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Chapter 7

After Stroke Movement Impairments: A Review of Current Technologies for Rehabilitation

Pablo Aqueveque, Paulina Ortega, Esteban Pino, Francisco Saavedra, Enrique Germany and Britam Gómez

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http://dx.doi.org/10.5772/67577

Abstract

This chapter presents a review of the rehabilitation technologies for people who have suffered a stroke, comparing and analyzing the impact that these technologies have on their recovery in the short and long term. The problematic is presented, and motor impairments for upper and lower limbs are characterized. The goal of this chapter is to show novel trends and research for the assistance and treatment of motor impairment caused by strokes.

Keywords: stroke, hemiparesis, rehabilitation, assessment technologies, upper limb, lower limb, FES

1. Introduction

Stroke is the most common acquired neurological disease in the adult population worldwide (15 million every year [1]). Based on recently published studies, incidence of stroke in Europe at the beginning of the twenty-first century ranged from 95 to 290/100,000 per year [37]. Between 2000 and 2010, the relative rate of stroke deaths dropped by 35.8% in the United States and other countries. However, each year stroke affects nearly 800,000 individuals, becoming the first cause of chronic disability and the third cause of death. It is a global public health problem worldwide that generates a significant burden of illness for healthy life years lost due to disability and premature death.

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One-third of stroke survivors achieve only a poor functional outcome 5 years after the onset of stroke. Although there is great progress in the management of acute stroke, most of the care to reduce dependence on post-stroke patients depends on rehabilitation. Optimal functional recovery is the ultimate goal of neurorehabilitation after acute brain injury, mainly by optimizing sensorimotor performance in functional actions. New brain imaging techniques are making it clear that the neurological system is continually remodeling throughout life and after damage through experience and learning in response to activity and behavior.

Rehabilitation in stroke patients seeks to minimize the neurological deficit and its complications, encourage family, and facilitate social reintegration of the individual to ultimately improve their quality of life. Stroke rehabilitation is divided into three phases. The acute phase usually extends for the 1st weeks, where patients get treated and stabilized in a hospital and get stabilized. Subacute phase (1–6 months) is the phase where the rehabilitation process is more effective for recovering functions. In chronic phase (after 6 months), rehabilitation is meant to treat and decrease motor sequels.

The potential ability of the brain to readapt after injury is known as neuroplasticity, which is the basic mechanism underlying improvement in functional outcome after stroke. Therefore, one important goal of rehabilitation of stroke patients is the effective use of neuroplasticity for functional recovery [38].

As mentioned before, neural plasticity is the ability of nervous system to reorganize its structure, function, and connections in response to training. The type and extent of neural plasticity is task—specific, highly time-sensitive and strongly influenced by environmental factors as well as motivation and attention.

Current understanding of mechanisms underlying neural plasticity changes after stroke stems from experimental models as well as clinical studies and provides the foundation for evidence-based neurorehabilitation. Evidence accumulated during the past 2 decades together with recent advances in the field of stroke recovery clearly shows that the effects of neurorehabilitation can be enhanced by behavioral manipulations in combination with adjuvant therapies that stimulate the endogenous neural plasticity.

Nowadays, a large toolbox of training-oriented rehabilitation techniques has been developed, which allows the increase of independence and quality of life of the patients and their families [39]. The recovery of function has been shown to depend on the intensity of therapy, repetition of specified-skilled movements directed toward the motor deficits and rewarded with performance-dependent feedback.

The use of technological devices not only helps to increase these aspects but also facilitates the work of therapists in order to enhance the abilities of patients and a higher level of functional recovery. They create environments with a greater amount of sensorimotor stimuli that enhance the neuroplasticity of patients, translating into a successful functional recovery. The use of technological devices can transfer the effects of rehabilitation to the different environments where patients spend their daily life allowing a favorable social reintegration. In this chapter, a review of technologies for rehabilitation of mobility in upper and lower extremity is presented.

http://dx.doi.org/10.5772/67577

2. Motor impairments after stroke

One of the most important areas affected by stroke is motor skills. The patients may have disabilities in different degrees (mid, acute, severe), in different hemispheres (one or both), and at different levels: upper (face, neck), medium (trunk, upper limbs) and lower (lower limbs). Hemiparesis and motor recovery have been the most studied of all stroke impairments. Hemiparesis defined as muscular weakness or partial paralysis restricted to one side of the body is an impairment present in 88% of the stroke patients, affecting lower and upper limbs. Six months after stroke about 38% of patients lightly recovers dexterity in the arm and only 12% shows full recovery after conventional rehabilitation therapy [2]. Weakness and paresis are the most important impairments on the early stages after stroke as they lead to a learned nonuse of limbs. Immobility, chronic pain, and some sensory impairments can also contribute to the learned nonuse state. As the recovery progresses, spasticity and spastic co-contractions can induce some compensatory movements, which if are persistent in time and repeated may contribute to a learned bad use [3].

For healthcare organizations, it is difficult to assess in a general and accurate way the effects that a stroke can have on people given the variety of areas involved. However, there are tools that assessing in a global way the degree of disability of the condition, regardless of the area where the impairment is found. In recent times, there are new technological tools to obtain data and also there are several tests that evaluate upper limb motor functions, trunk functions, gait capacity, and spasticity. This allows health professional determine diagnosis and appropriate therapeutic interventions.

3. Upper limb problems

Many of the activities we do during the day involve using the upper limbs such as when eating, dressing, and writing. Their use is not only associated with the use of everyday instruments but also with the contact with the world and the way we interact with other people. The accomplishment of these tasks requires sequences of complex movements that integrate the activation of appropriate muscular groups and the sensorimotor coordination of the hands, which translates into an effective functional action.

Grasp and manipulation are strategies of movement that are mainly affected in stroke patients. Recent studies have found that recovery is minimal in some individuals, particularly those with a flaccid paretic limb in the first few weeks. This is why dysfunction in upper limbs is a major clinical, economic, and social problem for neurorehabilitation teams. Hemiparesis on upper limb usually affects the hand causing weakness and spasticity, leading to a decrease in movement precision, muscle fatigue, lack of coordination, and an impaired ability to grasp objects, having a great impact on daily living activities [41].

Impairments such as a decreased motor impulse, a lower frequency of neuronal activation, poor sequencing and coordination of segmental movements, and sensory deficits have a marked influence on the functional performance of the upper limb. Muscle weakness and loss of manual dexterity may be accompanied by the development of soft tissue changes and shoulder pain.

Many studies have shown that increasing therapy time in the upper limb from the acute stage reduces associated impairments and improves function satisfactorily from a clinical standpoint. This must be related to an intensity and dose of therapy appropriate to generate substantial changes.

It have been shown that patients have a better motor function when performing a specific task involving a useful interaction with an object, practice of strengthening exercises and functional actions is as important after stroke as for anyone attempting to gain strength and ability in motor actions [40].

3.1. Treatment-oriented devices and assistive devices for upper limb rehabilitation

In upper extremity rehabilitation, we can make a distinction between two categories of technologies. In the first category, we have treatment-oriented devices that are used to assist the exercises during the early rehabilitation process. The second category is made up of assistive devices, designed to aid patients in their daily living activities. Both categories may apply different therapeutic approaches, such as constraint-induced therapy, biofeedback therapy, and robot-aided therapy.

3.1.1. Treatment-oriented devices

This type of devices aims to help therapists in the flaccidity stage of hemiparesis due to the lack of neurologic connections. There is an agreement between therapists that early focused and repetitive exercise is the most important aspect for future recovery [4]. There is also evidence that early rehabilitation treatments may induce muscular reinnervation processes that can recover motor functions [5]. This category device can be subdivided into two more groups. The first consists mainly on mechanical structures to bring support to the limb and set constraints for the movements, like The Armeo® by Hocoma, and the Saebo ReJoyce (see **Figure 1**). They are used for exercising purposes promoting in this way the reinnervation of muscles in the affected limb.

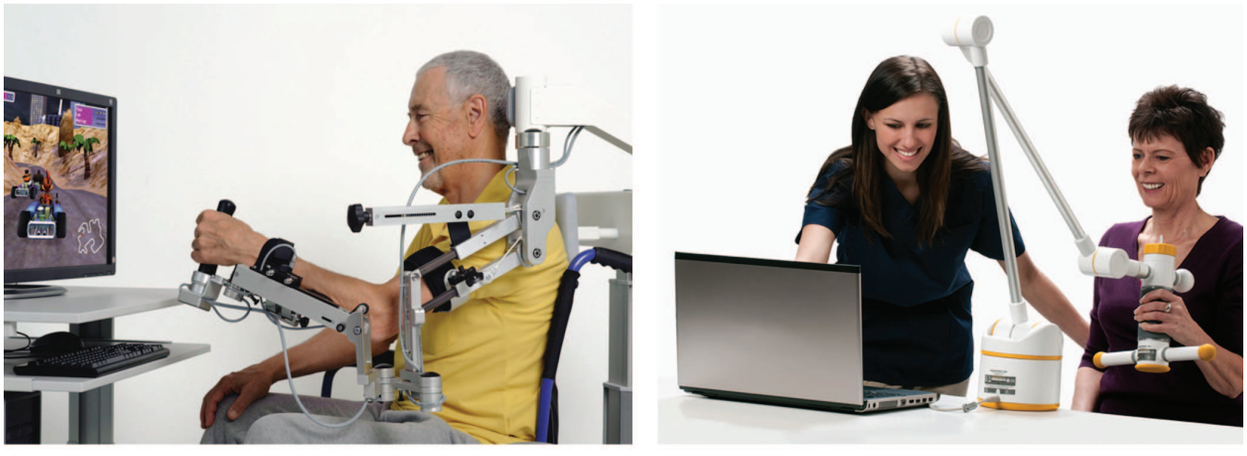

Figure 1. Mechanical treatment devices. (a) Armeo Spring and (b) Saebo ReJoyce.

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Armeo Spring is an arm and hand rehabilitation exoskeleton with 5 degree-of-freedom (three in the shoulder, one in the elbow, one in the forearm) orthosis, which covers an individual's arm to protect, achieve a larger active range of motion and automatically guide his/her therapy by applying repetitive movements in an environment in which the subject is stimulated by interactive rehabilitation methods (videos, games, and instructions). The goal of this system is to restore the movement and functionality of the affected limb in less time than conventional therapeutic methods. This system is used in individuals who have suffered from strokes, traumatic brain injury, or other neurological disorders that induce hand and arm impairments [6].

Saebo Rejoyce is an upper limb training system used in people who have suffered upper limb impairments after strokes or other neurological conditions. It is a gaming system to practice gross and fine motor tasks, simulating functions like opening doors, opening jars, grasping and turning a cup, turning a key, and manipulating coins and other small objects, assessing and tracking his performance in order to generate a progress report by session [7].

In the second group, we find therapeutic stimulators like MyoTrac Saebo Infiniti and Neuromove 900, which use functional electrical stimulation (FES) to exercise the grasping movements based on the acquisition of electromyography signals to trigger the stimulation pulse, in order to enable a more natural control using the user movement intent (see **Figure 2**) [8].

MyoTrack Infinity is a device used to reach the skeletal muscle re-education and the rehabilitation of the arm, or other parts of the body, after strokes (or other affection), through the application of electrical stimulation by the measure of a high-resolution surface electromyography.

Neuromove 900 is an electrical stimulator triggered by electromyography, sensing the muscular activity through reusable surface electrodes. The device evaluates the activity present in the muscle and then sets a higher standard that the patient should try to reach. Upon reaching the threshold, the patient is rewarded with electrical stimulation that makes the muscle move for a few seconds. Success is measured in the actual movement and gives the patient greater control over his/her extremity. It is used for stroke rehabilitation, spinal cord injury, manual, or stim only.

Figure 2. Treatment devices with FES capabilities. (a) Saebo MyoTrack Infinity and (b) Neuromove 900.

3.1.2. Assistive devices

These types of systems are designed to aid sequel patients in their daily life activities, due to chronic conditions and lack of normal movement and functions. Besides the assistive goal of these devices, they also seek to promote a long-term recovery process. As expected these types of devices are designed to be portable and wearable. We could also subdivide this category into two: the one that uses stimulation and the mechanical only device. Some commercially available devices are the Bioness NESS H200 and the Saebo Glove. The Bioness NESS H200 is an FES device that consists of an orthosis that stabilizes the wrist of the affected limb to stimulate and contract the hand. Once positioned, this device allows grasp, hold, and release by neurostimulation. The Saebo Glove and Aider Stroke Rehabilitation Glove (see **Figure 3**) are glove-shaped devices that allow the extension of the hand by the action of elastic materials, generating support in patients who present a decreased grasping strength. These systems are used in patients that can only generate a limited closing grasping function and have almost fully compromised its ability to extend-back the fingers.

Bioness NESS H200 is an electronic device that consists in an orthosis and his control unit. The control unit transmits electrical pulses to the peripheral nerves through electrodes into the orthosis, activating five muscle groups of the forearm and the hand to generate the grasping moves of the hand. The advantage of this system is that it provides a proprioceptive input to the user, facilitating the normal control of the movements of the hand. Other benefits of the use of this device are reducing the muscle spasms, increasing or maintaining range of the movements, improving the blood circulation, and retarding the atrophy of the muscle.

SaeboGlove is an orthopedic glove that facilitates the movements of grasping of the hand supporting the extension of the fingers by elastics whose tension is adjusted according to the characteristics of the individual. This system is fixed to the hand by means of two straps placed in the hand and in the forearm. It can also be combined with electrical stimulation techniques to support the hand closing movement. Individuals who had stroke, brain injury, brachial plexus injury, radial nerve palsy, individuals with limited wrist and finger extension are eligible to use this system.

Figure 3. Assistive devices for daily living support. (a) Bioness NESS H200 and (b) Saebo Glove.

http://dx.doi.org/10.5772/67577

3.2. Upper limb assessment indexes and tests

During assessment of patients, there are different indexes that therapists use to evaluate the capabilities of the upper extremity functions. Reviewing literature and clinical trials, the most used are as follows:

The *Fugl-Meyer assessment (FMA)* is a stroke-specific, performance-based impairment index. It is designed to assess motor function, balance, sensation, and joint function in patients with post-stroke hemiplegia. It is applied clinically and in research to determine disease severity, describe motor recovery, and to plan and assess treatment.

The *action research arm test* (MAS) is a performance-based scale to assess everyday motor function in patients with stroke. The MAS is based on a task-oriented approach, assessing performance of functional tasks rather than isolated patterns of movement.

The *Chedoke-McMaster stroke assessment* measures physical impairment and disability in patients with stroke and other neurological impairment. The measure consists of an impairment inventory and an activity inventory. The first inventory aims to determine the presence and severity of common physical impairments, to classify or stratify patients when planning, selecting interventions, and evaluating their effectiveness and to predict outcomes. The second inventory measures changes in physical function. The Chedoke-McMaster stroke assessment is a discriminative, predictive and evaluative tool.

The *box and blocks test* (*BBT*) is a functional test used in upper limb rehabilitation. The test is used to measure the gross manual dexterity of a patient or of a person using an upper limb prosthetic device.

3.3. Clinical evidence supporting technological devices in upper limb rehabilitation

Many studies regarding these types of systems have been reported in the literature, they all base their finding on randomized controlled trials, involving stroke patients to short-term therapies using this kind of devices and a control group subject to conventional therapy to determine whether rehabilitation protocols that use these technologies are improving the functional aspects and quality of life of stroke survivors with upper-limb deficits. In **Table 1**, we summarize some recent studies that compare hand function improvements between groups in rehabilitation with and without technological support.

As we can observe from the results above, the groups that were treated with this type of devices showed greater improvements in some of the evaluated aspects than the ones that received traditional manual therapy. Devices that offered mechanical support and mechanical movement assistance did report an increase in strength and hand reaching. This improvement can be explained by muscle recovery from atrophy state due to cyclical exercising and also to the reduced force needed to maintain the arm position from the gravity compensation, effort that can be focused on extension muscles. Other important factor to notice is the usage of FES to aid the movements in some devices. Almost every device with FES capabilities reported an improvement compared to the control groups in hand opening and reaching. An important factor to notice here is that the benefits from FES were maintained after the

Reference	Hemiparetic side	Post-stroke time	N of patients	Intervention time	Device type	Assistance type	Improvements
Krabben et al. [9]	Single side	12 months (AVG)	8	–	Assistive w/FES	GC* and FES	Hand opening
Kim et al. [10]	Single side	<6 months	30	5 weeks	Treatment w/FES	EMG-triggered NMES	RT** of hemiparetic wrist
Knutson et al. [11]	Single side	<6 months	6	6 weeks	Treatment w/FES	CCFES***	Dexterity, MAFEA****, reaching, hand opening
Knutson et al. [11]	Single side	>6 months	21	12 weeks	Treatment w/FES	CCFES***	MAFEA****
Fischer et al. [12]	Single side	<6 months	15	5 weeks	Treatment	Cyclic stretching	Strength gain,
Makowski et al. [13]	Single side	>6 months	3	–	Treatment w/FES	Arm support and FES	Hand opening and reaching

* GC, gravity compensation.

** RT, reaction time.

*** CCFES, contralaterally controlled functional electrical stimulation.

**** MAFEA, maximum active finger extension angle.

Table 1. Clinical reports for upper extremity improvements compared with traditional therapy.

interventions (follow-up tests) only when the stimulation was triggered by the user itself, such as EMG-triggered or contralaterally controlled therapy. The main idea that resides here is the treatments that involve cognitive awareness from the user generate favorable conditions in rehabilitation and promote faster motor control recovery. Motivation is a key factor that determines the achievements during rehabilitation therapies; in this way, devices that maximize cognitive engagement during the process are the ones that report the most improvements in contrast with traditional therapy. EMG-triggered devices with FES capabilities are the most promising regarding clinical results. Even though many of the clinical reports with use of technological assistive devices are relatively short-term evaluations, trends in rehabilitation achievements are positive in almost every aspect of the assessment indexes used. Long-term evaluation and clinical reports are underway as stated in many of the cited publications, considering also a most representative number of patients to obtain statistical data that would allow to validate the favorable trends observed in these studies.

4. Lower limb problems

The ability to walk independently is a prerequisite for most activities of daily living. The ability to walk in a community environment requires the ability to walk at speeds that allow the individual to cross the street in the time set by traffic lights, under or over objects or handling curbs.

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Gait dysfunction is common in individuals with neurological disorders not only due to injury-related disorders but also to the cardiovascular and musculoskeletal consequences of disuse and physical inactivity. Impairments following stroke usually involve an excessive energy cost during walking, which limits the type and duration of activities. Stroke patients are generally unable to comfortably maintain the most efficient walking speed beyond a very short distance [42]. These individuals are often restricted only to activities of daily living within confined spaces in the home and with little possibility of performing functional activities at community level, which restricts their social participation and ultimately affects their quality of life and independence. Some of the limitations that can be observed in patients with stroke are related to poor motor control, muscle weakness and/or soft tissue shortening, sensory and balance disturbances, among others. These impediments are specifically translated into pathological characteristics of gait that affect the proper sequential activation of the muscles in the different stages of gait, causing compensatory strategies that decrease gait speed and efficacy and that may increase the risk of falls from the patients.

One of the most common impairments observed in walking of stroke patients is the reduction of ankle dorsiflexion during hill contact and during the support phase associated with a hyperextension of the knee, which results in a fall of the foot during gait. This may be due to decreased activation of the anterior tibial muscle, as well as to premature activation of the calf muscles. This condition not only affects the gait speed but also limits the ability to walk in irregular ground and surfaces and go up and down stairs. This impairment is commonly known as drop foot. Drop foot is a disorder characterized by a lack of voluntary control of dorsiflexor muscles. A person with foot drop cannot lift the front of the foot before the heel comes in contact with the ground, which can cause tripping or falling. As a result, patients develop compensatory strategies including pelvic obliquity, hip hiking, and hip abduction with circumduction gait pattern to preserve foot clearance, see **Figure 4**. These strategies increase significantly the energy consumption of the person. With the objective of improving gait efficiency and safety, and overall improvement of the gait pattern to reduce musculoskeletal stress from altered biomechanics, many treatment modalities have been used. Treatment modalities include stretching, exercise, rehabilitation, orthotics, and assistive devices.

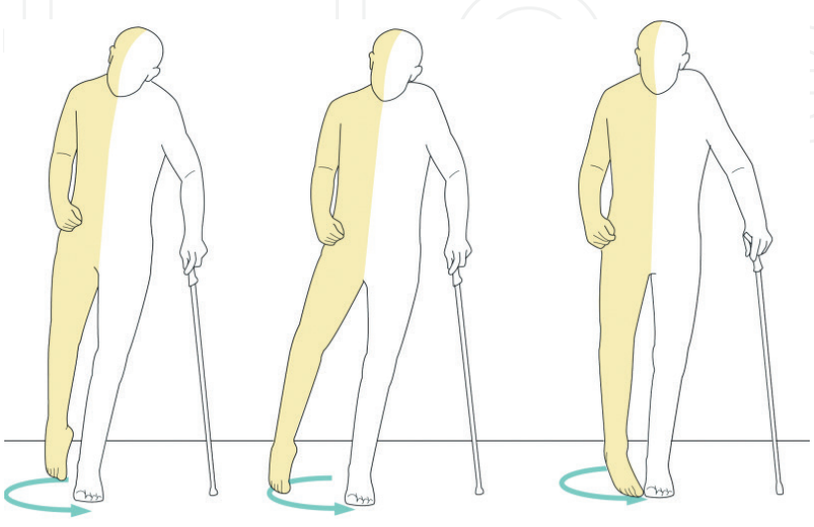

Figure 4. Walking pattern in person with drop foot [14].

4.1. Assistive technologies devices for lower limb rehabilitation

4.1.1. Ankle foot orthosis (AFO)

Regarding assistive-type technologies, the common method for the treatment of the droop is ankle-foot orthoses (AFO). In general, AFOs stabilize the foot and ankle by lifting the tip of the toes when the foot loses contact with the surface while walking, providing stability, control, and protection for the foot. Moreover, this assistive tool grants proprioceptive feedback to know the position that the foot has in space.

There are a large number of AFOs, which differ from one other according to the medical and biomechanical needs of the individual. Some types of AFOs are flexible ankle-foot orthoses, hinged ankle-foot orthoses, tubular ankle-foot orthoses, silicone ankle-foot orthoses (SAFO), Charcot restraint orthotic walker, and plantar fasciitis night-splint (see **Figure 5**).

Flexible ankle-foot orthoses are lightweight orthoses whose design prevents the foot from performing plantar flexion, preventing its fall, allowing a smooth sway of the foot without the finger dragging on the floor. In general, the shape of these orthoses depends on the needs of the user. Flexible AFOs are made with propylene plastic, with a Velcro that allows closing and fixing the orthosis to the leg. They are used for people who have suffered a stroke, multiple sclerosis, poliomyelitis, or other nerve damage.

Hinged AFOs are effective elements that are used for the control of plantar flexion, dorsi flexion, and lateral movements. Many designs are used with a wide variety of hinges, which are selected based on the requirements of the user and considerations regarding the weight and shape of the device. Hinged AFOs are used for people who suffer from droop foot such as strokes (CVA) or cerebral palsy. They are generally made of plastic.

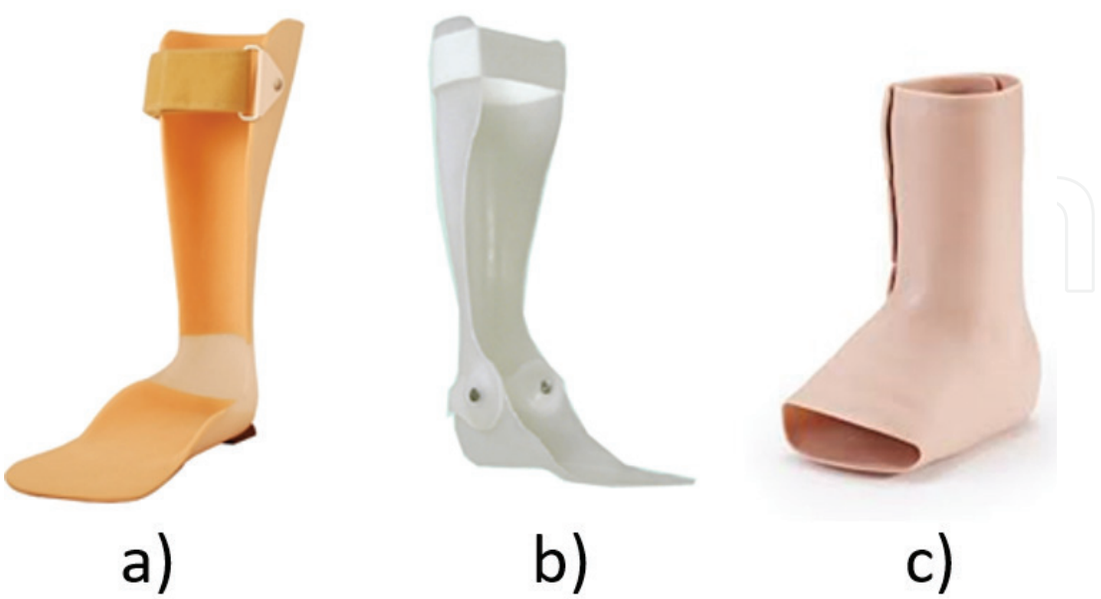

Figure 5. Ankle-foot orthoses described. (a) Flexible ankle-foot orthoses, (b) hinged ankle-foot orthoses, and (c) silicone ankle-foot orthoses.

Tubular AFOs also called circumferential AFOs enclose the leg and foot completely. The detachable strap provides great stability and protection for the leg and foot. The clamp is lined with foam and antimycotic leather to add protection for sensitive skins. Tubular AFO is most commonly used for people with diabetic complications or other peripheral neuropathies.

SAFO is a more current design, used for people who have flaccid foot paralysis as a sequel to pathologies such as Charcot-Marie-tooth disease, multiple sclerosis, poliomyelitis, stroke, and spinal cord injury. Its design offers an optimal proprioception so that the user can know and feel in a more comfortable way the position of his foot in space, giving a great control to the plantar flexion. The orthosis has a very low profile, adapting to the shape of the individual's foot, allowing it to be worn with or without shoes.

These types of elements have proven to be very useful, significantly improving the dynamics with which the gait exercise is performed [15–17]. Studies show that regardless of the material and the type of AFO used, the measurable parameters for gait exercise (cadence, joint angles, balance) do not differ from each other, the most important being the comfort and security that these elements confer to the individual at the time of choosing them.

Lately, control systems have been developed for AFOs in order to dampen the force with the foot reaches the ground in the support stage of the gait and generates a certain level of dynamics in the movement of the foot adjusting the rigidity between the foot and ankle. These systems are called *active ankle-foot orthoses* (*AAFO*) (see **Figure 6**). The control system, developed by Joaquin A. Blaya and Hugh Herr, works by applying a dynamically controlled torque to the orthosis joint, to cushion the shock of the foot on the floor while

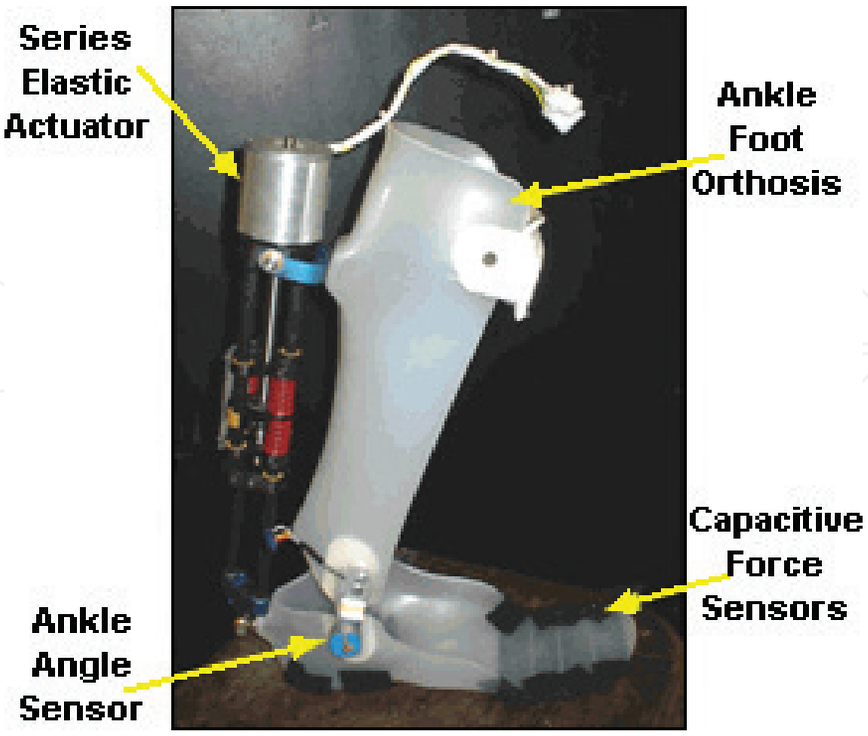

Figure 6. Active ankle-foot orthoses (AAFO) developed by Joaquin A. Blaya and Hugh Herr [18].

the foot is falling. Then, after the placement of the foot, the control system minimizes the stiffness of the orthosis to allow plantar flexion of the subject until the foot loses contact with the ground entering the swing phase of the gait, where a constant stiffness is applied to force the dorsiflexion of the foot. Tests show that the active stiffness adjustment reduces the occurrence of slap foot, allows greater powered plantar flexion, and provides for less kinematic difference during swing compared to normal, presenting a system that has clinical benefits compared to the conventional orthoses [18].

However, AFOs have a number of disadvantages and limitations, since these devices do not promote active movement, can be uncomfortable, bulky and, if misplaced, produce areas of pressure pain and tissue breakdown. This is why functional electrical stimulation (FES) is used as an alternative to AFOs.

4.1.2. Functional electrical stimulation (FES)

Functional electrical stimulation is a rehabilitation technology that uses electrical periodic pulses to stimulate the nerves that produce contractions in paralyzed muscles and recover lost functions. There are two ways to apply FES: surface FES and implanted FES.

4.1.2.1. Surface FES

Liberson in 1961 [19] proposed the use of FES to correct drop foot. He created a system that uses electrical stimulation applied to the common peroneal nerve, recruiting muscles involved in dorsiflexion and eversion of the ankle. The operation of the system is as follows: two superficial electrodes are located just below the head of the fibula bone. Using a foot switch placed in the shoe under the heel, the stimulation pulses are synchronized with the gait cycle. Then, the foot is lifted through the swing phase. The typical stimulation profile (see **Figure 7**) is often a ramping up and down of the stimulus. The rise and fall of the stimulation envelope can be adjusted to prevent a stretch reflex in the calf muscles and to prevent foot flap due to the premature ending of dorsiflexion.

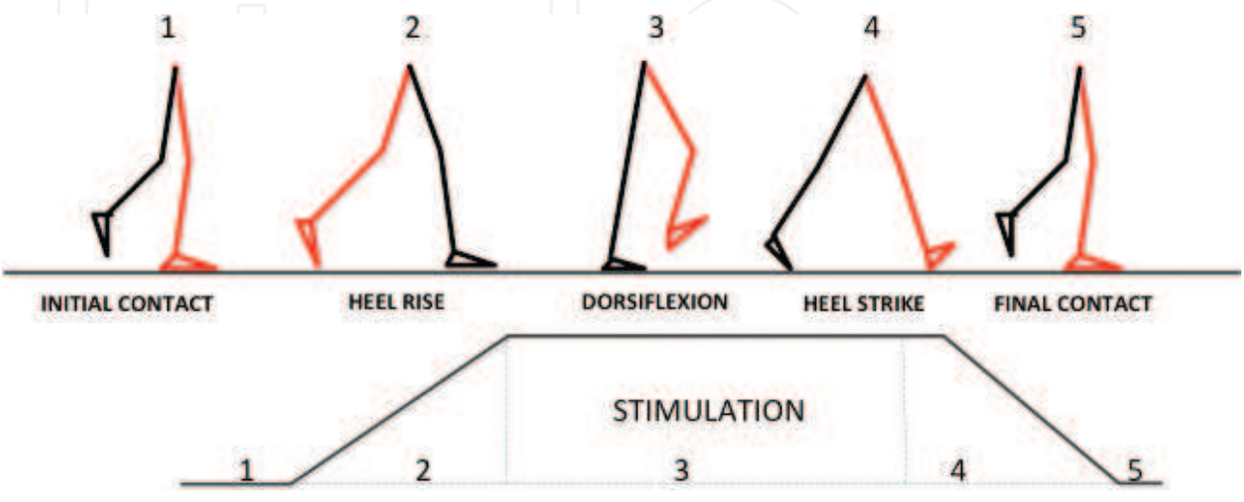

Figure 7. Typical stimulation pulse profile on drop foot FES in each stage of the gait cycle.

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The use of these devices can be classified in two ways [20]: the first is *the orthotic effect* that is the direct effect of using the FES (lift the toe). The second effect is the therapeutic effect and relates to changes in walking ability when not using FES. Although not widely used or universally available, there is growing evidence that treatment with FES improvements in gait speed, cadence, improved confidence in walking, reduction in the risk of falling, less effort during walking, and the active contraction produced by FES can help to prevent muscle atrophy.

Since, many research groups have designed and studied new stimulators that are based on the work of Liberson, creating FES devices currently commercially available, such as the Odstock dropped foot stimulator (ODFS®, Odstock Medical Limited, Salisbury, UK), the WalkAide® system (Innovative Neurotronics Inc., Austin, TX, US), the Bioness NESS L300® foot drop system (Bioness Inc., Valencia, CA, US), and the MyGait® system (Ottobock, Duderstadt, Germany).

Odstock dropped foot stimulator: The ODFS is single channel; it is controlled with a wired foot switch placed in the shoe, which is used to turn on and off the stimulation at the right time while walking (see **Figure 8a**). In 2016, a wireless version of the footswitch began to be commercialized. Typically, skin surface electrodes are placed over the common peroneal nerve as it passes over the head of the fibula bone and the motor point of the tibialis anterior.

Walkaide system: The Walkaide is also cuff-based surface stimulator (see **Figure 8b**). The main difference from other systems is that it uses an inertial gait sensor to trigger the stimulation based on acceleration thresholds. However, it has the option of a wired foot switch. Internally, it has an algorithm that auto-adjusts the parameters for each patient.

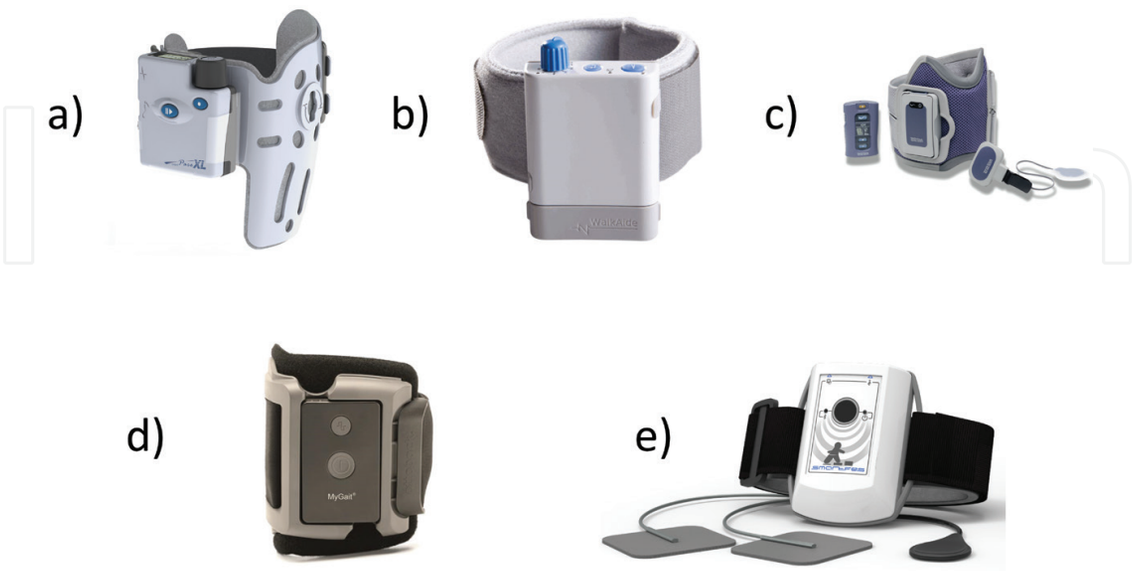

Figure 8. Surface FES systems available commercially: (a) ODFS system [21], (b) Walkaide System [22], (c) My Gait System [23], (d) Ness L300 [24], (e) SmartFES System [43].

Ness L300 system: The Ness L300 is a surface FES system that includes the stimulation unit based in a cuff, a wireless foot switch, and hand-held control for intensity control (see **Figure 8c**). Recently, the L300 plus was released. This consists of a thigh cuff to give you greater control over bending and straightening your knee, which may help you walk more naturally.

My Gait: Is the newest surface stimulator launched in 2013. It is a cuff-based surface stimulator (see **Figure 8d**). The novelty of this stimulator is that it provides two channels. The second channel is integrated and does not need an additional device. By stimulating additional muscle groups, gait performance can be further improved. It can be employed to support in flexion or extension of the knee, improved triggering of the swing phase, and minimized compensatory movements.

SmartFES: Surface stimulator launched in 2016. The SmartFES Is a low cost single channel stimulator, it is controlled with a wired foot switch placed in the shoe. The main difference from other systems is the Unit Interface (UI). The UI is implemented in an Android application and allows to modify the stimulation parameters in order to obtain the best response of dorsiflexion. The unit interface communicates via Bluetooth with the stimulator. This allows an easy and fast operation. Actually the SmartFES is being commercialized in Chile.

Table 2 summarizes the technical characteristics of the systems mentioned above.

Many research studies have demonstrated that FES combined with conventional physio leads to further improved results, compared to conventional therapy alone [25]. Taylor et al. test the ODFS stimulator in 32 subjects [26]. The results show that 71% of ODFS users were able to walk further. Additionally, it was reported that 33% of users used the device to keep them fit, 70% used the

	Ness L300®	**Walkaide®**	**ODFS Pace®**	**MyGait®**	
Manufacturer	**Bioness Neuromodulation Ltd.**	**Innovative Neurotronics Inc.**	**Odstock Medical Ltd**	**Ottobock Healthcare Products GmbH**	**Neurotech Spa. SmartFES**
Amplitude (mA)	0–80 @ 1 k	0–121 @ 1 k	10–100 @ 1k	0–90 @ 1k	10–100 @ 1kΩ
Number of channels	1	1	1	2	1
Frequency (Hz)	20–45	16.7–33	0–60	10–80	10–60
Pulse width (us)	100/200/300	25–300	0–360	50–400	10–300
Foot switch	Wireless	Inertial/wired	Wired/wireless	Wireless	Wired Foot Switch
Waveform	Biphasic symmetrical/ asymmetrical	Biphasic asymmetrical	Biphasic symmetrical/ asymmetrical	Biphasic symmetrical/ asymmetrical	Biphasic Asymmetrical
Regulated current or regulated voltage	Regulated current	Constant voltage	Regulated current	Regulated current	Regulated Current
Battery	1 built in	1 replaceable	1 replaceable	1 built in	1 built in
Rechargeable	Yes	No	No	Yes	Yes
Country	USA	Canada	UK	Germany	Chile

Table 2. Commercial surface FES stimulator to correct drop foot.

ODFS for shopping and trips out, 57% used for social events, 19% for work; 79% users reported that their confidence was increased when walking and 52% reported that their independence was increased. Van Swigchem et al. [27] reported similar increases in gait velocity and cadence of 26 stroke patients with the Ness L300. Stein et al. [28] did an analysis with the Walkaide system of the orthotic and therapeutical effect among patients with a nonprogressive (stroke) and progressive (multiples sclerosis) disease. The mean walking speed at all times was typically 5–15% higher with the device than without the device for both the progressive and nonprogressive groups. Therefore, the immediate improvement is referred to as an orthotic effect. With respect to long-term changes as therapeutic effects, after 11 months the therapeutic effect was much larger for the nonprogressive group (about 30%) than for the progressive group (about 5%). It is necessary to make clear that the use of FES is not appropriate for all stroke patients. The patient has to be well motivated, able to walk with assistance or alone, and the muscle that raises the foot must not be denervated.

Despite the benefits of these devices, the surface FES devices have some disadvantages. When using surface electrodes, the lack of selectivity of muscles and nerves affected by superficial electrodes is a problem. The stimulation could be felt as "pins and needles" that in some cases can cause pain or discomfort. The other problem reported is skin irritation [29], and these cases are usually treated by changing the type of electrodes or modifying the stimulation settings. These problems can be solved by using implanted stimulators.

4.1.2.2. Implanted FES

Implanted devices eliminate the need to position electrodes on the skin each day and reduce all problems associated with surface stimulation. No soft tissue or skin reactions, no need for technically challenging electrode placement and no discomfort or pain due to constant electrical sensation through the skin.

These stimulators work by activating directly the nerve that controls the lifting of the foot, called common peroneal nerve. At a point, just below the knee, this nerve splits into two branches: the deep branch and the superficial branch. The deep branch goes to the muscles that lift (dorsiflex) and turn inward (inversion) the foot, while the superficial branch innerves the muscles that turn the foot outwards (eversion). In normal walking, a combination of these movements is required. Like a surface stimulator, the implanted stimulator uses a foot switch to detect the step and an external FES device activates the implant through a wireless antenna worn on the outside of the body.

Currently, there are two implantable devices to correct drop foot available in the market: the STIMuSTEP system (Finetech Medical Ltd., Welwyn Garden City, UK) and the ActiGait system developed by Neurodan A/S (Aalborg, Denmark), a subsidiary of Ottobock group (Berlin, Germany).

STIMuSTEP system: This system is a passive implantable dual channel peroneal nerve stimulator triggered by a foot switch (see **Figure 9a**). Communication between the external control unit and the foot switch is wired. Electrodes are surgically inserted, one in the deep branch and other in the superficial branch enabling the movements (dorsiflexion, eversion end inversion) to be controlled separately.

Figure 9. Implanted FES systems available commercially: (a) STIMuSTEP System [31] and (b) ActiGait System [32].

ActiGait system is an implantable four-channel nerve stimulator with a 12-contact electrode cuff (see **Figure 9b**). It works with a foot switch, which is worn in a sock, which triggers the initiation and termination of each stimulation sequence by a radio frequency wireless signal to the external control unit. The nerve stimulator contains a receiver for power and control and transmits the stimulation to the 12-electrode cuff through a subcutaneous cable [30]. The four channels can be programmed to allow for selective nerve bundle stimulation and balanced dorsiflexion/eversion.

Table 3 summarizes the technical characteristics of the systems mentioned above.

In general, surface and implanted FES reported similar results. The prescription of an implantable peroneal nerve stimulator is only a treatment option when the main goal is to achieve an orthotic effect for the long term in drop foot patients [32]. Burridge et al. [33] reported significant increases in mean gait distance and velocity (19%) using the ActiGait system. In a research conducted by Taylor et al. [26] 46 drop foot patients were selected from ODFS system users that had skin irritation, difficulties with electrode placement or anticipated long-term use with the device. Increases of 18% in gait velocities were reported. Additionally, patients also reported a more comfortable gait. In general, these devices are safe; however, an implant always has the risk of infection/rejection.

	ActiGait	**STIMuSTEP**
Manufacturer	Developed by Neurodan A/S a subsidiary of Ottobock Medical Ltd.	Finetech Medical Ltd.
Amplitude (mA)	1.2	16
Number of channels	4	2
Frequency (Hz)	5–50	30
Pulse width (us)	0–300	300
Sensor	Wireless foot switch	Wired foot switch
Waveform	Biphasic symmetrical	Biphasic asymmetrical
Regulated current or regulated voltage	Regulated current	Constant voltage
Country	Denmark/Germany	UK

Table 3. Commercial implanted FES stimulator to correct drop foot.

http://dx.doi.org/10.5772/67577

4.2. Robotic devices

Another technology that improves gait rehabilitation is robotic devices. These devices are characterized by providing safe, intensive and task-oriented rehabilitation. Lokomat Hokoma and the G-EO system (Reha-Technologies, Germany, GT) are some examples of low-limb robotic rehabilitation devices, which base their operation on restoring movement through repetitions in an assisted way, improving muscle strength, coordination, and locomotor retraining, reducing the rehabilitation, and/or recovery times of patients with stroke compared to methods based only on conventional kinesiological treatment techniques [34].

Lokomat is an exoskeleton consisting of a treadmill, a harness that allows different degrees of support of body weight and articulated arms that are placed embracing both legs (see **Figure 10**). These electromechanical arms mobilize hips and knees to perform the proper walking movements on the treadmill, in which the patient actively intervenes according to his possibilities [35]. It offers a physiological gait pattern with constant feedback and therapy assessment. It improves patient outcomes by increasing therapy volume and intensity, providing task-specific training, and increasing patient engagement.

G-EO SYSTEM is a device that consists of a harness, pedals for the user's feet, a central acquisition and control, where you can select the threshold levels for rehabilitation and incorporate two modes (see **Figure 11**). This is one of the most modern systems and has the capacity to simulate a walking on a level and on a ladder. It has two modes of operation. The first one, active mode, helps the patient to self-initiate the gait activity when a pre-selected mechanical

Figure 10. Lokomat®Nanos, using the same principles as LokomatPro Hocoma, but more compact.

Figure 11. The G-EO system for gait rehabilitation.

resistance "threshold" was adjusted. The second one, active-assistive mode, senses the patient's efforts to overcome the preselected-resistance threshold and then augments the patient's effort during the initiation of their gait movement [36].

Both systems previously described allow patients to regain their ability to walk in less time when compared to conventional therapy approaches, but it is strongly linked to the follow-up and type of therapy to which they are subject, since there is also evidence that indicates poor results [34].

5. Conclusions

The stroke (ACV) is a condition that in most cases leaves people who suffered it in an invalidating condition, ranging from cognitive problems to physical problems. From the point of view of physical affections, a great number of technologies and devices have been implemented that support not only the recovery and treatment of people but also their daily chores. In this chapter, a large number of assistive and rehabilitation systems have been presented, from the simplest ones like gloves, that serve to assist the opening of the hand, to more advanced systems like exoskeletons that are focused on facilitating complex movements in large degrees of freedom through interactive rehabilitation techniques.

With respect to the assistive systems, there are focused on recovering a certainly lost function of the user, allowing the increase of its independence. At present, a large number of systems based on functional electrical stimulation have been developed, applying electrical pulses to the muscles and/or nerves that are involved in the control of the intended movement. Recent applications seek to make these systems more portable, even moving to implantable solutions.

For the rehabilitation devices, it can be seen that the developing systems focused on rehabilitation are aimed at the creation and implementation of automated care methods that allow keeping the user motivated and thus improve their time of rehabilitation and/or recovery.

However these systems are promising, their performance will be strongly linked to the program that the professional in charge applies with them.

Acknowledgement

This work was supported by the National Fund for Scientific and Technological Development, FONDECYT, Chile, through FONDECYT N° 1140469

Author details

Pablo Aqueveque*, Paulina Ortega, Esteban Pino, Francisco Saavedra, Enrique Germany and Britam Gómez

*Address all correspondence to: pablo.aqueveque@udec.cl

University of Concepción, Concepcion, Chile

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