Case Study

Ankle dorsiflexion training with a newly developed Hybrid Assistive Limb for a patient with foot drop caused by common peroneal nerve palsy: a case report

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Abstract. [Purpose] An ankle disorder (foot drop) caused by common peroneal nerve palsy or cerebrovascular accident (stroke) interferes with patients’ ability to walk and hinders in activities of daily living. A new robotic ankle, the Hybrid Assistive Limb, has been developed for the treatment of foot drop caused by common peroneal nerve palsy or sequelae of stroke. The purpose in this study was to report and examine the efficacy and feasibility of a case who was treated with voluntary ankle dorsiflexion training with the ankle Hybrid Assistive Limb. [Participant and Method] A 60-year-old man with foot drop due to peroneal nerve palsy that occurred without a contributory cause was treated via ankle dorsiflexion training with the use of a new robotic ankle, the “Ankle Hybrid Assistive Limb”. [Results] Following total ankle rehabilitation training with the Ankle Hybrid Assistive Limb, improvements in ankle dorsiflexor strength, gait, and sensory function of the lower leg and foot were observed. [Conclusion] The newly developed ankle Hybrid Assistive Limb could be an effective training tool for foot drop caused by common peroneal nerve palsy.

Key words: Robotic ankle rehabilitation, Ankle Hybrid Assistive Limb, Foot drop

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INTRODUCTION

Foot drop caused by common peroneal nerve palsy or an ankle disorder resulting from cerebrovascular accident is one of the factors that hinders walking and activities of daily living (ADL)1-2). The peroneal nerve is located proximal to the head of the fibula. It is vulnerable to damage caused by trauma or to compression resulting from the limb being in a poor resting position. Furthermore, it is difficult to assess the degree of the damage from the surface, and axonal regeneration occurs at a rate of 1 mm/day, which makes it difficult to decide whether to proceed with surgery or continue with follow-up observation. Open surgery is generally indicated when there is no sign of recovery following approximately six months of follow-up observation3). However, there are many patients who experience difficulty in postoperative recovery due to long-term denervation and develop permanent residual foot drop caused by common peroneal nerve palsy. Furthermore, a stroke can cause hemiplegia, a serious and disabling health problem commonly observed worldwide4). The majority of
stroke survivors suffer from sequelae such as ankle spasticity\(^5\). Therefore, it is highly desirable to alleviate ankle paresis and increase ankle dorsiflexor strength for foot drop caused by common peroneal nerve palsy and reduce ankle spasticity for ankle disorders resulting from stroke.

The Hybrid Assistive Limb (HAL) is an exoskeleton robot that provides real-time assistance to the wearer for walking and limb movements through bioelectrical potentials (myoelectric signals). These are detected from the lower limb muscle groups using actuators and surface electrode sensors mounted on both hips and knees\(^6\). There are various versions of HALs, such as a double-leg version\(^7\), single-leg version\(^8\), single-joint version (for a shoulder, elbow, or knee\(^9\)–\(^11\)), and a version for hips\(^12\). Indeed, previous studies showed the benefits of HAL gait training in cases of spinal cord injury\(^13\), acute and chronic myelopathy\(^7, 14, 15\), spinal dural arteriovenous fistula\(^16\), and spinal cord infarction\(^17\). However, there have been no reports on the use of the ankle HAL in cases of peroneal nerve palsy, and its effectiveness in this regard has not been fully investigated.

In this case report, we examined changes in the strength of ankle dorsiflexors, sensory function in the lower leg and foot, and gait after seven training session with the ankle HAL in a patient who developed foot drop due to peroneal nerve palsy.

**PARTICIPANT AND METHODS**

Following discharge from hospital after receiving treatment for liver cancer, our patient, a 60 year-old male (height: 175 cm, weight: 63.5 kg), developed sensory disturbance in the area extending from the lateral compartment of the right lower leg to the dorsum of the foot and right foot drop (Fig. 1). A lumbar magnetic resonance imaging (MRI) scan showed mild disc herniation and spinal stenosis at L3–4 but no obvious findings at the L4–5 and L5–S1 levels. As the hernia at the L3–4 level is not a cause for radicular symptoms in peroneal nerve palsy, its association with the right foot drop was disconfirmed. We conducted an MRI scan of the right lower leg and observed high signal intensity in the tibialis anterior (TA) and extensor digitorum longus (EDL) muscles, innervated by the deep peroneal nerve, as well as in the peroneus longus (PL) and peroneus shortus (PB) muscles, innervated by the superficial peroneal nerve (Fig. 2A, B). Thus, a diagnosis of common peroneal nerve palsy was made. We initiated follow-up observation and conservative treatment. Two months after the diagnosis of common peroneal nerve palsy affecting the right ankle, right ankle training with the ankle HAL was commenced at our institution (Fig. 3). Before the start of the training, we observed sensory disturbance in the area extending from the lateral compartment of the right lower leg to the dorsum of the foot. The results of manual muscle testing (MMT) of the right lower-limb muscle strength were as follows: 4− for plantar flexion, 2− for dorsiflexion, 2− for eversion, and 2− for inversion. The range of motion of the ankle was (passive/active) 45/40° during plantar flexion, 20/0° during dorsiflexion, 20/0° during eversion, and 20/0° during inversion. The maximum calf girth of the both legs were 37 cm/38 cm (right/left). The participant was able to maintain a single-leg stance with his eyes open for 8 seconds on the right leg and for 50 seconds on the left one. He could walk independently, but he walked with a cock-walk gait, often stumbling on small steps, and had an unstable gait (with a history of falls).

The ankle HAL is a wearable exoskeleton-type cyborg that is used to train plantar and dorsiflexion, and for voluntary assistive training of the ankle joint of patients with palsy using an actuator, which is placed on the lateral side of the ankle joint and detects bioelectrical signals from the tibialis anterior (TA) and gastrocnemius muscles. The ankle HAL is a newly developed wearable exoskeleton-type cyborg based on the knee/elbow single joint version HAL. First, the weaner was
placed in the sitting position on the bed. The surface electrode sensors of the HAL were then attached to the TA and gastrocnemius muscle in the sitting position. Next, the code of the surface electrode sensors was connected to that of the control device, and the therapists turned on the ankle HAL. Subsequently, the ankle HAL with shoes were attached to the weaner’s ankle while in the sitting position. After completing ankle HAL attachment, the therapists regulated the movement and assistive quantity of the HAL using a manual controller during the ankle HAL exercises. Attachment of the ankle HAL requires assistance from two persons and takes approximately 3 min to be completed. He received training with the ankle HAL once a week as an outpatient for a total of seven sessions (Fig. 3). A physical therapist supervised all of the training sessions with the ankle HAL. The training program consisted of the following four steps: (1) Confirmation of the ankle dorsiflexion exercise

Fig. 2. A: Magnetic resonance imaging (MRI) of both lower legs (coronal section of both lower legs, T2-weighted short-tau inversion recovery (STIR T2WI)) before training with the ankle Hybrid Assistive Limb (HAL), showing high signal intensity in tibialis anterior (TA), extensor digitorum longus (EDL), and peroneus shortus (PB) muscles (arrowheads). B: MRI images of both lower legs (transverse section of both lower legs, STIR T2WI) before training with the ankle HAL, showing high signal intensity in TA, EDL, peroneus longus (PL), and PB muscles (arrowheads). C: MRI images of both lower legs (coronal section of both lower legs, T2-weighted fat-saturated images (T2 FAT SAT)) one year after the completion of training with the ankle HAL. The areas with high signal intensity in TA, EDL, and PB that were observed before the training with the ankle HAL changed into areas with low to iso signal intensity (arrowheads). D: MRI images of both lower legs (transverse section of both lower legs, T2 FAT SAT) one year after the completion of training with the ankle HAL. The areas with high signal intensity in TA, EDL, PL, and PB that were observed before training with the ankle HAL changed into areas with low to iso signal intensity.

Fig. 3. Diagnosis of common peroneal nerve palsy with foot drop and the duration of the ankle Hybrid Assistive Limb (HAL) training.
prior to the training with the ankle HAL and preparation for attaching the ankle HAL (surface electrodes of the ankle HAL were attached to TA and gastrocnemius muscles), (2) ankle dorsiflexion exercise in a sitting position with the ankle HAL attached (50–70 repetitions per session) (Fig. 4 and Supplementary video), (3) ankle dorsiflexion exercise of the unaffected side, (4) guidance on self-directed exercise and lifestyle modification. A single training session with the ankle HAL took approximately 30–40 minutes.

This study was approved by the ethics committee of Kyushu Medical Sports Vocational School (No. 21005). The patient received a detailed explanation of the study, information on participation, and data usage before signing an informed consent form.

**RESULTS**

The results at baseline and after the sessions are shown in Table 1. He completed right ankle dorsiflexion training using ankle HAL training for total seven sessions (Fig. 4). After seven training sessions with the ankle HAL, we observed improvements in muscle strength (by MMT) in the right lower limb. Ankle plantar flexion grade increased from 4 to 5. Grades for dorsiflexion, external rotation, and internal rotation each increased from 2– to 4. Figure 5 showed the right maximum ankle dorsiflexion without ankle HAL after completion of all training sessions with the ankle HAL. We also observed improvements in the ankle range of motion (ROM) (passive/active). Passive ROM increased from 45° to 45° in plantar flexion, from 20° to 20° in dorsiflexion, from 20° to 20° in eversion, and from 20° to 25° in inversion. Active ROM increased from 40° to 40° in plantar flexion, from 0° to 20° in dorsiflexion, from 0° to 20° in eversion, and from 0° to 25° in inversion. We observed improvement in the maximum calf girth of the lower leg only on the right side (from 37 to 37.5 cm). The participant’s ability to maintain a single-leg stance with eyes open also improved (from 8 to 60 seconds on the right leg and from 50 to 70 seconds on the left leg). In addition, active dorsiflexion ROM improved from 0° to 5° immediately after the training with ankle HAL. Moreover, immediately after the final training session with ankle HAL, the sensation in the area extending from the lateral compartment of the right lower leg to the dorsum of the foot reverted to normal, and the abnormal sensation disappeared. However, the dorsal region of toes of the right foot remained mildly numb. Also, following the completion of all training sessions with ankle HAL, the participant’s “cock-walk” gait disappeared. He no longer stumbled on steps and was able to climb stairs and run. One year after the completion of the training with ankle HAL, the MRI scan (T2) of the participant’s right lower leg showed that the signal intensity pertaining to TA and EDL, which are innervated by the deep peroneal nerve, as well as PL and PB, which are innervated by the superficial peroneal nerve, had changed from high intensity to low- to iso signal intensity (Fig. 2 C, D).

![Fig. 4. Right ankle dorsiflexion training using the ankle Hybrid Assistive Limb (HAL) at session 1.](image)

| Muscle power of right leg (MMT) | At baseline | After the ankle HAL training |
|---------------------------------|-------------|-----------------------------|
| Plantar flexion                 | 4           | 5                           |
| Dorsiflexion                    | 2–          | 4                           |
| Eversion                        | 2–          | 4                           |
| Inversion                       | 2–          | 4                           |

| Ankle ROM (passive/active)      | At baseline | After the ankle HAL training |
|---------------------------------|-------------|-----------------------------|
| Plantar flexion                 | 45/40       | 45/40                       |
| Dorsiflexion                    | 20/0        | 20/20                       |
| Eversion                        | 20/0        | 20/20                       |
| Inversion                       | 20/0        | 25/25                       |

| Limb girth of leg (cm)          | At baseline | After the ankle HAL training |
|---------------------------------|-------------|-----------------------------|
| Right                           | 37          | 37.5                        |
| Left                            | 38          | 38                          |

MMT: manual muscle testing; ROM: range of motion; HAL: Hybrid Assistive Limb.

All these data were acquired at before (baseline) and after (after HAL) all seven sessions ankle HAL training to evaluate the effectiveness of ankle HAL training.

Table 1. Muscle power of right leg (MMT), ankle range of motion (ROM), and limb girth of leg at baseline and after the ankle Hybrid Assistive Limb (HAL) training.
DISCUSSION

In this case report, we described the use of ankle HAL in a patient with peroneal nerve palsy who showed ankle function and gait improvement. We, thus, demonstrate that ankle dorsiflexion training with the ankle HAL may be an effective method for functional rehabilitation from peroneal nerve palsy. However, further research is necessary to determine the mechanism underlying the improvements brought about by the training carried out in this study. Furthermore, in the MRI examination (T2) performed after the completion of training with the ankle HAL, the histological changes seen in the paralyzed muscles may have occurred because the signal intensity pertaining to the muscles that showed high signal intensity at the beginning of the training with the ankle HAL changed into low to iso signal intensity, the same range of signal intensity as that seen in normal muscles (Fig. 2A–D). However, reports of three cases of transient peroneal nerve palsy that occurred during head and neck surgery showed improvement following conservative treatment with oral administration of anti-inflammatory analgesics, application of poultices, and oral administration of vitamin B12\(^{18}\). As a result, all the cases were reported to have fully recovered without any sequelae such as foot drop and without the need for rehabilitation. Since it is known that spontaneous recovery is also possible in these cases, it is possible that the symptoms in our patient also improved spontaneously and not necessarily as a result of training with the ankle HAL. Moreover, the patient in our report had undergone regular rehabilitation before commencement of training with the ankle HAL. In the present case, the decrease in the ankle dorsiflexor strength and the changes in sensory function in the lower leg and foot, gait, and the MRI images may have been due to the synergistic effect of combining conventional rehabilitation with ankle dorsiflexion exercises based on the use of the ankle HAL.

Recovery from peripheral neuropathy requires a certain time period, but the interaction between the body and the environment continues during the recovery period. For this reason, patients often learn incorrect movements due to peripheral neuropathy. In the present case, foot clearance was secured with hip and knee flexor muscle groups to compensate for the inability to perform ankle dorsiflexion, which appeared as a “cock-walk” gait. Therefore, training that combines dorsiflexion exercises involving the use of motor imagery of the unaffected side and dorsiflexion exercises involving the use of the ankle HAL, which provided motor assistance in accordance with the patient’s will, may have been effective for the functional reorganization of the muscle groups innervated by the peroneal nerve. In other words, it is necessary to treat peripheral neuropathy with the aim of inducing motor learning as well as restoring muscle strength\(^{19,20}\). It is the authors’ opinion that the training with the ankle HAL, which can provide motor assistance, was an effective tool from the aspect of motor learning for the treatment of peroneal nerve palsy, a type of peripheral neuropathy. To evaluate the specific effects of the Ankle HAL, the study should be carried out with a larger group of patients with foot drop caused by ankle paresis.

In conclusion, a case of foot drop caused by common peroneal nerve palsy was treated with voluntary ankle dorsiflexion training with the ankle HAL. Improvements in dorsiflexor strength and the ROM of the ankle were observed after training with the ankle HAL. The findings of this study suggest that the newly developed ankle HAL may be an effective training tool for the treatment of foot drop caused by common peroneal nerve palsy.

Fig. 5. Right maximum ankle dorsiflexion without Hybrid Assistive Limb (HAL) after completion of all training sessions with the ankle HAL.
Funding

None.

Conflict of interest

Yoshiyuki Sankai is the CEO and stockholder of Cyberdyne Inc., Ibaraki, Japan. Cyberdyne is the manufacturer of the robotic suit HAL. This study was proposed by the authors. Cyberdyne was not directly involved in the study design; collection, analysis, or interpretation of data; preparation of the manuscript; or the decision to submit it for publication.

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