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Case Report

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Robotic rehabilitation training with a newly developed upper limb single-joint Hybrid Assistive Limb (HAL-SJ) for elbow flexor reconstruction after brachial plexus injury: A report of two cases

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Abstract

This study aimed to evaluate the effectiveness and safety of using the upper limb single-joint Hybrid Assistive Limb (upper limb HAL-SJ) during elbow flexion training following elbow flexor reconstruction for brachial plexus injury (BPI). We present the cases of two patients in whom the upper limb HAL-SJ was implemented 5 and 7 months postoperatively following elbow flexor reconstruction for BPI. They underwent elbow flexor reconstruction with intercostal nerve crossing-to-musculocutaneous nerve (ICN-MCN crossing) after BPI. Postoperative training using the upper limb HAL-SJ was started from the Medical Research Council (MRC) grade 1 elbow flexion power to MRC grade 3 once every week or every 2 weeks. Both patients could implement elbow training using the upper limb HAL-SJ even in MRC grade 1 of their elbow flexion power. Training with the upper limb HAL-SJ was performed safely and effectively in two patients with elbow flexor reconstruction with ICN crossing after BPI.

Keywords

biofeedback therapy, brachial plexus injury, elbow flexor reconstruction, hand therapy, robotic rehabilitation, the upper limb single-joint Hybrid Assistive Limb (HAL-SJ)

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Introduction

Traumatic brachial plexus injury (BPI) is a severe peripheral nerve palsy resulting in upper limb dysfunction. intercostal nerve crossing-to-musculocutaneous nerve (ICN-MCN crossing) represents one method of elbow flexor reconstruction and allows approximately 60–90% of patients to actively flex their elbow against gravity postoperatively after BPI.[1–6] However, some patients have poor voluntary elbow flexion and shortening of the duration of muscle contraction even when they can perform voluntary elbow flexion postoperatively. Although the main factors in recovery include age, time from injury to operation, and surgical technique, postoperative

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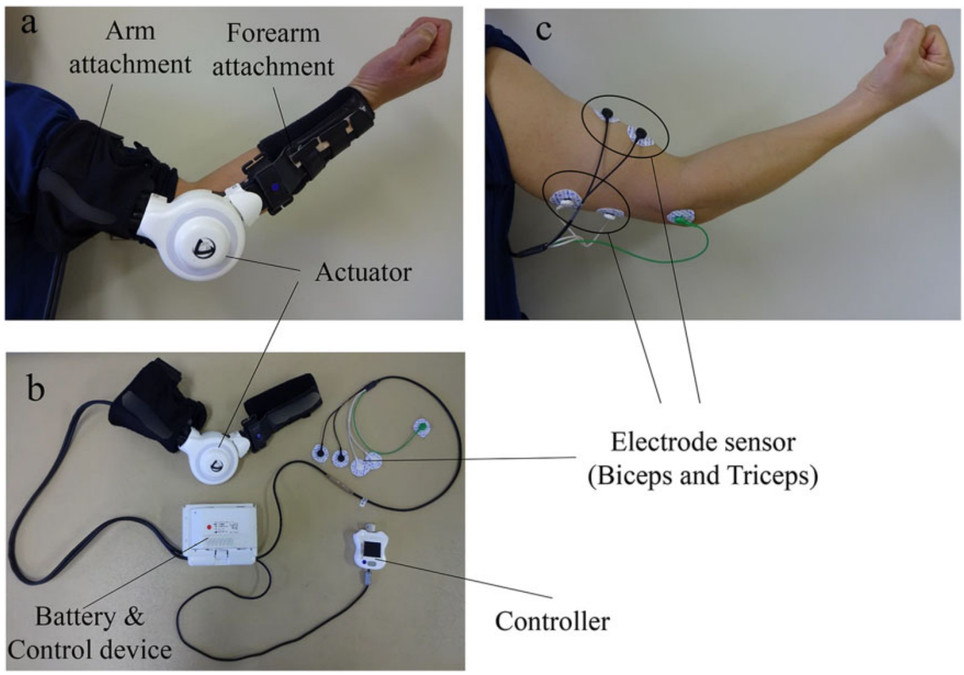

Figure 1. (a and b) The upper limb HAL-SJ. HAL-SJ consists of the actuator in the elbow joint on the lateral side, arm/forearm attachments, battery and control device, controller, and electrode sensor. (c) Surface electrode sensors on the biceps and triceps. HAL-SJ: single-joint Hybrid Assistive Limb.

rehabilitation is also an important factor in long-term recovery.[7,8] The conventional visual–audio electromyographic (EMG) biofeedback therapy is needed to obtain a good result from the rehabilitation of the arm and to support the reinnervation of the biceps approximately 6 months postoperatively, following an ICN-MCN crossing for BPI,[9] and is used to facilitate voluntary muscle contraction independently from the original function of the ICN, which innervated the respiratory muscles.

The upper limb single-joint Hybrid Assistive Limb (upper limb HAL-SJ) is a wearable robot that can support elbow flexion and extension motion (Figure 1(a) and (b)). The highest features of the upper limb HAL-SJ enable real-time voluntary elbow motion by the wearer through muscle action potentials (bioelectric signals) that are detected by surface electrodes on the anterior and posterior skin of the arm (Figure 1(c)). Therefore, the original purpose of treatment using the upper limb HAL-SJ is the application of biofeedback techniques using the robot, which enables elbow flexion training even in patients with insufficient strength to elbow flexion of Medical Research Council (MRC) grade 1.[10]

Training with the upper limb HAL-SJ following ICN-MCN crossing for BPIs has the potential to be a novel biofeedback therapy using robotic technology. The upper limb HAL-SJ has only been implemented to treat hemiplegia due to stroke.[11] Kubota et al. reported a case on patient-implemented training with the upper limb HAL-SJ following elbow flexor reconstructive surgery for BPI.[12] However, that patient was started at MRC grade 3 of elbow flexion.[12] No case report exists starting at MRC grade 1 of elbow flexion. This is the first report of treatment using the upper limb HAL-SJ starting at MRC grade 1 following elbow flexor reconstruction for BPI.

Case reports

Case 1

A 51-year-old man sustained a right traumatic BPI (whole type, C5, C6, C7 postganglionic injury, C8, Th1 preganglionic injury), right proximal humeral fracture, and fracture of the right radius and ulna in a motorcycle traffic accident. Two months after the injury, the patient underwent elbow flexor reconstruction with ICN-MCN crossing because active elbow flexion showed no apparent recovery. He received conventional rehabilitation such as range of motion (ROM) exercises of the unaffected joints and muscle training immediately postoperatively. Four months postoperatively, contraction of the biceps (MRC grade 1) was observed.

Five months postoperatively, elbow flexion training was initiated using the upper limb HAL-SJ (Figure 1(a) and (b)) once every week or every 2 weeks as an outpatient. Simultaneously, the patient also started conventional visual–audio EMG biofeedback therapy. The patient's elbow flexion power was MRC grade 1 just before the initiation of training using the upper limb HAL-SJ. The

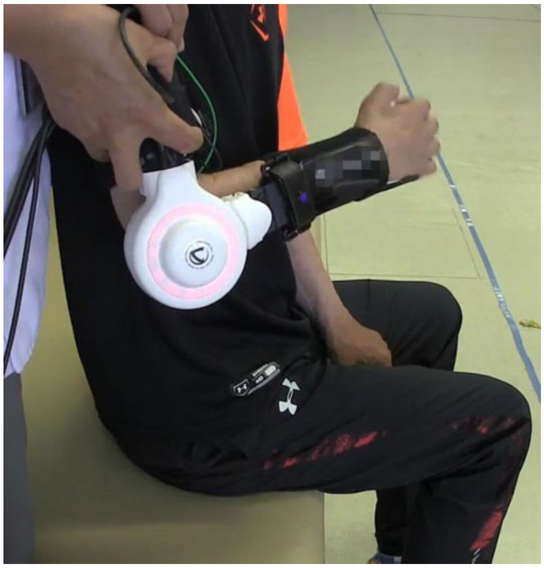

Figure 2. Elbow flexion exercises using the upper limb HAL-SJ in case 1. HAL-SJ: single-joint Hybrid Assistive Limb.

surface electrodes of HAL-SJ were attached to the biceps and triceps (Figure 1(c)). Elbow flexion exercises using the upper limb HAL-SJ were performed about 20–100 times per session in a seated position. An operator or a therapist handled the controller and supported the device during the performance of the elbow exercises (Figure 2; see Online Supplementary Video). Elbow flexion times using the upper limb HAL-SJ per session were determined according to patient factors such as fatigue, motivation, and pain. Because the just reinnervated biceps muscle demonstrated weak bioelectrical signals, the motor point of the biceps was searched on palpation. This mode was chosen because it makes it easy to detect the bioelectrical signals of the biceps. Case 1 also received conventional rehabilitation during the upper limb HAL-SJ training. However, all the muscles below the deltoid muscle did not recover while maintaining MRC grade 0 in case 1, because this patient had the whole type of BPI.

The patient was instructed to report any adverse events during training using the upper limb HAL-SJ at every session. Clinical evaluation included the MRC grade, active flexion ROM of the elbow joint, the Disability of the Arm, Shoulder, and Hand (DASH) questionnaire,[13] and the limb girth of the upper arm. The MRC grade and active flexion ROM of the elbow joint were evaluated at the start of every session. The DASH questionnaire and the limb girth of the upper arm were evaluated before and after all HAL-SJ training sessions. Active flexion ROM at the elbow joint was measured using a goniometer. The DASH questionnaire was also performed to investigate physical function and other symptoms.[13]

The upper limb HAL-SJ could be used as a feasible voluntary elbow flexion training even for MRC grade 1,

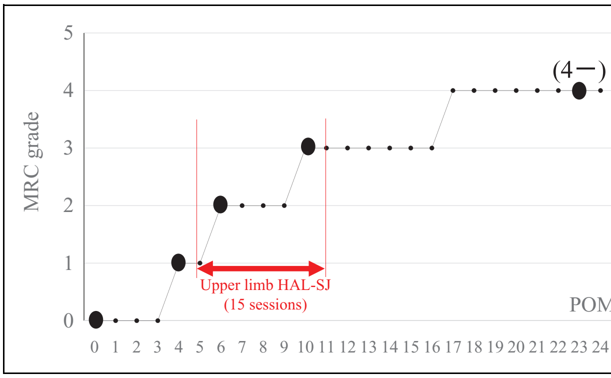

Figure 3. Change in the postoperative elbow flexion power (MRC grade) in case 1. Upper limb HAL-SJ training was implemented in 15 sessions from MRC grade 1 to MRC grade 3 in case 1. Case 1 achieved an MRC grade 4– at POM 23. HAL-SJ: single-joint Hybrid Assistive Limb; MRC: Medical Research Council; POM: postoperative month.

Figure 4. Case 1 could support 1 kg for 15 s on the arm at 90° of elbow flexion at the final HAL-SJ session (15th session) at POM 11. HAL-SJ: single-joint Hybrid Assistive Limb; POM: postoperative month.

wherein the patient could not flex his elbow due to weak bioelectrical signals detected from reinnervation of the biceps. HAL-SJ can be implemented for 15 sessions with no serious adverse events from 5 months to 11 months postoperatively. Improvement in elbow flexion power of MRC grade 3 was observed after 15 sessions using the upper limb HAL-SJ at 10 months postoperatively (Figure 3). The patient could support 1 kg for 15 s on the arm at 90° of elbow flexion at the final HAL-SJ session (15th session; Figure 4). Active flexion ROM of the elbow joint at 7, 8, and 10 months postoperatively was 10°, 65°, and 90°, respectively (Table 1). Table 1 shows the DASH questionnaire and the limb girth of the upper arm at pre–post using

Table 1. MRC grade, active flexion ROM of the elbow joint, DASH questionnaire, and limb girth of the upper arm at pre- and post-upper limb HAL-SJ training in cases 1 and 2.

	Before HAL-SJ Case 1 (POM 5)/ Case 2 (POM 7)	After HAL-SJ Case 1 (POM 11)/ Case 2 (POM 16)
MRC grade	[1]/[1]	[3]/[3]
Active flexion ROM of elbow joint (°)	0/0	90/115
DASH questionnaire	25.8/61.7	10.3/42.5
Limb girth of upper arm (cm)	21.0/20.0	20.0/23.0

HAL-SJ: single-joint Hybrid Assistive Limb; MRC: Medical Research Council; ROM: range of motion; DASH: Disability of the Arm, Shoulder, and Hand; POM: postoperative month.

HAL-SJ. The patient could support 2 kg for 20 s (MRC grade 4–) on the arm at 90° of elbow flexion at the final evaluation (23 months postoperatively and 12 months after HAL-SJ training).

Figure 5. Elbow flexion exercises using the upper limb HAL-SJ in case 2. HAL-SJ: single-joint Hybrid Assistive Limb.

Case 2

A 43-year-old man sustained a right traumatic BPI (upper type, C5, C6 preganglionic injury) and right leg incomplete amputation in a motorcycle traffic accident. On the day of the accident, below knee surgical amputation was performed on his right leg. Three months after the accident, he underwent elbow flexor reconstruction with ICN-MCN crossing. He received conventional rehabilitation with ROM exercises and muscle training of the hand, wrist, and fingers on the affected side. Six months postoperatively, reinnervation (MRC grade 1) of his biceps was detected on needle EMG examination.

Seven months postoperatively, elbow flexion training was initiated using the upper limb HAL-SJ (Figure 5) once every 2 weeks as an outpatient. The patient also started conventional visual–audio EMG biofeedback therapy at the same time. The patient's elbow flexion power was MRC grade 1 just before the initiation of training using the upper limb HAL-SJ. Elbow flexion exercises using HAL-SJ were performed about 20–100 times per session. Similar to case 1, an operator or a therapist handled the controller and supported the device during the performance of the elbow exercises (Figure 5). Similar to case 1, elbow flexion times using the upper limb HAL-SJ per session were determined according to patient factors such as fatigue, motivation, and pain. Because the immediate reinnervated biceps demonstrated weak bioelectrical signals similar to those in case 1, the motor point of the biceps was searched on palpation. The mode was chosen, which the bioelectrical signals of the triceps (MRC grade 2) do not reflect to assistive torque using HAL-SJ, since case 2 sustained a BPI of the upper type; therefore, the bioelectrical signals of the triceps could be detected. Case 2 also received conventional rehabilitation during HAL-SJ training.

Figure 6. Visual–audio EMG biofeedback therapy using a conventional biofeedback device with an elbow flexion power classified as MRC grade 1 in case 2. He learned the timing of his biceps muscle activity through visual–audio information of the surface electrode on his biceps, but he could not perform elbow motion. MRC: Medical Research Council; EMG: electromyographic.

Any adverse events during HAL-SJ training were carefully observed and evaluated at every session. In addition, a clinical evaluation of the MRC grade for elbow flexion power, active flexion ROM of the elbow joint, the DASH questionnaire, and the limb girth of the upper arm was performed similar to case 1. In the conventional visual–audio EMG biofeedback therapy (Figure 6; Myotrace 400, EM-501; Noraxon USA Inc., Scottsdale, Arizona, USA and SAKAI Medical Co., Ltd, Japan) in the 11th session of HAL-SJ training in case 2, the muscle activity

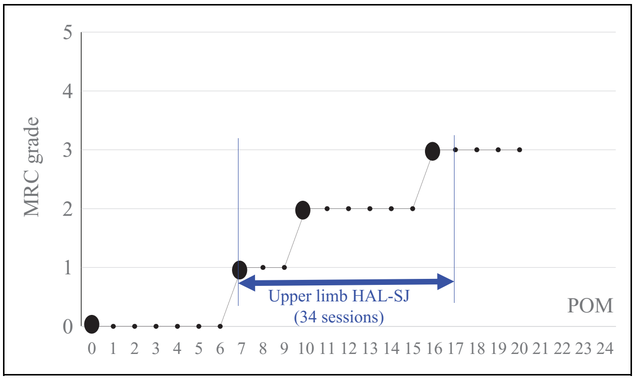

Figure 7. Change in the postoperative elbow flexion power (MRC grade) in case 2. Upper limb HAL-SJ training was implemented in 34 sessions from MRC grade 1 to MRC grade 3 in case 2. Case 2 achieved an MRC grade 3 at POM 16. HAL-SJ: single-joint Hybrid Assistive Limb; MRC: Medical Research Council; POM: postoperative month.

of the biceps and triceps during elbow flexion exercises was evaluated using a Trigo™ Lab Wireless Surface EMG system (Delsys Inc., Boston, Massachusetts, USA).

The use of the upper limb HAL-SJ shows feasibility and safety during voluntary elbow flexion training even for MRC grade 1. HAL-SJ could be implemented for 34 sessions once every 2 weeks with no serious adverse events from 7 months to 17 months postoperatively. Remarkable improvements in elbow flexion power were observed, as indicated by improvements in MRC grades from 1 to 3, after 32 sessions using the upper limb HAL-SJ at 16 months postoperatively (Figure 7). Seventeen months postoperatively, the patient could actively flex his elbow three times for 10 s after the final 34 sessions. He could also support 500 g for 15 s on the arm at 90° of elbow flexion at 16 months postoperatively. Active flexion ROM of the elbow joint at 10, 14, and 16 months postoperatively was 30°, 80°, and 115°, respectively (Figure 8 and Table 1). He could also support 1 kg for 10 s (MRC grade 3) on the arm at 90° of elbow flexion at the final evaluation (20 months postoperatively and 3 months after HAL-SJ training). Table 1 shows the DASH questionnaire and the limb girth of the upper arm. Compared to the conventional visual–audio EMG biofeedback therapy, the upper limb HAL-SJ training decreasing the muscle activity of the triceps during elbow flexion exercises was observed (Figure 9). The muscle activity of the biceps was observed to be equal in both training methods (Figure 9). Twenty-one months postoperatively, arthrodesis of the shoulder was performed for the improvement of elbow flexion.

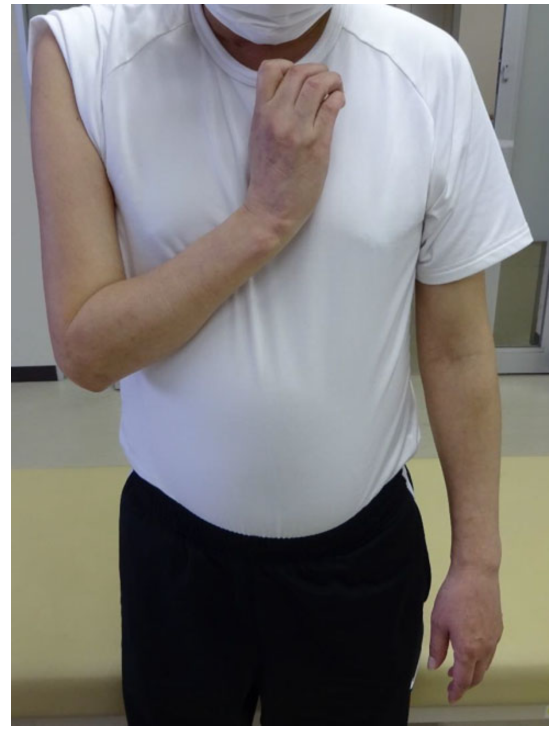

Figure 8. Elbow flexion power was observed, as indicated by improvements in MRC grades from 1 to 3 after 32 sessions using the upper limb HAL-SJ at 16 months postoperatively in case 2. Active flexion ROM of the elbow joint at 16 months postoperatively was 115°. HAL-SJ: single-joint Hybrid Assistive Limb; MRC: Medical Research Council; ROM: range of motion.

Research ethics and patient consent

The study was approved by the Institutional Review Board (IRB) of each institution involved in this study and was conducted according to the principles of the World Medical Association (WMA) Declaration of Helsinki—Ethical Principles for Medical Research Involving Human Subjects with the amendments made in Seoul, South Korea, in October 2008, with a note of clarification on paragraph 29 added by the WMA General Assembly in Washington (2002) and a note of clarification on paragraph 30 added by the WMA General Assembly in Tokyo (2004). This study was also conducted in accordance with the Japanese Medical Research Involving Human Subjects Act (WMO) and other guidelines, regulations, and acts.

This study was conducted with the approval of the Ethics Committee of the University of Tsukuba Faculty of Medicine and was registered with the University Hospital Medical Information Network (UMIN) Clinical Trials Registry (UMIN000014336).

The patient was informed about the aim and design of this study, and she provided written informed consent.

Discussion

We observed that the two patients with MRC grade 1 for elbow flexion power with elbow flexor reconstruction after BPI who received training with the upper limb HAL-SJ had no serious adverse events.

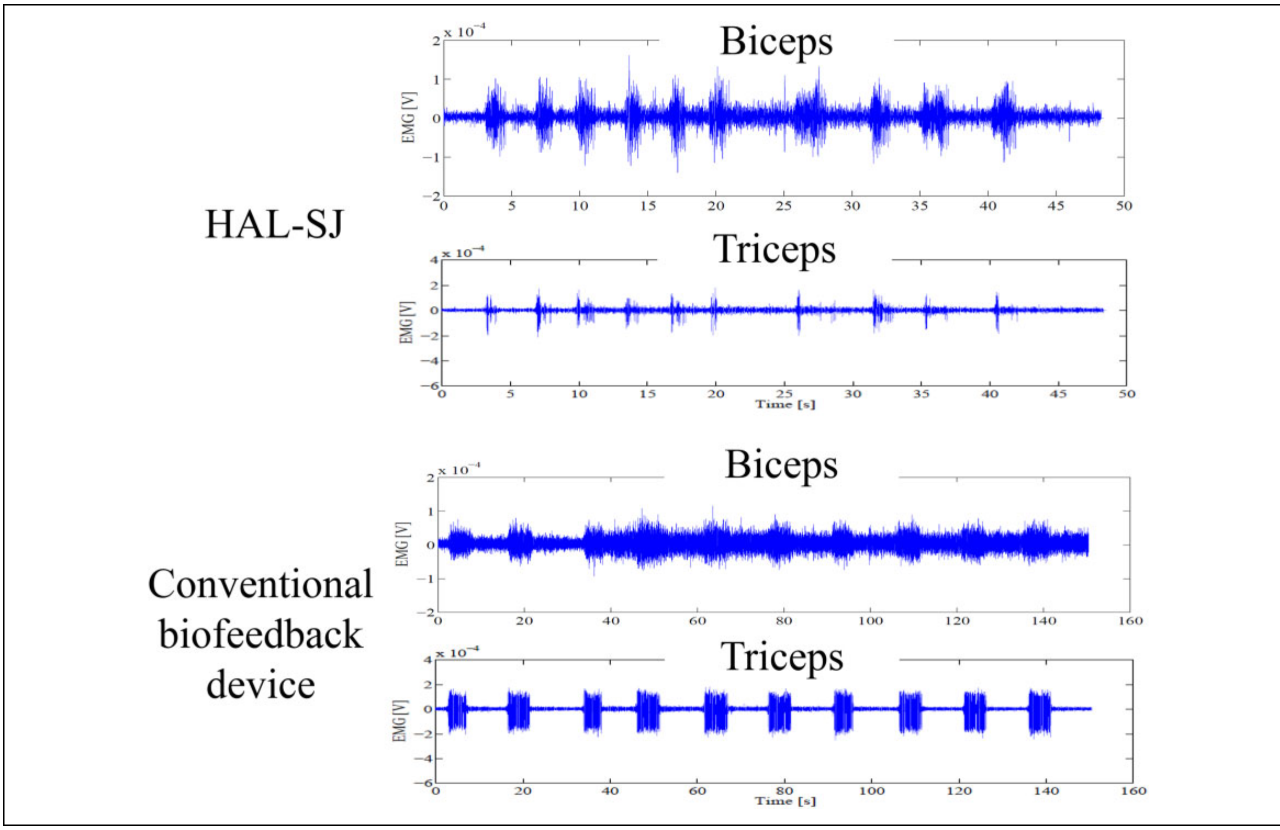

Figure 9. The muscle activity of the biceps and triceps during elbow flexion performed 10 times using HAL-SJ and a conventional visual–audio EMG biofeedback device. The upper row shows the muscle activity of the biceps and triceps during elbow flexion using HAL-SJ. The lower row shows the muscle activity of the biceps and triceps during elbow flexion using the conventional biofeedback device. Although the muscle activity of the biceps was equal when using HAL-SJ and the conventional biofeedback device, the muscle activity of the triceps (antagonist) during elbow flexion when using HAL-SJ was lower than the activity when using the conventional biofeedback device. It is suggested that HAL-SJ is a better biofeedback therapy for elbow flexion without blocking the elbow extension movement of the triceps. HAL-SJ: single-joint Hybrid Assistive Limb; EMG: electromyographic.

New biofeedback therapy techniques using the upper limb HAL-SJ also have the potential to enhance effective rehabilitation following an ICN-MCN crossing with elbow flexor reconstruction. With regard to rehabilitation after elbow flexor reconstructive surgery for BPI, if biofeedback therapy enables elbow flexion in patients with grade 1 strength on MRC, it might also be able to support visual input from real elbow flexion, thereby affecting the proprioceptors in the muscle spindle (deep sensibility), and could enable repetitive joint motion training with real muscle contraction earlier after surgery. Hence, training with the upper limb HAL-SJ might accelerate the achievement of voluntary motion of equivalent to grade 3 on MRC by stimulating changes in plasticity of the central nervous system following an ICN-MCN crossing. The upper limb HAL-SJ might also facilitate strong elbow flexor power, prolongation of the duration of muscle contraction, and shortening of the therapeutic period after surgery.

Conventional visual–audio EMG biofeedback therapy also starts with an MRC grade 1 with reinnervation of the biceps in 6–8 months after ICN-MCN crossing. Patients in this training can see and hear EMG wave and sounds on a monitor from their biceps that were recorded through a surface electrode.[14] However, the conventional visual–audio EMG biofeedback therapy cannot create voluntary elbow motion. In case 2, the muscle activity of the triceps during elbow flexion training using HAL-SJ was lower than the conventional EMG biofeedback therapy. It suggested that the muscle activity of the triceps during elbow flexion training was inhibited by assisted elbow flexion using HAL-SJ. Hence, we consider that the upper limb HAL-SJ has the potential to be an effective training in patients whose triceps activity is preserved (elbow extension) in the upper type of BPI. It might also have the potential to be an effective training for co-contractures due to misdirection phenomenon of birth palsy.

Elbow training using the upper limb HAL-SJ once every week or every 2 weeks was implemented. Cases 1 and 2 required 15 and 34 sessions, respectively. We believe that in biofeedback training using the upper limb HAL-SJ, numerous sessions (as many as possible) are necessary to facilitate voluntary muscle contraction independent of the original function of the ICN, which innervates the respiratory muscles. However, in reality, outpatients have several limitations regarding the frequency of training. We therefore propose that concentrated training using the upper limb HAL-SJ be implemented in hospital as much as possible.

Nagano et al. reported that three of eight (37.5%) patients in their study, aged 31−40 years at the time of ICN crossing, achieved MRC grade 4 elbow flexion, whereas no (0.0%) patients aged 41−50 years at the time of surgery achieved MRC grade 4.[4] Maldonado et al. reported on 31 patients who underwent ICN transfer (mean age 30.1 years at the time of surgery) and found that 8 (26.0%) patients achieved MRC grade 4 elbow flexion.[15] Coulet et al. reported on four patients from 30 years to 40 years of age at the time of surgery who underwent ICN transfer and found that no (0.0%) patients achieved MRC grade 4 elbow flexion.[2] Our patients were 51 and 43 years old at the time of surgery and achieved elbow flexion of MRC grades 4– and 3, respectively.

Conclusion

Training using the upper limb HAL-SJ was performed safely and effectively in patients with elbow flexor reconstruction with ICN crossing after a traumatic BPI. There were no serious adverse events. We anticipate that the upper limb HAL-SJ has the potential to be an effective rehabilitation tool in elbow flexor reconstruction after BPI.

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Declaration of conflicting interests

A commercial party having a direct financial interest in the results of the research supporting this article has conferred or will confer a financial benefit on one or more of the authors. Yoshiyuki Sankai is the CEO and a stockholder of Cyberdyne Inc, Ibaraki, Japan. Cyberdyne is the manufacturer of the robot suit HAL. This study was proposed by the authors. Cyberdyne was not directly involved in the study design; collection, analysis, or interpretation of data; writing the report; or the decision to submit the article for publication. No commercial party having a direct financial interest in the results of the research supporting this article has conferred or will confer a benefit on the remaining authors or on any organization with which the authors are associated (Shigeki Kubota, Hideki Kadone, Yukiyo Shimizu, Yuki Hara, Tadashi Kubo, Hiroki Watanabe, Yasushi Hada, Naoyuki Ochiai, Masashi Yamazaki).

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