LSI of the extension and flexion peak torque.[17] Thus, we aimed to determine how knee HAL training contributed to the results from a neurophysiological perspective, and found that it does not influence muscle strength through muscle hypertrophy. In agreement with the previous study, this case report showed an increased LSI in the extension and flexion peak torque. Knee HAL training may have facilitated improvement in muscle strength due to CCI improvement. Consequently, our patient could have used her hamstring and quadriceps muscles more efficiently during training. A previous study showed that knee muscle strength of the LSI reached >90% at least 12 months after ACL reconstruction.[19] This study evaluated the peak extension and flexion torque at 4 and 5 months, which was a shorter follow-up than that of the previous study. However, the post-HAL peak extension and flexion torque values were 180°/s and 300°/s, respectively, with the LSI reached >90%, thus supporting our consideration.

Neuromuscular and movement asymmetries have been identified as risk factors for a second ACL injury.[4] Moreover, it is suggested that reduced ST activity and elevated VL activity during side-step cutting increase the risk of future noncontact ACL rupture; hence, upregulating ST activity is recommended as an essential component of preventive neuromuscular training.[25] Knee HAL training has a bioelectric signal balancing capability, which can help adjust the balance of detected flexion and extension signals

Table 1
Results of medial and lateral hamstring and quadriceps muscle co-contraction index during knee extension and flexion and the H:Q ratio and VL-ST difference during a closed-chain squat.

Electromyography examinations		HAL session 1		HAL session 2		HAL session 3	
		pre-HAL	post-HAL	pre-HAL	post-HAL	pre-HAL	post-HAL
Co-contraction index							
Semitendinosus:	Extension	2.18	3.12	2.42	2.39	4.32	3.19
Vastus medialis	Flexion	1.30	1.09	3.14	3.36	1.37	2.23
Biceps femoris:	Extension	3.86	2.81	10.63	9.12	7.41	6.26
Vastus lateralis	Flexion	1.00	0.87	2.59	3.96	2.98	4.80
VL-ST difference		9	4.7	0.8	−1.2	22.6	16.9
H:Q ratio	ST:VM	0.67	0.76	0.84	0.94	0.58	0.77
	BF:VL	0.26	0.19	0.75	1.0	0.35	0.35

HAL, hybrid assistive limb; Pre-HAL, before knee HAL training; Post-HAL, after knee HAL training; VM, vastus medialis; VL, vastus lateralis; ST, semitendinosus; BF, biceps femoris.

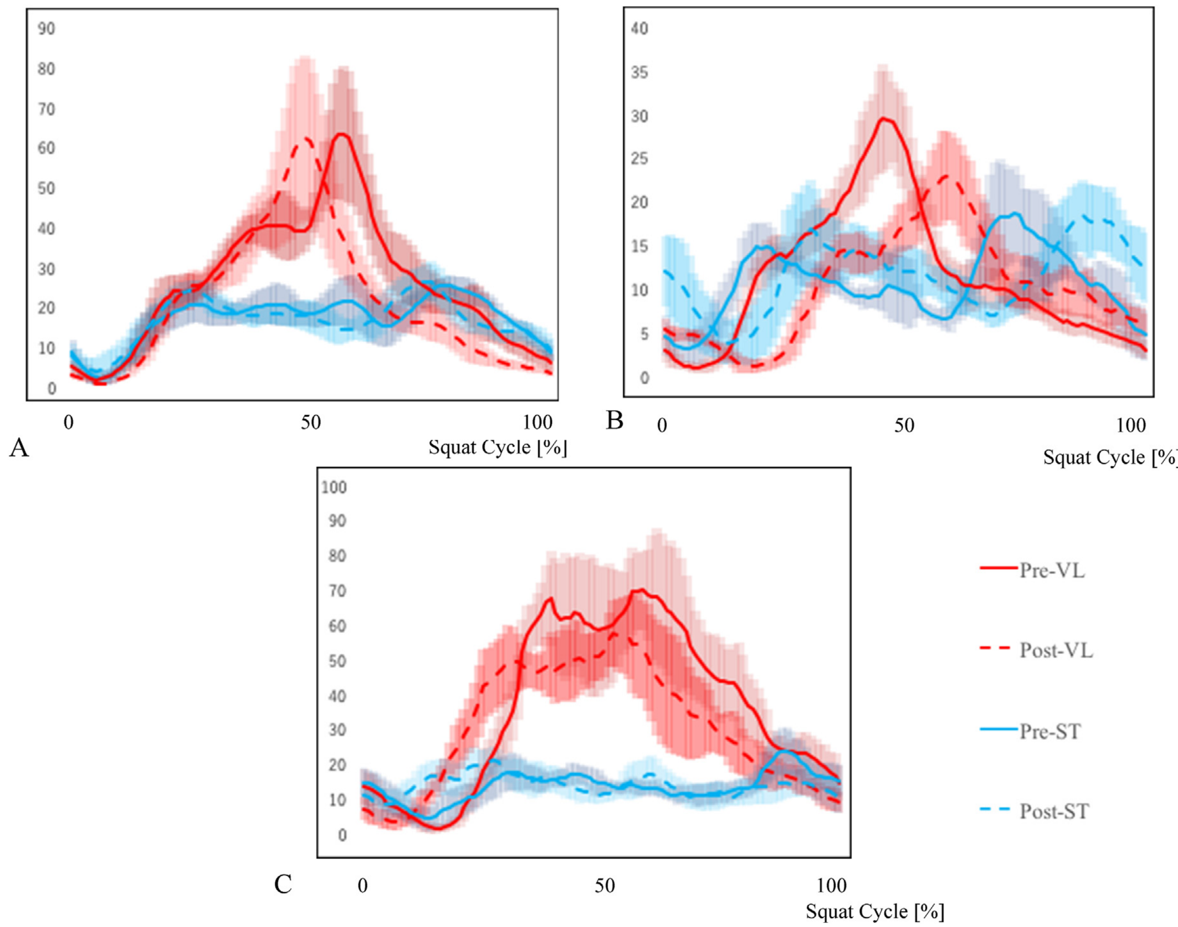

Fig. 2. Electromyography (EMG) traces for the average muscle amplitude during a closed-chain squatPre
- and post-HAL training, the difference between VL and ST EMG. **(A)** Session 1, **(B)**, Session 2, **(C)**, Session 3 pre-ST, semitendinosus pre-knee HAL training; post-ST, semitendinosus post-knee HAL training; pre-VL, vastus lateralis pre-knee HAL training; post-VL, vastus lateralis post-knee HAL training.

Table 2
Results of the physical evaluations pre- and post-HAL intervention.

Physical evaluations		pre-HAL	post-HAL
LSI peak extension torque (%)	at 60°/s	76	76
	at 180°/s	85	92
	at 300°/s	87	93
LSI peak flexion torque (%)	at 60°/s	69	68
	at 180°/s	77	94
	at 300°/s	99	127
Active range of motion (°)	extension	0	0
	flexion	132	133
Anterior drawer test result		0	0
Pivot shift test result		0	0
Lachman's test result		0	0
Tegner activity scale score		5	6
Lysholm knee questionnaire score		74	87
KT-2000 (mm)		0	1
IKDC subjective knee form score		A	A

HAL, hybrid assistive limb; IKDC, International Knee Documentation Committee; LSI, limb symmetry index; Pre-HAL, before training; Post-HAL, after training.

using computer processing.[17,18] Therefore, knee HAL training can provide useful biofeedback to improve muscle and movement asymmetries. Accordingly, it can provide neuromuscular training for patients with high agonist and antagonist muscle group activation or asymmetrical movement post-ACL reconstruction.

This case report had some limitations. Further studies with a larger sample size should investigate other neurophysiological perspectives, such as muscle timing, or compare patient groups with healthy controls. This study only assessed the difference between VL and ST EMG magnitudes; moreover, the VL EMG peak occurs at a different cycle motion. Therefore, assessments from a time to peak or a task from time perspective should be included.

8. Conclusions

Knee HAL training contributed to improved peak muscle torque through coordinating or decreasing higher levels of muscle co-contractions in our patient and decreasing the difference between ACL reconstructed leg hamstring and quadriceps muscle activity EMG data.

Ethical approval

This study was approved by the local ethics committee (approval no.: TCRB18-077). The patient provided both oral and written informed consent to participate in this study, along with informed consent for the publication of her case details and any accompanying images.

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Role of the funding sources

The funding sources had no involvement in the study.

Declaration of competing interest

The authors declare that they have no conflicts of interests.

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