Universidad
Carlos III de Madrid

TESIS DOCTORAL

Robotic Exoskeleton With an Assist-as-Needed Control Strategy for Gait Rehabilitation After Stroke

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To my parents,
who always believed in my dreams

"When nothing seems to help, I go look at a stonecutter hammering away at his rock, perhaps a hundred times without as much as a crack showing in it. Yet at the hundred and first blow it will split in two, and I know it was not that blow that did it, but all that had gone before."

Jacob A. Riis

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Firstly, I would like to thank God for allowing me one more achievement in my life.

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Abstract

Stroke is a loss of brain function caused by a disturbance on the blood supply to the brain. The main consequence of a stroke is a serious long-term disability, and it affects millions of people around the world every year. Motor recovery after stroke is primarily based on physical therapy and the most common rehabilitation method focuses on the task specific approach. Gait is one of the most important daily life activity affected in stroke victims, leading to poor ambulatory activity. Therefore, much effort has been devoted to improve gait rehabilitation.

Traditional gait therapy is mostly based on treadmill training, with patient's body weight partially supported by a harness system. Physical therapists need to manually assist patients in the correct way to move their legs. However, this technique is usually very exhausting for therapists and, as a result, the training duration is limited by the physical conditions of the therapists themselves. Moreover, multiple therapists are required to assist a single patient on both legs, and it is very difficult to coordinate and properly control the body segments of interest.

In order to help physical therapists to improve the rehabilitation process, robotic exoskeletons can come into play. Robotics exoskeletons consist of mechatronic structures attached to subject's limbs in order to assist or enhance movements. These robotic devices have emerged as a promising approach to restore gait and improve motor function of impaired stroke victims, by applying intensive and repetitive training. However, active subject participation during the therapy is paramount to many of the potential recovery pathways and, therefore, it is an important feature of the gait training. To this end, robotics devices should not impose fixed limb trajectories while patient remains passive.

These have been the main motivations for the research of this dissertation. The overall aim was to generate the necessary knowledge to design, develop and validate a novel lower limb robotic exoskeleton and an assist-as-needed therapy for gait rehabilitation in post-stroke patients. Research activities were conducted towards the development of the hardware and the control methods required to proof the concept with a clinical evaluation.

The first part of the research was dedicated to design and implement a lightweight robotic exoskeleton with a comfortable embodiment to the user. It was envisioned as a completely actuated device in the sagittal plane, capable of providing the necessary torque to move the hip, knee and ankle joints through the walking process. The device, that does not extend above mid-abdomen and requires nothing to be worn over the shoulders or above the lower back, presumably renders more comfort to the user. Furthermore, the robotic exoskeleton is an autonomous device capable of overground walking, aiming to motivate and engage patients by performing gait rehabilitation in a real environment.

The second research part was devoted to implement a control approach that assist the patient only when needed. This method creates a force field that guides patient's limb in a correct trajectory. In this way, the robotic exoskeleton only applies forces when the patient deviates from the trajectory. The force field provides haptic feedback that is processed by the patient, thus leading to a continuous improvement of the motor functions.

Finally, research was conducted to evaluate the robotic exoskeleton and its control approach in a clinical study with post-stroke patients. This study aimed to be a proof-of-concept of all design and implementation applied to a real clinical rehabilitation scenario. Several aspects were evaluated: the robotic exoskeleton control performance, patients' attitudes and motivation towards the use of the device, patients' safety and tolerance to the intensive robotic training and the impact of the robotic training on the walking function of the patients.

Results have shown that the device is safe, easy to use and have positive impact on walking functions. The patients tolerated the walking therapy very well and were motivated by training with the device. These results motivate further research on overground walking therapy for stroke rehabilitation with the robotic exoskeleton.

The work presented in this dissertation comprises all the way from the research to implementation and evaluation of a final device. The technology resulting from the work presented here has been transferred to a spin-off company, which is now commercializing the device in different countries as a research tool to be used in clinical studies.

Resumen

Un accidente cerebrovascular es una pérdida de la función cerebral causada por una perturbación en el suministro sanguíneo al cerebro. La principal consecuencia de esta enfermedad es una grave discapacidad a largo plazo, que afecta a millones de personas en todo el mundo a cada año. La recuperación motora después de un accidente cerebrovascular se basa principalmente en la terapia física, y el método de rehabilitación más frecuente se centra en un entrenamiento específico. La marcha es una de las más importantes actividades de la vida diaria afectada por un accidente cerebrovascular, conduciendo a una capacidad ambulatoria deficiente. Debido a eso, mucho esfuerzo se ha dedicado a la rehabilitación de la marcha.

La terapia tradicional de la marcha se basa principalmente en el entrenamiento en cinta rodante, con descarga de peso parcial usando un sistema de arnés. Los fisioterapeutas ayudan manualmente a los pacientes a mover sus piernas en la forma correcta. Sin embargo, esta técnica suele ser muy extenuante para los terapeutas, limitando la duración de la terapia por las condiciones físicas de estos. Además, se requieren múltiples terapeutas para asistir a un solo paciente en ambas piernas, siendo muy difícil de coordinar y controlar adecuadamente los segmentos corporales de interés.

Con el fin de ayudar a los terapeutas físicos a mejorar el proceso de rehabilitación, los exosqueletos robóticos pueden ser muy útiles. Los exoesqueletos robóticos consisten en estructuras mecatrónicas conectadas a las extremidades del usuario, con el fin de asistir sus movimientos. Estos dispositivos robóticos han surgido como una forma prometedora de restaurar la marcha y mejorar la función motora en víctimas de accidentes cerebrovasculares, aplicando un entrenamiento intensivo y repetitivo. Sin embargo, la participación activa del paciente en la terapia es primordial para muchas de las posibles vías de recuperación y, por lo tanto, es una característica importante del entrenamiento de la marcha. Para este fin, los dispositivos robóticos no deben imponer trayectorias fijas en las extremidades del paciente mientras este permanece pasivo.

Estos desafíos en los procesos de rehabilitación han sido la principal motivación para la investigación en esta tesis doctoral. El objetivo principal es generar los conocimientos necesarios para diseñar, desarrollar y validar un exoesqueleto robótico y una terapia de asistencia bajo demanda para la rehabilitación de la marcha en pacientes tras un

accidente cerebrovascular. Actividades de investigación fueron llevadas a cabo para el desarrollo del hardware y de los métodos de control necesarios para una prueba de concepto mediante una evaluación clínica.

La primera parte de la investigación fue dedicada a diseñar e implementar un exoesqueleto robótico ligero y cómodo para el usuario. Fue concebido un dispositivo completamente actuado en el plano sagital, capaz de proporcionar el par necesario para mover las articulaciones de la cadera, rodilla y tobillo durante la marcha. El dispositivo no se extiende por encima de mitad del abdomen y no requiere llevar nada sobre los hombros o en el tronco, proporcionando más comodidad al usuario. Además, el exoesqueleto robótico es un dispositivo autónomo capaz de asistir marcha ambulatoria, con el objetivo de motivar a los pacientes por medio de rehabilitación en un entorno real.

La segunda parte de la investigación fue dedicada a implementar una estrategia de control para ayudar al paciente bajo demanda. El método crea un campo de fuerzas que guía la extremidad del paciente en la trayectoria correcta. De esta manera, el exoesqueleto robótico sólo aplica fuerzas cuando el paciente se desvía de la trayectoria. El campo de fuerza proporciona retroalimentación háptica que es procesada por el paciente, lo que conduce a una mejora continua de las funciones motoras.

Por último, fue llevada a cabo una investigación para evaluar el exoesqueleto robótico y su estrategia de control en un estudio clínico con pacientes que han sufrido un accidente cerebrovascular. Este estudio fue una prueba de concepto del diseño y de la implementación del dispositivo aplicada a un escenario de rehabilitación clínica real. Se evaluaron varios aspectos: el desempeño de la estrategia de control, las actitudes y motivación de los pacientes hacia el uso del dispositivo, la seguridad del paciente y su tolerancia a la terapia robótica intensiva y el impacto de la rehabilitación en la marcha de los pacientes.

Los resultados han demostrado que el dispositivo es seguro, fácil de usar y tiene un impacto positivo en la marcha. Los pacientes toleraron la terapia robótica muy bien y estuvieron motivados por el entrenamiento con el dispositivo. Estos resultados motivan a seguir la investigación con el exoesqueleto robótico aplicado a la rehabilitación de marcha en pacientes que han sufrido un accidente cerebrovascular.

El trabajo presentado en esta tesis doctoral comprende todo el camino desde la investigación hasta la ejecución y evaluación de un dispositivo terminado. La tecnología resultante del trabajo que aquí se presenta ha sido transferida a una empresa spin-off, que ahora está comercializando el dispositivo en diferentes países como una herramienta de investigación para ser utilizada en estudios clínicos.

Contents

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Nomenclature

ADL	Activity of Daily Living
AFO	Ankle-Foot Orthosis
ARM	Advanced Risk Machine
ARTHuR	Ambulation-assisting Robotic Tool for Human Rehabilitation
ALEX	Active Leg Exoskeleton
BLDC	Brushless Direct Current
CAN	Control Area Network
CRC	Cyclic Redundant Check
CSIC	Spanish Research Council
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DARPA	Defense Advanced Research Projects Agency
DC	Direct Current
DOF	Degrees of Freedom
DSP	Digital Signal Processor
EEG	Electroencephalography
eLEGS	Exoskeleton Lower Extremity Gait System
FDA	Food and Drug Administration
FES	Functional Electrical Stimulation
FP5	Fifth Framework Programme
HAL	Hybrid Assistive Limb
IHMC	Institute for Human and Machine Cognition
IP	Internet Protocol
IRB	Institutional Review Board
ISS	International Space Station
KAFO	Knee-Ankle-Foot Orthosis
LED	Light Emitting Diode
LOPES	Lower Extremity Powered Exoskeleton
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MSB	Most Significant Byte
NASA	National Aeronautics and Space Administration
PAM	Pelvic Assist Manipulator
PD	Proportional Derivative

PID	Proportional Integral Derivative
POGO	Pneumatically Operated Gait Orthosis
PWM	Pulse Width Modulation
ROM	Range of Motion
SCI	Spinal Cord Injury
SEA	Series Elastic Actuator
sEMG	Surface Electromyography
UDP	User Datagram Protocol

Chapter 1

Introduction to Stroke and Gait Rehabilitation

This introductory chapter presents the background and rationale of this dissertation. It starts by giving an overview about the main consequences of a stroke, including physiological, functional, social and economical impacts. Next, the chapter highlights the importance of rehabilitation for improving quality of life of persons affected by stroke, with special emphasis on gait restoration. Trends for walking rehabilitation currently available in clinical settings are reviewed. Recent evidences show that novel approaches based on robotic interventions can potentially increase the rehabilitation outcomes. Subsequently, robotics devices developed for gait restoration after stroke are reviewed. The chapter follows by explaining the reasons that encouraged the development of the exoskeleton for gait rehabilitation: the large number of people affected by stroke, the high costs of hospitalized patients, the high level of physical effort demanded from multiple therapists when performing manual therapy and some limitations of existing robotic devices. Objectives and organization of the work are presented in the last section of this chapter.

1.1 Stroke

The human brain is always bursting with energy. It consist of about 86 billions of cells called neurons, with a roughly equal number of non-neuronal cells called glia [1]. The brain consumes about 20% of the total energy used by the human body, more than any other organ [2]. Its metabolism basically uses glucose as energy source and oxygen, both carried to the brain by the bloodstream.

The human brain weights about 1.5 kg [3]. Although this represents only about 2% of the human body mass, the brain uses 15% of the cardiac blood stream, 20% of total oxygen consumption in the body and 25% of total glucose utilization [4]. The energy consumption in the brain does not vary quite a lot over time, but some active regions of the cortex can consume more energy than other temporarily inactive parts [5].

The brain can soak so much information that not even the most sophisticated computer in the world can compare to it. The billions of neurons settled in specific brain regions are responsible for controlling everything we do, from moving a finger to doing a complex math calculation. The exact understanding of which functions are controlled by each brain region remains under investigation. Although there is not a strict relationship between brain region and function, current knowledge shows that they are closely related [6], and, as represented in figure 1.1, left brain hemisphere controls the right side of the body and vice-versa. If a brain region is damaged, its functions can be sometimes assumed by a neighboring region in the ipsilateral side or a corresponding region in the contralateral side, depending on the damaged area [7].

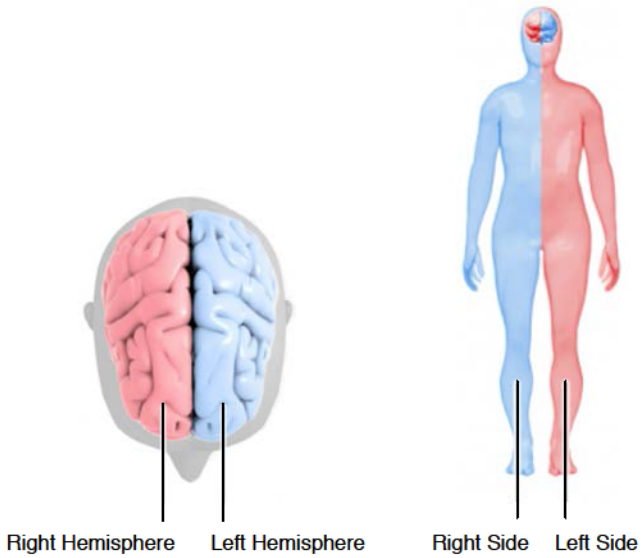

FIGURE 1.1: Regions of the human brain and functions performed seems to be closely related. In general, left brain hemisphere controls the right side of the body and vice-versa.

A leading case of brain damage occurs when the blood supply stops flowing to the brain, leading neurons to start dying very quickly. Deprived from oxygen and glucose in the brain, humans normally looses consciousness within five to ten seconds. If oxygen and glucose supply is not restored soon, the brain start experiencing irreversible damages. The loss of brain function due to a disturbance in the blood supply is known as stroke [8]. The brain area affected after a stroke cannot function normally due to neurons' death, which might result in permanent neurological damage or death. More commonly, a person affected by stroke has inability to move the limbs on one side of the body, fails to speak or to understand speech and exhibits vision impairment [9]. More specifically, the level of impairment after a stroke depends mainly on the brain region affected.

Plasticity is defined as the property of the human brain to adapt to environmental challenges and experiences, including brain damage [10–12]. Due to plasticity, lost functions can be compensated or relearned after stroke, based on mechanisms of reorganization [13], unmasking previously inactive synapses and/or generating new ones. The advances in non-invasive technologies have increased our understanding of brain reorganization after stroke [14–16].

The main factors that determine functional recovery after stroke are the location of the lesion in the brain, the extension of that lesion and the nature of stroke (ischemic or hemorrhagic) [17]. Motor impairment can be caused by injury in the motor cortex, pre-motor cortex or associated pathways in the cerebrum or cerebellum [18]. Such impairments affect an individual's ability to complete everyday activities and participate in everyday life situations [19]. Recovery is hindered above all by the involvement of major white-matter tracts and by damage or disconnection of the hippocampus, a structure that plays a key role in the learning of neurological functions [20]. Functional recovery is based on the restitution of the brain tissue and on the relearning and compensation of lost functions.

1.2 Classification of Stroke

Stroke is a medical condition that can be better prevented with appropriate care, changes in lifestyle and treatment of some risk factors with adequate medications [20]. Risk factors include age, high blood pressure, diabetes, high cholesterol, smoking, lack of exercise, overweight and atrial fibrillation [9]. Stroke can be either ischemic or hemorrhagic. The management of these subtypes is different, therefore, the clinical distinction between these subtypes is the first important and urgent step in stroke management. Classification can be done in the emergency room and conveys important prognostic information, because the type of stroke will influence both acute treatments and secondary prevention strategies. Ischemic strokes are the most prevalent type, accounting for about 85% of all cases [20, 21].

1.2.1 Ischemic Stroke

Figure 1.2 illustrates how an ischemic stroke occurs. Basically, an artery inside or close to the brain becomes clogged, thus preventing the bloodstream to correct flow to some brain region. The brain cells beyond the clogged point die due to the lack of nutrients and oxygen. Therefore, the function those dead cells were controlling is now gone, even the tissue is structurally intact [22]. This tissue is known as the ischemic penumbra [9].

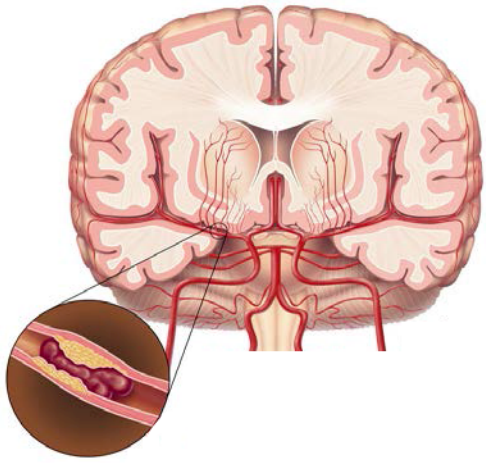

FIGURE 1.2: Representation of how an ischemic stroke occurs. An artery inside or close to the brain become clogged, preventing the bloodstream to correct flow to some brain region. The brain cells beyond the clogged point die from the lack of nutrients and oxygen, leading to stroke.

Ischemic stroke is also divided into embolic or thrombotic. Embolic stroke occurs when a blood clot or plaque fragments formed elsewhere in the circulatory system, usually in the heart or large arteries leading to the brain, break off and move towards the brain. In the brain, the clot occludes a blood vessel, leading to stroke. In the case of thrombotic stroke, the blood clot forms inside an artery already in the brain. The clot slowly interrupts the blood flow, causing stroke. The main cause for that is atherosclerosis, a hardening of arteries caused by cholesterol.

1.2.2 Hemorrhagic Stroke

In hemorrhagic strokes, a weak artery inside the brain eventually ruptures, spilling blood into or around the brain. The bleeding causes brain cells to die and the brain part affected stops working correctly. The most common mechanism that leads to a hemorrhagic stroke is hypertension, which causes aneurysms, an excessive dilation of an artery caused by a weakening of its walls (figure 1.3) that subsequently rupture [23]. More than 65% of patients with primary cerebral hemorrhage have either pre-existing or newly diagnosed hypertension [24].

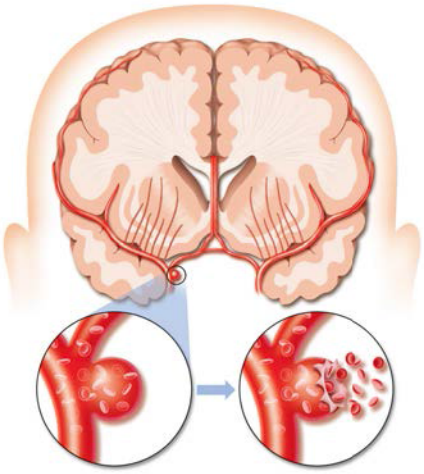

FIGURE 1.3: Representation of how an hemorrhagic stroke occurs. A weak artery inside the brain eventually ruptures, spilling blood into or around the brain. The bleeding causes brain cells to die, leading to stroke.

Hemorrhagic stroke is much more deadly than ischemic stroke, but fortunately, it is much less frequent. There are also different kinds of hemorrhagic stroke, including intracerebral and subarachnoid hemorrhage. Intracerebral stroke happens when a vessel ruptures and bleeds into brain tissue. The bleeding causes brain cells to die. In subarachnoid hemorrhage, a blood vessel bursts near of the brain surface, causing blood to leak between the brain and skull. This blood may cause other nearby vessel to spasm and reduce the blood flow to a certain brain region, leading to a stroke.

1.3 Socioeconomic Impact of Stroke

Stroke is responsible for 9% of all deaths worldwide [9]. It is a serious and disabling global health-care problem that takes more than 4% of total direct health-care costs in industrialized countries [18] and exorbitant amounts of money to the society every year: around US$ 13 billion in the United Kingdom, US$ 1.3 billion in Australia and US$ 41 billion in United States [9], where a stroke patient costs more than US$ 1,000 per day in a hospital. Stroke occurrence is predominantly in older people, about 75% of stroke patients are over 65 [25].

There are about 800.000 cases of stroke every year only in the United States [26], which means that someone has a stroke every 40 seconds. Also in United States, stroke is the third most common cause of death and the leading cause of long-term disability [18, 27]. Around 80% of stroke victims will survive the initial injury. Therefore, the widely recognized problem caused by stroke is not death, but motor impairment, which can be understood as loss or limitation in muscle control or a limitation in mobility [28].

Stroke motor impairment usually affects movement control of the face, arm and/or leg on one side of the body. Many patients loose the ability to walk independently and a large number of patients do not regain their normal walking speeds [29]. Consequently, gait impairment is one of the main contributors to long-term disability in daily living of people that have been affected by stroke [30]. This limitation in daily life activities have a big effect on patients and their families. Fortunately, with proper care and rehabilitation most stroke survivors can resume their lives.

1.4 Stroke Rehabilitation

It is recognized that stroke rehabilitation presents specific challenges [31]. Theories of motor control and skills learning are crucial in the rehabilitation interventions [32]. However, neurophysiology supporting stroke rehabilitation is often poorly established and interventions tend to be complex, containing several interrelated components [33].

The main principles for a successful rehabilitation after a stroke include a functional approach targeting specific activities, intense practice and an early start few days after the stroke [34]. Different mechanisms can improve function, thereby alleviating the various impairments caused by stroke. Recovery of function in stroke patients typically occurs within six months after onset, with larger improvements taking place in the first three months [29]. Indeed, early start of training tends to yield better rehabilitative outcomes [35–37]. Nevertheless, functional gains can still continue in the chronic phase of stroke [38, 39].

About 80% of stroke victims are affected by motor impairment [18]. Therefore, one primary goal of physical and occupational therapy is the recovery of functions affected by motor impairment. Function and motor impairment seems to be directed related, for instance, the ability to walking (function) can be correlated with lower limb strength (impairment) [29].

Functional recovery can occur via different mechanisms, as restitution or compensation [40]. In the case of restitution, the function in the neural tissue that was initially lost is restored by finding alternative means to activate the same muscles used for a task prior to injury. The movement is performed as it was before the injury [41]. Motor compensation, instead, is associated with the acquisition by the neural tissue of a function that it did not have before and the use of alternative muscles in compensatory strategies [42].

1.5 Gait Rehabilitation in Stroke Survivors

Stroke imparts several physical and cognitive disorders that produce disability [43–45]. Gait is one of the most important activities affected in stroke survivors, leading to poor

ambulatory activity [46]. Most victims experience significant sensory-motor impairments [47, 48] and require rehabilitation to achieve functional independence again.

In this context, hemiparesis is a manifestation of stroke that affects the contralesional side of the body, and commonly impacts gait [29, 49]. A negative impact on output forces, not just for the paretic leg, but also for the unaffected leg, has been found in stroke victims [50–53]. Nevertheless, walking velocity and endurance is greatly reduced and patients usually walk in a typical asymmetric manner, as they avoid to load the paretic limb. Knee flexion is also reduced and most patients tend to compensate the lack of knee flexion during swing, creating an abnormal compensatory movement in the hip commonly known as hip hiking [54].

The rehabilitation process toward regaining mobility after a stroke can be divided into three phases [55]:

1. Mobilization of bedridden patient into the wheelchair;
2. Gait restoration;
3. Improvement of gait in order to meet the requirements of daily mobility.

In the first phase, an early mobilization policy is generally accepted. The patient at the edge of the bed is transferred to a chair as soon as possible. Once the patient can sit and tolerate verticalization for at least 10 minutes, the gait restoration training can begin [20].

The approach used in the second phase of rehabilitation has seen major changes in the last decade. The traditional methods used by physiotherapists have been replaced by task-specific, repetitive gait training approaches. To help therapists during this task, electromechanical devices can come into play, enabling patients to practice walking over and over again. It has been hypothesized that the combination of machines and physiotherapists can be more effective than the latter alone, preventing many cases of inability to walk [56].

1.5.1 Traditional Therapy

The theoretical bases assumed by the physical therapists to approach stroke rehabilitation are diverse. Traditional methodology includes neuro-developmental training [57], motor relearning programs, proprioceptive neuromuscular facilitation and the Rood approach [58]. However, the results of different kinds of training on gait have been shown to be modest and independent of the methodology adopted [43].

Neuro-developmental training is the most usual rehabilitation approach [48, 59–61], where the best well-known stream is the Bobath concept. This therapy attempts an

approach where social, emotional and functional problems are targeted, in addition to sensory-motor deficits. The main objective is to suppress abnormal movement synergies and move towards normal motor patterns [62]. It involves intensive preparatory training for walking in the sitting and standing positions. Despite the acceptance of Bobath concept and other conventional techniques in stroke rehabilitation, there is still a lack of evidence demonstrating their efficacy [35, 63–68].

In gait rehabilitation, the task-specific repetitive approach is increasingly being used in addition to conventional therapeutic approaches. The motor task to be learned should be practiced as many times as possible [20]. Better outcomes have been attained with the strategy of treadmill training with body weight support [67, 69–73]. With this technique, patients walk on a treadmill with they body partially supported by a harness system. Physical therapists manually assist patients in the correct way to move their legs, providing some guidance based on patient's disability level.

This type of therapy has the advantage of being task specific and repetitive, providing a high degree of training. However, it is usually very exhausting for therapists and, as a result, the training duration is limited by the physical conditions of the therapists themselves. Moreover, multiple therapists are required to assist the patient in both legs, which can lead to poor coordination and synchronization of movements, and the cost of multiple therapists for a single patient is not always covered by health care systems.

As a solution to these limitations, with the advance of the technology, therapies driven by robotic machines were proposed as an addition to physiotherapy programs targeting neurological impairment [74]. Gait therapy assisted by robotic actuators rather than a therapist is becoming an increasingly prominent feature of rehabilitation worldwide. More than alleviating the physical burden on therapists, robotic machines can accurately apply repetitive training and more objectively measure patient's outputs in terms of joint kinematics and kinetics [44, 75].

1.5.2 Robotic Technology for Gait Rehabilitation

"Who wants to walk, has to walk" [76] has become a key concept for gait rehabilitation. Towards this goal, robotic machines can allow more effective training sessions, where patients can train around 1000 steps within a typical training session (30 minutes in average), whereas during manually assisted training only approximately 100 steps per session can be performed [55].

In the past years, different studies have been conducted in order to demonstrate the efficacy of robot-based therapy over conventional, therapist-assisted training. Some publications yield results in favor of conventional therapy [77, 78], others conclude that robot-aided training is more effective [79–82] and other studies find no significative difference in functional gait improvements between both [83–85]. One argument always

in favor of the robotic approach is that it is roughly as effective as the manual treadmill therapy guided by therapists, but requiring much less effort from therapists [79].

A recent Cochrane review [86] comprising 23 trials involving 999 patients investigated the effects of robotic-assisted gait training for improving walking after stroke. Results show that patients receiving robotic-assisted gait training in combination with physiotherapy are more likely to achieve independent walking than patients that do not train with those devices. Also, a number of therapeutic benefits in gait training assisted by robotics in stroke patients have been found in the literature: improvements in walking independence and mobility [67, 87], functional walking ability [79, 88], muscle activation patterns [80, 88], gait speed [80, 89] and joint range of motion [89].

In the following paragraphs it will be reviewed the state of the art of the robotic technology for gait rehabilitation. Rehabilitation robots can be broadly classified as stationary devices and ambulatory exoskeletons, some of which are already available as commercial products on the market.

1.5.3 Stationary Devices

The first machines developed for gait rehabilitation were not ambulatory. They are based on a gait orthosis and a body weight support system in combination with a treadmill [90]. Using predetermined movement patterns, they usually do not allow variation in the gait pattern. Sometimes those platforms also use virtual reality environments, in a strategy to motivate and engage the patient to actively perform movements.

Stationary devices for gait training can be distinguished in two groups: end-effector systems and exoskeletons based solutions [91, 92]. End-effectors simulate the stance and swing phase during gait cycles, while the patient's feet are placed on footplates. On the other hand, exoskeleton-based systems consist of robots attached to subject's limbs, working in parallel with them.

1.5.3.1 Lokomat

Lokomat [74] is probably the most used stationary robotic machine for gait rehabilitation in clinics nowadays. Lokomat is a commercially available device manufactured by Hocoma, a company in Zurich, Switzerland. The system, that uses a lower limb orthosis coupled to a treadmill, was initially developed for spinal cord injury treatment [93, 94]. It has an advanced body weight support system that can partially lift the user during the training. DC (Direct Current) motors are used for actuation of hip and knee joints in the sagittal plane, while the ankle is kept passive. The motor's drives are precisely synchronized with the treadmill speed, assuring a precise match between the speed of the gait orthosis and the treadmill. Figure 1.4 illustrates the Lokomat.

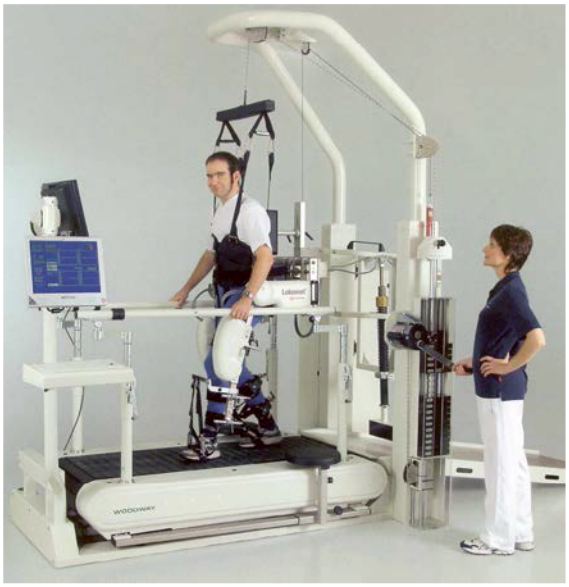

FIGURE 1.4: Lokomat is a commercially available device that uses a lower limb orthosis coupled to a treadmill for gait training. It has an advanced body weight support system that can partially lift the user during the training. DC motors provide actuation on hip and ankle joints.

The first version of Lokomat was strictly a position controlled device, but other control algorithms have also been proposed [95, 96] to provide control methods that better interact with the patient. Lokomat is the treadmill gait training device that has received the most extensive clinical evaluation. Many studies, including randomized clinical trials for stroke rehabilitation [77, 78, 84, 85, 97–100] were carried out using the Lokomat. Also, spinal cord injury rehabilitation was targeted using Lokomat in clinical studies [101–104].

Different studies about the efficacy of Lokomat when compared with traditional therapy yielded different results, but a recent review [86] concludes that patients receiving robotic-assisted gait training have higher probabilities to achieve an independent walk. In this review, Lokomat was used in 13 of 23 total randomized clinical trials.

1.5.3.2 ALEX

ALEX (Active Leg Exoskeleton) [105, 106] is a motorized leg orthosis developed at the University of Delaware, Newark, United States. It is intended for gait training and rehabilitation of patients with walking disabilities. ALEX orthosis, see figure 1.5, has a total of seven DOF (Degrees of Freedom) with hip and knee actuated in the sagittal plane. The device is stationary and coupled to a treadmill. A force field control applies forces on user's feet to help the legs move on a desired trajectory. First experiments performed on six healthy subjects walking on a treadmill have shown that a healthy

person could be retrained in about 45 minutes with ALEX to walk on a treadmill with a considerably altered gait [107].

Other studies with ALEX [108, 109] were conducted with two stroke survivors that participated in fifteen sessions of gait training. The results show that by the end of the training period, patients' gait pattern improved and became closer to a healthy subject's gait pattern. Improvements were seen as a change in patients' gait pattern by increasing knee and ankle joint excursions and increasing their walking speeds on the treadmill.

ALEX mechanical structure and control strategy were redesigned in a new version, ALEX-II [110]. This control strategy uses an assist-as-needed algorithm that provides less encumbered motion for its users [111]. This new version was only tested with healthy subjects. No further studies using ALEX or ALEX-II for stroke gait rehabilitation were found in the literature.

After ALEX, the same group at the University of Delaware also developed a non-motorized bilateral orthosis [112] that can be used to assist training of motor impaired patients on a treadmill, such as patients with incomplete spinal cord injury. The device design uses torsional springs at the hip and the knee joints to assist the swing motion. The springs get charged by the treadmill during stance phase of the leg and provide force propulsion to the leg during the swing. Simple dynamic models of walking in the sagittal plane are used to optimize the parameters of the springs, so the foot can clear the ground and have a desirable forward motion. The device was tested on a healthy subject during treadmill walking for a range of walking speeds. Authors found that at 3.2 km/h the device was effective in reducing the maximum hip torque requirement and

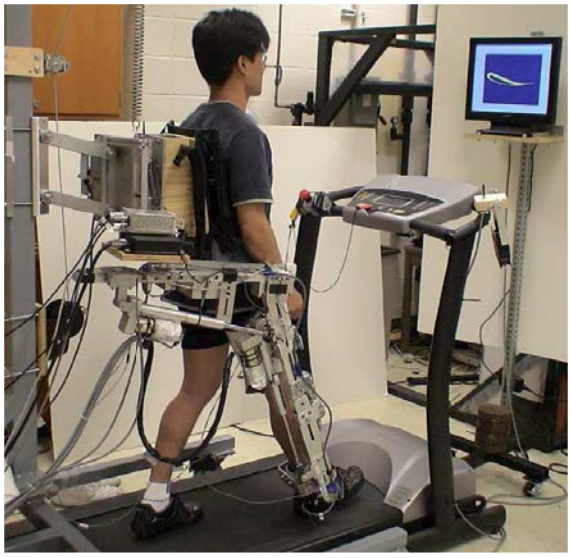

FIGURE 1.5: ALEX is motorized leg orthosis with a total of seven degrees of freedom. Hip and knee joints are actuated in the sagittal plane, while the device is coupled to a treadmill.

the knee joint torque during the beginning of the swing. No results were shown with impaired persons training with this non-powered device.

1.5.3.3 LOPES

LOPES (Lower Extremity Powered Exoskeleton) [113] is a lower limb exoskeleton coupled to a treadmill developed at the University of Twente, Enschede, The Netherlands. The device is illustrated in figure 1.6. It combines a two dimensional actuated pelvis segment with a leg exoskeleton containing three actuated rotational joints: two at the hip and one at the knee. The actuators consist of a servomotor and a flexible Bowden cable transmission [114, 115]. The joints are impedance controlled based on a force feedback loop to allow bidirectional mechanical interaction between the robot and the training subject.

Different control approaches have been developed for LOPES. One approach, called Virtual Model Controller and presented in [116], tries to translate traditional gait rehabilitation therapy programs into robotic rehabilitation therapy for selective control of gait functions. In a subsequent work [117] this approach was tested in four healthy subjects to control the step height, while leaving the remaining walking pattern unaffected. The Virtual Mode Controller is also used in [118], as an alternative method to support body weight, and in [119] to provide virtual support to the ankle and increase foot clearance.

In the work presented in [120], a free walk mode of LOPES based on impedance control is assessed. Results with healthy subjects showed that overall, walking with LOPES

FIGURE 1.6: LOPES combines a two dimensional actuated pelvis segment with a lower limb exoskeleton containing three actuated rotational joints: two at the hip and one at the knee. The actuators consist of a servomotor and a flexible Bowden cable transmission.

resembled free walking, although this required several adaptations in muscle activity. A different approach presented in [121] was also implemented in LOPES: in this study, the desired states of the disabled leg are generated online based on the movements of the other leg. Results indicate that the interference of the robot is lower when compared with a fixed reference trajectory, but no results were shown with impaired persons.

The study with LOPES in [122] tested the feasibility of providing assistance during foot clearance by defining a virtual spring between the desired and the actual ankle height. The algorithm automatically adapts the stiffness of the virtual spring, adapting the amount of support to the experienced movement error in the previous steps. Results were shown in four chronic stroke survivors, demonstrating that the training resulted in improved foot clearance, which was accompanied by an increased walking speed.

In a recent study [123], ten individuals with chronic SCI (Spinal Cord Injury) participated in an explorative clinical trial with LOPES. Participants trained three times a week for eight weeks using an impedance based controller. Results showed that participants experienced significant improvements in walking speed and distance after training and in eight weeks follow-up. It was concluded that the device is feasible in gait rehabilitation of chronic SCI individuals.

1.5.3.4 Gait Trainer GT I

The Gait Trainer GT I follows an end-effector principle [91]. It was developed by Professor Dr. Stefan Hesse and his team in Germany. In 1999 they established a company in Berlin called Reha-Stim focusing on technology for rehabilitation. Gait Trainer GT I is a stationary machine with two footplates that simulates the phases of gait [124–126]. It consists of a double crank and rocker gear system, composed of two footplates positioned on two bars, two rockers and two cranks that provide the propulsion. Users are secured in a harness and positioned on the two footplates, whose movements simulate the stance and the swing phases. The machine controls the movement of the center of mass in both the vertical and horizontal direction [88, 127]. A servo controlled motor assists gait movement by controlling the gear velocity [128, 129].

Figure 1.7 illustrates the Gait Trainer GT I, which was developed aiming to lower the effort of therapists in traditional gait training on a treadmill. In case reports [128, 129] and a randomized crossover study [79], the authors found no difference in effectiveness between treadmill training and the Gait Trainer GT I. However, they stated that the Gait Trainer GT I helped to reduce manual guidance from the therapist and provided a highly symmetric, more independent gait practice for non ambulatory participants.

Many studies were carried out with a large number of stroke patients using Gait Trainer GT I. The study [82] comprised a non-blinded randomized trial with fifty stroke patients,

FIGURE 1.7: Gait Trainer GT I follows an end-effector principle. The stationary machine has two footplates that simulates the stance and the swing phases of the gait.

which were recruited within six weeks after stroke onset. Results showed that participants who trained on the robotic device with body weight support had a faster gait, better mobility and improvements in functional ambulation compared to participants who underwent conventional gait training. Other study in [87] evaluated 155 sub-acute stroke patients in a randomized trial. Conclusion was that intensive locomotor training plus physiotherapy resulted in a significantly better gait ability and daily living competence in patients compared with physiotherapy alone. The same conclusion was obtained in [130], with a total of 48 participants with motor and gait dysfunction following subacute stroke. Iosa et al [131] performed a study with twenty stroke subjects in order to select the best parameters for the electromechanical Gait Trainer GT I.

In [132], Gait Trainer GT I was evaluated in combination with transcranial direct current stimulation in thirty patients with chronic stroke. In this pilot study, it was found that transcranial direct current stimulation had no additional effect on robot assisted gait training in patients with chronic stroke. The effects of Gait Trainer GT I was also tested with children with cerebral palsy [133]. The study evaluated the effectiveness of repetitive locomotor training with eighteen ambulatory children with diplegic or tetraplegic cerebral palsy. Results showed that Gait Trainer GT I may improve gait velocity and endurance, as well as spatiotemporal and kinematic gait parameters in patients with cerebral palsy.

1.5.3.5 HapticWalker

HapticWalker [134] was developed by the same team that developed Gait Trainer GT I, as a successive machine. As improvements, HapticWalker has fully programmable trajectories, therefore enabling patients to train arbitrary gait trajectories and daily life walking situations, as stair climbing up and down [76]. The device is illustrated in figure 1.8.

HapticWalker comprises a translatory and rotatory footplate workspace, allowing permanent foot contact along arbitrary walking trajectories during all phases of gait. The footplate dynamics were designed for smooth foot motions at moderate speeds and also realistic simulation at higher speeds up to 5 km/h. The purpose for that was to enable realistic simulation of gait perturbations like stumbling, sliding and other asynchronous walking events [55]. The device is equipped with electrical direct drive motors and six force/torque sensors mounted under each foot platform [135]. It is controlled by software and hardware based on industrial standards and interfaces. The software is based on RTLinux and runs on an industrial computer [134]. The real-time motion generator includes a Fourier-based algorithm for interpolation of natural cyclic walking trajectories.

Differently to Gait Trainer GT I, no randomized clinical trials were found using HapticWalker, but only a few studies with healthy users [136, 137].

FIGURE 1.8: HapticWalker is an end-effector machine with fully programmable trajectories that enables patient to train arbitrary gait trajectories and daily life walking situations, as stair climbing up and down.

1.5.3.6 LokoHelp

LokoHelp [138] is another stationary device developed for improving gait after brain injury. It is placed on a treadmill and fixed onto the band of the motor that driven the treadmill, transmitting the movement to levers positioned on both sides of the device. In this way, simulation of gait is achieved by tracking the levers that imitate the stance and swing phases sequentially. Step length is fixed at 40 cm and speed can be adjusted from 0 to 2.5 km/h.

LokoHelp is a device that, in some way, lies between Lokomat and Gait Trainer GT I approaches. It consists of a treadmill with body weight support system, like the Lokomat, but the device itself consists of a pair of boots that guide the feet along a fixed trajectory. Although it uses a treadmill, the device is considered end-effector based [91]. Figure 1.9 illustrates the LokoHelp.

The first LokoHelp study [138] was a feasibility study recruiting six patients with impaired walking function. The intervention consisted of a training period of six weeks. Results showed that LokoHelp may improve locomotor function and decrease the effort experienced by therapists carrying out the training. A later study [139] comprising sixteen non-ambulatory patients after stroke, severe brain or spinal cord injury, concludes that training with the device did not significantly improve gait when compared with traditional training. However, the use of LokoHelp requires less therapeutic assistance, reducing therapist discomfort.

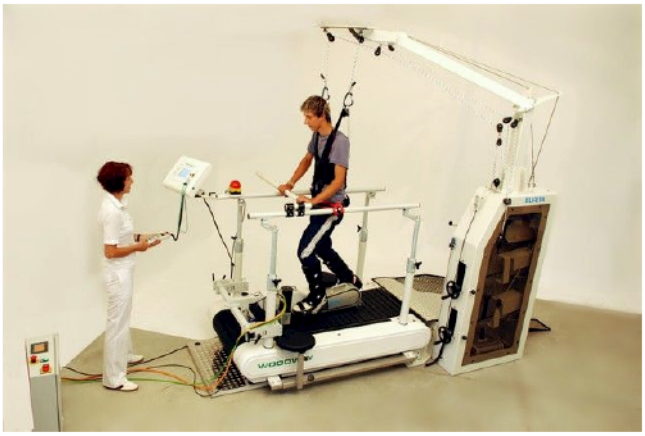

FIGURE 1.9: LokoHelp is placed on a treadmill and fixed onto the band of the motor that driven the treadmill, transmitting the movement to levers positioned on both sides of the device.

1.5.3.7 Other Stationary Devices

Other stationary devices have been developed around the world to improve gait training. ARTHuR (Ambulation-assisting Robotic Tool for Human Rehabilitation) is an end-effector system where leg movements are controlled via a moving coil [140]. The device was designed to measure and manipulate human stepping on a treadmill.

A gait trainer developed in Korea, called Walkbot [141], has been under investigation to see the immediate effects on knee joint stiffness with an individual with spastic hemiplegia. PAM (Pelvic Assist Manipulator) was developed to assist pelvic motion during gait training in a treadmill [142]. POGO (Pneumatically Operated Gait Orthosis) was designed as an attachment to PAM [143], providing assistance for leg swing. Both devices are actuated by pneumatic cylinders. Autoambulator [144] is a treadmill device exoskeleton-based with a body weight support system. It has four DOF corresponding to flexion/extension of the hip and the knee. Robotic Gait Rehabilitation Trainer [54] is a single actuator system that works on the pelvis, targeting the correction of secondary gait deviations.

1.5.4 Ambulatory Exoskeletons

End-effector gait machines as Gait Trainer GT I or LokoHelp lack a structure that support the knee joint. The absence of such structure may be challenging for some stroke patients [145]. Furthermore, rehabilitation devices such as Lokomat, ALEX, LOPES, Gait Trainer GT I and others, have to be physically installed in specialized hospitals or clinical centers due to their significant sizes and costs [146].

In addition, stationary devices may not be optimal for most patients in terms of engagement for gait practice. For more effective results in the rehabilitation process, it is known that patient's involvement and participation in voluntary movements of the affected limbs is critical [147, 148]. As an alternative to the static gait training offered by these platforms, some mobile robotic devices have been developed, providing the capability of overground walking. These robotics devices are usually called wearable exoskeletons or robotic exoskeletons.

Wearable exoskeletons consist of mechatronic structures attached to the subject's limbs and working in parallel with them, in order to assist, replace or enhance movements [149]. Performance augmentation based on exoskeletons have been mainly sponsored by DARPA (Defense Advanced Research Projects Agency) in the United States [150], targeting the increase of capabilities of soldiers in the battlefield [151].

Exoskeletons for rehabilitation (movement assistance) or functional compensation (movement replacement) are being developed by different groups around the world [90, 152,

153]. Some robotic exoskeletons are also used in conjunction with FES (Functional Electrical Stimulation) [154, 155].

In the following paragraphs it will be reviewed the state of the art in lower limb robotic exoskeletons for gait rehabilitation or gait compensation. From now on in this dissertation, it will be sometimes referred to wearable robotic exoskeletons as just exoskeletons.

1.5.4.1 HAL

HAL (Hybrid Assistive Limb) is an exoskeleton designed for rehabilitation, heavy labor and rescue support. It is built in different versions: full body, lower body and one leg models are available [156]. A new version of this device, HAL5 (full body) targets paraplegic users [157].

HAL was developed at Tsukuba University, Japan, and it is marketed by Cyberdyne. Research with this exoskeleton has been led and conducted by Dr. Sankai, a Professor of the Tsukuba University. Cyberdyne does not sell HAL, instead, it rents it to hospitals and medical facilities in Japan, for a monthly fee of about US$ 2,000. In February 2013 HAL has received a clearance for the European market, based on the requirements of the Medical Device Directives in European Union. The device has not yet been certified as a medical device in Japan neither have FDA (Food and Drug Administration) approval in the United States.

The lower body model of HAL weights about 15 kg and the full body model about 23 kg. It is battery operated and has an autonomy of approximately two and a half hours. Hip and knee joints actuators are based on DC servo motors and Harmonic Drive gearboxes, while the ankle joint is passively controlled [156]. HAL has a control unit that communicates to a remote monitoring computer by wireless Local Area Network [158]. The lower limb model of HAL is represented in figure 1.10.

Two different control strategies are used with HAL, depending on the treatment purpose and user's capabilities [159]. The main actuation mechanisms are based on sEMG (surface Electromyography) signals, which adjusts the robot torques for assistance depending on the measured muscle activity. The second algorithm reproduces a stored movement pattern based on acceleration and ground contact forces [160].

HAL has been used to conduct clinical trials in different hospitals [161–163]. In the study carried out by Maeshima et al [162], with comprised sixteen stroke patients with severe hemiplegia, four patients required gait assistance and twelve needed supervision while walking. They have compared stride length, walking speed and physiological cost index on wearing bilateral HAL suit and a KAFO (Knee-Ankle-Foot Orthosis). The results showed that HAL suit increased the stride length and walking speed only in four out of sixteen patients. The physiological cost index increased in twelve patients after

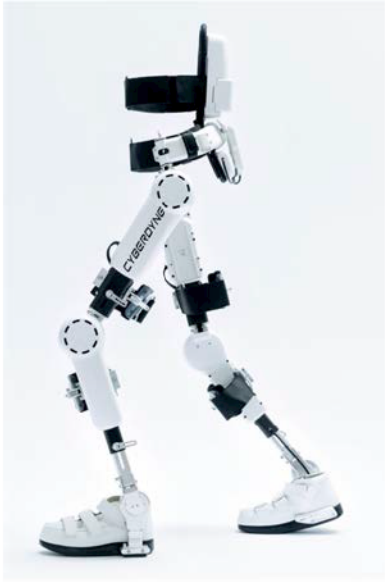

FIGURE 1.10: HAL is an overground exoskeleton with actuation on hip and knee joints and a passive ankle. The device is designed for rehabilitation, heavy labor and rescue support.

the gait training, but removing the suit led to a decrease in the physiological cost index values to equivalent levels prior to the use of HAL.

As authors conclude in their study, sEMG signals used to provide power assistance can make it difficult for severely hemiplegic patients to perform activities using their own muscles. This could lead to instability, consequently decreasing stride length and walking speed. Also, the availability and quality of sEMG signals can vary from patient to patient. Fragility and installation requirements of electrodes can also be restrictive outside the laboratory [164]. The system based on sEMG signal requires a process of adaptation and adjustment to a specific user that can take up to two months [165].

Recent studies [163, 166] have demonstrated that locomotor training using the HAL is feasible for rehabilitation of chronic and sub-acute stroke patients. However, the effectiveness of HAL-based rehabilitation over conventional therapies is still unclear and requires further studies.

1.5.4.2 ReWalk

ReWalk is a wearable motorized suit from Argo Medical Technologies Inc. developed and patented by its inventor Dr. Amit Goffer [167]. Goffer became quadriplegic after an accident in 1997 and was through his own personal experience in utilizing mobility devices for people with SCI that he developed this exoskeleton. ReWalk has hip and knee movements powered in the sagittal plane. It comprises a light wearable brace support

suit, which integrates DC motors at hip and knee joints, rechargeable batteries, an array of sensors and a computer control system [90]. The ankles are supported using simple orthotic joints that have limited range of motion and spring assisted dorsiflexion [168].

The device is powered by rechargeable batteries intended for all-day use and overnight charging. The batteries are located on a backpack carried by the user. The device is customized and sized for each patient [169], see figure 1.11.

Changes in the user's center of gravity are detected and used to initiate and maintain the walking process. The user also has a remote control placed on his/her arm, similar to a watch. With this interface, it is possible to start different tasks, such as sit-to-stand or climbing stairs. ReWalk is intended for persons with lower limb disabilities that have suffered injuries in the spinal cord. It cannot keep balance control, so the user should always be supported by crutches for additional stability when walking, standing and rising up from a chair.

ReWalk underwent clinical trial testing in some rehabilitation centers in the United States, e.g. Moss Rehabilitation Hospital in Philadelphia [170] and Veterans Affairs Medical Center in Bronx, New York [171].

Argo Medical sells two models of its exoskeleton, called ReWalk Rehabilitation and ReWalk Personal. The first one in intended for clinical use and has been deployed in rehabilitation centers across Europe, Israel and United States. Training with it allows walking, standing, sitting and the capacity to ascend/descend stairs in the rehabilitation center environment. The system can accommodate a range of heights from 1.6 to 1.9 meters and weights up to 100 kg. The key prerequisites to use ReWalk include the ability

FIGURE 1.11: ReWalk comprises a light wearable brace support suit, which integrates DC motors at hip and knee joints, rechargeable batteries, an array of sensors and a computer control system.

to use hands and shoulders (walking with crutches), healthy cardiovascular system and bone density.

ReWalk Personal was designed for everyday use as an assistive system. It is customized and sized for each individual user. After a training period with the device and after meeting requirements from a medical examination, the user can buy one to use it at home. In 2012 Argo started selling ReWalk Personal model in Europe. In the United States this personal model became the first exoskeleton with FDA clearance for use at home and in the community on June, 2014. The device is now available throughout the United States for personal purchase, at a cost of around US$ 70,000.

1.5.4.3 Ekso Bionics

Ekso Bionics (earlier Berkeley Bionics) is a North American company that originally developed exoskeletons for military use. In October 2010 they have unveiled an assistive version called eLEGS (Exoskeleton Lower Extremity Gait System) intended for patients with complete and incomplete SCI [172]. In 2011 eLEGS was renamed as Ekso.

Ekso weights approximately 23 kg and has a battery life of an average of four hours. The device uses DC motors for actuation of hip and knee joints in the sagittal plane and the ankle is kept passive. Ekso system uses pressure sensors under the soles, potentiometers and an accelerometer/gyroscope sensors [173]. The device can be commanded by a user interface, controlling Ekso step by step. The control strategy is based on position control, relying on a standard walking trajectory and foot sensors to determine the walking state. Ekso requires the use of crutches for patients to keep balance. The device was primarily tested on four paraplegic patients [174] and on three stroke survivors with chronic symptoms [175].

A recent study [176] has evaluated feasibility and safety of the Ekso when helping ambulation of individuals with SCI. Eight individuals with complete lesion participated in the six week study. Conclusions are the device is safe for SCI patients in a controlled environment in the presence of experts. Ekso Bionics exoskeleton units (figure 1.12) costs around US$ 150,000.

1.5.4.4 Vanderbilt Exoskeleton

The Vanderbilt exoskeleton is a prototype developed at the University of Vanderbilt in Tennessee, United States, in the Center for Intelligent Mechatronics. The device weights about 12 kg and has hip and knee joints actuated. Ankle and foot support are not present on the device and it has to be used with an off-the-self AFO (Ankle-Foot Orthosis).

FIGURE 1.12: Ekso uses DC motors for actuation on hip and knee joints in the sagittal plane, while the ankle is kept passive. Ekso system uses pressure sensors under the soles, potentiometers, and an accelerometer/gyroscope sensors.

The device is powered by brushless DC motors through a 24:1 gear reduction, which provides a maximum continuous torque of 12 Nm for hip and knee joints [177]. Additionally, knee motors are equipped with electromechanical brakes that lock knee joints in an event of power failure. Potentiometers are used as angular position sensors. A lithium polymer battery of 29.6 VDC and 3.9 Ah brings one hour of autonomy for a continuous walk with the device at a speed of 0.8 km/h [178, 179].

The control of the orthosis is based on postural information measured on the device, that the authors claim, enables the user to control autonomously the device in a safe, reliable and intuitive manner [180]. The device is designed to provide legged mobility for people with paraplegia [181], including the possibility to aid paraplegic individuals to ascend and to descend stairs [182]. It is modular and split into three pieces, which makes it easy to dress on and off, even if the user is in a wheelchair. The device can support people weighting up to 91 kg. In figure 1.13 a picture of Vanderbilt exoskeleton is depicted. The authors indicated that a trade-off associated with the design of the device is that it needs a custom fitting for each user of different sizes.

In October, 2012, the Vanderbilt University has signed an exclusive agreement with Parker Hannifin Corporation for further development and commercialization. Parker has named the exoskeleton as Indego and is planning to make the device available commercially in Europe in 2015 and in the United States in 2016. To date, Indego still does not have been submitted for FDA approval and still does not have regulatory approvals for European market. The device is currently undergoing clinical testing with

FIGURE 1.13: The Vanderbilt exoskeleton is powered by brushless DC motors through gear reductions that provides a maximum continuous torque of 12 Nm for hip and knee joints.

SCI patients in different hospitals, but no further results have been published to date.

1.5.4.5 Rex

Rex Bionics is a company in New Zealand that manufactures the exoskeleton named Rex (Robotic EXoskeleton). They have been working on the development and construction of the device since 2003 [173]. Compared to other robotic exoskeletons, Rex is much bigger and bulky, weighting about 52 kg. The advantage is that, to the best of the author's knowledge, Rex is the only exoskeleton that can balance itself, eliminating the need of any additional supportive aid such as crutches.

Rex, shown in figure 1.14, is not intended for rehabilitation, but for functional compensation in SCI patients that can operate hand controls. It is commanded by a joystick allowing the user to sit, stand, walk at level ground and turn left or right. The maximum speed that can be achieved by Rex is about 0.5 km/h. As such, Rex is obviously not a complete replacement for the wheelchair at this stage, but instead it is a complementary device with its own benefits.

Rex Bionics sells two models of its exoskeleton: one for personal use and other intended for clinical rehabilitation. The main difference between the two models is the possibility of rapidly adjusting the rehabilitation model for multiple users who may vary in height, weight and medical needs. The personal model is licensed for the European market, selling for about US$ 150,000 plus servicing costs. Public research about the device and clinical data have not been published to date.

FIGURE 1.14: Rex is not intended for rehabilitation, but for functional compensation in SCI patients that can operate hand controls. Rex can balance itself, eliminating the need of any additional supportive aid such as crutches.

A version of Rex, called NeuroRex, augmented with a brain-machine interface based on EEG (Electroencephalography) for the control of the locomotion functions of Rex, has been developed at the University of Houston [183–185]. NeuroRex is intended for use by patients with SCI, and it is the first powered exoskeleton that can be controlled by the patient's brain waves.

1.5.4.6 X1

The exoskeleton X1 [186] was developed by NASA (National Aeronautics and Space Administration) in Texas, United States, in partnership with IHMC (Institute for Human and Machine Cognition) in Florida, United States. The technology used in X1 is a combination derived from two different projects: the basic actuator design, safety systems, communication and control schemes are inherited from Robonaut2, a humanoid robot developed to operate aboard the ISS (International Space Station) [187]; the series elastic actuation scheme was leveraged from the IHMC Mobility Assist Exoskeleton, designed for assisted walking [188].

X1 is a tethered device with a backpack carried by the user, represented in figure 1.15. The total weight of the device is about 26 kg. Actuation on the X1 is based on series elastic rotary actuators for hip and knee on sagittal plane. Ankle has a passive degree of freedom, as well as hip abduction/adduction and internal/external rotation.

X1 exoskeleton has been developed for possible future use in the ISS. Since astronauts need to exercise in space to keep bone density and muscle tone, X1 is planned as a

FIGURE 1.15: X1 exoskeleton has been developed by NASA in partnership with IHMC. The device is intended for possible future use in the ISS as a compact exercise tool for astronauts.

compact exercise tool to be aboard of the ISS. Meanwhile, a recent study [189] has tested X1 with two healthy subjects and one post-stroke victim. The objective was to demonstrate the feasibility of implementing a neural interface with the X1, capable of decoding lower limb movement during walking based on EEG signals. Authors pointed out that actuation on the ankle joint would be very clinically relevant for stroke patients, to counteract the foot drop problems.

1.5.4.7 Other Lower Limb Exoskeletons

A number of groups have published different works on lower limb exoskeleton devices that are still in the early stages of research and/or development. In the work presented in [190], a different assistive concept with a combination of active orthosis, mobile platforms and telescopic crutches are used. In [191], authors have developed an EMG-based lower limb robot based on a neuro-fuzzy controller.

Mindwalker [192] is an exoskeleton developed at the University of Twente, The Netherlands, that targets SCI population. A recent study [193] shows the changes in EMG patterns during the assisted walking with Mindwalker.

The IHMC in Florida, United States, has also developed different prototypes of exoskeletons, as the IHMC Mobility Assist Exoskeleton [188] and Mina [194, 195], both with actuation on the hip and the knee joints, intended for assistance in paraplegic persons.

A different approach to achieve more portability was developed at Sogang University in Korea [196]. Researchers put together a lower limb exoskeleton and an active walker.

The active walker has a handle and move on wheels, thereby providing support and maintaining the patient's balance. The walker also holds batteries, control unit and motors, while power is transmitted by cables. The orthosis has 1 DOF active joint at both hips and knees.

1.6 Conclusion

Stroke is a brain lesion caused by the lack of blood supply to the brain. The main consequence of a stroke is a serious long-term disability, and it affects a large number of people around the world. Recovery after stroke is primarily based on physical therapy and there have been some changes in the past decade. The most common rehabilitation method is based on the task specific approach, with physical therapists manually assisting patients.

Gait is one of the most important daily life activity affected in stroke victims and, therefore, much effort has been spent on gait rehabilitation. The physical work required from therapists is one of the main limitation of the current methods for gait rehabilitation. Moreover, multiple therapists are required to train only one patient and still the movement coordination of both legs is far from being synchronized.

In order to help physical therapists to improve the rehabilitation process, robotic devices have been developed. The main devices for this purpose rely on stationary machines that help patients to perform gait on a treadmill. Although these machines can alleviate the physical effort required from therapists and provide intensive training, motivation and participation of patients are not always achieved. Active subject participation in robotic gait therapy is vital to many of the potential recovery pathways and, therefore, it is an important feature of gait training.

Ambulatory exoskeletons have emerged as a promising approach to restore gait and improve motor function. Two main objectives are targeted with ambulatory exoskeletons: gait compensation and gait rehabilitation. Most ambulatory exoskeletons target gait compensation, which is understood as a replacement for lost movements. The main attempt is to substitute the wheelchair with a device that can bring more benefits to the user.

A few overground exoskeletons have shown the first results with patients. Although the effectiveness of these devices is still unclear, the literature suggests that they are feasible systems that can provide intensive training and superior motivation to patients.

Nevertheless, many challenges remain. Actuation at the ankle, which is not present on rehabilitation overground exoskeletons, would enable implementation of real-time strategies that can better target foot drop problems in stroke victims. Assist-as-needed control

strategies must also be implemented, leading to an active participation of the patient during the rehabilitation task. This approach should be used to promote user involvement by performing gait in a challenging real environment. Lastly, clinical evaluation with exoskeletons must be comprehensive, addressing gait performance and user-perception through clinically validated functional scales and protocols.

1.7 Objectives and Organization of the Dissertation

1.7.1 Framework

The work presented in this dissertation was carried out at the Neural Rehabilitation Group of the CSIC (Spanish Research Council). This section will position this work in the context of the several projects conducted by the Neural Rehabilitation Group. The group has a large experience developing robotic devices for gait rehabilitation.

Developments started with the FP5 (Fifth Framework Programme) GAIT Project, which aimed to provide an integrated approach to active functional compensation and biomechanical evaluation of lower limb joint disorders. To achieve this goal, GAIT designed a KAFO which comprised sensors, actuators and an intelligent control system to regulate joint functions during walking and other ADLs (Activity of Daily Living). The system, illustrated in figure 1.16, was also conceived as a biomechanical monitoring tool, for both laboratory and daily use, capable of storing data and communicating wirelessly with a software platform for medical analysis.

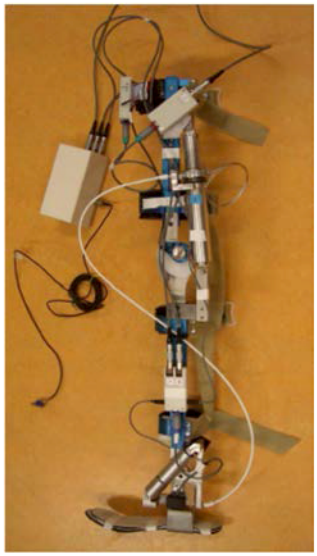

FIGURE 1.16: GAIT exoskeleton: a KAFO provided with sensors, actuators and an intelligent control system to regulate joints functions during walking and other ADLs.

Aiming at a population of polyo myelitis and young patients with cerebral palsy, the GAIT Project approach had two main applications: improvement of the orthosis functionality by means of compensation strategies during walking and ADLs; and tracking of kinematics, kinetics and comfort data of interest for the patient, physician or physical therapist during daily use and also at the laboratory.

After GAIT, the FP6 ESBIRRO Project was carried out aiming to develop Limit Cycle control and biomimetic recovery reactions for the control of walking, in order to apply these paradigms to design and construct an autonomous walking biped and a robotic exoskeleton for gait (figure 1.17).

Limit Cycle controlled robots exploit the dynamics of the mechanical systems (pendulum behavior of the swinging leg), showing lower energy consumption, whereas walking stability is comparable to the trajectory controlled humanoid robots. Considering that the starting point of the Limit Cycle robots was inspired on human gait, the ESBIRRO Project proposes one step further in the evolution of such robots: implementation of recovery reactions from perturbations that can be found in biological systems, e.g., human stumble reaction. These new generation robots can keep lower energy consumption with improved stability. The modeling and control of a biped robot provide further understanding of human gait, paving the way for novel actuated orthoses regarded as robotic extensions of the human being: exoskeletons.

Subsequently, the REHABOT Project proposed research in the field of hybrid actuation and control for rehabilitation of motor disorders, in particular to prove the concept of the hybrid walking therapy for paraplegic individuals. The overall aim was to generate the necessary knowledge to design a novel hybrid walking therapy with fatigue management for incomplete spinal cord injured subjects. Research activities were conducted towards

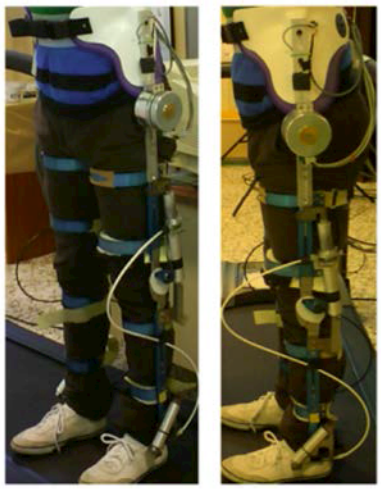

FIGURE 1.17: Exoskeleton designed in the ESBIRRO Project that aims to develop Limit Cycle control and biomimetic recovery reactions for the control of walking.

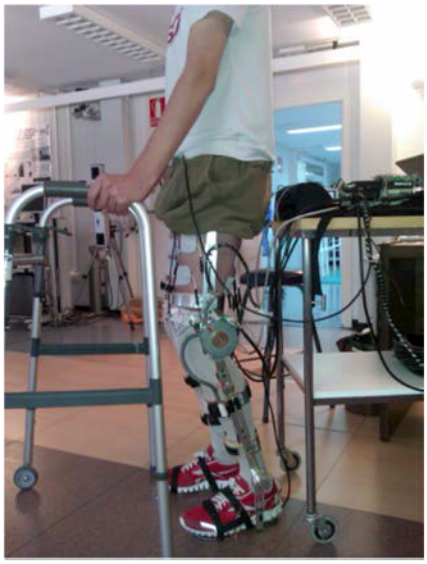

FIGURE 1.18: Spinal cord injured patient using the REHABOT exoskeleton. The device comprises a knee actuated exoskeleton working in close cooperation with FES for gait rehabilitation.

the establishment of the required methods, hardware and software systems to proof the concept with a pilot clinical evaluation.

A knee actuated exoskeleton was developed to work in close cooperation with FES in gait rehabilitation, illustrated in figure 1.18. Technically, assist-as-needed was implemented over the basis of a compliant control of the exoskeleton and a closed-loop control of the FES.

A clinical evaluation protocol in REHABOT allowed to assess the impact of the hybrid walking therapy in paraplegic patients. Results demonstrate that the hybrid controller adapts to patient residual function during walking and that the therapy is tolerated by patients. Furthermore, the walking function of patients was improved after participating in the study. In conclusion, the hybrid walking therapy holds potential for rehabilitate walking in incomplete paraplegic patients, guaranteeing further research on this topic.

FP7 BETTER was the next project, that designed a new approach for gait retraining post-stroke, in which existing and novel robotic technologies could be improved when combined with non-invasive Brain/Neuronal Computer Interaction. BETTER proposed a multimodal Brain/Neuronal Computer Interaction system that interacts with gait exoskeletons, implementing new control methods and monitoring functions. This concept is represented in figure 1.19. The ultimate goal is to promote the active participation of patients and to improve the functional outcome.

The project explores a top-down approach research in order to combine signals from central and peripheral nervous systems with biomechanical data and provide a means

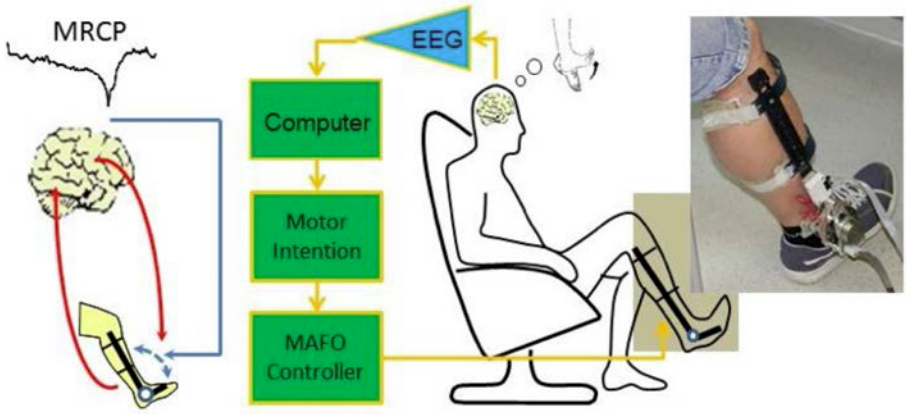

FIGURE 1.19: Scheme that illustrates the concept in the BETTER Project: closed loop brain computer interface triggering an active AFO for inducing cortical neural plasticity.

to evaluate the physical rehabilitation, its usability and acceptability. Furthermore, BETTER provided means to assess patient's compliance through the Brain/Neuronal Computer Interaction, characterize the user involvement and modify the intervention at the periphery with the robots. In this project a robotic AFO and KAFO were developed. Each of these components are stand alone tools for earlier phases of stroke rehabilitation, when patients are still not able to control trunk and hence to walk. Different studies were conducted in BETTER with the developed devices as a proof of concept for stroke rehabilitation.

Subsequent work was developed in the HYPER Project (Hybrid Neuroprosthetic and Neurorobotic Devices for Functional Compensation and Rehabilitation of Motor Disorders), in which framework the work presented in this dissertation was carried out. The research in HYPER project offers a significant advance in investigating wearable exoskeletons and neuroprostesics devices in close interaction with the human body. The objective is both rehabilitation and functional compensation of motor disorders in ADLs. HYPER focuses its activities on the development of novel configurations that aggregate exoskeletons, neuroprostesics and virtual reality. These devices, by their combined action, can enhance and help restore the latent capacities of patients suffering from stroke or SCI.

The project aims to validate, both clinically and functionally, the concept of developing hybrid devices for rehabilitation and functional compensation of motor disorders, under an assist-as-needed paradigm. It combines artificial and biological structures integrated to restore motor function in patients. The main challenges are to improve the outcome of therapy and allow an early recovery, overcoming the major limitations of the current rehabilitation solutions.

FIGURE 1.20: H1 exoskeleton is the first version of a wearable exoskeleton developed in the HYPER Project. The integration of wearable exoskeletons and neuroprosthetic devices in this project aims to overcome the major limitations of current rehabilitation solutions for stroke and spinal cord lesions.

In the framework of this project the author also obtained his Master Degree working on the development of a first version of the lower limb exoskeleton, called H1 and illustrated in figure 1.20. Based on experiments conducted with healthy subjects, we propose a new version of the device, called H2, with significant improvements when compared to the H1. This dissertation will present the H2 design, implementation and evaluation with stroke patients.

H2 exoskeleton presented in this dissertation has been already integrated into a new ongoing FP7 project called BIOMOT. The main objective of BIOMOT is to improve existing wearable exoskeletons by exploiting dynamic sensory-motor interactions and by developing cognitive capabilities that lead to symbiotic gait behavior in the human-robot interaction. BIOMOT proposes a cognitive architecture for robotic exoskeletons exploiting neuronal control and learning mechanisms aiming to enable positive co-adaptation and seamless interaction with humans.

1.7.2 Objectives

The main objective of this dissertation is **to design, develop and validate a lower limb robotic exoskeleton and an assist-as-needed therapy for gait rehabilitation in post-stroke patients.** Around this main objective, several scientific and

technical challenges are addressed in this dissertation, which constitute the following partial objectives:

1. First objective is to design a lightweight and ambulatory exoskeleton. Most state of the art ambulatory exoskeletons include a backpack that should be carried by the user, therefore resulting in a non-comfortable embodiment to the user. This work focuses on designing a device that does not extend above mid-abdomen and requires nothing to be worn over the shoulders and nothing above the lower back, which presumably renders the user more comfort when using the device.

2. Another objective is the development of an adjustable device that can be used by a broader range of patients. The adjustments should be simple and easy to be performed by therapists, enabling a fast donning and doffing process when using the exoskeleton in a clinical environment. This should lead to a reduced time from the moment that patients arrive at the clinics to the moment they start practicing walking.

3. Actuation on all three joints in both legs is another important aspect targeted in the development. Ankle joint actuation is never addressed in overground rehabilitation exoskeletons, but it is very important to counteract the foot drop problems in post-stroke patients. We envisioned a completed actuated device in the sagittal plane, capable of providing the necessary torque to completely assist patients through the walking process.

4. Further objective is the implementation of an untethered device with high autonomy. The device should be battery powered with all electronic systems embedded and wireless communications for data collection and user interface interaction. This objective aims to give more freedom to the user while performing overground walking, allowing intensive and repetitive gait training, freeing physiotherapists from doing a laborious manual work.

5. A safe device is another objective and a main consideration in the development. The design should account for safety features on the hardware and software, avoiding any kind of dangerous situations that could lead to patient's injury.

6. The development of a robust control approach that does not need manual adjustments to each user is aimed. The exoskeleton should adapt to patient disabilities, but without any sensors physically attached to human limbs. All sensory information should come from sensors placed on the exoskeleton. This will lead to robustness, more comfort and reliability.

7. Another important objective is the engagement and motivation of patients. Ambulatory exoskeletons that challenge patients to perform movements in real environments can be more effective to reinstate neuroplasticity and to improve motor functions when compared with treadmill training. Performing gait in a real

scenario may also help patients to improve others functions as weight shift and balance.

8. Patient active participation in the rehabilitation process is another goal. This will be created by an assist-as-needed control algorithm that only applies the necessary torque to complete the gait process, instead of fully driving the lower limbs while the patient remains passive. The exoskeleton should guide each patient's joint in a correct trajectory, only applying a restoring force when the patient deviates from the correct trajectory.

9. A further objective is the development of an open architecture that will allow the exoskeleton to be integrated and/or commanded by third party systems. This feature allows the exoskeleton to be integrated into a more sophisticated rehabilitation scenario and interface with external devices that can further engage patients. It also generates the possibility of developing future therapies for retraining balance, sit-to-stand, etc.

10. One last objective of this dissertation is the validation of all aspects related to the usability and safety of the device with post-stroke patients. The validation will be a proof-of-concept of all design and implementation applied to a clinical rehabilitation scenario. The clinical study should also generate feedback for further implementation of a randomized clinical trial with a large cohort of patients.

1.7.3 Organization

This dissertation is organized in five chapters. Chapters 2 to 4 addresses specific topics that relate to the development and validation of the lower limb exoskeleton, while Chapter 5 presents the main conclusions of the work and provides future research and development activities, proposed to improve the work presented in this dissertation.

Chapter 2 presents the mechanical and electronic design and the development of the robotic exoskeleton. The chapter starts with the criteria for the mechanical design and its implementation. Afterwards, the rationale for actuator selection is given and the joint actuation implementation is explained. Power supply system and exoskeleton sensors are detailed subsequently. Next, all the electronic development is detailed, including the joint embedded electronics, the main controller board and the deterministic real-time communication bus used to connect all joints to the main controller. Finally, an explanation about the safety systems incorporated on the exoskeleton is given.

Chapter 3 presents the development of all the software components implemented in the exoskeleton. It starts with the software implemented at the actuation level, followed by the close loop controllers' implementation. Subsequently, it is addressed a strategy for implementing an assist-as-needed therapy for gait rehabilitation in a clinical scenario.

The user interface developed for therapist interaction with the H2 is also presented. Finally, the chapter describes the open architecture of the device that allows it to be integrated with third party devices, detailing the integration with a neural interface.

Chapter 4 presents the evaluation of safety and usability of the exoskeleton as a proof-of-concept. First, experimental results about the use of the device with a group of healthy subjects are presented. The experiment aims to validate the hardware and software development prior to the clinical evaluation with post-stroke patients. With the clinical study, it is validated the safety and usability of the device when applied to stroke victims in a rehabilitation scenario. The study also investigates the effects of the overground walking therapy implemented to assist patients as needed.

Chapter 5 concludes the dissertation, gathering the main results and conclusions. Publications and patents originated from this dissertation are also summarized. Finally, future research and development activities originated in this dissertation are proposed.

Chapter 2

H2 Lower Limb Exoskeleton[1]

This chapter presents the H2 hardware design and implementation. The device is conceived as a lower limb robotic exoskeleton for gait rehabilitation in stroke patients. The chapter begins with a brief introduction about human walking, which gives background for the exoskeleton mechanical design. It follows the rationale behind the actuators' choice and power requirements for designing an untethered device. As a result, the robotic exoskeleton comprises active actuation on the hip, knee and ankle joints and it is powered by a lithium polymer battery for autonomous overground walk capabilities. Sensory system of H2 includes different types of sensors placed on the exoskeleton, but not a single sensor placed on the user's body. This approach aims at improving user's comfort, system reliability and a fast and simple donning/doffing process. Subsequent sections detail the electronic architecture that was specifically customized for H2. The architecture comprises a distributed control system, designed to be more reliable and to avoid the bulkiness and difficulty of wiring sensor and actuator's cables over the H2 mechanical frame. Lastly, the chapter presents the safety features that have been implemented in different levels to avoid possible injuries to patients during training.

[1]This chapter is partially based on the following:
M. Bortole, A. del Ama, E. Rocon, J. C. Moreno, F. Brunetti, and J. L. Pons. **A robotic exoskeleton for overground gait rehabilitation**, in Proceedings of IEEE International Conference on Robotics and Automation, pp. 3356–3361, 2013.

M. Bortole. **Design and control of a robotic exoskeleton for gait rehabilitation**, Master Thesis, Universidad Carlos III de Madrid, 2013.

2.1 Introduction

It is a general assumption that robotics will play an important role in future activities within rehabilitation of disabled people. The interest in rehabilitation robotics has grown exponentially in the last decade mainly due to the growing demand caused by increasing numbers of stroke victims and the associate costs of rehabilitation [90]. As a result, robotic-based therapies have been developed worldwide. However, the majority of the existing robotic-based gait rehabilitation systems commercially available are stationary. Thus, patient's displacement between two different places during training is not possible. In an attempt to overcome this disadvantage, virtual reality systems have been applied with the objective of to encourage and motivate patients [197].

However, motivation and engagement can be better achieved with exoskeletons capable of overground walking. In these devices, actuators placed at the joints of the robot control patient's joint motions, helping them to perform close to normal walking patterns.

Understanding the biomechanics of the human walking is essential to design such exoskeletons. Figure 2.1 represents a simplified diagram of the human gait. It is worth to note that the event's timing during the gait cycle labeled in the figure is approximate, slight varying across individuals and conditions. The gait cycle during human walking is typically represented as starting and ending at the point of heel strike on the same foot (represented from 0 to 100%). The heel strike on the adjacent foot occurs at approximately 60% of the gait cycle.

In general terms, the human leg can be thought as a structure with seven DOF: three rotational DOFs at the hip, one at the knee and three at the ankle. The sagittal plane is

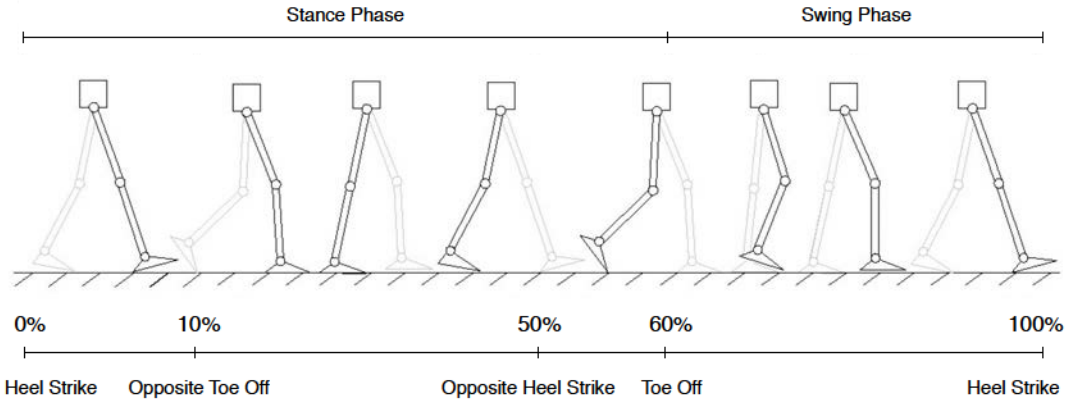

FIGURE 2.1: Simplified diagram of the human walking through one cycle, beginning and ending at the heel strike. Percentages showing contact events are given at their approximate location in the cycle, since there is a slightly variation across individuals and conditions. Adapted from [151].

the dominant plane of motion during human locomotion. Joint movement in this plane is simply referred to as flexion (positive direction) and extension (negative direction).

The practical implementation of an autonomous exoskeleton to assist human walk faces a number of scientific and technological challenges. Power supply, lightweight and efficient actuators and compliant control systems are among the many issues that a researcher has to face. In an advanced exoskeleton development, off-the-shelf components as actuators, batteries, electronics and other subsystems, usually do not meet the low weight, autonomy and high efficiency needed to accomplish the design objectives [151]. Consequently, most of the parts have to be developed and customized to fulfill the implementation requirements.

This chapter presents a novel lower limb exoskeleton, called H2, designed to drive the human legs during overground gait rehabilitation. It is shown that designing a customized actuation structure, power supply system and all electronic architecture can result in a more lightweight, compact and efficient system. Also, the right choice of the joints that should be actuated is very important, as well as the number of degrees of freedom. Too many actuated joints can result in a bulky and heavy device with a much more complex control system. However, lack of actuation in some important joints can lead to some drawbacks, as missing actuation on the ankle joint, which is clinically relevant for stroke patients to counteract the foot drop problems.

The design of the H2 robotic exoskeleton is based on the background presented in Section 1.7. With the stroke population in mind, it was developed a lower limb exoskeleton with six actuated joints (hip, knee, ankle on both legs) in the sagittal plane, since this is the main plane of motion during human walking.

This chapter starts by presenting the rationale for the design and the mechanical implementation of the exoskeleton in Section 2.2, with a description of the structure, adjustments, degrees of freedom and range of motion of the device. Section 2.3 describes the rationale behind the actuators' choice and the mechanical implementation on the H2 joints. Section 2.4 presents the power supply system developed for running H2. Subsequently, the electronic control architecture is presented in Section 2.6. Section 2.7 explains the safety mechanisms implemented in the hardware and software of the H2. The chapter ends with conclusions that summarize the major results of the design and development of this exoskeleton.

2.2 Mechanical Design

H2 exoskeleton is designed for gait rehabilitation of adults between 1.50 and 1.95 meters in height, with a maximum body weight of 100 kg. The device is primarily intended for rehabilitation of stroke victims, but it can also be used for gait compensation in patients

who have paralysis of the lower limbs following spinal cord injuries. It is conceived for overground gait training in a clinical environment as a bilateral wearable device. The H2 has six DOF, in which hip, knee and ankle are powered joints.

One novel characteristic in the H2 is the actuation on the ankle joint. Existing exoskeletons for rehabilitation (please refer to Section 1.5.4) are constructed without actuated foot segments and patient's ankle joints are not controlled. Usually, patients move their feet freely or the feet are lifted during the swing phase of walking using passive mechanisms as elastic straps, springs or passive orthoses. However, the ankle plantar flexors play a key role in propulsion, body-weight support and swing initiation during walking [198]. After a stroke, propulsive impulses delivered by plantar flexors muscles are often highly asymmetric. Push-off asymmetry results in increased metabolic energy consumption and slow walking speeds [199–201]. Also, actuation of ankle joint can be very clinically relevant to counteract the foot drop problems that typically affect stroke survivors [189].

H2 mechanical design is a totally improved version of the exoskeleton H1 developed by the author on his master thesis and published in [202]. Improvements in the H2 with respect to the H1 account for a stronger and simpler actuation structure on the knee and the ankle joints, a more durable and reliable knee joint mechanism and a more lightweight hip joint. The H2 electronic architecture and control software is totally new and will be presented in Chapter 3.

Various criteria informed the H2 mechanical design. As pointed out in the literature [203], an exoskeleton design should be ergonomic, comfortable, lightweight, safe, with a strong structure and adaptable to different users. Low mass is an important aspect, since inertia cannot be easily compensated during training [204]. Therefore, aluminum 7075 is primarily used in the mechanical structure in consideration of mechanical resistance and lightweight. The final device weights about 12 kg including its battery pack. The exoskeleton frame has bilateral uprights for the thigh and the shank, hinged hip, knee and ankles and articulated footplates (distally) and a waist support (proximally).

The mechanical structure is designed to allow active and passive movements in the sagittal plane for hip, knee and ankle joints. In the frontal plane, hip ab/adduction is accommodated by compliance embedded into the hip segment. Such compliance is intended to provide stability to the wearer, admitting passive movements of about twenty degrees, which allows for turns while walking. Figure 2.2 (a) illustrates the anatomical planes of human body used as reference. H2's ROM (Range of Motion) in actuated joints is mechanically limited for safety reasons. The maximum ROM possible across all joints is shown in table 2.1. These values were chosen based on normal gait on healthy subjects [205], also allowing users to perform sit-to-stand and stand-to-sit movements. To be consistent with the reference used by clinicians, flexion was considered the positive

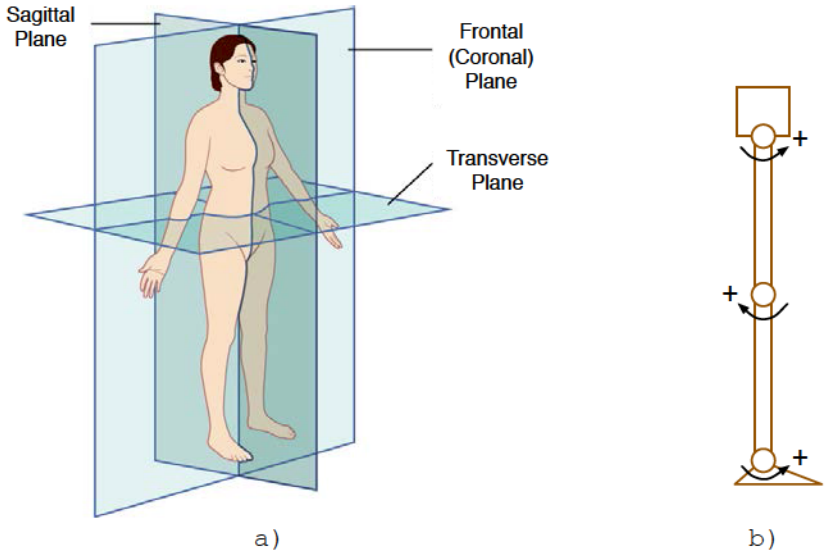

FIGURE 2.2: a) Representation of the anatomical planes of human body. b) Diagram of the exoskeleton leg in the rest position (all joints at 0 degree) and positive direction of movement indicated. The positive direction represents flexion and it is in accordance with clinicians' definition.

TABLE 2.1: H2 degrees of freedom and range of motion across all joints.

Joint	Degree of Freedom	Actuation	Range of Motion
Hip	Flexion/Extension	active	100°/20°
Hip	Ab/Adduction	passive	10°/10°
Knee	Flexion/Extension	active	100°/3°
Ankle	Dorsi/Plantar Flexion	active	20°/20°

direction of movement and extension the negative direction. Figure 2.2 (*b*) illustrates the reference adopted.

The length of the thigh and the shank of the exoskeleton can be adjusted by a mechanism of two telescopic bars that are pushed one inside the other, and are securely fixed in different positions by screws. The same mechanism is used to change the position of the footplate relative to the exoskeleton's ankle. The size and position of the adjustable rounded leg braces with Velcro straps allow for customization to individual requirements. H2 mechanical structure is shown in figure 2.3. Foam pads are used to minimize pressure against the skin and prevent damage. The exoskeleton supports its own weight through the mechanical frame to the ground, so the users do not feel any extra weight on their trunks or lower limbs.

Importantly, the H2 design is modular, particularly relevant for stroke rehabilitation. Mechanical design was conceived in such way that all segments of the device can be

FIGURE 2.3: Aluminum 7075 is primarily used in the mechanical structure of the H2 in consideration of mechanical resistance and lightweight. Hip, knee and ankle joints are actuated in the sagittal plane.

used independently in a very simple way. The H2 offers means of using unilateral Hip-Knee-Ankle, Knee-Ankle or just one joint versions of the device, allowing customized treatment protocols to each patient's specific needs.

2.3 Actuators

Most types of actuators used in robotics cannot be used in exoskeletons, since for this application high torques are required while operating at higher speeds that most actuators can provide [206]. Main candidates available for use as actuators on exoskeletons are electric, pneumatic, hydraulic and SEAs (Series Elastic Actuator). The design and selection of the H2 actuators were based on the average torque and power of each joint during normal gait (not pathological) at normal speed [205]. A study of different possible candidates was evaluated. The most relevant criteria to select the actuation technology to drive the human joints were the specific power (ratio of actuator power to actuator weight) and portability.

Hydraulic and pneumatic actuators have high power density. Hydraulic actuators have been used in military exoskeletons such as BLEEX [207, 208] and Sarcos [165]. Pneumatic actuators were applied to some stationary devices for rehabilitation, such as PAM [142] and POGO [143]. The main drawbacks of hydraulic and pneumatic actuators are that they are bulky, which can make their use prohibitive on lightweight overground

exoskeletons. They also present problems of internal friction and leakage [207], which could not be acceptable in devices used in clinical environments.

SEA actuation is based on a elastic element, usually a spring, placed in series with the actuator output, where the force is calculated based on its compression [188]. They have been used in some rehabilitation devices [209], but they still face a common limitation about the fixed spring constant of the elastic element. The smooth coordination of force and position between patient and exoskeleton can be difficult between different subjects [210].

Electric motors have been used in most ambulatory exoskeletons [156, 169, 172, 177]. The literature suggests that the use of electric motors provide a reduction in power consumption during gait [207]. DC motors meet the criteria of necessary power with a compact and portable solution for wearable devices. Within the DC motors category, brushless motors offer several advantages for wearable devices, including higher efficiency, more torque density, increased reliability, reduced noise, longer lifetime and reduction of electromagnetic interference. To meet the challenging goal of using a lightweight actuator and, at the same time, efficient and able to provide enough torque, BLDC (Brushless Direct Current) motors were chosen as actuators for the H2 joints. Moreover, flat type motors were selected, which brings the possibility of placing the motors coaxially with the joints and maintaining a small volume parallel to the user's legs.

As the exoskeleton joints need more torque and lower speed than BLDC motors can provide directly, a possible solution for increasing torque and reducing the speed is coupling a gearbox to the motor shaft output. To achieve a lightweight and a small volume solution, strain wave gears were selected as a gearbox. Strain wave gears are a special type of mechanical gear system, usually known as "harmonic drive", because they are produced by the Harmonic Drive. The main advantages of this type of gearbox, when compared to traditional gearing systems, include: no backlash, compactness, high gear ratios, high torque capability, coaxial input and output shafts, good resolution and excellent repeatability when repositioning inertial loads [211, 212].

A 100 W flat BLDC motor (EC60-100W, Maxon) is used in all six joints. This motor has a rated nominal voltage of 24 VDC and nominal torque of 220 mNm. Furthermore, a strain wave gear (CSD20-160-2A, Harmonic Drive) with a gear ratio of 160:1 is coupled to each motor shaft and gives to the joints a continuous net torque of 35 Nm and peak torques of 180 Nm. According to [93], an average torque of 35 Nm for the hip actuator is presumed to be adequate enough for most patients. Based on experiments with the previous version of the exoskeleton, it was concluded that 35 Nm is enough for driving knee and ankle joints as well. Moreover, the human gait cycle does not require a continuous torque, but higher torques in specific moments, which will be provided by the peak torque of the actuators that can reach up to 180 Nm.

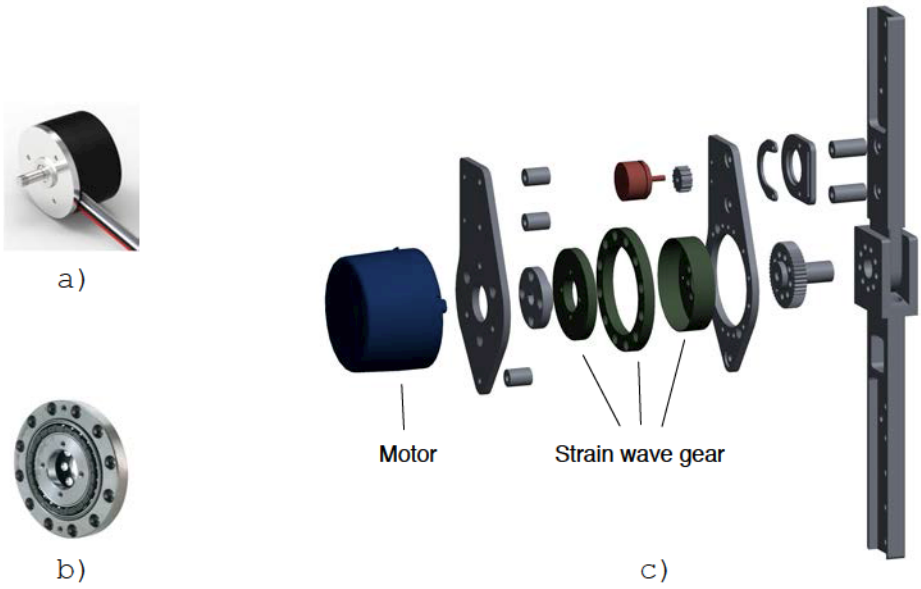

FIGURE 2.4: a) BLDC motor used in the H2 joints. b) Strain wave gear used in the H2 joints. c) Exploded view of one knee joint, which can provide 35 Nm of continuous net torque. All six joints use similar design and actuation system.

Therefore, we designed the three joints with the same actuation system. In figure 2.4 is shown an exploded view of the knee joint, as well as the Maxon motor and the Harmonic Drive gearbox used in the H2.

2.4 Power Supply

The power supply can be one of the most limiting factors for an untethered exoskeleton embodiment. Although the H2 exoskeleton is designed to be used in a clinical setting, a tethered device can lead to some drawbacks when performing overground walking. Thus, the exoskeleton was developed as an autonomous device. Different types of energy sources have been used to power exoskeletons [206]. With improvements in battery technologies over the years, a compact and high capacity battery pack can provide enough power for running an exoskeleton.

Autonomy also has to do with the performance of the actuators. The developed exoskeleton was designed with high efficiency motors and gearboxes, and state-of-the-art electronic drives with very low dissipation. Additionally, a compact lithium polymer battery pack was specifically designed to power the H2. The pack has a nominal voltage of 22.5 VDC and a capacity of 12 Ah. The battery pack is integrated with the mechanical frame and placed at the hip level, providing a comfortable embodiment for the user and no extra weight on the trunk or lower limbs.

The battery pack was designed to run the exoskeleton for an average of four hours of continuous walking. Also, since the battery pack is detachable from the mechanical frame, it is very easy to replace an empty one with a fully recharged pack for continuous work. An external charger was also developed to charge the H2 batteries.

2.5 Sensors

The interaction between user and exoskeleton is very important for user's comfort and safety in a wearable robotic device [213]. Also, when sensors have to be physically placed on human limbs, several issues, specially related to safety, comfort, reliability and donning/doffing process need to be expected and appropriately dealt with.

In terms of physical interface with the human user, H2 is designed in such a way that there are no sensors physically attached to the human. All sensory information comes from sensors placed on the exoskeleton: 6 potentiometers, 25 Hall Effect sensors, 24 strain gauges and 4 foot switches are used to determine parameters such as angular position and velocity, force and interaction torque, motor torque and foot ground contact.

Each joint is equipped with a precision industrial potentiometer (157S103MX, Vishay Spectrol) used as an absolute angular position sensor. It exhibits a tight linearity of $\pm 0.25\%$ and long rotational life. Its stainless steel shaft is coupled to a toothed pulley and a toothed belt is used to transmit the joint's motion. This avoids slippage and therefore a loss of reference position. The position sensor placement at the joint is represented in figure 2.5.

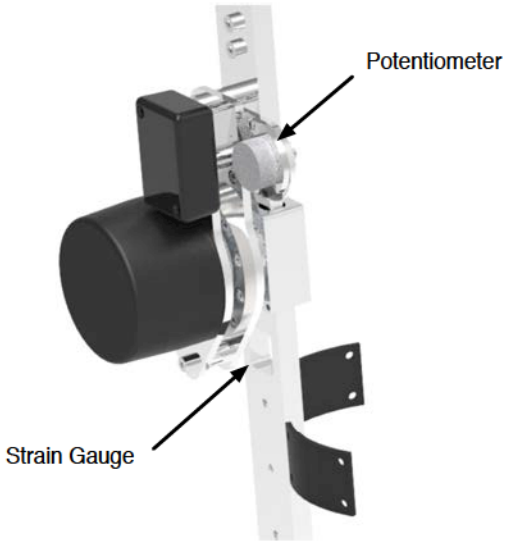

FIGURE 2.5: H2 joint illustrating the position sensor placement, as well as where the strain gauges are attached to the mechanical link, in order to measure the interaction torque between user and exoskeleton.

Strain gauges attached at each exoskeleton's link are used as force sensors. These sensors are designed to measure the torque produced by the interaction between the user's limb and the exoskeleton. Four strain gauges are connected in a full Wheatstone bridge configuration to enhance the measurement accuracy and insensitivity to temperature variations. The bridge is excited with 5 VDC and a custom-made electronic circuit balances the bridge for null point measurement, also amplifying the output 500 times. Thus, the output signal is in a range that allows torque measurements from –50 to +50 Nm. This range was chosen based on the maximum torque of the actuators with a safety factor for peak torques. A calibration constant was obtained using a set of calibrated weights and minimized with a least squares algorithm.

Figure 2.5 illustrates the place where the strain gauges are attached to the mechanical link. After the attachment to the links, strain gauges are covered and protected by a hard resin. This avoids humidity and external contamination that can cause damage to the strain gauges or interfere with measurements.

Besides the interaction torque between the subject and the exoskeleton, the system can also measure the actuator's torque. This task is carried out using a Hall Effect sensor that measure the motor's current, which is directly related to the motor's torque. The system also uses the Hall Effect sensors inside the motors to compute the actuators' angular speed.

The footplate of the exoskeleton is equipped with two foot switches based on resistive sensors, which binary detect the contact between subject's foot and the ground. These sensors are located under the heel and the toe, and their main goal is to detect the different phases during gait segmentation. The H2 exoskeleton, its actuators and sensors are shown in figure 2.6.

2.6 Control Architecture

The H2 control architecture is represented in figure 2.7. The electronic hardware is composed of three main parts:

1. The main board, responsible for running all controllers and synchronizing the joints' movements;
2. The motor drives, dedicated to sensor data acquisition and actuator control of each joint independently;
3. The data bus, a real time network connecting the main board and the motor drives.

Modularity is an important consideration when designing an exoskeleton control architecture. When the device has to deal with complex tasks and/or have many DOFs, a

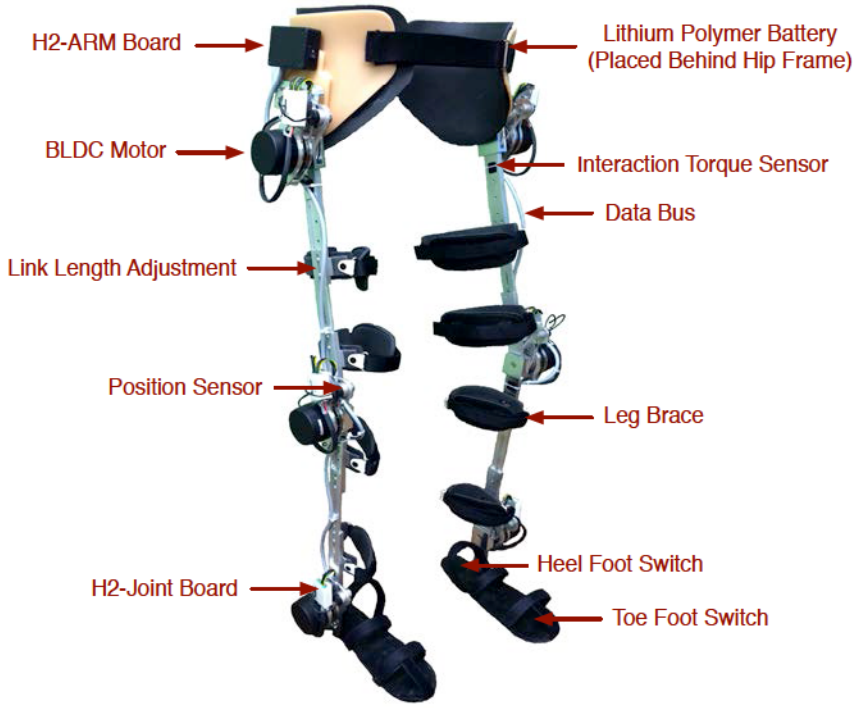

FIGURE 2.6: Illustration of the H2 exoskeleton, its actuators and sensors. All sensory information comes from sensors placed on the exoskeleton: 6 potentiometers, 25 Hall Effect sensors, 24 strain gauges and 4 foot switches.

centralized control architecture would not be effective anymore [214]. Therefore, a distributed architecture is implemented in the H2. It also makes easy to use each segment of the device independently in a very simple way. Unilateral Hip-Knee-Ankle, Knee-Ankle or only one joint versions of the device can be easily applied in customized treatments depending on the therapy goals.

2.6.1 Main Board

The main controller is based on a customized electronic board called H2-ARM, designed specifically for real-time control of the H2. The small size of the H2-ARM board (56 x 44 mm) allows it to be placed on the exoskeleton frame, reducing the bulk, as well as complexity and difficulty of wiring and connections. Moreover, it eliminates the need of a backpack being carried by the user, as most lower limb exoskeletons have. Figure 2.8 depicts the board and its electronic architecture.

H2-ARM computational power relies on an ARM (Advanced Risk Machine) microcontroller (STM32F405, STMicroelectronics) running at 168 MHz. The board has two independent CAN (Control Area Network) transceiver channels for real time communication: one is used to connect to all six motor drives (H2-Joint) boards, receiving sensory

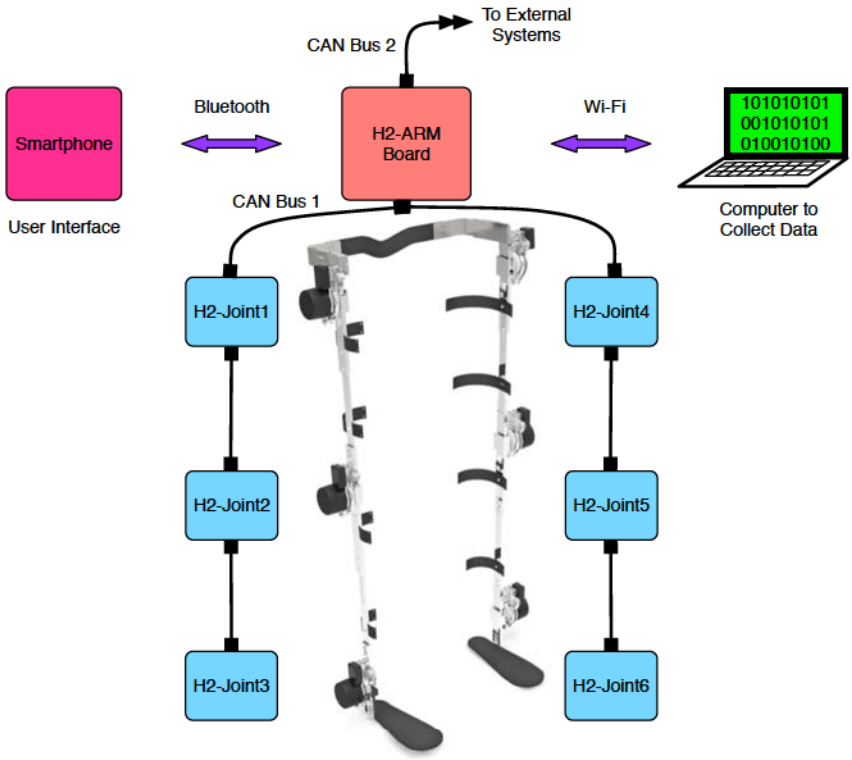

FIGURE 2.7: Representation of the H2 control architecture. Modularity is an important characteristic in the architecture design of an exoskeleton that has to deal with complex tasks.

information and commanding the six joint's actuators; the other channel is intended to connect to external devices.

The board also has two more communication ports, both wireless: Bluetooth and Wi-Fi. Bluetooth communication is intended to connect to a user interface on a smartphone or tablet. The user interface is an application that allows physical therapists to change some parameters as needed within the H2 during rehabilitation. The user interface will be discussed in detail in Section 3.6. Wi-Fi link is used to send data wirelessly via UDP (User Datagram Protocol) to a laptop, where the data and information generated in the exoskeleton can be visualized in real time and stored for offline analysis. Wi-Fi link can also be used to connect to external devices.

H2 presents an open architecture that allows it to be integrated with and/or to be controlled by external devices or systems. Both the CAN channel and the Wi-Fi link are interfaces present on the device for this purpose. This feature open means for combined studies, allowing integration or augmentation of the H2 with distinct types of devices. The open architecture will be detailed in Section 3.4.

The H2-ARM board is powered by 3.3 VDC generated by a high efficient switched voltage regulator connected to the battery power. Two LEDs (Light Emitting Diode)

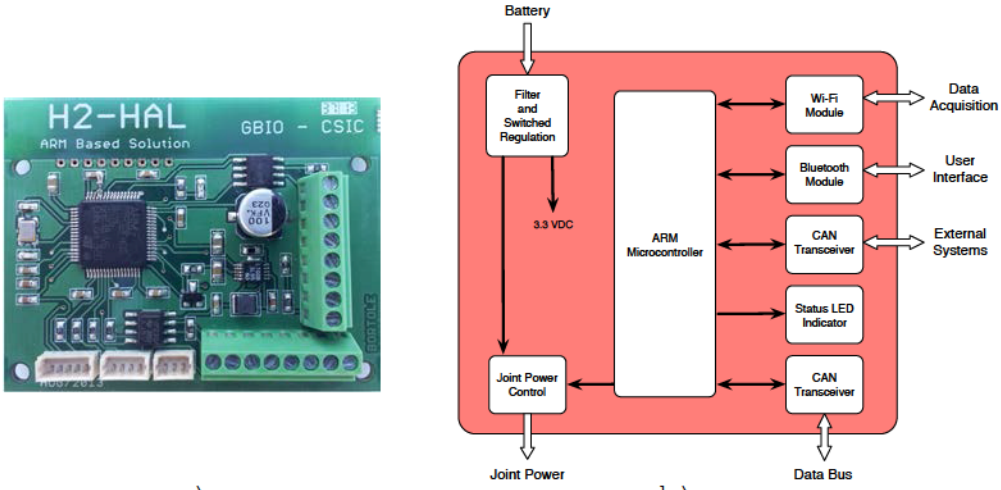

FIGURE 2.8: a) The H2-ARM electronic board has a small size of 56 x 44 mm. b) Scheme of the H2-Joint board that is designed specifically for real-time control of the H2.

are used to report the H2 state: LED 1 turns on in green color when H2 is switched on. LED 2 turns on in blue color if any failure occurs in the communication with the motor drives. If this happens, the joints' power is turned off for safety reasons. The H2-ARM also monitors the battery level of the H2.

2.6.2 Motor Drives

H2 is a multi-DOF device with a large number of sensor inputs and control outputs. The classic approach in robotic design to route all sensor and actuator signal wires to a central processor would mean tens of wires along the H2 mechanical frame. By creating a network structure and distributing nodes in each joint, it is only required four wires: two for distributing the power supply and two for routing all sensors' and actuators' information.

Taking advantage of the distributed approach, the six H2 joints are equipped with an H2-Joint board (numbered from 1 to 6) developed specifically for the H2 application. Two main tasks are carried out by the H2-Joint1∼6 boards: sensors' data acquisition and control of joint's motor. Figure 2.9 illustrates the electronic board mounted on its aluminum case and its functional scheme.

The H2-Joint1∼6 boards are located at the hip, knee and ankle joints at motor's side. The boards include a power management module, a computation module, a MOSFET (Metal Oxide Semiconductor Field Effect Transistor) drive module, a communication transceiver, the signal conditioning and the sensors' interface.

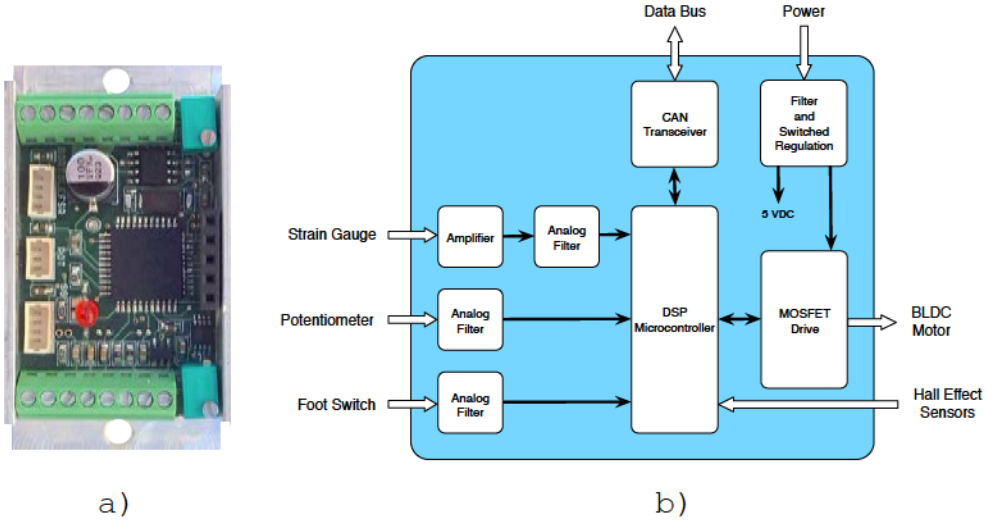

FIGURE 2.9: a) The H2-Joint electronic board mounted on its aluminum case of 58 x 30 mm. b) Scheme of the H2-Joint board that is responsible for sensors' data acquisition and control of joint's BLDC motor.

The power management module receives the power supply voltage coming from the H2-ARM board and convert it to 5 VDC using switching regulators for efficient conversion. The 5 VDC powers the computation module, the communication transceiver and the amplifiers used for signal conditioning. The computational module consists of a 64 MHz DSP (Digital Signal Processor) microcontroller (DsPIC30F4011, Microchip), with a 48 kB FLASH memory and 2 kB of RAM, with a very low power consumption (less than 350 mW).

H2-Joint1∼6 boards are in charge of the data acquisition of all joint's sensors: angular position, interaction torque, motor torque, joint velocity and foot-ground contact (this last one only for the ankle joints). H2-Joint1∼6 contain all the circuitry of the analog filters for each joint sensor and the amplifiers for the strain gauges. The sensor's analog input are converted to a digital value with 10 bits of resolution by the computational module, after the filtering and amplifying process. A small data packet of six bytes aggregates the sensor's information on each joint and is sent to H2-ARM board every one millisecond through the communication transceiver that connects all the joints to the main controller. Detailed information about sensors' data transmission will be given in Section 3.2.

The BLDC motor's drives are embedded directly into the H2-Joint1∼6 boards. The DSP microcontroller controls the joint's motor via six high speed MOSFETs connected in a three phase bridge configuration. The MOSFET bridge are controlled by PWM (Pulse Width Modulation) at a frequency of 32 kHz. This approach ensures very low dissipation and high efficiency in the motor control. The MOSFETs maximum voltage is 40 VDC and maximum current is 31 A, which make them suitable for controlling the

100 W motor at 24 VDC. Adequate heat dissipation is provided by an aluminum case, in which the MOSFETs are internally attached.

H2-Joint∼6 boards are very compact and lightweight, small enough to be mounted directly on the motor's side in the exoskeleton's frame. This approach decreases the amount of electromagnetic noise and the number of wires on the exoskeleton. Moreover, the drives are designed in a four-quadrant mode configuration, which allows them to regenerate power when an external force moves the exoskeleton joint. The regenerated energy is stored back into the battery.

2.6.3 Data Bus

The data bus used on the H2 consists of a network structure with a deterministic real-time communication based on CAN technology running at 1 Mbps. In this design, only two serial wires between any two consecutive nodes are required to form a complete network. This topology is particularly useful when cabling a network where all nodes are physically oriented on a line, as on the H2 legs.

The data bus was designed to enable the H2 main controller (H2-ARM) to interact with distributed sensors and actuators, reduce the bulk, complexity and difficulty of wiring and achieve high-speed real-time control. Figure 2.10 illustrates the network topology, where the six H2-Joints nodes are serially connected to the H2-ARM. The network allows an unlimited number of nodes (limited only by the electrical load on the bus) and does not require any alteration to add or remove nodes. A simple loop-back terminator is used in both sides of the network in the last node (the ankle boards).

Bus nodes are not addressed in this network protocol. Instead, the address information is contained in the messages that are transmitted. This is done by an identifier, which also indicates the message priority. The lower the binary value of the identifier, the higher the priority of the message.

The network is flexible in terms of configuration, automatically avoids data collision and corrects data packets errors in the transmission. Bus arbitration is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance), which is a non-destructive arbitration. If a node wants to transmit a message across the network, it first checks if the bus is in the idle state (Carrier Sense), i.e., no node is currently transmitting. In the case of two or more nodes start a transmission at the same moment (Multiple Access), collision of the messages is avoided by bitwise arbitration mechanism (Collision Avoidance), and the node with the higher priority becomes the dominant node and sends its message. All other nodes will automatically stop transmission and switch to receive mode. After correct reception of the message, which is acknowledged by each node, the message is stored when required for that node, otherwise, it is discarded.

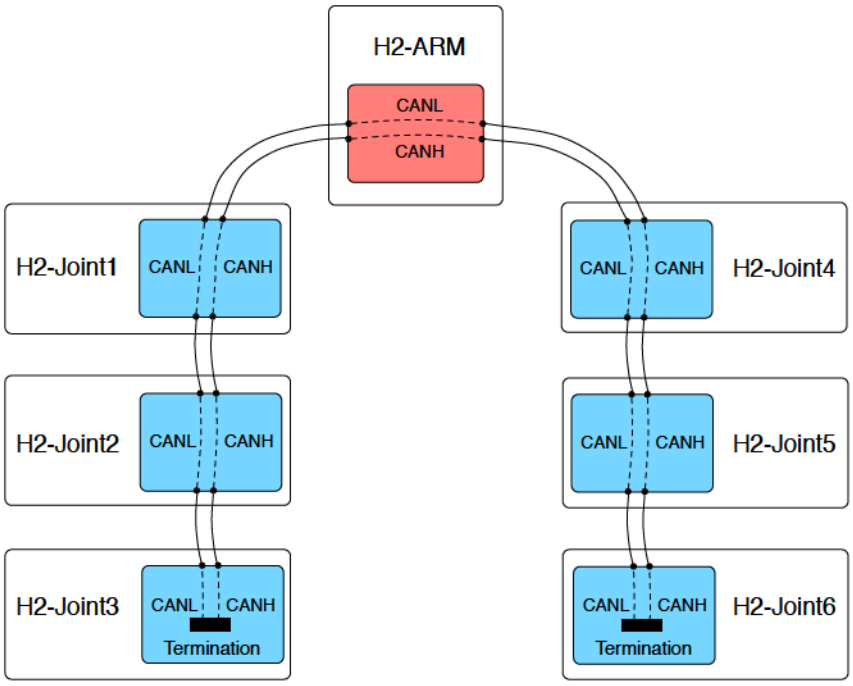

FIGURE 2.10: Illustration of the H2 network topology, where the six H2-Joints nodes are serially connected to the H2-ARM board. The network runs at 1 Mbps.

Each communication cycle in the network protocol involves passing a message from the H2-ARM node to all H2-Joint∼6 nodes in the network. The message payload consist of six bytes preceded by an ID of eleven bits. Each message data packet also includes bits that indicate start of the frame, data length, CRC (Cyclic Redundancy Check), acknowledgment and end of the frame.

As the message travels on the bus, each H2-Joint∼6 reads its assigned actuator command data byte by looking the message ID and the payload message (H2-Joint1 reads byte 1, H2-Joint2 reads byte 2 ... H2-Joint6 reads byte 6). The MSB (Most Significant Bit) represents the motor rotation direction and the remain seven bits give the voltage level that should be applied to the motor joint (in increments of 0.78%). After reading the command actuators message, each H2-Joint∼6 returns one message back to H2-ARM node with a specific ID and its locally collected sensor data.

The control scheme on the H2-ARM controller runs at 1 kHz. At this frequency, one new message is sent to all H2-Joint∼6. Since the communication cycles occur at a fixed rate, this protocol allows for deterministic control. Also, it provides built-in network error detection as, for every message received, each H2-Joint∼6 has to return data information to the H2-ARM. As a result, H2-ARM has a robust means to determine the integrity of the network and the correct operation of the joint's actuators. If some failure occurs on the network that cannot be corrected automatically (for instance, a cable disconnection), H2-ARM instantly stops the exoskeleton and shuts off the joints power for safety reasons.

To illustrate the whole hardware and electronic architecture of the H2, figure 2.11 links a video of the final system working. The software running on the H2-ARM board and on each one of the H2-Joint∼6 boards will be detailed in Chapter 3.

FIGURE 2.11: Click here or scan this code to see a demonstration video about the H2 exoskeleton.

2.7 Safety

Safety is one of the most important features in robotic exoskeletons. Since the device is attached to the humans limbs, it should be very compliant with user's movements. Specially in exoskeletons for clinical applications, where patients can have some physical limitations or weakness, safety features should be incorporated in different levels, including the exoskeleton control system. Very few exoskeletons consider the safety aspect in the control system [164]. Most of them only implemented safety in the mechanical design.

H2 has multiple safety features, including the mechanical design, the control system, the data bus protocol and the software. The first aspect is the mechanical limitation in the range of motion in actuated joints. The maximum range of motion across all joints is shown in table 2.1, which is shorter than the human limits. Therefore, the H2 actuators cannot damage the human legs by applying over extension or over flexion movements.

The second safety aspect is an extend of the ROM limitation. The H2 ROM can be individually shortened and limited by software when necessary. In case of patients with reduced extension and/or flexion movements due to spasticity (very common in stroke patients) or any other reason, the maximum joint range can be simply reduced in anyone or a combination of the six joints.

Two more safety mechanisms rely on the protocol used on the H2 data bus. The protocol based on CSMA/CA guarantees at hardware level data error and data collision avoidance. The sensors' data and joints' actuation commands exchanged between H2-ARM and H2-Joint1∼6 are protected against errors, being checked by all nodes in the

network. If any node detects an error in a message transmitted, the message is automatically discarded and repeated by the sender. The second mechanism avoids data collision in the bus without destroying messages being transmitted. The node with less priority transmitting a message can recognize that another node with higher priority is transmitting at the same time. The lower priority node then automatically switches to receive mode without interfering in the message being transmitted. When the higher priority node finishes its transmission, the other node will proceed with its data. This protocol guarantees strict determinism for real time communication, ensuring stability of the control system.

Safety is also implemented in the high level software control in the H2-ARM. The assist-as-needed control, that will be detailed in Section 3.5, implements safety strategies in the coordination of the joint movements, avoiding, for instance, H2 to perform two consecutive steps with the same leg.

Another important issue on the exoskeleton is the controller stability. In general, instabilities can be caused by high-frequency and/or high-amplitude external perturbation induced by robot-human interaction or overshoots in controller's response. These instabilities were considered and avoided by adequate sensor's signal filtering and controller parameters' adjustments, thus avoiding oscillations or vibration in actuators' performance.

Furthermore, one last safety feature is implemented on the H2-ARM board. The software determines the integrity of the network by monitoring the frequency of the data received from all joints. For each actuator command sent by H2-ARM, H2-Joint$\sim$6 boards have to acknowledge the message reception by returning their sensor data information. If some failure occurs in any joint or in the network, H2-ARM instantly stops the exoskeleton by shutting off the joints power. The mechanical impedance of the joints is enough to stabilize the patient if this occurs. This failure is reported to the therapist by a LED status.

2.8 Conclusion

This chapter described the mechanical design and the development of the H2 exoskeleton, as well as the electronic hardware that was specifically customized to the H2. The device is a powered lower limb exoskeleton for rehabilitation of post-stroke patients that need gait training in order to recover their impaired motor function. H2 has a total mass of 12 kg including its battery pack, which fulfills the first objective of this dissertation: an ambulatory exoskeleton with a lightweight design.

The H2 exoskeleton can be easily adjusted to be worn by persons from 1.5 to 1.95 meters in height, achieving objective number 2, which accounts for a device that can be used

by a broader range of patients. Moreover, the H2 provides assistive torques at both hip, knee and ankle joints, also achieving objective number 3, by means of a completed actuated device in the sagittal plane. The device is capable of providing continuous joint torques of 35 Nm to all six joints.

A custom distributed embedded electronic architecture was designed with power being provided by a lithium polymer battery which provides power for running the device untethered. This approach fulfills objective number 4, which is the implementation of an autonomous exoskeleton. Also, H2 does not extend above mid-abdomen and requires nothing to be worn over the shoulders and nothing above the lower back, which presumably renders the user more comfort when using the device. The compact design of the exoskeleton is greatly facilitated by the customization of all single electronic boards and by the development of a distributed control system integrated with the mechanical structure.

Moreover, the battery pack is integrated with the mechanical frame and placed at the hip level, providing no extra weight on the trunk or lower limbs of the user, thereby creating a much more comfortable embodiment. The battery pack is detachable and very easily replaced with a fully recharged one for continuous work. Also, looking for comfort and reliability, H2 is designed with no sensors physically attached to the user. All sensors are integrated in the exoskeleton, thus facilitating the dressing on and off process with patients.

Finally, many features were implemented in the exoskeleton hardware and software for increased patient's safety, fulfilling objective number 5. In the mechanical design, limitation in the ROM of each joint guarantees that H2 will never exceed humans range of motion. Still, each range of motion can be individually shortened by software if necessary. The electronic hardware uses a CAN data bus that guarantees a correct communication between all nodes and in case a failure that cannot be automatically fixed by software, powers off the H2.

Chapter 3

Assist-As-Needed Control Strategy

This chapter presents the software development for the H2 robotic exoskeleton, as well as the integration of the device with a neural interface. The software was developed in a layered architecture, with three different levels. This approach makes easy the development of new therapies or control strategies without rewriting all the code. The chapter begins with the description of the software implemented to control each H2 joint actuator. It follows the description of the middle layer of software, which was implemented to synchronize the movement of all joints and to provide close loop control based on position, torque or stiffness. Each joint can be independently controlled by the high level control layer, where the therapies are implemented. The high level control can be implemented on the H2-ARM board and directly interface the middle layer or can be implemented on external devices and communicate to the middle layer by means of UDP or CAN protocols. For the experiments presented in this thesis, a therapy intervention based on assist-as-needed control strategy was implemented on the H2-ARM board. Also, for the same experiments, H2 was integrated with a neural interface intended for monitoring brain changes during the rehabilitation period.

3.1 Introduction

The main considerations when designing an exoskeleton control is how to achieve the best control performance, best user interaction, high stability and safe operation. However, other important issues have to be considered when designing control strategies for patient's rehabilitation. For inducing motor learning, studies have shown that training is only effective if associated with task-oriented movements involving effort by the patient [215]. This approach is thought to be an essential requirement to achieve effective cortical reorganization.

Therefore, simply having an exoskeleton imposing physical therapy by rigidly moving patient's limbs will have limited success, especially when the patient is passive and not contributing to the exercise. To achieve full neurorehabilitation, the brain must work in association with the motion of limbs to promote corticospinal rehabilitation.

In order to accomplish this, researchers have implemented different control approaches on their exoskeletons. HAL, the overground exoskeleton with more studies in rehabilitation of post-stroke patients [161–163, 216], uses sEMG signals for adjusting the joints' torque. However, stroke affects the normal function of the brain, and the EMG signal, which is a further downstream in the neurological pathway, gets affected as well. Therefore, sEMG to torque conversion method will be a more challenging task that may need a long time for adaptation and adjustments [165].

A different strategy, which has been implemented in stationary gait trainers or upper limb rehabilitation devices [108, 217–220] to promote user participation, is the so called assist-as-needed controller. This approach modulates the robot assistance according to parameters measured during task execution. It seems to be suitable for hemiplegic post-stroke patients because the emphasis is more on guidance towards a correct pattern than on a simple rigid repetition.

The H2 control approach implements an assist-as-needed algorithm based on a force field control, where the joint torque is generated based on the trajectory deviation, resulting in a corrective proportional force that guides patient's limb. This algorithm concept has the benefit that the controller will always generate enough torque to stabilize both, the affected and unaffected leg, without the need of any model of the exoskeleton or the user.

The assist-as-needed control of the H2, together with the overground capability, is intended to create a highly motivated environment for patients, leading to a faster recovery and higher gains in motor functions. Moreover, the use of this robotic tool will facilitate the work carried out by physical therapists, allowing a more intensive training for patients without fatiguing therapists.

Another novelty in the H2 software is the open architecture developed for H2 augmentation or integration with third party devices. The software architecture was developed in such way that it allows H2 to be externally controlled by means of wired and wireless communication interfaces present on the device.

This chapter presents the development of all H2 software components and its open architecture integrated with a neural interface. Section 3.2 in this chapter presents the software design implementation of the H2 at actuator level, responsible for motor control and sensor data acquisition. Section 3.3 describes the second software layer that comprises three type of close loop controllers actuating on each joint independently: position, torque and stiffness. Section 3.4 describes the H2 open architecture and the interfaces present on the device intended for integration or augmentation with external systems. Section 3.5 presents the implementation of a therapy intervention that provides assistance based on patient's impairment level. Section 3.6 explains the user interface designed to help therapists adjust H2 parameters during training sections. Section 3.7 describes the H2 integration with a neural interface intended to track cortical changes over the rehabilitation time. The chapter ends with conclusions that summarize the major achievements of this software implementation.

3.2 Actuator Control

The H2 software was designed with a layered architecture containing three different levels. Figure 3.1 associates the software layers with the electronic hardware presented in Section 2.6. This structure makes easy the development of new therapies or control strategies without rewriting all the code. Only the top layer needs to be replaced with the new therapy software.

The first software layer implemented on the H2, called "Actuator Control" on figure 3.1, runs on the H2-Joint1∼6 electronic boards. The software was written in C language and compiled with the CCS Compiler (PCWHD, CCS Inc.) to be embedded into the DSP microcontroller. The objective of this firmware is to read and digitalize all sensors' information and to control the BLDC motor on each joint.

A timer routine is used to read all sensors each 300 microseconds, which includes the position sensor, the interaction torque sensor, the motor torque sensor and the temperature sensor. In the ankle joints, the foot ground contact sensor is also included. An analog to digital conversion with 10 bits of resolution is performed and the digital values are stored in a local buffer. When the H2-ARM board request the data (each 1 ms), an average of the last three analog values are performed and a mathematical function is used to convert the values to the physical variables that they represent, before sending the data to the main controller.

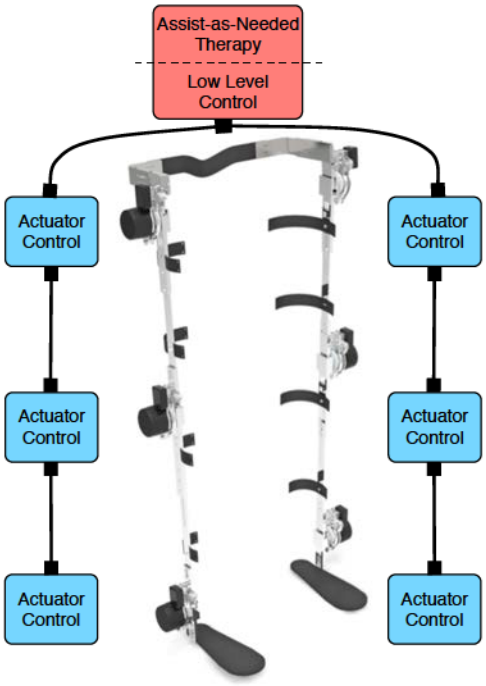

FIGURE 3.1: Association of the software layers with the H2 electronic hardware. Actuator Control software runs on H2-Joint1∼6 boards. Low Level Control and Assist-as-Needed Therapy algorithms run on the H2-ARM board.

The potentiometers signals are converted to degrees, based on the range of motion of each specific joint. Interaction torques signals measured by the strain gauges are proportionally converted to Nm. Actuator torques are measured with the current sensor on the MOSFET bridge and proportionally converted to Nm. The ground contact detected by the foot switches are converted to a binary signal. A hysteresis comparison is used to avoid noise in the process of detecting the gait cycles. Temperature information is the only data not sent to the H2-ARM board. Instead, this information is used as safety measure in the H2-Joint board: if the temperature rises up more than 70 degrees, the microcontroller disables the MOSFET bridge to prevent it to be damaged. A notification message is sent to the H2-ARM controller.

The second task carried out by this software layer is the BLDC motor control. A BLDC motor have three windings on the stator and the rotor is a permanent magnet. To make the rotor turn, there must be a rotating electric field in the stator, that is created by exciting two windings at a time. The excitation on the stator must be sequenced in a specific manner, while knowing the exact position of the rotor magnets. Position information comes from the three Hall Effect sensors inside the motor. There are six distinct regions or sectors in which two specific windings are excited. By reading the Hall Effect sensors, the microcontroller obtains a 3-bit code value ranging from 1 to 6 that represents a sector in which the rotor is presently located. Each code, therefore, gives

information on which windings need to be excited. Thus, a lookup table is implemented in the program to determine which two specific windings need to be excited based on sensors' information.

The three Hall Effect sensor outputs are connected to input pins of the DSP microcontroller, enabled along with an interruption. If a change occurs on any of these three pins, an interrupt is generated. Then, the program reads the Hall Effect sensor values and uses them to generate an offset in the lookup table for correctly driving the windings of the BLDC motor. Figure 3.2 represent the sequence commutation of the three phases of the BLDC based on the rotor location.

Using the above explained method, it is possible to get full speed rotation of the motor. However, to be able to control the speed of the BLDC motor, it is necessary to apply a variable voltage to the terminals of the windings. By varying the voltage across the windings of the motor, we can directly control the speed of the motor. A PWM approach is an efficient way to digitally control the motor speed. Variation of the motor voltage can be achieved by changing the duty cycle of the PWM signal. Six PWM channels are implemented in the DSP and connected to the three-phase MOSFET bridge that drive the motor. The digital command to control motor direction and speed is received from the H2-ARM main controller. Figure 3.3 illustrates this control scheme running on the H2-Joint1∼6 electronic boards.

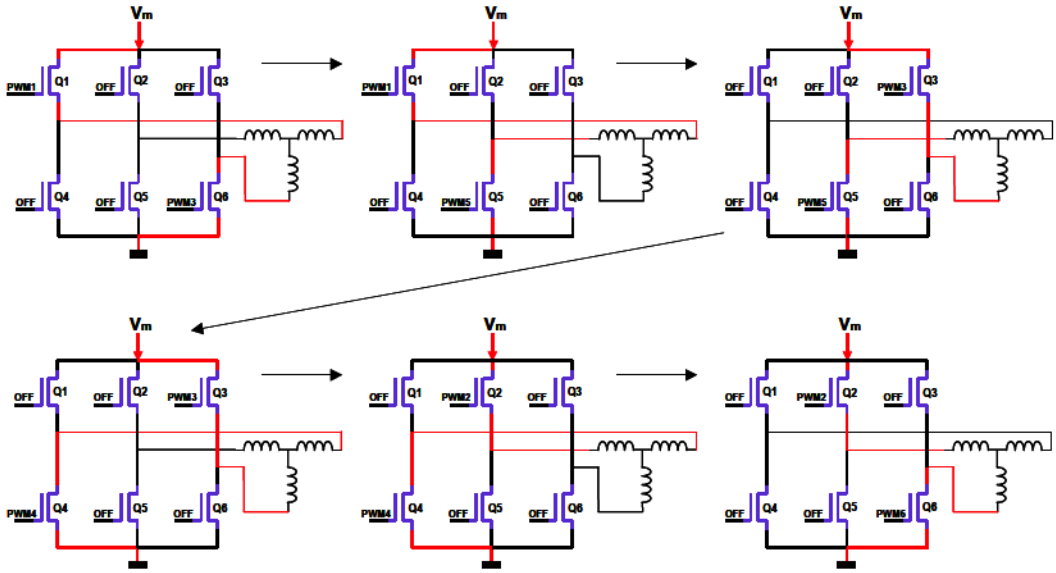

FIGURE 3.2: Representation of the three phases MOSFET bridge and the commutation sequence of the BLDC motor. By reading the Hall Effect sensors, the microcontroller obtains the information on which sector the rotor is presently located and, therefore, information on which windings need to be excited.

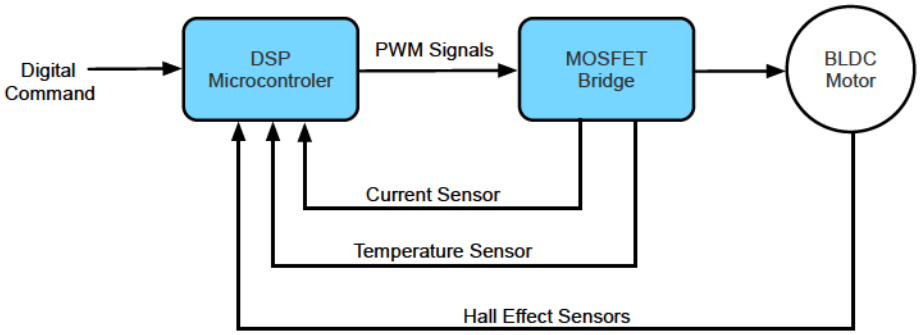

FIGURE 3.3: Representation of the Actuator Control scheme running on the H2-Joint1~6 electronic boards. The DSP microcontroller receives a command from the main controller and generates six PWM channels to control the three-phase MOSFET bridge that drive the BLDC motor.

3.3 Low Level Control

The actuator control firmware is the lowest software layer implemented for H2. A next software layer, called low level control, is implemented in the H2-ARM board. The main objectives of this layer are the implementation of different types of real time close loop control and the synchronization of all joint movements.

The low level software layer was programmed in C language and compiled with the MikroC Compiler (MikroC Pro for ARM, MikroElektronika Ltd.) to be embedded into the ARM microcontroller. This software receives the sensor information from all joints in a digital format by means of the H2 data bus. This software layer can control each exoskeleton actuators in position, torque or stiffness independently, which means that different types of control can be applied to different joints at the same time. The H2-ARM can switch between the different control modes in execution time.

The idea behind the implementation of the low level software is to guarantee actuators real time control and make it transparent for a superior software layer. Therefore, a superior layer will be responsible for implementing therapy interventions, sending high level commands to this inferior layer. The following subsections explain the implementation of the low level controllers.

3.3.1 Position Control

The interaction between the exoskeleton and the user's limb should be as smooth as possible, avoiding abrupt movements that can cause discomfort and/or instability to the user. For this reason, the position controller should avoid oscillations in the trajectory and overshoot response. This behavior can be achieved through the correct tuning of a PID (Proportional-Integral-Derivative) controller.

The output reference $u(t)$ of a PID controller is given by:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{d}{dt} e(t) \tag{3.1}$$

where:

- K_p is the proportional gain, a tuning parameter;
- K_i is the integral gain, a tuning parameter;
- K_d is the derivative gain, a tuning parameter;
- e is the error between the set point and the actual condition;
- t is the instantaneous time (the present);
- τ is a variable of integration that takes values from time 0 to the present.

A discretization process is required in order to design a digital implementation of a PID controller. Equation (3.1) can be adapted to a discrete function for a digital controller, based on the sample time $\triangle t$, which in the present work is 1 ms. The integral term can be discretized as follows:

$$\int_0^t e(\tau)\, d\tau = \sum_{n=1}^{k} e(n) \triangle t \tag{3.2}$$

The derivative term can be approximated as a first order function:

$$\frac{d}{dt} e(t) = \frac{e(k) - e(k-1)}{\triangle t} \tag{3.3}$$

Based on equations (3.2) and (3.3), the digital PID is given by:

$$u(k) = K_p e(k) + K_i \sum_{n=1}^{k} e(n) \triangle t + K_d \frac{e(k) - e(k-1)}{\triangle t} \tag{3.4}$$

where k is the present sample time. In order to tune the PID controller, the parameters K_p, K_i and K_d have to be calculated. For H2 position controller it was used the Ziegler-Nichols tuning method [221]. This tuning method is performed by setting K_d and K_i gains to zero and increasing K_p gain until the control loop oscillates with a constant amplitude. This ultimate gain, called K_u, and the oscillation period T_u are used to set the PID gains as indicated in table 3.1.

TABLE 3.1: Ziegler-Nichols tuning parameters for adjusting a PID controller.

K_p	K_i	K_d
$0.6\ K_u$	$2.0\ K_p/T_u$	$K_p\ T_u/8.0$

For a practical application in a rehabilitation scenario, overshoot and oscillations in the actuator's response are characteristics to be avoided, for the sake of safety and stability when using the exoskeleton. To fulfill with these requirements, after calculating the PID gains, an empirical correction is applied to the parameters K_p, K_i and K_d, in order to avoid overshoot and oscillations in each actuator's response.

A scheme of the position controller implemented for H2 is illustrated in figure 3.4. The controller also takes into account the ROM limitation for each joint. By default, the algorithm uses the values presented in table 2.1, but these values can be independent shortened. Moreover, a program routine was created to reset the integral part of the PID when H2-ARM switch to a different control mode. Otherwise, the controller keeps the integration process and would go unstable next time H2-ARM switches back to it.

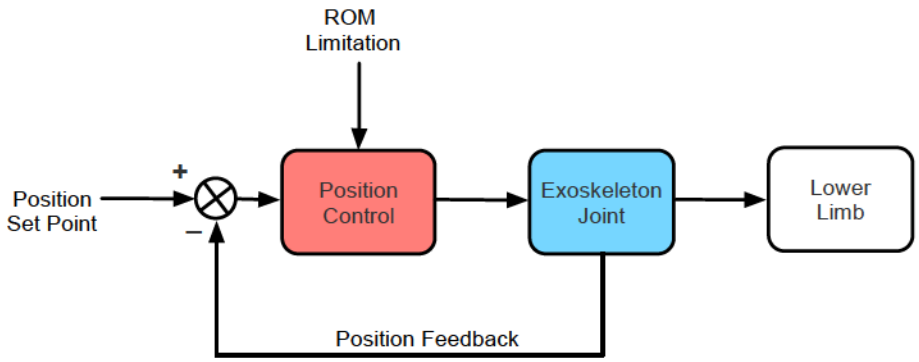

FIGURE 3.4: Representation of the position control scheme running on the H2-ARM board. Position feedback is received from the H2-Joint board that acquires joint sensors' signals.

3.3.2 Torque Control

The second low level control implemented in H2-ARM is based on torque close loop control. Two feedback possibilities exist for this control: interaction torque between the H2 and the user and the actuator torque. Figure 3.5 illustrates the scheme implementation that control the torque delivered to each joint independently. The implementation uses a digital PID controller as presented in equation (3.4) and a similar design strategy presented for position control, except for tuning the parameters K_p, K_i and K_d. Due to the fact that torque control is to a great extent dependent on the environment [222], the

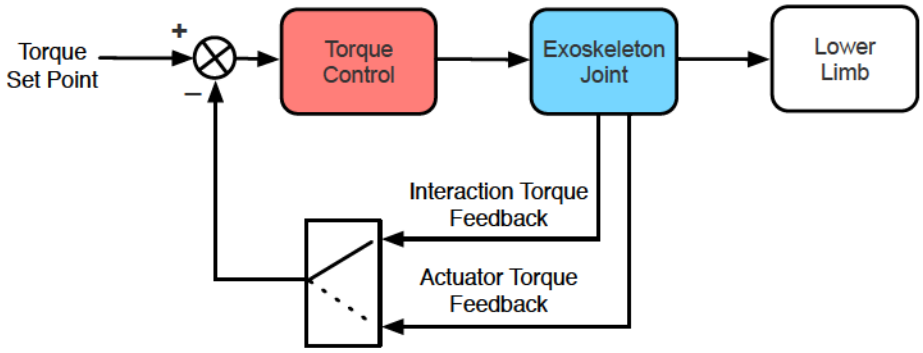

FIGURE 3.5: Representation of the torque control scheme running on the H2-ARM board. The two torque feedbacks are received from the H2-Joint board that acquires joint sensors' signals.

parameters are tuned empirically through bench testing while the actuators link interact with the user.

When the interaction torque feedback is selected, the controller keeps the desired output level of torque in each joint based on the H2 and the user interaction. This control scheme has a special application in lowering the mechanical impedance of the exoskeleton when the desired output torque is set to zero. In this scenario, the controller will actuate at the joints in such way that the user feels very low (ideally zero) resistance when moving their limbs attached to the exoskeleton.

The mechanical impedance is known as the relationship between the force exerted in the exoskeleton actuators and the resulting motion [223]. A low impedance behavior is also known as backdriveability [224]. Good backdriveability has important advantages in robotic therapeutic systems [140], including the ability to act as a passive actuator to capture movements [225].

The users would not feel any resistance when moving their limbs if the mechanical impedance of the exoskeleton could be zero. This zero impedance can only be achieved theoretically, due to inertia and friction of the actuators and the controller time delay [226]. However, low impedance can be achieved if the controller drives the motors based on the interaction with the user. Thus, to make the exoskeleton act as a passive actuator, this control strategy uses the torque applied by the user to the exoskeleton links and move the joints trying to maintain at a minimum value the resistance felt by the user. The controller should be very stable, avoiding high frequency oscillation that can cause patients to lose balance. Since the interaction torque signal usually exhibits high frequency components, a digital Butterworth low-pass filter (5 Hz, 4th order) is applied to the torque signal in the feedback loop of the controller.

An important application of the low impedance mode is the possibility for the exoskeleton to capture user's movements to create a strategy called learning mode. A learning

mode strategy requires that the movement of the legs should not be hindered, and thus, the mechanical impedance of the exoskeleton should be minimized. However, since the actuators used in H2 have a high mechanical impedance output, this control strategy has to be used to make it compliant with user's motion. The physical therapist is now able to manually assist the movements of the patient, while the high level control can record the joints trajectories. After the task is completed, for example, a sit-to-stand movement, the high level control can use the recorded data to replicate the movement actively.

3.3.3 Stiffness Control

Stiffness is defined as the rigidity of an object, i.e., how much deformation an object withstands in response to an applied force [227]. In case of an articulated joint, stiffness can be defined as how much the joint deviate from its reference position based on a certain amount of torque applied at the joint.

For a wearable exoskeleton, which is attached to the patient's limbs, compliance with user's movement is very important. Otherwise, the exoskeleton may cause injuries to the patients by applying too much torque on their joints in specific occasions. Stiffness control can be implemented to make the exoskeleton's joints more compliant with user's movement and not as rigid as when controlled in position. This control is, in some way, equivalent to a torque limitations into the motors.

The stiffness control was implemented aiming to drive the joints with a variable stiffness from 0 to 100%. If the joint stiffness is set to 0, the joint controller does nothing and the joint is free to move, only limited by the intrinsic mechanical impedance of the joint. With a stiffness value of 100% the joint is allowed to use full torque power to reach a given position. Therefore, the behavior in this particular condition is similar to position control. Between these two extremes, the joint is more or less compliant proportionally to the selected stiffness level. When trying to reach a desired position, the controller will apply a limited torque. If the provided torque is not enough, since the user apply higher opposite torque, the joint does not reach the target position.

Figure 3.6 represents the stiffness close loop controller. It was implemented by means of a digital PD (Proportional-Derivative) controller, given by the equation (3.5), that derives from equation (3.4):

$$u(k) = K_p e(k) + K_d \frac{e(k) - e(k-1)}{\triangle t} \tag{3.5}$$

where u is the controller output, K_p is the proportional gain, K_d is the derivative gain, e is the error between the set point and the actual condition, k is the present sample and $\triangle t$ is the sample time. Similar to the PID controller, the parameters K_p and K_d

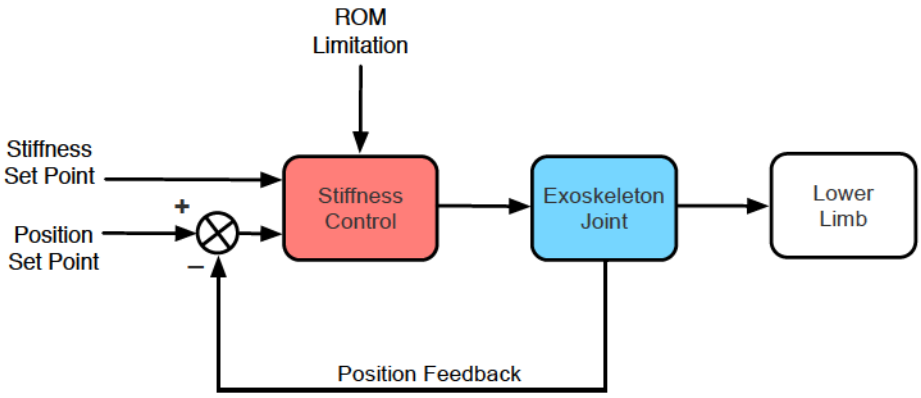

FIGURE 3.6: Representation of the stiffness control scheme running on the H2-ARM board. Position feedback is received from the H2-Joint board that acquires joint sensors' signals.

have to be calculated in order to tune the PD controller. The Ziegler-Nichols tuning method was also used for this controller. With the parameter K_d set to zero, K_p gain was increased until the control loop oscillates with a constant amplitude. This ultimate gain K_u and the oscillation period T_u are used to set the PD gains as indicated in table 3.2.

TABLE 3.2: Ziegler-Nichols tuning parameters for adjusting a PD controller.

K_p	K_d
$0.8\ K_u$	$K_p\ T_u/8.0$

For the same reasons as discussed in the implementation of the position controller, after calculating the PD gains, an empirical correction is applied to the parameters K_p and K_d, in order to avoid overshoot and oscillations in each actuator's response.

Two set points are defined for the stiffness controller. The first one represents the desired position that the joint should reach and the second one is the stiffness percentage, which is an indication of the maximum torque that the actuator should provide. Variations in the stiffness value will proportionally changes the parameter K_p. As a result, the controller output $u(k)$ is reduced, proportionally reducing the torque generated by the actuator.

3.4 Open Control Architecture

Most, if not all, robotic machines for rehabilitation have a close architecture, which means that they cannot be easily integrated with other devices or externally controlled. H2, however, presents an open architecture that allows it to be integrated with other

devices or systems and to be externally controlled. The architecture was developed in such way that not only permits it to be externally controlled, but make the task simple by means of both wired and wireless communication interfaces present on the device.

The wired interface is based on a CAN bus working at 1 Mbps. Through this interface, an external device can access the low level controllers of the H2, being able to control each joint of the device independently in real time. The external system can control H2 joints in position, torque or stiffness. Also, all the kinematic and kinetic data generated in the exoskeleton is sent by the same bus to the external devices connected to the bus. Since CAN communication protocol allows an unlimited number of nodes connected to the same bus, multiple devices can receive the H2 data and send commands to it simultaneously.

A message protocol was created to be used when connecting with external devices by using CAN. Four types of commands are defined. Each command is based on a standard CAN message with a unique ID and six data bytes. Table 3.3 summarizes commands accepted and their functions. Table 3.4 represents kinematic and kinetic data sent by the H2 in three messages of six bytes each.

TABLE 3.3: CAN messages format accepted by the H2 from external devices.

Message	**Joint Control**	**Min Angles**	**Max Angles**	**Start/Stop**
ID	70	75	80	85
Byte 1	Motor ID	Right hip	Right hip	Start/Stop Data
Byte 2	Type of control	Right knee	Right knee	Reserved
Byte 3	Pos/torque set point	Right ankle	Right ankle	Reserved
Byte 4	Stiffness set point	Left hip	Left hip	Reserved
Byte 5	Reserved	Left knee	Left knee	Reserved
Byte 6	Reserved	Left ankle	Left ankle	Reserved

The command *Joint Control* can be used to control each one of the six joints independently. *Motor ID* values means: 1 = Right Hip; 2 = Right Knee; 3 = Right Ankle; 4 = Left Hip; 5 = Left Knee; 6 = Left Ankle. *Type of Control* values means: 1 = Position control; 2 = Stiffness control; 3 = Torque control; 4 = Motors disabled; 5 = Motors stopped. When *Position Control* is used, byte 3 is the set point for that joint and bytes 4, 5 and 6 are not used. For *Torque Control*, byte 3 is the set point for that joint and bytes 4, 5 and 6 are not used. *Stiffness Control* uses byte 3 as the set point for position and byte 4 as the percentage of stiffness for that joint (where the value 0 means no stiffness and the value 100 means the maximum possible stiffness).

The commands *Min Angles* and *Max Angles* can be used to set the minimum and maximum angles accepted as set point for *Position* and *Stiffness Control*, shortening

TABLE 3.4: Kinematic and kinetic data sent by the H2 through CAN to external devices.

Message	**Joint Angle**	**Joint Torque**	**Foot Switch**
ID	110	120	130
Byte 1	Right hip angle	Right hip torque	Right heel foot switch
Byte 2	Right knee angle	Right knee torque	Right toe foot switch
Byte 3	Right ankle angle	Right ankle torque	Left heel foot switch
Byte 4	Left hip angle	Left hip torque	Left toe foot switch
Byte 5	Left knee angle	Left knee torque	Battery voltage
Byte 6	Left ankle angle	Left ankle torque	Reserved for future use

the ROM of the joints. The command *Start/Stop* is used to start or stop sending data via CAN (byte 1 = 1 starts data; byte 1 = 0 stops data).

In order to make the integration task with external devices even easier, H2 features a wireless communication port based on Wi-Fi. When turned on, the H2-ARM board creates an Wi-Fi spot that allows any Wi-Fi enabled device to connect to its network. The H2-ARM automatically assigns an IP (Internet Protocol) address to devices connected to the network. Through UDP protocol, similar commands are implemented in packets of 8 bytes. Table 3.5 summarizes commands structure accepted by the H2 and table 3.6 represents kinematic and kinetic data sent back.

TABLE 3.5: UDP data frame accepted by the H2 from external devices.

Message	**Joint Control**	**Min Angles**	**Max Angles**	**Start/Stop**
Byte 1	115 (Start frame)	115 (Start frame)	115 (Start frame)	115 (Start frame)
Byte 2	70 (Message ID)	75 (Message ID)	80 (Message ID)	85 (Message ID)
Byte 3	Motor ID	Right hip	Right hip	Start/Stop Data
Byte 4	Type of control	Right knee	Right knee	Reserved
Byte 5	Pos/torque set point	Right ankle	Right ankle	Reserved
Byte 6	Stiffness set point	Left hip	Left hip	Reserved
Byte 7	Reserved	Left knee	Left knee	Reserved
Byte 8	Reserved	Left ankle	Left ankle	Reserved

3.5 Assist-As-Needed Therapy

During rehabilitation, assisting patients only when they need is, amongst others, a prominent aspect to make robotic rehabilitation successful [220]. In the rehabilitation

TABLE 3.6: Kinematic and kinetic data sent by the H2 through UDP to external devices.

Byte	Data	Byte	Data
Byte 1	115 (Start frame)	Byte 12	Left knee torque
Byte 2	Right hip angle	Byte 13	Left ankle torque
Byte 3	Right knee angle	Byte 14	Right heel foot switch
Byte 4	Right ankle angle	Byte 15	Right toe foot switch
Byte 5	Left hip angle	Byte 16	Left heel foot switch
Byte 6	Left knee angle	Byte 17	Left toe foot switch
Byte 7	Left ankle angle	Byte 18	Battery voltage
Byte 8	Right hip torque	Byte 19	Reserved
Byte 9	Right knee torque	Byte 20	Reserved
Byte 10	Right ankle torque	Byte 21	Reserved
Byte 11	Left hip torque	Byte 22	120 (End frame)

process it is important to activate efferent motor pathways and afferent sensory pathways simultaneously. Fully assisting patients by imposing fixed limb trajectories can lead the motor cortex to habituate to the repetitive activation of the same sensory pathways, thus limiting the motor function recovery [228].

There are different possibilities to increase human involvement in the therapy and, thus avoiding bounding the person to a fixed reference trajectory. The two general approaches are either adding more compliance to the robot or adapting the reference trajectory to the individual movements of a person [229]. The extent of robotic assistance depends on the purpose of the rehabilitation program. In the acute phase of stroke more guidance is necessary, while after a certain progress of therapy, when the person is able to generate own effort, less guidance and more freedom are desirable.

Different methods have been used in robotic rehabilitation to provide assist-as-needed therapy, sometimes called by different names, as "patient-cooperative" or "subject-driven" [95, 228]. The idea behind the assist-as-needed concept is that the assistance provided by the robot should be sufficient to guide and complete the desired physiological movements, while challenging patients to provide maximal own effort [230, 231]. In this way, neuroplasticity can be stimulated and motor learning regained.

For this reason, we have proposed a control approach that extends the assist-as-needed concept to all lower limbs joints. This control is applied to the H2 to implement a gait rehabilitation therapy designed to stroke victims. The general algorithm consists in the generation of a symmetric gait pattern, an automatic adaptation of this reference pattern to each subject and a force field control that assist patient's movements when

performing this trajectory. Patient's joint are individually assisted to keep the leg on its trajectory. Deviations from the adapted trajectory will result in corrective forces. The magnitude of the forces depends on the extent of the trajectory deviation.

3.5.1 Pre-Recorded Gait Pattern

The human musculoskeletal and neural-motor system is highly optimized for efficient biped locomotion [232, 233]. The efficiency is because muscles do not power the joints independently, but often span multiple joints and transfer power from one joint to another. A 75 kg human consumes only approximately 165 W of metabolic power during level-ground walking [207, 234].

The human gait is a cyclic movement pattern mainly executed in the sagittal plane of the body. One gait cycle is defined as the period between two consecutive heel strikes of the same foot with the ground. Each cycle comprises a stance phase (when the foot is in contact with the ground) and a swing phase (when the foot is off the ground) [205, 235, 236].

A challenge when implementing gait training using robotic exoskeletons is the generation of the gait trajectory. A study with healthy subjects in [121] suggests that the desired states of the disabled leg can be generated online based on the movements of the other leg. However, stroke greatly impacts the output forces, not just for the paretic leg but also for the unaffected leg [50–53], and stroke victims walk in an asymmetric manner avoiding to load the paretic limb. Therefore, the unaffected leg also has an abnormal compensatory gait pattern, and reflecting it to the paretic leg will not lead to improvements on the gait of post-stroke patients.

Other works in the literature [178, 195] suggest that gait patterns can be predefined trajectories based on offline simulations or gait data captured from healthy subjects. This last approach was chosen to be used in the H2 gait implementation, since symmetry of gait is of special importance to stroke recovery. The reference trajectory was recorded using a motion system capture based on high speed infrared cameras (Vicon Motion Systems Ltd, United kingdom). During the data collection, the subject uses special markers attached to the body segments of interest, both lower limbs in this case. These markers reflect the infrared light. Thus, the motion system can track the markers online using a system with multiple cameras. Then, the performed trajectory can be reconstructed offline, and hip, knee and ankle angles are obtained for both legs. In taking advantage that the human gait is a cyclic process, we just need to acquire and store the angles for one step. A lookup table is then generated with the six joints angles and stored in the microcontroller memory in the H2-ARM board.

3.5.2 Force Field Controller

Position or trajectory control is a widely implemented robotic strategy [93, 143, 223, 237, 238]. In this control approach, a position controller guides the patient's limb to a fixed reference path, while receiving the joint angles as a feedback. For the lower limbs, the reference trajectory can be the pre-recorded gait pattern from a healthy subject.

However, some previous works suggest that position control strategies do not sufficiently challenge patients to actively move their limbs during gait training assisted by robots [239]. A better technique to regain motor control skills in stroke survivors is the use of force fields that guide patient's movements during goal-oriented therapy [240]. The force field provides haptic feedback that is processed by the patient, thus leading to a continuous improvement of motor performance and retraining of motor functions.

This force field strategy is implemented in the H2 algorithm, which is responsible to assist the patient's gait based on their disability level. To achieve this, the first step is the generation of an adjusted trajectory. The reason for this is that the gait pattern differs slightly between individuals. Therefore, there are some disadvantages to the implementation of a trajectory control based on a pattern of another individual. In order to allow for a more compliant operation, the algorithm takes into account an stiffness gain to generate an adjusted trajectory for the gait assistance.

The algorithm scheme is illustrated in figure 3.7. The maximum value that the adjusted trajectory can deviate from the pre-recorded trajectory can be adjusted using the gain G_{int}, which is a normalized gain value between 0 and 1. The gain value 1 (meaning 100%) allows no deviation from the reference trajectory and the value 0 gives a totally free trajectory. With the user interface, physical therapists can change this gain value ad-hoc for each patient when necessary.

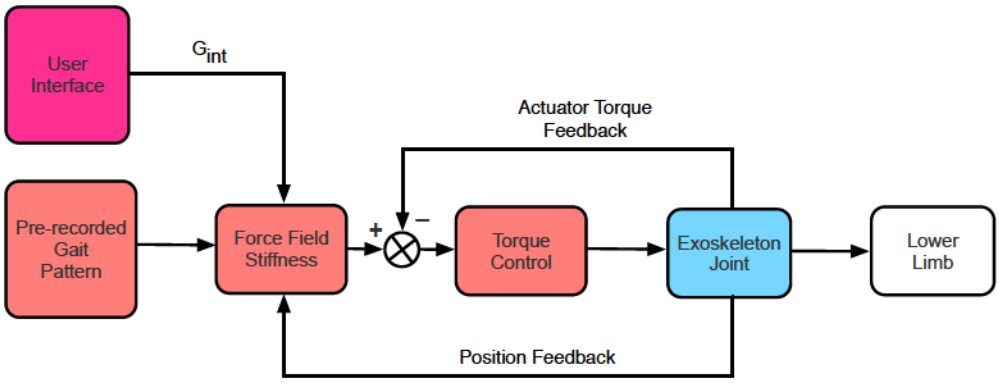

FIGURE 3.7: Control scheme for the assist-as-needed gait therapy. A pre-recorded gait pattern from a healthy subject is used as reference. Based on this reference, a force field controller guides the patient limbs, applying the necessary torque to complete the gait in each joint independently.

The adjusted trajectory output is converted to an input to the torque controller. Consequently, the H2 provides an output torque to the actuators that is proportional to the trajectory deviation. This algorithm creates a force field control that guides patient's limb in a correct pattern, only assisting the patient when he/she deviates from the trajectory. Because all joints on the exoskeleton have their own dedicated electronics and control parameters, each actuator can be independently controlled. This allows the algorithm to generate specific assistance for each joint separately. Specially for hemiparetic stroke patients, who have asymmetric functioning across both lower limbs, this exoskeleton can adapt its functionality in real time based on each individual patient's needs, without requiring a manual adjustment for each patient.

Figure 3.8 depicts a scheme that illustrates the concept of this control method. A virtual tunnel is created around the reference trajectory. The actuator torque act as a spring, allowing a proportional deviation from reference, but keeping the trajectory inside the defined tunnel.

The implemented algorithm can also control the walking speed of the exoskeleton. Speed selection is available to the physical therapists by means of a user interface. During training they can adjust the H2's gait speed across 10 different possible speeds, approximately between 0.5 to 1.8 km/h, to personalize the training for each patient. Since the H2 adapts the pre-programmed reference trajectory, the absolute final speed is, in some way, user-dependent.

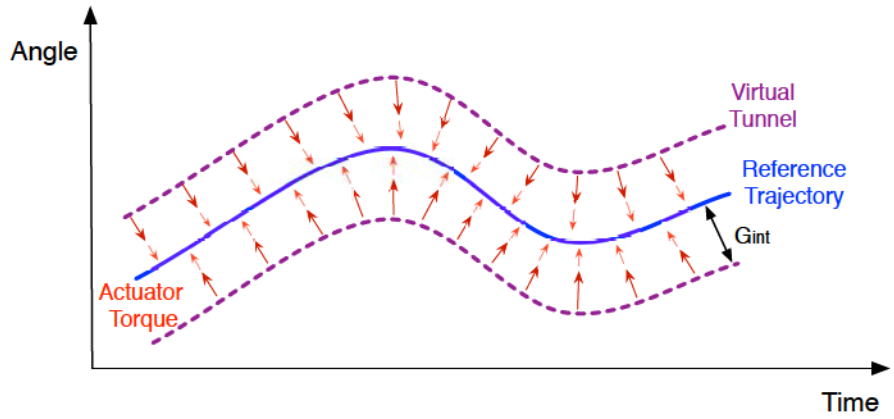

FIGURE 3.8: Concept representation of the force field controller. A virtual tunnel is created along the reference trajectory. The actuator torque act as spring, allowing a proportional deviation from the reference, but keeping the trajectory inside the tunnel.

3.6 User Interface

The H2 exoskeleton is designed in such way that its operation by physiotherapists is very simple. All the complexity in the control scheme is carried out by the embedded software and is transparent to the operator. In order to facilitate even more the operation, a simple mobile and wireless user interface was developed.

Figure 3.9 represents a screenshot of the interface developed to operate the H2. It is programmed in Java and runs in a smartphone or tablet with Android operating system. The interface communicates with the H2 by a Bluetooth link. When the application is started, it first checks the communication link with the exoskeleton and informs the user about the success or not in establishing communication.

Once the communication is successfully established, therapists can start or stop the exoskeleton gait sequence by simply pressing a button. Furthermore, using the interface during training, physical therapists can also adjust the H2's gait speed, as previously discussed, to personalize training for each patient.

Another feature of the interface is the possibility of adjusting the gain G_{int} for each leg independently. Ten possible levels are used to adjust how much the adjusted trajectory can deviate from the recorded trajectory, where the value 10 (meaning 100%) allows no deviation from reference trajectory and the value 0 gives a totally free trajectory. With

FIGURE 3.9: Screen illustration of the interface developed to operate H2. It allows therapist to start and stop the gait process, change gait speed and adjust maximum deviation of the pre-recorded trajectory.

this interface, physical therapists can change the gain value ad-hoc for each situation based on the patient's disability.

One last feature of the interface is the possibility of choosing the gait sequence. The default setting corresponds to a continuous walk, where the exoskeleton starts walking when the start button is pressed and only stops when the stop button is pressed. However, to train some patients that are too weak to walk continuously, a step-by-step strategy is also implemented. In this mode, when the walking button is pressed, H2 performs only one step and automatically stops. When the therapist presses the button again, H2 performs a step with the other leg and stops again. This strategy is also useful at the first training session to get the patient familiarized with the use of the device.

3.7 Neural Interface Integration

The experiments with stroke patients to validate the use of the H2 exoskeleton (detailed in Chapter 4) were performed in Houston, United States. This was a collaboration study with the laboratory of Noninvasive Brain-Machine Interface Systems at the Department of Electrical and Computer Engineering at the University of Houston together with the TIRR Memorial Hermann Hospital.

For this collaboration study, the open architecture of the H2 was integrated with a neural interface developed at the laboratory of Noninvasive Brain-Machine Interface. When associated to exoskeletons, neural interfaces can be used for correlating the aspects of learning during rehabilitation, as well as creating brain-machine interfaces that further engage the patients [241].

Whole-head 64-channel active EEG were collected using a wireless system (BrainAmpDC with Acticap, BrainProducts Inc.), depicted in figure 3.10, and labeled in accordance with the extended 10-20 international system. The EEG data was acquired during each training session, sampled at 1 kHz and referenced to FCz. The system is totally non-invasive and only requires a small portion of water-based gel between each electrode and the scalp of the patient.

To synchronize the EEG and the H2 collected data, an external trigger circuit was developed to label the start and stop of data collection during training session with patients. The trigger signal was transmitted wirelessly using two 2.4 GHz radio transceivers (Wixel, Pololu Corporation). One transceiver is placed together with the EEG set and has a button that allows the experimenter to manually place trigger labels. The other transceiver is placed together with the H2-ARM control board to receive the manual triggers sent by the experimenter.

EEG data were recorded in order to characterize neural correlations of user-H2 interface interaction and learning, as well as to develop algorithms for creating a brain-machine

FIGURE 3.10: Whole-head 64-channel active EEG cap used to acquire brain signals from the scalp. The data is sampled at 1 kHz and send wirelessly.

interface for the H2 in future rehabilitation applications. Further discussion about the EEG data and the neural interface system are outside of the scope of this dissertation and is left as future work.

3.8 Conclusion

This chapter presents the design of the H2 control architecture. The control relies on a structure of layers, where the lowest level is responsible for controlling the actuators and acquiring the sensors' information. This software layer is implemented on the electronic boards placed on each H2's joint. The second software layer implement three different close loop controllers for each joint: position, torque and stiffness control. The objective of this layer is to serve as an open architecture that allows other systems to control the H2. In this way, different therapies can be implemented in a higher level layer, by abstracting the H2 hardware level, which is controlled in real time by the main processor in the H2-ARM board.

To validate to device in a real scenario of gait training, one therapy was also implemented in the high level software layer. This is an assist-as-needed control that was designed to help patients to actively participate in the gait training assisted by the exoskeleton.

The algorithm behind this therapy relies on a pre-recorded normal gait trajectory. When necessary, this trajectory is adjusted in real time to the patient wearing the exoskeleton.

The patient's gait is then guided through this trajectory. The guidance has a main objective of providing torque only when patient deviates from the correct trajectory. Each joint is independently controlled, to better provide the correct level of assistance. This normal gait pattern provided by the H2 aims to correct the asymmetric gait developed by post-stroke patients.

To validate the hypothesis that this algorithm can provide assistance to retrain gait, we design a pilot clinical study where post-stroke volunteers train with the H2 along several sessions of physical therapy. This clinical study to validate the H2 exoskeleton and the assist-as-needed algorithm is presented in the next chapter.

This chapter has presented results that fulfill objectives 6, 7, 8 and 9 stated in Section 1.7.2. Objective number 6 is fulfilled with the development of a control approach that adjusts gait patterns to a specific subject without prior training. Moreover, the algorithm does not need any sensor physically attached to the subject's body.

Following, objectives number 7 and 8 are achieved by the implementation of an assist-as-needed therapy with gait training performed overground in a real environment. This can further motivate patients in the rehabilitation process, that guarantee patient's active participation. The developed algorithm, instead of fully driving the lower limbs while patient remains passive, provides assistance by only applying a restoring force when patient deviates from the correct trajectory that they should follow.

Objective number 9 is the design of an open architecture for H2. This is achieved by the so-called middle software layer that allows external systems to command or to be integrated with the exoskeleton. A neural interface was already integrated with the H2 to be used during the experiments with post-stroke patients. These experiments are detailed in the subsequent chapter.

Chapter 4

Functional and Usability Evaluation[1]

The preceding chapters of this dissertation have presented in detail the theoretical and technological developments required to design and construct a lower limb robotic exoskeleton. This chapter presents the experimental evaluation of the device, including its hardware and the assist-as-needed walking therapy. The evaluation comprised experiments performed with healthy subjects first, aiming to debug and optimize hardware and software of the device and validate its safety and control approach prior to testing with patients. The second and most extensive part of the evaluation consisted of a usability and clinical pilot study with post-stroke patients. In this study, H2 functionality, safety and usability were evaluated on six post-stroke hemiparetic users during four weeks of ambulatory gait training. This evaluation analyzed several aspects: the H2 control performance, patients attitudes and motivation towards the use of the device, patients' safety and tolerance to the intensive robotic training and the preliminarily impact of the robotic training on the walking function of the patients. Results shown that the device is safe and easy to use. The patients tolerated the walking therapy very well and were motivated by training with the device. These results motivate further research on overground walking therapy for stroke rehabilitation with the H2 exoskeleton.

[1]This chapter is partially based on the following manuscripts:
M. Bortole, A. Venkatakrishnan, F. Zhu, J. C. Moreno, G. E. Francisco, J. L. Pons, and J. L. Contreras-Vidal. **The H2 robotic exoskeleton for gait rehabilitation after stroke: Early findings from a clinical study**, Journal of NeuroEngineering and Rehabilitation. Submitted on August 30th, 2014.

M. Bortole, F. Zhu, A. Venkatakrishnan, Z. Hernadez, J. L. Pons, and J. L. Contreras-Vidal. **H2 NeuroExo: Integration of the H2 lower body powered exoskeleton and mobile brain monitoring to improve gait rehabilitation**, International Workshop on Wearable Robotics, 2014.

4.1 Introduction

The innate ability for reorganization in the nervous system raises questions about the best rehabilitation scenario, in order to maximize gains from brain plasticity. Literature suggests that repetitive, specific task training is more effective for cortical and task learning reorganization [242, 243]. Most improvements will be seen with respect to the specific task that is trained. Therefore, when conducting gait therapy with post-stroke patients, the number of footsteps practiced per training session, i.e., the training intensity, appears to be very important. The physical work expended by therapists helping patients to practice a large number of steps is, however, difficult to carry out unaided. To accomplish this objective, robotic devices can be used, since they enable the patient to practice walking over and over again. Robotic devices do not replace the physiotherapist, but can act like a tool that, in combination with the physiotherapist, is more effective than the therapist alone [76].

But more important than repetition, active subject participation in gait therapy is vital to many of the potential recovery pathways [147] and it is, therefore, an important feature of gait training. Higher levels of subject participation and challenge could be promoted through designs of robotic assist-as-needed therapies and performing overground walking in a real environment. Assist-as-needed control strategies focus on the idea that when patient moves along a desired trajectory, the robot should not intervene. If the patient deviates from the desired trajectory, the robot should create a restoring force, that increase proportionally with the trajectory deviation [244].

To evaluate all aspects of the H2 lower limb exoskeleton presented in the preceding chapters of this dissertation, we proposed a clinical pilot study in order to validate the functionality, safety and usability of the device in a real rehabilitation scenario. Large-scale randomized and controlled trials are hard to conduct for a specific therapy or patient group. The reasons for that are, first, because of the difficulty of recruiting patients and, secondly, because of the heterogeneity of functional disturbances after stroke, like the site and extent of lesions and severity of neurological deficit [20]. On the other hand, small-scale trials can help to validate new concepts and devices for rehabilitation, pointing to the correct direction to be followed in a more specific and larger study.

The organization of this chapter is as follows. First, Section 4.2 presents the experimental protocol designed to be used with healthy subjects and post-stroke patients. Section 4.3 describes the experimentation with healthy volunteers and validate the safety and control approach of the device to be used with post-stroke patients. Section 4.4 presents the clinical study with six post-stroke patients, with a discussion of each case study separately. The results are presented in Section 4.5. The discussion about results obtained with the H2 in gait training is given in Section 4.6. Finally, Section 4.7 draws the conclusions and main findings.

4.2 Experimental Protocol

The experimental protocol, including all procedures with stroke patients and healthy subjects were approved by the IRB (Institutional Review Board) at the University of Houston. Appendix A presents the document with the approval details, under the Application ID number 14107-01(4838). The study protocol is also registered and available at ClinicalTrials.gov, under the reference number NCT02114450. All subjects enrolled on this study provided informed consent prior to participation. Appendix B presents a copy of the consent form signed by participants before to be enrolled in the study. Eligible participants for this study were adult healthy subjects with no history of neurological, neuromuscular or physical disability and post-stroke hemiparetic subjects, both groups including volunteers between 18 and 75 year olds.

4.2.1 Inclusion and Exclusion Criteria

Inclusion criteria for healthy subjects participating in the study with the H2 were male and female able-bodied adults aged between 18 and 75 years. Regarding the post-stroke participants, it was included in the study both male and female adults who met the following criteria:

- Age between 18 and 75 years old;
- Individuals with unilateral stroke resulting in hemiparesis;
- Sub-acute or chronic stroke, i.e., interval of at least 3 months or interval of at least 6 months from stroke onset to time of enrollment, respectively;
- Cognitive ability to assimilate and participate actively in the treatment protocol (Mini Mental State Examination score $>$ 24 points, within a total of 30 points indicating normal cognitive ability);
- Ranchos Los Amigos Level of Cognitive Functioning $\geq$ VI (with stage VIII being the highest level of cognitive function);
- Mild-moderate functional disability post-stroke (Rankin Scale scores between 2 and 4);
- Modified Ashworth Scale of Spasticity score ≤ 2 (range is 0 to 4, where 4 reflect maximum spasticity);
- Height range between 1.50 to 1.95 meters (H2 adjustment limitations);
- Maximum weight of 100 kg (H2 adjustment limitations);
- No skin integrity issues;

- Sufficient passive range of motion at the hip (at least 90 degrees flexion, 15-20 degrees extension), knee (90 degrees flexion, complete extension) and ankle (15 degrees dorsiflexion, 15 degrees plantarflexion);
- No contraindications to standing or walking;
- Good physical conditioning to allows the treatment;
- Adequate familiar and social support.

Exclusion criteria for healthy subjects were any history of neurological, neuromuscular or physical disability. Exclusion criteria for post-stroke participants were:

- Severe cognitive and/or visual deficit;
- Hemi neglect;
- Severe sensory deficit;
- Joint contracture of any extremity that limits normal range of motion during ambulation with assistive devices;
- Skin lesions that may hinder or prevent the application of exoskeleton;
- Uncontrolled angina;
- Severe chronic obstructive pulmonary disease;
- Severe osteoporosis;
- Cardiac contraindications for exercise;
- Allergy to the materials used;
- Any other medical contraindications;
- Any medical co-morbidities that would prevent standard rehabilitation;
- Changes in behavior that prevent treatment: no cooperation or aggression.

Determination if patients meet or not the necessary requirements to participate in this study were based on clinical examination by clinical doctors collaborating in this study, as listed in the IRB Approval document in the Appendix A.

4.2.2 Usability and Clinical Study Design

The usability and clinical study consists of four weeks of gait training, in a total of twelve sessions per patient, in conjunction with two assessment sessions, one before and one after the training period. The objectives of this study design are: 1) to assess patient walking function before training; 2) to apply four weeks of gait training assisted by the H2, aiming to evaluate the safety and usability of the device; 3) to assess patient walking function after training, in order to look for possible improvements after training with the H2.

The training period accounted for four consecutive weeks, three sessions per week in separated days. In this pilot clinical investigation, the study design consisted of an open-label assignment of participants to H2 robot-assisted gait training. After patient arrives at the clinical training place, the first step was to proceed with the EEG system setup. This included instrumenting the patient with the EEG cap containing 64 electrodes and applying a small portion of gel in each contact point between the electrodes and patient's scalp. Then, the final step was the H2 donning process, which basically consisted on the correct attachment of the robot to patient's legs and waist. The H2 was prior adjusted to the patient anthropometric measures.

During each training session, subjects were asked to perform an overground walking task guided by the H2 in assist-as-needed mode with a self-selected gait speed along a 50-meter circular or 120-meter linear path. After wearing the exoskeleton, patients were instructed to walk as much as they were able, without exceeding 40 minutes of net walking. During training, patients were encouraged to take rest breaks as necessary.

Figure 4.1 illustrates a patient wearing the H2 and the EEG cap at the beginning of a training session. An experienced physical therapist followed patients during the whole training period. At least two more persons were present during training sessions and followed patients to ensure patient safety. The gait start and stop process was controlled by the patient using two hand buttons placed on a walker, which was used as a balance assistive device during training. If the patient was not able to press the button by him/herself, he/she gave verbal commands and the physical therapist started or stopped the gait process.

Patients were allowed to change the walking speed in real time during continuous walking from level 1 (approx. 0.5 km/k) to 10 (approx. 1.8 km/h) based on their comfort level. Based on patient feedback, the therapist used the smartphone interface to adjust gait speed as necessary.

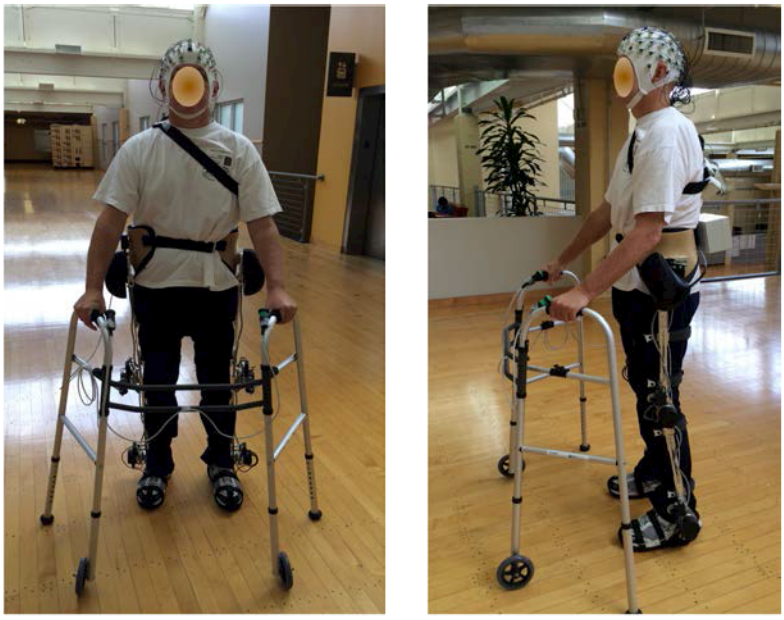

FIGURE 4.1: Patient wearing the H2 and the EEG cap at the beginning of a training session. The gait start and stop process was controlled by the patient using two hand buttons placed on a walker, which was used as a balance assistive device during the training.

4.2.3 Clinical Outcomes

Pre- and post-training assessment sessions were based on standard clinical outcomes and were performed by an independent rater, i.e., a second physical therapist that did not participated in the robotic training. The assessment sessions took place in separated days and the protocol was equal for pre- and post-sessions for all patients.

The walking assessment tests were performed by the patients using their regular assistive devices for walking, like AFOs and/or canes, if any. Thus, results from these tests ought to reflect patient walking ability in a daily basis. These assessments were included to help document any clinically relevant behavioral changes that may occur in response to training with the H2 powered exoskeleton. The following assessment scales were included:

- **Berg Balance Scale** [245, 246]: It is a psychometrically sound measure of balance impairment for use in post-stroke assessment and the most commonly used assessment tool across the continuum of stroke rehabilitation [247]. The ease with which the Berg Balance Scale can be administered makes it an attractive measure for clinicians, since it requires minimal equipment and space. It measures both static and dynamic aspects of balance and risk for falls through direct observation of patient's performance. The 14 items comprised by the scale are scored from 0

to 4, with a score of 0 representing an inability to complete the task and a score of 4 representing independent item completion. A global score is calculated out of 56 possible points. Scores of 0 to 20 represent balance impairment, 21 to 40 represent acceptable balance, and 41 to 56 represent good balance.

- **Functional Gait Index** [248]: The Dynamic Gait Index was originally developed to assess postural stability during gait in people older than 60 years of age at risk for falling [249]. The scale consists of 8 tasks with varying demands, such as walking at different speeds, ambulating over and around obstacles, walking while turning the head, ascending and descending stairs and making quick turns. The Functional Gait Index consists of a 10-item gait test that comprises 7 of the 8 items from the original Dynamic Gait Index and 3 new items. The 3 new tasks include gait with narrow base of support, ambulating backwards and gait with eyes closed. These new tasks have been added because it was noted that these particular tasks are difficult to be performed by people with vestibular disorders [250]. Performing gait with eyes closed is probably the most informative task because the person must rely on vestibular and somatosensory inputs in order to maintain postural control. Each one of the 10 items in the Functional Gait Index is scored in a scale from 0 to 3, with a maximum possible score of 30 points.

- **6 Min Walk Test** [251]: The 6 Min Walk Test is safer, easier to administer, better tolerated, and better reflects activities of daily living than other walk tests [252]. The test has the guidelines standardized by the American Thoracic Society. The primary measurement of this test is the distance walked by the patient during 6 minutes. When performing the 6 Min Walk Test, the patient should walk alone and not assisted by clinicians. However, they are allowed to use their usual walking aids during the test (cane, walker, etc.). Patients should perform overground walk, as opposed to walking on a treadmill. The 6 Min Walk Test is a useful measure of functional capacity, targeted at people with at least moderately severe impairment.

- **Timed Up-and-Go Test** [253]: The Timed Up-and-Go Test is a simple balance test that is commonly used to assess a person's functional mobility in the community. The test measurement consists of the time needed for a patient to stand up from a regular chair, walk 3 meters in a straight line, turn around, walk back and sit down. Elderly who are able to complete the test in less than 20 seconds have been shown to be independent in transfer tasks of daily living and walk at gait speeds that should be sufficient for community mobility. In contrast, a person completing the test in 30 seconds or longer tends to be more dependent in activities of daily living.

- **Fugl-Meyer Lower Extremity** [254]: The Fugl-Meyer assessment is a cumulative numerical scoring system for evaluation of balance, motor function, joint function and some sensation qualities in hemiplegic patients. The test was constructed assuming that motor function recovery follows an obligatory sequence

[255]. A score from 0 to 2 is applied to each item of the test, where: 0 means it cannot be performed, 1 means it can be partially performed and 2 means it can be fully performed. The maximum motor score for the lower extremity is 34 points in total.

- **Barthel Index of Activities of Daily Living** [256, 257]: The Barthel Index measures functional disability by quantifying patient performance in activities of daily life, that are grouped according to self-care and mobility tasks. The test was first developed in 1965 by Mahoney and Barthel [256] and later modified by Granger et al [258]. The original test comprises 10 activities of daily life, but a short form including 5 items is also available [259]. A score from 0 to 4 is applied to each item, with a maximum possible score of 20 points. Lowest scores represent more dependent patients. The Barthel Index is considered easy to use, reliable and sensitive to change.

4.2.4 Data Acquisition

During all training sessions, kinematic and kinetic data generated by the H2 were acquired for offline analysis. The data included angular position, interaction torques and motor torques for left and right hip, knee and ankle joints, toe and heel ground contact, H2 walking state (right step, left step or stopped), battery voltage and current. All data were sampled at 100 Hz by the H2-ARM board and sent wirelessly via Wi-Fi. Data were collected using a Simulink program developed to store and visualize the data in a laptop. Matlab was used to process all collected data.

In addition, for this study, the open architecture of the H2 was integrated with a neural interface, as detailed in Section 3.7. Whole-head wireless 64-channel active EEG was acquired during each training session, sampled at 1 kHz. The H2 and the EEG data were synchronized by means of a manual trigger sent to both systems. The EEG data were recorded in order to characterize neural correlates of user-H2 interface interaction and learning, as well as to develop algorithms for creating a brain-machine interface for the H2 for future rehabilitation applications. As stated in Section 3.7, the EEG data and the brain-machine interface are not discussed in this dissertation.

All data were transmitted wirelessly, including the H2 and the EEG data. This aspect provides much more freedom to the patients to perform the overground walking therapy. The main goal was to engage patients and motivate them to participate actively during the training.

In addition to the H2 and the EEG data, patient's attitudes towards H2 training were captured by using a Likert scale. Patients were asked to rate the ease of use of the H2 at the beginning and at the end of all training sessions, ranging from 0 (very hard to use)

to 10 (very ease to use). Further, relevant comments from patients were documented during the training sessions.

4.3 Study With Healthy Subjects

This section presents the experimental validation of the H2 exoskeleton integrated with the EEG system on healthy subjects. In more detail, the experiments aim to validate the hardware and software presented in Chapters 2 and 3 respectively, as well as to evaluate the usability and safety of the device in experiments in a real walking scenario. These experiments also aim to test the whole system operation and synchronization with the EEG system, thus validating the protocol prior to testing with stroke patients.

4.3.1 Experiments

Five healthy subjects with no history of neurological, neuromuscular or physical disability participated in the experiments. The experimental protocol mainly consisted of walking guided by the H2 while wearing the EEG system. Prior to start the experiment, the subjects signed the informed consent. The H2 lengths were adjusted to match subject's height prior to donning, and subjects were first instructed about how the system works. Then, the first step was to set up the EEG system, putting the EEG cap on the subject's head and applying a small portion of gel on each contact point between electrodes and the scalp. After checking the correct functioning of the EEG system, the last step was the H2 donning process, which basically consisted of the correct attachment of the exoskeleton around subject's legs and waist.

At the beginning of the experiment, the H2 speed was adjusted to the lowest speed value (about 0.5 km/h). Subject used the walker buttons to start and stop the gait process. During the experiments, subjects were followed by another person for safety reasons. This person was also in charge of adjusting the H2 gait speed with the mobile user interface, according to subject comfortable speed.

During the experiments, subjects were instructed to follow the H2 guidance through the walking process. They were free to start walking when they felt comfortable and instructed to stop at least every five minutes, to better simulate the functional ability of the target stroke population. The walking trial consisted of walking with H2 for about 20 minutes in a 50 meters circular or 120 meters linear path. Subject's skin under the leg braces of the exoskeleton was inspected after the walking trial, as well as the exoskeleton, its cables and connections.

4.3.2 Results

All subjects completed the walking experiment. Operation of H2 was well tolerated and was perceived as comfortable. No dangerous situations were reported. After removing H2 at the end of the experiment, some subjects using short pants revealed some red skin points that disappeared within 10 minutes. This was generated due to some H2 leg braces attachment, but was not observed in subjects using long pants. Furthermore, no adverse effects were reported during or after the experiments.

A few problems were identified in the experiments regarding the H2 operation. A software bug was preventing the correct synchronization of the H2 and the EEG data at the first experiments. The problem was solved for future data collection. It was observed malfunction in some interaction torque and foot ground sensors. The sensors were recalibrated and/or replaced to solve the problem. It was also observed that the EEG wireless data transfer presented a reduced range in some occasions, due to some environment interference. To avoid this problem in the future, its was decided to use a mobile cart equipped with the EEG receptor and the laptop, allowing the experimenter to follow the subject more closely if necessary.

To illustrate the H2 operation during walking experiments, results from one subject are shown in figure 4.2. The figure depicts the reference trajectories and the trajectories performed by the subject during the walking. For a better representation, trajectories are shown in the cycle domain based on the stride length, with an average of all steps performed during the whole session.

It can be observed from the results that the H2 can successfully guide the joints through the gait pattern, with a small compliant deviation. Transitions amongst stance and swing phases were smooth during the experiments and no jerky movements were noticed. Subjects needed around five to ten minutes to get used to the H2 operation. After this period, subjects were able to walk without any aid to keep their balance. They were also able to rapidly increase their walking speed.

4.3.3 Conclusion

The study with healthy subjects presented in this section aimed to verify the correct operation of the H2. In addition, it was also aimed to test the protocol to be used with stroke patients, in order to prepare it for clinical experimentation. Results have shown that the developed robotic exoskeleton and its control approach are able to assist the locomotor activity. This has been confirmed by experiments with healthy subjects. However, the application in a clinical study with stroke patients is further investigated in Section 4.4.

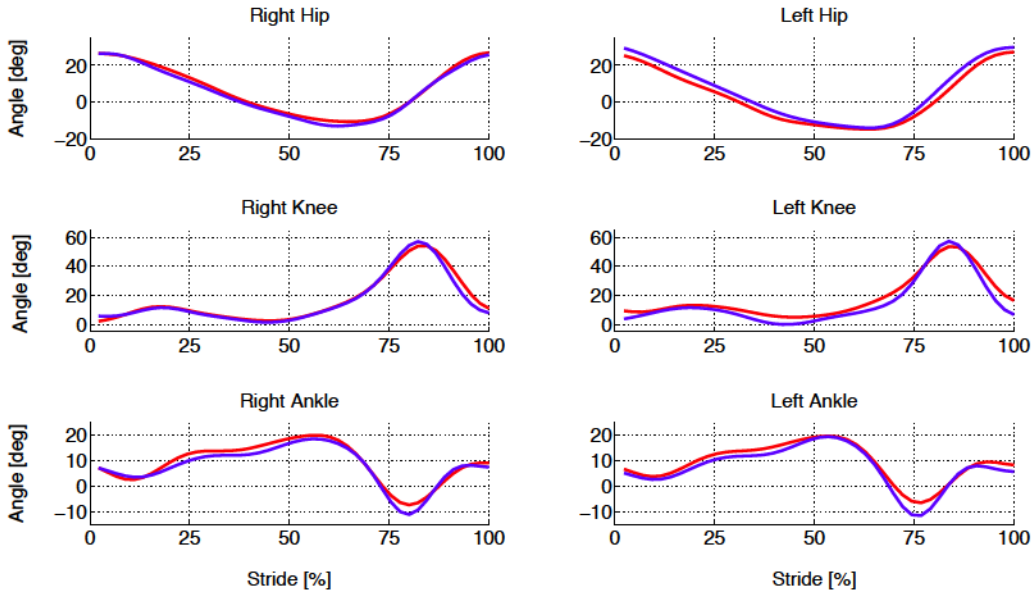

FIGURE 4.2: Hip, knee and ankle trajectories performed by the healthy subject. Blue lines are the reference trajectories that subject is guided through by means of a force field. Red lines represent the average trajectories performed by subject during the experimental test.

Walking velocity of the H2 exoskeleton (max. 1.8 km/h) could be considered slow for healthy subjects, after a period of training with the device. However, post-stroke patients present a reduced strength [50, 51] and consequently, lower gait speeds when compared to healthy subjects. Therefore, the H2 walking speed range is expected to be suitable for post-stroke rehabilitation.

Tests with healthy subjects prior to patients could ensure system stability and integrity, besides fine tunning the control methods. Minor problems were detected and solved. In conclusion, the H2 proved to be safe to use and able to assist gait training. Donning and doffing process was simple and fast, and users were able to get used to the exoskeleton in a short period of time.

From experimentation with healthy subjects it was noted that some temporary skin irritation could occur when subject used short pants. Since this effect did not occur when using long pants, this aspect was taken in consideration for future tests, including patients. However, it does not create any limitation, since H2 do not use any sensors attached to subject's body.

Experiments with stroke patients have to confirm the usability and safety of the system when applied to a clinical study.

4.4 Study With Stroke Patients

This section presents the case studies for each patient, comprised by the experimental results of the gait training and patient's feedback about H2 (Sections 4.4.1 to 4.4.6). Six patients were recruited to participate on the clinical study. All six participants were chronic stroke patients and were not receiving any additional gait training or physical therapy during this period of experimental training. Patients are named here SA01, SA02, SA03, SA04, SA05 and SA06. There was only one dropout, i.e. subject SA03. After completing three training sessions, this patient had his medicine prescription for blood pressure changed by his doctor, which frequently caused him to feel dizzy when standing or walking, preventing him to continue the walking therapy. The remaining five patients completed the study protocol of four weeks of training. Due to personal schedule conflicts, some patients missed one or two training sessions.

4.4.1 Case Study 1

Patient SA01 is a male, 58-year old, 1.92 meter tall and weights 84 kg. He had a stroke five years prior to participation in the study. In consequence of the stroke, SA01 has his left body side affected. He is able to walk without any assistive device, but present an asymmetric gait pattern, reduced left knee flexion and a compensatory movement at hip, known as hip hiking. He was not receiving any physical therapy but exercised his walking regularly.

SA01 completed twelve sessions of training plus the two assessment sessions. He was able to complete 30 to 40 minutes of gait training per session with just a few breaks for rest. Table 4.1 presents the clinical outcomes related to this patient. After the four weeks of training with the H2, he improved his scores in the Berg Balance Scale and Fugl-Meyer for lower extremity. There was no variation in Barthel Index and he decreased his performance in the 6 Min Walk Test, Functional Gait Index and Timed Up-and-Go Test.

TABLE 4.1: Pre- and pos-assessment data for SA01.

Clinical Outcomes	Scale	Pre-assessment	Post-assessment
Berg Balance Scale	0 to 56	47	49
Functional Gait Index	0 to 30	22	20
6 Min Walk Test	meters	328	213
Timed Up-and-Go Test	seconds	16.2	17.9
Fugl-Meyer Lower Limb	0 to 34	25	26
Barthel Index ADL	0 to 20	18	18

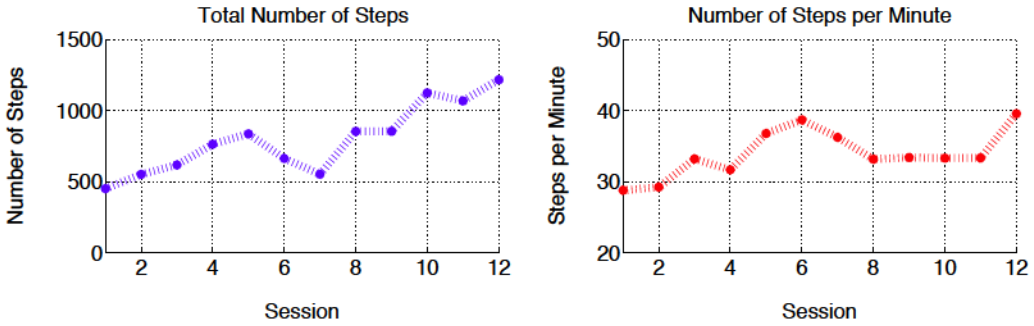

FIGURE 4.3: Left side plot corresponds to the number of total steps performed in each session by SA01, which is direct related to the walking distance. Right side plot corresponds to the number of steps per minute in each session, which relates to the gait speed.

SA01 was very motivated about training with the H2. He had only some difficulty at first session to keep his balance, which is considered normal because all users need a training time to get used to the device. This was expected and happened even with healthy subjects. After 10 to 15 minutes of training, he was more confident and able to walk guided by the symmetric gait pattern generated by the exoskeleton. The number of steps performed in each session (see figure 4.3), which reflects the walking distance, increased over all sessions for patient SA01. Also, as it can be seen in figure 4.3, the number of steps per minute, which reflects the walking speed, increased along the therapy. Both walking distance and speed are dependent on patient's condition and mood on the training day, which generate inter-session variation.

Lastly, figure 4.4 represents the average trajectories performed by each joint of the patient when using the exoskeleton. For comparison, we plot the reference trajectory and the average trajectory of all steps performed in the first and last training sessions with the H2. Trajectories are represented in the cycle domain, based on the stride length percentage, from heel strike to the next heel strike. As it can be observed in the results, patients guided by the force field are being able to perform a more symmetric gait pattern. Additionally, knee flexion on the paretic leg is being improved with training.

4.4.2 Case Study 2

Patient SA02 is a male, 45-year old, 1.78 meter tall and weights 88 kg. He is the less chronic patient participating on the study. His stroke onset occurred six months prior to starting the training with the H2. As a consequence of the insult, SA02 has his left body side affected. He is able to walk but with the assistance of a passive AFO on the affected leg. SA02 presents an asymmetric gait pattern, reduced left knee flexion, hip hiking movement and he was still taken some medication for stroke treatment, but without participation in any physical therapy. It is worth to note that SA02 was invited

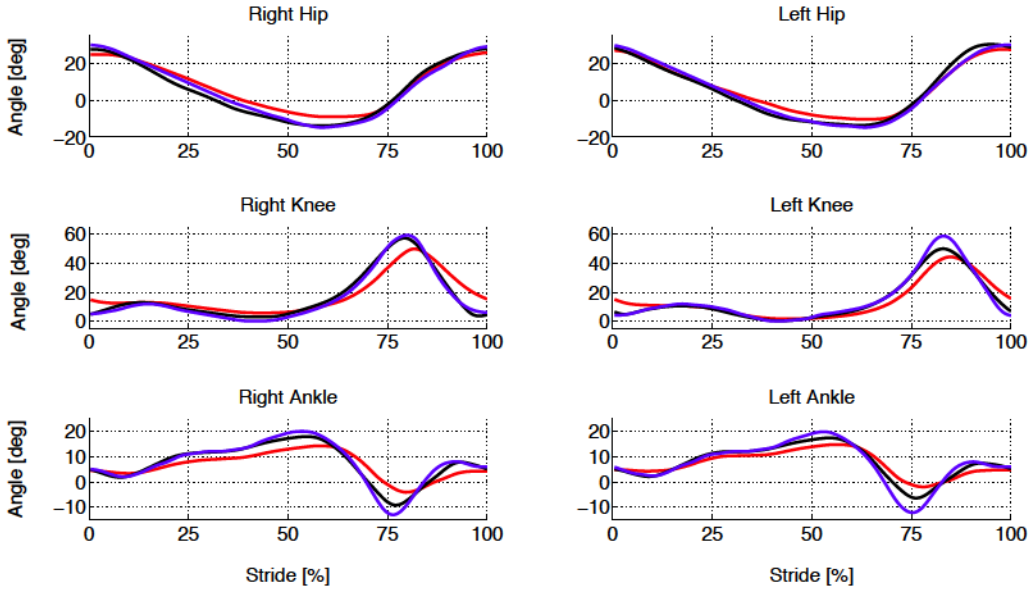

FIGURE 4.4: Hip, knee and ankle trajectories performed by the patient SA01. Blue lines are the reference trajectories that patient is guided through by means of a force field. Red lines represent the average trajectories performed by the patient in the first training session. Black lines represent the trajectories performed at the last session.

to participated in a similar study with another ambulatory exoskeleton before training with the H2, but he performed only one session and dropped out. He explained that the device was cumbersome and the device's backpack that he had to carry was causing him low back pain.

When invited to participate of the H2 study, SA02 completed ten sessions of training plus the two assessment sessions. He only missed two training sessions due to a personal conflict schedule with the training. SA02 stated that the H2 was simpler and lighter to use. During pre- and post-assessment sessions, he was allowed to used his AFO as he does in a daily basis. During the training sessions, he was not using the AFO since H2 can completely replace its function and, moreover, with an active actuation.

Table 4.2 presents the clinical outcomes related to the patient SA02. After the four weeks of training with the H2, he improved his scores in the 6 Min Walk Test, Timed Up-and-Go Test, Fulg-Meyer and Barthel Index. Berg Balance Scale and Functional Gait Index scores did not present any variation, possibly because the patient has scores close to ceiling and the outcome measures are not sensitive enough to capture the variations.

SA02 had almost no difficulties to use the H2, even at the first session. He was able to use the walker properly to keep his balance and started and stopped the gait process on his own, by using the hand buttons placed at the walker. The number of total steps performed by SA02 in each session and the number of steps per minute, both represented in figure 4.5, increased during training time.

TABLE 4.2: Pre- and pos-assessment data for SA02.

Clinical Outcomes	Scale	Pre-assessment	Post-assessment
Berg Balance Scale	0 to 56	54	54
Functional Gait Index	0 to 30	28	28
6 Min Walk Test	meters	274	290
Timed Up-and-Go Test	seconds	11.8	9.3
Fugl-Meyer Lower Limb	0 to 34	27	28
Barthel Index ADL	0 to 20	17	18

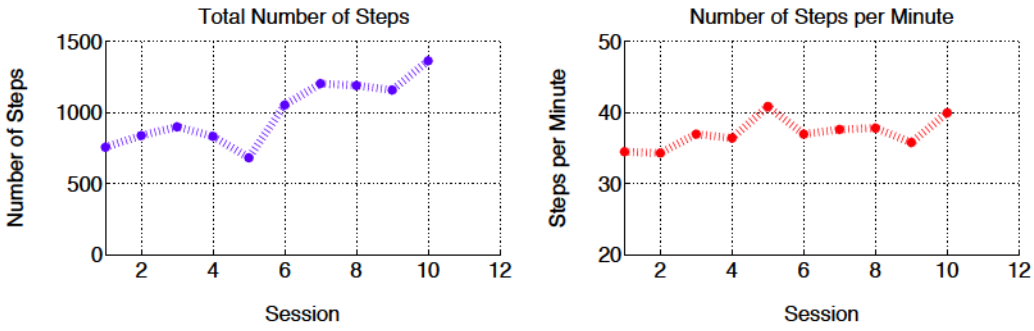

FIGURE 4.5: Left side plot corresponds to the number of total steps performed in each session by SA02, which is direct related to the walking distance. Right side plot corresponds to the number of steps per minute in each session, which relates to the gait speed.

Figure 4.6 represents the average trajectories performed by each joint of patient's leg when using the exoskeleton. For comparison, we plot the reference trajectory and the average trajectory of all steps performed in the first and the last training session with the H2. Trajectories are represented in the cycle domain, based on the stride length percentage, from heel strike to the next heel strike. Similar to SA01, SA02, when guided by the force field, is able to perform a more symmetric gait pattern. Additionally, knee flexion on the paretic leg is being improved as well.

4.4.3 Case Study 3

Patient SA03 is a male, 68-year old, 1.83 meter tall and weights 82 kg. He had his stroke two and a half years before participating on the study and got the right side of the body disabled. SA03 has reduced ambulation and uses a wheelchair for locomotion. He is able to walk only if assisted and at low speeds. He used a four contact point cane when walking. SA03 presents an asymmetric gait pattern, reduced right knee flexion, hip hiking movement and reduced strength in both legs.

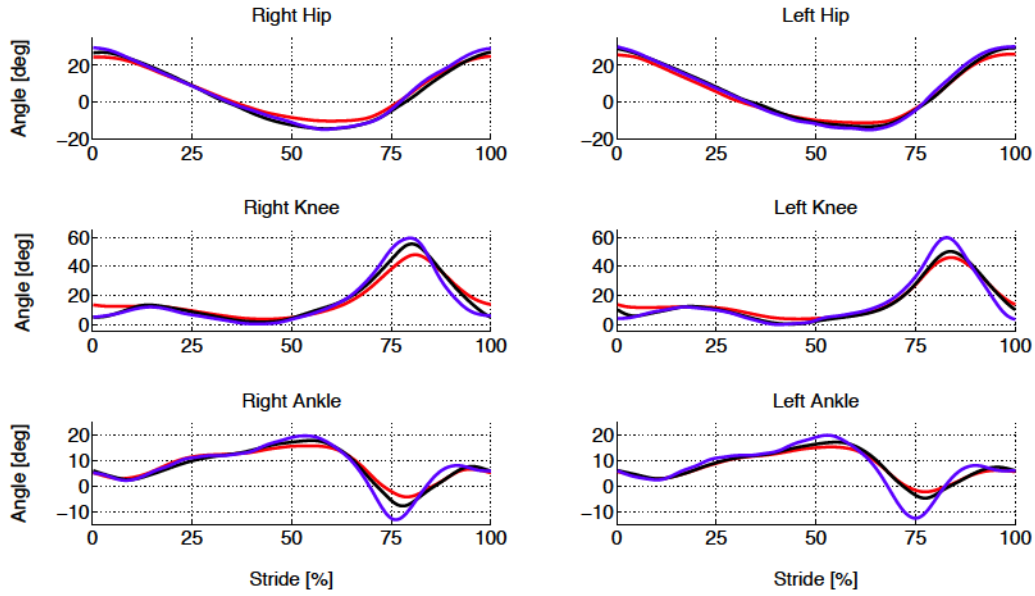

FIGURE 4.6: Hip, knee and ankle trajectories performed by the patient SA02. Blue lines are the reference trajectories that patient is guided through by means of a force field. Red lines represent the average trajectories performed by the patient in the first training session. Black lines represents the trajectories performed at the last session.

SA03 was excited about training with the H2. His weakness caused him to need some extra assistance to keep balance at the beginning of the training. He was improving his performance over the training period, but after three sessions he had to drop out the study. He explained that after this period, he had his medicine prescription for blood pressure changed by his doctor, which frequently caused him to feel dizzy when standing or walking, preventing him to continue the walking therapy. Table 4.3 presents clinical outcomes related to patient SA03 pre-assessment. Post-assessment was not performed since the patient dropped out.

Even with reduced ambulation, which is confirmed by the poor performance in the Timed

TABLE 4.3: Pre- and pos-assessment data for SA03.

Clinical Outcomes	**Scale**	**Pre-assessment**	**Post-assessment**
Berg Balance Scale	0 to 56	32	-
Functional Gait Index	0 to 30	10	-
6 Min Walk Test	meters	200	-
Timed Up-and-Go Test	seconds	52.0	-
Fugl-Meyer Lower Limb	0 to 34	11	-
Barthel Index ADL	0 to 20	16	-

Up-and-Go Test, added to low scores in the Berg Balance Scale, Functional Gait Index and Fugl-Meyer measurements in the pre-assessment, subject SA03 was improving his performance with the training. Guided by the H2 during only three training sessions, he was being able to perform a more symmetric gait pattern and to improve knee flexion on the paretic leg, which is illustrated on figure 4.7.

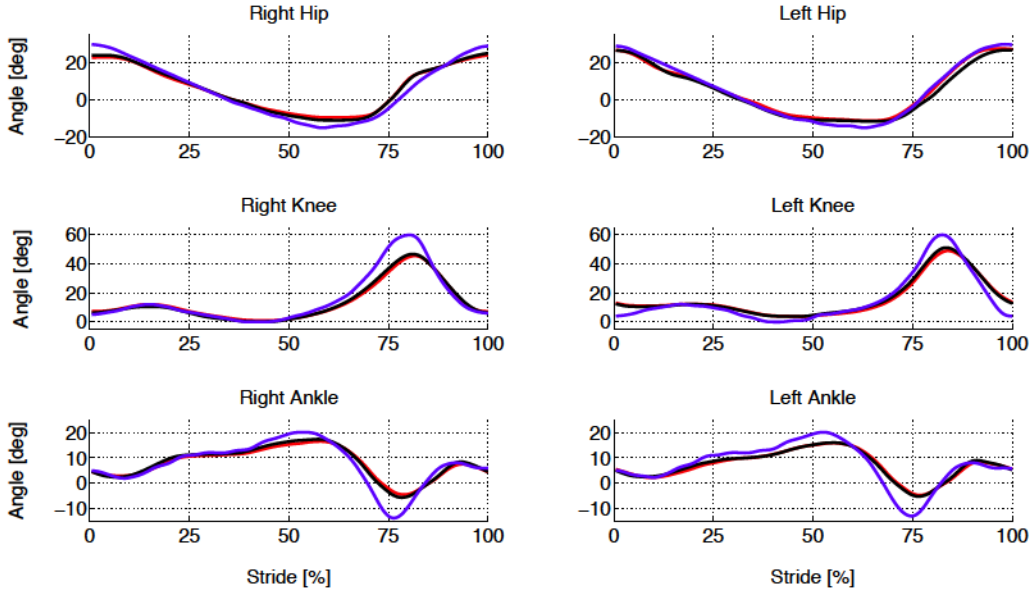

FIGURE 4.7: Hip, knee and ankle trajectories performed by the patient SA03. Blue lines are the reference trajectories that patient is guided through by means of a force field. Red lines represent the average trajectories performed by the patient in the first training session. Black lines represent the trajectories performed at the last session.

4.4.4 Case Study 4

Patient SA04 is a male, 43-year old, 1.88 meter tall and weights 99 kg. He is the second youngest participant and second closest participant to the stroke onset, which occurred eleven months prior to participation on the study. SA04 has his left body side affected by the stroke. He is able to walk but uses a cane as assistance and presents an asymmetric gait pattern, reduced left knee flexion and hip hiking movement. He was not receiving any physical therapy and was very motivated about training with the H2 exoskeleton. He even comment that he wished to have a robotic device like H2 at the beginning of his training just after the stroke onset.

SA04 completed twelve sessions of training as well as the two assessment sessions. He was able to complete 30 to 40 minutes of gait training per session with just a few breaks for rest. Table 4.4 presents the clinical outcomes for SA04, who achieved a great improvement. He improved his walking distance by about 76% after the four weeks of training and reduced the Timed Up-and-Go Test for about 20%. The Berg Balance Scale

TABLE 4.4: Pre- and pos-assessment data for SA04.

Clinical Outcomes	Scale	Pre-assessment	Post-assessment
Berg Balance Scale	0 to 56	56	56
Functional Gait Index	0 to 30	25	26
6 Min Walk Test	meters	134	237
Timed Up-and-Go Test	seconds	13.2	10.7
Fugl-Meyer Lower Limb	0 to 34	25	26
Barthel Index ADL	0 to 20	18	18

was at maximum score for pre- and post-assessment. Functional Gait Index and Fugl-Meyer scores presented improvements too. There was no variation on Barthel Index, which is also close to the ceiling score.

SA04 presented only a few difficulties at the first session to get used to the device. In all sessions the subject performed the training with very high level of balance, which is corroborated by his maximum score on the Berg Balance Scale. At the end of the training, SA04 was very confident and was able to walk guided by H2 without any additional device to keep his balance. He increased the number of steps performed in each session and the number of steps per minute, both illustrated in figure 4.8. He was able to walk at the maximum speed with the H2, around 1.8 km/h at the last training session.

Lastly, figure 4.9 represents the average trajectories performed by each joint of the patient when using the exoskeleton. The assist-as-needed algorithm generating the force field helped SA04 to perform a more symmetric gait pattern and to improve the knee flexion on his paretic leg.

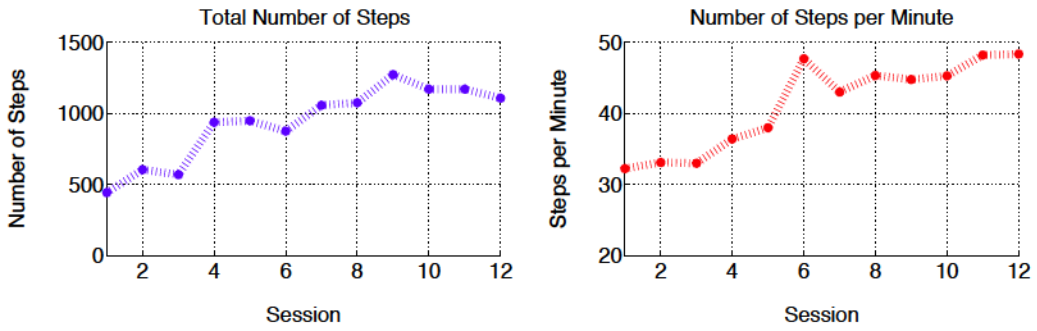

FIGURE 4.8: Left side plot corresponds to the number of total steps performed in each session by SA04, which is direct related to the walking distance. Right side plot corresponds to the number of steps per minute in each session, which relates to the gait speed.

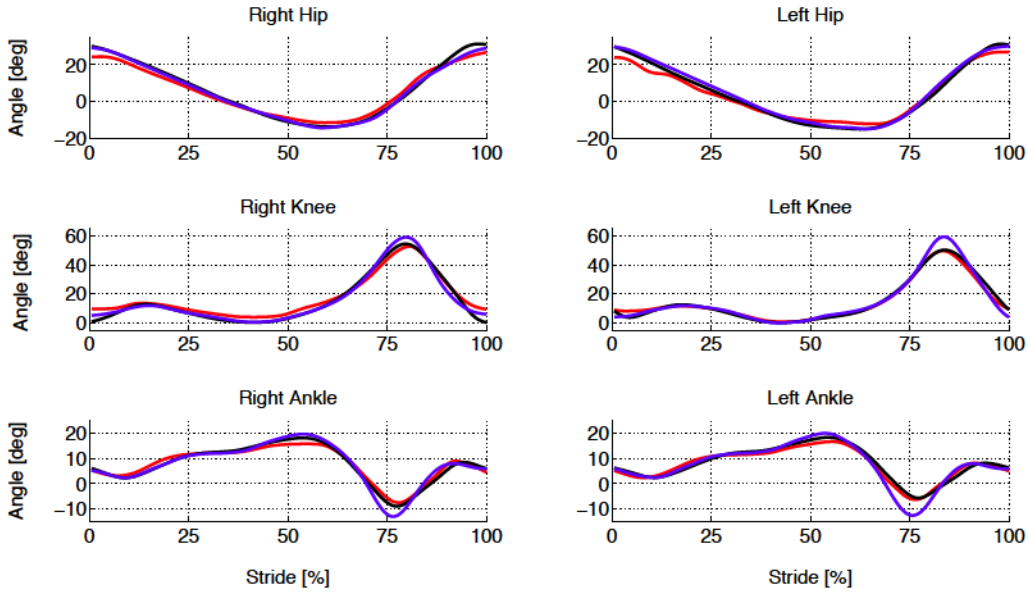

FIGURE 4.9: Hip, knee and ankle trajectories performed by the patient SA04. Blue lines are the reference trajectories that patient is guided through by means of a force field. Red lines represent the average trajectories performed by the patient in the first training session. Black lines represent the trajectories performed at the last session.

4.4.5 Case Study 5

Patient SA05 is a male, 40-year old, 1.80 meter tall and weights 84 kg. He is the youngest subject participating on the study, but the most chronic stroke patient, since he had a stroke fourteen years prior to participation on the study. SA05 has the right side of body affected by the insult. He is able to walk but with the assistance of a passive AFO on the affected leg. SA05 presents an asymmetric gait pattern, reduced right knee flexion and hip hiking movement. He was not participating in any physical therapy but walked regularly in a daily basis.

SA05 completed ten sessions of training, plus the two assessment sessions. Similar to SA02, he missed two training sessions due to a personal conflict schedule with the training. During pre- and post-assessment, he was allowed to used his AFO as he does normally. During the training sessions he was not using the AFO, since H2 can completely replace its functionality in an actuated manner.

Table 4.5 presents the clinical outcomes related to the patient SA05. After the four weeks of training with the H2, he greatly improved his score in the 6 Min Walk Test and improved four points in the Berg Balance Scale. The Functional Gait Index, Timed-Up-and-Go Test and Fugl-Meyer scores also presented improvements. The Barthel Index score was close to ceiling and did not presented variation.

TABLE 4.5: Pre- and pos-assessment data for SA05.

Clinical Outcomes	**Scale**	**Pre-assessment**	**Post-assessment**
Berg Balance Scale	0 to 56	49	53
Functional Gait Index	0 to 30	19	22
6 Min Walk Test	meters	289	386
Timed Up-and-Go Test	seconds	10.5	9.6
Fugl-Meyer Lower Limb	0 to 34	16	18
Barthel Index ADL	0 to 20	19	19

As the other subjects, SA05 had some difficulty at the first session to keep his balance assisted by the walker. After the first training session, he was more confident and able to walk following the symmetric gait pattern generated by the exoskeleton. The number of total steps performed in each session and the number of steps per minute are presented in figure 4.10. Patient SA05 increased a lot the number of steps per minute and was able to complete 30 to 40 minutes of gait training per session with just a few breaks for rest. In the session number seven, the reduced number of performed steps is due to the H2's footplate, that broke during the training session. The mechanical structure of the footplate was fixed and reinforced for the next training sessions.

Lastly, figure 4.11 represents the average trajectories performed by the subject when using the H2. Trajectories are represented in the cycle domain, based on stride length percentage, from the heel strike to the next heel strike. As results show, gait pattern has become more symmetric and knee flexion on the paretic leg is being improved with the robotic assisted training.

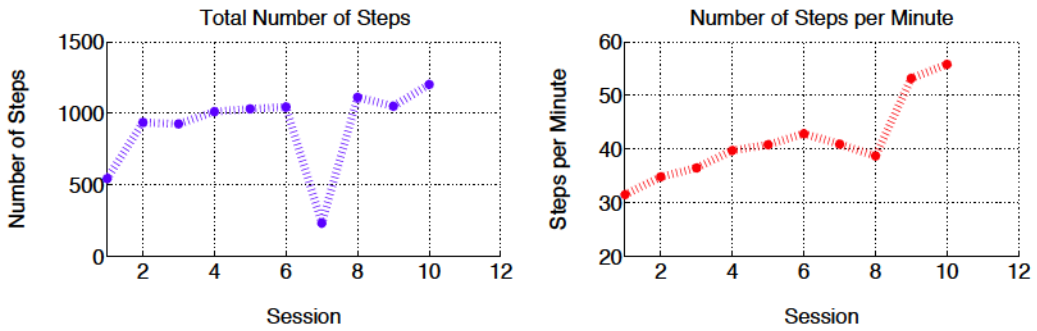

FIGURE 4.10: Left side plot corresponds to the number of total steps performed in each session by SA05, which is direct related to the walking distance. Right side plot corresponds to the number of steps per minute in each session, which relates to the gait speed.

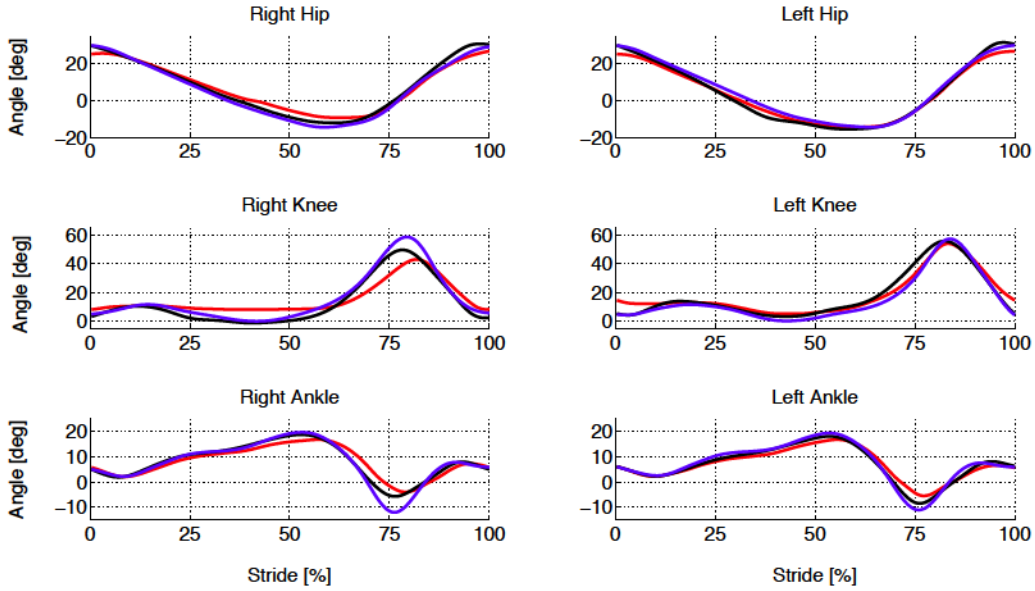

FIGURE 4.11: Hip, knee and ankle trajectories performed by the patient SA05. Blue lines are the reference trajectories that patient is guided through by means of a force field. Red lines represent the average trajectories performed by the patient in the first training session. Black lines represent the trajectories performed at the last session.

4.4.6 Case Study 6

Patient SA06 is a female, 67-year old, 1.60 meter tall and weights 62 kg. She is the only female participating on the study. Her stroke occurred six and a half years prior to participation on the study, letting her with the left side of the body affected. She was the weakest participant in the study, almost unable to walk. When walking, she was only able to do it at very low speed. Moreover, she used her passive AFO on the affected leg and a four contact point cane to assist her walking. SA06 presents an asymmetric walking pattern, reduced left knee flexion and high level of weakness on both legs. Moreover, she presents hyper-extension on the affected knee joint, which difficulty her walk and causes her to constant loose balance.

SA06 completed the twelve sessions of training plus the two assessment sessions within the scheduled time. During pre- and post-assessment, she was allowed to use her AFO as well as her cane to assist her walking. During the training sessions, she was not using the AFO, since H2 can completely replace its function actively and, to avoid her knee hyper extension, the H2 left knee ROM was limited in software to 10 degrees higher than normal maximum extension.

Table 4.6 presents the clinical outcomes related to patient SA06. With the four weeks of training with the H2, she improved her scores in the Berg Balance Scale, 6 Min Walk

TABLE 4.6: Pre- and pos-assessment data for SA06.

Clinical Outcomes	Scale	Pre-assessment	Post-assessment
Berg Balance Scale	0 to 56	38	39
Functional Gait Index	0 to 30	10	10
6 Min Walk Test	meters	54	67
Timed Up-and-Go Test	seconds	49.3	41.7
Fugl-Meyer Lower Limb	0 to 34	21	21
Barthel Index ADL	0 to 20	18	18

Test and Timed Up-and-Go Test. The Functional Gait Index, Fulg-Meyer and Barthel Index did not present variation.

Due to her weakness and difficult to keep balance, SA06 had difficulties to use H2 at the first session, performing only a few steps. With the constant training with the device, she was able to increase her strength and the number of steps walked in each session, reaching almost a 1000 steps at the final training session (see figure 4.12). She also increased her walk speed, represented by the number of steps per minute in the figure 4.12.

Figure 4.13 represents the average trajectories performed by patient SA06 when using the H2. She also achieved a more symmetric gait pattern and improved her knee flexion on the paretic leg with the training.

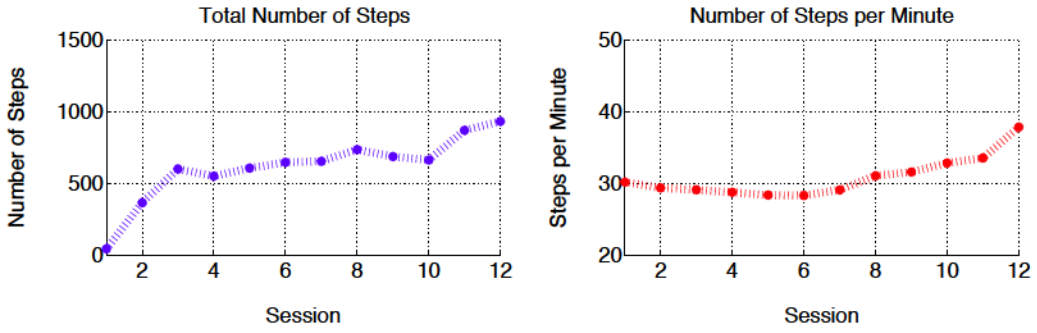

FIGURE 4.12: Left side plot corresponds to the number of total steps performed in each session by SA06, which is direct related to the walking distance. Right side plot corresponds to the number of steps per minute in each session, which relates to the gait speed.

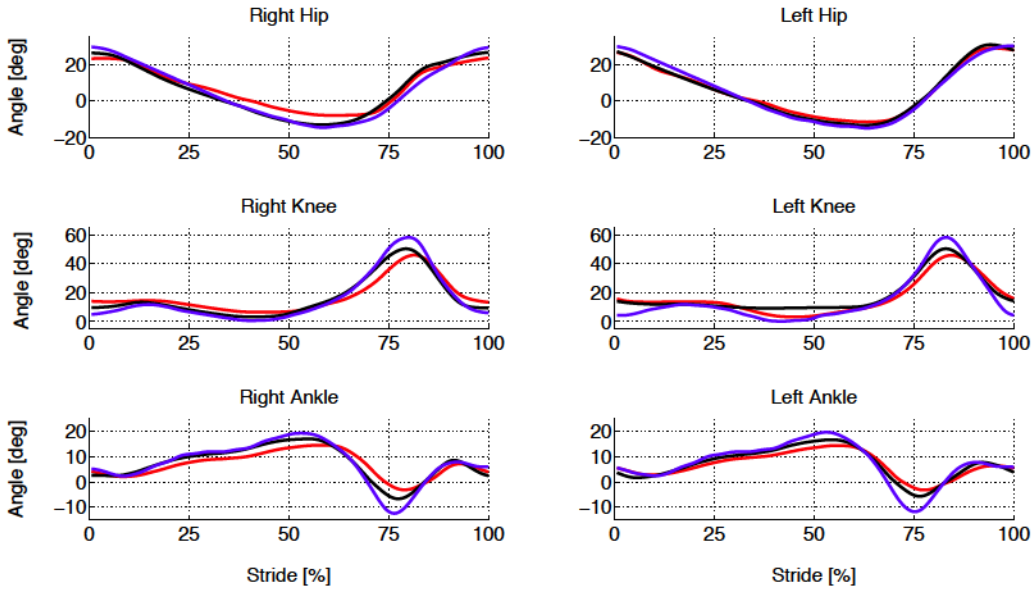

FIGURE 4.13: Hip, knee and ankle trajectories performed by the patient SA06. Blue line is the reference trajectory that patient is guided through by means of a force field. Red line represents the average trajectory performed by the patient in the first training session. Black line represents the trajectory performed at the last session.

4.5 Results

Hereby are presented the general results gathered from the six post-stroke patients participating on this pilot clinical study, related to the gait intervention, safety and usability of the H2 when applied to clinical rehabilitation.

4.5.1 Gait Intervention

In this pilot clinical study, the usability and safety of using the H2 for robot-assisted gait training in stroke patients has been evaluated and validated. Five from six participants with stroke were able to finish twelve sessions of training over a period of approximately four weeks. Subject SA02 and subject SA05 completed ten sessions only as they had to miss two sessions due to a personal schedule conflict with the training. Subject SA03 dropped out the study after three sessions of training due to reasons not related to H2 training.

At the first session, all participants started at the lowest walking speed (around 0.5 km/h) and were able to increase the gait speed across sessions as training progressed. Figure 4.14 links a video of a post-stroke patient during a rehabilitation session with the H2. The deviant gait pattern of the stroke patients could be retrained into a more

FIGURE 4.14: Click here or scan this code to see a video of a post-stroke patient during a rehabilitation session with the H2.

symmetric pattern during the training time. Symmetry of gait is of special importance to stroke recovery because the affected side promotes a persistent, uneven walking pattern.

Further, the number of steps walked, a measure indicative of walking distance, increased across sessions for all participants. The average number of steps performed by patients in each training session was around 900 steps, whereas during manually assisted training only approximately 100 steps per session can be performed [55]. Thus, H2 allows intensive gait training with much less effort from therapists.

Additionally, clinical outcome scores show improvements in all but one patient participating on the training. All participants were chronic stroke survivors and were not receiving any additional therapy. Since patients were in a stable phase of recovery after the stroke, the functional gains can be probably attributed to the robotic training itself.

4.5.2 H2 Safety and Usability

The time needed for donning and setup the H2 and the EEG system was short, around twenty minutes elapsed from the time participants arrived before gait training could start. The doffing process was even faster, less than two minutes. It is worth to note here that about 80% of required donning time was related to the EEG system setup, which included to apply a small portion of gel in all contact points of the 64 electrodes with the patient's scalp. H2 donning took no more than five minutes in general.

No adverse effects were observed during training, including no skin irritation or redness, no sore spots, any pain or discomfort during or after the training.

H2 also demonstrated significant autonomy in the context of battery power. A totally charged battery pack could run the exoskeleton for about nine training sessions of, on average, 40 minutes each session. Considering that in each session, a participant walked 30 minutes on average, H2 could run for more than four hours of continuous walking with

a single battery charge. Also since the battery pack is detachable from the mechanical frame, it is very easy for a therapist to replace an empty one with a fully charged battery pack.

The H2 exoskeleton tested in the experiments was the first device built and thus, issues might have been expected. Remarkably, the H2 robot-assisted gait training was conducted without any major problems. Only minor technical issues occurred without impacting user's safety and were easily fixed. Amongst those minor problems, we include the mechanical connection between the footplate and ankle joint that ruptured and was replaced with a reinforced one; some interaction torque sensors and foot ground contact sensors were not working property and were replaced for new ones.

Lastly, patients participating on the study were very motivated about training with the device. When asked to evaluate the ease to use of device in each session on a Likert scale, the average rating for the six patients in all twelve sessions were 7, where 0 indicates "extremely hard to use" and 10 indicates "extremely easy to use". The main positive feedback received from patients when training with H2 was: "the device is lightweight"; "wearing it is fast and simple"; "I can feel that it helps my knee flexion"; "it is more exciting walking overground with this device than my previous treadmill training with manual assistance" and "I wish I had access to this device when I was in the hospital for inpatient rehabilitation after my stroke". The main negative feedback received from patients was: "it felt weird at the first moment and took me some time to get used to it in my first training session, since I have never used a robotic device like this".

4.6 Discussion

The pilot clinical study conducted with post-stroke patients have presented the first evidence for safety and usability of the H2 wearable robotic exoskeleton in the context of post-stroke gait rehabilitation. The main finding of this work is that the H2 exoskeleton provides a means for safe and intensive gait training in hemiparetic stroke survivors. Across four weeks of training in six stroke subjects, the H2 exoskeleton proved to be easy to use, with a fast donning and doffing process and was very well accepted by patients as a potential rehabilitation device.

Importantly, the results from this pilot clinical study indicate that the H2, operated in assist-as-needed control mode, allows reshaping of the asymmetric, deviant hemiparetic gait in stroke survivors through a relatively short period of training. It is important to note that in most stroke victims, the lack of knee flexion during swing creates an abnormal compensatory movement in the hip, commonly known as hip hiking. Also, most patients do not rely on their paretic leg, hence, they do not shift weight equally on both lower limbs during walking. This behavior creates an asymmetric gait pattern where the stance phase on the paretic leg is shorter than the unaffected leg. The gait assistance

force field implemented in H2 guided patients in a correct gait pattern, creating a stance phase that is equal across both lower limbs and consequently preventing compensatory hip hiking. As a result, while using H2, patients are being trained to the correct pattern of weight shifting between lower limbs and knee flexion.

Actuation at the ankle was another important aspect of H2 design. During training it helped avoid foot drop and could help patients to work on dorsiflexion movements. The H2's control algorithm, therefore, helps these patients relearn a symmetric gait pattern across both lower limbs by providing assistance as needed at the appropriate limb segments and joints. Importantly, the ability to perform this training in a functional context such as overground walking is of major clinical significance. Furthermore, it is very interesting to note that this training is stimulating and challenging even for the participant with chronic stroke (fourteen years ago). Coupled with the motivational component of training provided by a novel robotic gait training regimen, the H2 allows these participants to experience kinesthetic feedback of near-normal gait patterns in overground walking. Since the six participants in this study were able to increase walking speed and distance across training sessions, it would appear that H2 robot-assisted training can potentially recruit extant neuroplasticity and promote improved motor control in these patients.

However, these findings must be considered with the caveat that this study is limited to a small subgroup of patients that is not representative of the entire stroke population and therefore, conclusions cannot be drawn regarding gait improvements after the use of the H2. Furthermore, as seen from the patient demographic data and functional outcome scores, the subgroup of stroke participants included in this study is also heterogeneous in terms of time at which H2-assisted training was provided with regards to their stroke onset as well as their individual functional impairments. This is an important factor to be considered as this population is very diverse, and therefore, no two patients are alike in terms of their impairments.

Therefore, it is critical that H2 robot-assisted training be personalized to each individual based on his/her needs. In this regard, further modifications can be implemented in the control algorithm to provide variable resistance once the user has reached a certain threshold in terms of torque generation and/or joint angular position/velocity. This will help ensure progressive, adaptive changes to the training regime and is a clinically significant issue that warrants further investigation.

Notably, the modular design of the H2 is particularly relevant for stroke rehabilitation. Since various segments of the device can be used independently, H2 offers promising means of using unilateral Hip-Knee-Ankle, Knee-Ankle or just one joint versions of the device, customizing treatment protocols to each patient's specific needs. These questions need to be addressed in future research, in order to help develop optimal control algorithms to use these modular components of the H2 for individualized rehabilitation.

Similarly, appropriate intervention durations and frequency of training, i.e., "dosing schedules", are still not well established for such wearable robotic rehabilitation protocols, which also needs to be examined in careful detail in further clinical investigations. Furthermore, in order to fully utilize the functionality of the lightweight wearable H2 device, future training protocols can also include other functional tasks such as sit-to-stand, stand-to-sit and stair climbing.

The lack of major changes in clinical outcomes precludes any conclusions about functional improvements when training with the H2 in this study. The author believes this is primarily because while the participants in this study had qualitative gait asymmetries and impairments, this is not captured by the granularity of the standard clinical outcome measures. Further, in some of the items such Berg Balance Scale and Functional Gait Index, if participants achieve scores closer to the ceiling, it is impossible to track any further qualitative improvement using those items. This brings to light the importance of developing novel metrics or outcome measures that are sensitive and capable of tracking behavioral changes quantitatively and qualitatively in robotic rehabilitation paradigms. However, it is important to study the relationship of these novel metrics to standard clinical outcomes, in order to describe the functional domain that is being assessed.

Finally, the factors discussed above such as inadequate "dosing" in terms of frequency and duration of training may have prevented sufficiently progressing treatment for each participant based on their functional levels. These questions need to be addressed in a clinical investigation with a larger population, along with comparison of H2 robot-assisted training to conventional physical rehabilitation regimes. A future work, therefore, is focusing on a controlled clinical study in a larger sample of participants with stroke.

4.7 Conclusion

In summary, this chapter fulfills the objective number 10, by presenting the evaluation of H2, a novel lower limb robotic exoskeleton for rehabilitation of stroke survivors. The device is lightweight and battery-powered, thereby allowing for gait training in functional contexts such as overground walking in comparison to more traditional tethered or treadmill-based robotic rehabilitation devices.

Further, the control of H2 is based on a custom assist-as-needed algorithm that creates a force field along a desired trajectory, proportionally applying torque only when patient deviates from the pre-programmed correct pattern. This force field control, therefore, helps restore a symmetric gait pattern in hemiparetic stroke survivors, by assisting only the segments that need it and preventing undesired compensatory movement patterns, such as hip hiking.

Additionally, a customized mobile-based user interface allows the therapist to personalize and adjust the maximum allowed deviation from the reference based on a specific patient's condition.

Finally, we also present early findings from a clinical evaluation of the H2 for gait rehabilitation in six participants with post-stroke hemiparesis. Participants have shown adaptive improvements in their gait trajectories across the training sessions over four weeks. These results are encouraging and provide the first evidence for safety and feasibility of using the H2 for functional gait training in stroke patients. A future work aims to evaluate the therapeutic benefits of active training with the exoskeleton in restoring gait function in a larger population of stroke patients.

In summary, the developed H2 device opens up future research avenues to study methods to optimize rehabilitation protocols that can be customized for individuals with gait impairments following neurological injuries and with the capacity to deliver high dosage and high intensity therapies. Taken together, these advances can have a huge clinical impact by helping accelerate recovery and improve functional independence and quality of life in these patients.

Chapter 5

Conclusions and Future Work

This last chapter summarizes the main conclusions of this dissertation and how they contributed to achieve its objectives. In addition, it also presents the technical and scientific contributions resulting from this work. In the last part, this chapter describes the future work that can give continuity to the research presented here. Two main areas are identified for further research, which are new control approaches for the exoskeleton and randomized clinical studies with a large cohort of post-stroke patients. The design of new control approaches is already being carried out in a new project that uses the H2 exoskeleton. Randomized clinical trial studies will aim to validate the effectiveness of the robotic therapy compared with conventional therapy.

5.1 Conclusions of the Dissertation

Stroke results from a disturbance on the blood supply that flows to the brain. As a consequence, the contra-lateral side of the body is affected, leading to lost or diminished motor functions. Stroke is among the most common causes of adult disability, and hemiparesis, the main manifestation of stroke, leads to a poor walk ability. Most patients walk to slowly to participate in the community activities. Gait disability is common after stroke and it is one of the main complains from patients who suffers a stroke insult.

Recovery after stroke has been based on physical therapy focusing on task specific activities. The translation of neuroscientific research into care, associated to the advance of the technology, has led to new approaches in rehabilitation. In order to help physical therapists to improve the rehabilitation process, robotic exoskeletons can come into play. These robotic devices have emerged as a promising approach to restore gait and improve motor function on impaired stroke victims.

Helping therapists to improve the outcomes of gait rehabilitation through robotics exoskeletons has been the main motivation for the research on this dissertation. The overall aim was to generate the necessary knowledge to design, develop and validate a novel lower limb robotic exoskeleton and an assist-as-needed therapy for gait rehabilitation in post-stroke patients. Research activities were conducted towards the development of the hardware and the control methods required to proof the concept with a clinical evaluation.

Several partial objectives were proposed in Section 1.7.2 and accomplished with the work presented in Chapters 2 to 4. The first five partial objectives were achieved by designing and implementing the H2 lower limb exoskeleton, a lightweight robotic device capable of overground walking. The device, weighting no more than 12 kg, provides a comfortable embodiment to the user, by not extending above mid-abdomen and requiring nothing to be worn over the shoulders or above the lower back. Furthermore, the robotic exoskeleton can be easily adjusted to fit adults between 1.50 and 1.95 meters in height. Taken together, these characteristics enabled a fast donning and doffing process, facilitating therapist's work and increasing the training time.

The H2 exoskeleton was envisioned as a completely actuated device in the sagittal plane, including the hip, knee and ankle joints. Actuation on the ankle joint, which is never addressed in overground rehabilitation exoskeletons, was very important to counteract the foot drop problems in post-stroke patients, improving their dorsiflexion movements. Additionally, the H2 exoskeleton presented a great autonomy powered by battery. The device was designed with high efficiency motors and gearboxes, integrated with customized electronic drives presenting very low dissipation and able to regenerate power. As a result, the H2 could run for more than four hours of continuous walking with a

single battery charge. When empty, the battery pack is easily replaced by a fully charged one.

Partial objectives 6 to 9 were achieved by implementing a control approach that assist the patient only when needed. This method creates a force field that guides patient's limbs along a correct trajectory. In this way, the robotic exoskeleton only applies forces when patient deviates from the trajectory, therefore, helping them to relearn a symmetric gait pattern across both lower limbs. Importantly, H2 has the ability to perform this training therapy overground in a real environment, which can greatly motivates patients to actively participate on the training.

Finally, research was conducted to evaluate the robotic exoskeleton and its control approach in a study with six post-stroke patients, achieving the last partial objective. This clinical study aimed to be a proof-of-concept of all design and implementation applied to a real clinical rehabilitation scenario. Several aspects were evaluated: the robotic exoskeleton control performance, patients attitudes and motivation towards the use of the device, patients' safety and tolerance to the intensive robotic training and the impact of the robotic training on the walking function of the patients.

Patient's attitudes towards the use of the device were very positive. All patients were motivated to train with the exoskeleton. No adverse effects were observed neither during nor after the training sessions. Typical training sessions lasted for about 40 minutes, with 30 minutes of net walking time. Most patients were able to complete the training sessions with just a few brakes for rest, and the number of steps walked on each session increased over all sessions for all patients, as well as the gait speed.

The results from this usability and clinical study shown that the H2 operated in assist-as-needed control mode can help the deviant hemiparetic gait in stroke survivors to become more symmetric. The gait assistance force field guided patients in a correct gait pattern, creating a stance phase that is equal across both lower limbs. Therefore, while training with the H2, patients are working on the correct pattern of weight shifting between lower limbs, as well as improving the knee flexion. Furthermore, it is also notable that training with the H2 was motivating even for the participants that have a stroke long time ago. Since the six participants in this study were able to increase walking speed and distance across training sessions, it seems that H2 training can recruit exiting neuroplasticity and lead to better motor control in post-stroke patients.

The main findings of the usability and clinical study are that the H2 exoskeleton is safe and easy to use by experienced therapists in a rehabilitation set, besides enabling high intensive and repetitive gait training. Some factors as training frequency and duration may have prevented higher progress of functional level on participants. Although the study is limited regarding the validation of the H2 effectiveness compared to traditional gait therapy, the findings can guide furthers studies in this respect. A future work,

therefore, is to focus on a controlled clinical study in a larger cohort of post-stroke patients.

Lastly, the H2 and the neural interface integration during the clinical study has generated a large database of kinematic and kinetic data synchronized with EEG data. The open architecture of the H2 resulted in a simple way to integrate with third party systems. Based on the synchronized data collected during the clinical study, new algorithms are being developed to create a brain-machine interface to improve the H2 control. Future use can provide the patients with a more natural way to control the exoskeleton during gait training.

5.2 Contributions

This dissertation has contributed to the scientific knowledge with the design and development of a lower limb robotic exoskeleton intended for gait rehabilitation in post-stroke patients. Different aspects developed on this thesis were novel enough to give rise to a national design patent:

- J. L. Pons, J. C. Moreno, F. Brunetti, **M. Bortole**. "Exoesqueleto de miembro inferior". Patent Reference: Registered Design, Acta Notarial 546/2013.

  The patented technology resulting from the work presented in this dissertation has been transferred to a spin-off company, which is now commercializing the H2 robotic exoskeleton in different countries as a research tool to be used in clinical studies.

The work described in this thesis has also produced a number of published scientific contributions:

- **M. Bortole**, A. Venkatakrishnan, F. Zhu, J. C. Moreno, G. E. Francisco, J. L. Pons, and J. L. Contreras-Vidal. "The H2 robotic exoskeleton for gait rehabilitation after stroke: Early findings from a clinical study", *Journal of NeuroEngineering and Rehabilitation*. Submitted on August 30th, 2014.

  This manuscript describes the H2 assist-as-needed algorithm to provide gait assistance to post-stroke victims, as well as the clinical pilot study with patients. The training was well tolerated and the findings demonstrate that the H2 is safe and easy to use in clinical rehabilitation. The overground training employed as a means to enhance active patient engagement proved to be challenging and exciting for patients. This topic has been addressed in Chapter 4.

- **M. Bortole**, F. Zhu, A. Venkatakrishnan, Z. Hernadez, J. L. Pons, and J. L. Contreras-Vidal. "H2 NeuroExo: Integration of the H2 lower body powered exoskeleton and mobile brain monitoring to improve gait rehabilitation", *International Workshop on Wearable Robotics*, 2014.

  This paper presents the augmentation of the H2 robotic exoskeleton with a mobile brain imagining technology, based on scalp EEG, and algorithms to allow the tracking of changes in cortical activity patterns emerging from a robotic gait intervention in stroke patients. Synchronization and use of both systems provide a window to study cortical adaptation during robotic rehabilitation. This topic has been addressed in Chapter 3.

- A. Venkatakrishnan, F. Zhu, **M. Bortole**, Z. Hernadez, J. Kung, S. Chang, G. E. Francisco, J. L. Pons, and J. L. Contreras-Vidal. "H2 NeuroExo: A clinical study in post-stroke gait rehabilitation", *International Workshop on Wearable Robotics*, 2014.

  In this work is presented the development of an algorithm to decode walking intent as well as to systematically characterize the nature of neural adaptation in terms of changes in cortical dynamics during user-H2 interaction. Taken together, the findings from this clinical study can help advance the clinical translation of the H2 exoskeleton for stroke rehabilitation. This topic has been partially addressed in Section 3.7.

- **M. Bortole**, A. del Ama, E. Rocon, J. C. Moreno, F. Brunetti, and J. L. Pons. "A robotic exoskeleton for overground gait rehabilitation", *in Proceedings of IEEE International Conference on Robotics and Automation*, pp. 3356–3361, 2013.

  This paper presents the exoskeleton hardware and software development. The device is a bilateral exoskeleton with six degrees of freedom and is designed to gait training in stroke survivors. Experimental results have shown that the exoskeleton can adapt a pre-recorded gait pattern for the gait pattern of a specific user. This topic has been partially addressed in Chapter 2.

- **M. Bortole**, and J. L. Pons. "Development of an exoskeleton for lower limb rehabilitation", *in 2012 International Conference on NeuroRehabilitation: Converging Clinical and Engineering Research on Neurorehabilitation*, pp. 85–90, 2012.

  This paper presents the first version of the robotic exoskeleton designed to assist overground gait, as well as the first experiments with a healthy subject. The results have shown that the robotic exoskeleton can replicate a normal gait pattern for walk assistance. This topic has been partially addressed in Chapter 2.

- E. Urendes, R. Ceres, **M. Bortole**, and J. L. Pons. "External support forces during assisted walking in a new rehabilitation system", *in 2012 International Conference on NeuroRehabilitation: Converging Clinical and Engineering Research on Neurorehabilitation*, pp. 805-809, 2012.

  In this work is described a novel system for rehabilitation of patients with limited motion capabilities. The approach is based on a combination of an exoskeleton to assist gait combined to a mobile platform to partially support body weight. An analyses of user-system interaction forces is performed in order to extract gait parameters. This topic is related to the use of the exoskeleton in another rehabilitation project.

- **M. Bortole**, and J. L. Pons. "Arquitectura de control distribuida para un exoesqueleto de rehabilitación de marcha", *in VII Congreso Iberoamericano de Tecnologías de Apoyo a la Discapacidad*, 2013.

  This paper presents the distributed control architecture of the robotic exoskeleton designed to assist overground gait. The architecture is based on nodes and connected by means of a deterministic bus that guarantees real time operation. This topic has been partially addressed in Chapter 2.

- **M. Bortole**, J. L. Pons, and E. Urendes. "Integración de una plataforma híbrida para rehabilitación y compensación funcional de la marcha", *in XXXIII Jornadas de Automática*, 2012.

  This paper describes the integration of a hybrid platform in order to improve the rehabilitation process of patients suffering from stroke or spinal cord injury. The platform is composed by an exoskeleton, a neuroprotesis and virtual reality. A first prototype of the lower limb exoskeleton already integrated with the platform is presented. This topic has been partially addressed in Section 3.4.

- A. J. del-Ama, **M. Bortole**, A. Garza-Cervantes, J. C. Moreno, A. Gil-Agudo, and J. L. Pons. "Actuadores multimodales para compensación de la marcha de personas con patología neurológica", *in XXXIII Jornadas de Automática*, 2012.

  It is presented in this paper the design of two exoskeleton actuators, one for the ankle and one for the hip. The design is based on the analysis of the gait biomechanics of the subjects with incomplete spinal cord injury. The actuator design aims to minimize the weight of the final actuator and to provide the ability to implement various control strategies, based on position and torque. This topic has been partially addressed in Section 2.3.

- E. Urendes, **M. Bortole**, J. L. Pons, and R. Ceres. "Influencia de la descarga parcial de peso en la lateralidad de la marcha humana", *in XXXIII Jornadas de Automática*, 2012.

  This paper presents a gait rehabilitation system with partial body weight support. In a first phase of the validation of the system, this work describes a study about the influence of weight discharge on the lateral component during gait. This topic is related to the use of the exoskeleton in another rehabilitation project.

5.3 Future Work

The research conducted in this thesis together with the results obtained, could serve as proof of concept to validate the safety and usability of the H2 exoskeleton when applied to post-stroke rehabilitation. To achieve this, a study with post-stroke individuals was carried out. However, this study was not intended to prove the effectiveness of the device when used in gait rehabilitation. Although patients have shown improvements in their gait functions, this study is limited in this aspect and further research has to be conducted to validate the effectiveness of H2 when compared to traditional therapy.

The knowledge and experience acquired during the clinical experimentation can be applied in future clinical trials with a large cohort of patients. Different aspects can be improved when carrying out a new rehabilitation study with the H2 exoskeleton. Here it is discussed some aspects based on the results and the feedback received from the therapists participating on the study.

The first further goal is to study the H2 effectiveness in gait rehabilitation. To this end, a randomized clinical trial with a large cohort of patients is proposed. This clinical study should compare the H2 training with a control group of patients receiving conventional therapy. Additionally, appropriate intervention durations and frequency of training are still not well established for such wearable robotic rehabilitation protocols. This aspect also needs to be examined in careful detail in further clinical investigations.

Participants on the study carried out were all chronic post-stroke individuals. However, sub-acute patients are likely to benefit more from the training, since most gains in motor functions are seen in this phase of recovery. Furthermore, sub-acute patients are usually weaker and with reduced ambulation capability, causing them to need more assistance from therapists. The H2 can better assist them, with higher degree of movement coordination, besides to alleviate therapist's physical effort. Also, in order to fully utilize the functionality of the lightweight wearable H2 device, future training protocols can also include other functional tasks such as sit-to-stand, stand-to-sit and stair climbing.

The use of a zero gravity harness system could be helpful in future clinical experimentation. It can better guarantee patient's safety during the ambulatory training, specially

the most impaired ones. The system has a harness that is placed around the subject and then attached to an overhead track by means of ropes, eliminating the risk of falls. As the subject ambulates, the system quietly slides along the overhead track, maintaining its position above the individual, making it nearly imperceivable to the patient. If the patient loses their balance and falls at any time, the zero gravity system will catch them, preventing any injury.

It was also noted from the clinical tests that the walker used to help patients to keep their balance could not be the best option, since it may prevent the patients to perform larger steps sometimes. Instead, the use of parallel bars as an aid for balance could better help the patients, encouraging them to perform larger steps and walking at higher speeds.

In addition, one last future work proposed from the results of this dissertation is the design of new control approaches to the H2 exoskeleton. It is critical that H2 robot-assisted training be personalized to each individual based on his/her needs. In this regard, further modifications can be implemented in the control algorithm to provide variable resistance once the user has reached a certain threshold in terms of torque generation and/or joint angular position/velocity. This will help ensure progressive, adaptive changes to the training regime and is a clinically significant issue that warrants further investigation.

In terms of developing new control methods, H2 has been already adopted as the experimental platform for the BIOMOT Project. The main objective of BIOMOT is to improve existing wearable exoskeletons by exploiting dynamic sensory-motor interactions and by developing cognitive capabilities that lead to a symbiotic gait behavior in the human-robot interaction. BIOMOT proposes a cognitive architecture for robotic exoskeletons exploiting neuronal control and learning mechanisms aiming to enable positive co-adaptation and seamless interaction with humans.

Within BIOMOT, research will be carried out to provide novel capabilities to perform walking in unstructured environments. This will provide not only extended capabilities to the therapy, but a way to extend the therapy beyond clinical environment to daily living activities. The research conducted in this framework will bring transparent robotic devices, in which the boundary between functional compensation and rehabilitation of walking is interleaved.

Finally, the H2 integration with the neural interface for the clinical study has generated a large database of kinematic, kinetic and EEG data. Based on the study of this data, new algorithms are being developed to create a brain-machine interface to improve the H2 control. The brain-machine interface could provide the patients with a more natural, direct and intuitive way to control the exoskeleton during gait. Additionally, for patients with limited voluntary movement control, this technique could enhance their engagement during the training session, consequently inducing greater functional recovery. Moreover, further EEG data analysis can show how the neural activity of patient's brain is changing

during the rehabilitation process. Understanding these changes could lead to the design of better techniques to improve motor recovery of the disabilities caused by stroke.

Appendix A

Protocol Approval

The experimental protocol, including all procedures with stroke patients and healthy subjects described in this dissertation were approved by the Institutional Review Board at the University of Houston. In the next following pages is presented the document with the approval details, under the Application ID number 14107-01(4838). The study protocol is also registered and available at ClinicalTrials.gov, under the reference number NCT02114450. All subjects enrolled on this study did it voluntary and provided informed consent prior to participation.

UNIVERSITY OF HOUSTON
Division of Research
Institutional Review Board Application

Generated at: 8/19/2014 3:55:58 PM

Institutional Review Board Application ID : 14107-01 - (4838)

Title : Human-machine system for the H2 lower limb Exoskeleton

Approval details for the Application Id: 4838

	Decision	Approver Name	Date	Comment
PI signature	Approved	Contreras-Vidal, Jose Dr.	07/28/2014	
DOR signature	Approved	Admin, IRB	08/04/2014	

Application Data for Application ID: 4838

Title	Human-machine system for the H2 lower limb Exoskeleton
Application Type	Revision
Review Type	Full
Expedite Code	Not Applicable
Exemption Code	Not Applicable
Research Reason	Unfunded Research,Longitudinal Study

Investigator Data for Application ID: 4838

PI Name	Is Pricipal?	Is Co-Investigator?	Is External?	Other Personnel Type?	Is Student?	Faculty Sponsor Name
Venkatakrishnan, Anusha Dr.		Yes	No		No	Not Applicable
Contreras-Vidal, Jose Dr.	Yes		No		No	Not Applicable
Kilicarslan, Atilla Dr.			No	Other Research Personnel	No	Not Applicable
Agashe, Harshavardhan Mr.			No	Other Research Personnel	Yes	Not Applicable
Paek, Andrew Mr.			No	Other Research Personnel	Yes	Not Applicable
Nathan, Kevin			No	Other Research Personnel	Yes	Not Applicable
He, Yongtian Mr.			No	Other Research Personnel	Yes	Not Applicable
Ozdemir, Recep Mr.			No	Other Research Personnel	Yes	Not Applicable
Francisco, Gerard Dr.			Yes	Other Research Personnel	No	Not Applicable
Cruz, Jesus Mr.			No	Other Research Personnel	Yes	Not Applicable
Bhagat, Nikunj Mr.			No	Other Research Personnel	Yes	Not Applicable
Hernandez, Zachary Mr.			No	Other Research Personnel	Yes	Not Applicable
Zhu, Fangshi Mr.			No	Other Research Personnel	Yes	Not Applicable
Yozbatiran, Nuray Dr.			Yes	Other Research Personnel	No	Not Applicable
Bortole, Magdo Mr.			Yes	Other Research Personnel	Yes	Not Applicable
Soto , Rogelio Dr.			Yes	Other Research Personnel	No	Not Applicable
Pons, Jose Dr.			Yes	Other Research Personnel	No	Not Applicable

Chang, Shuo-Hsiu Dr.			Yes	Other Research Personnel	No	Not Applicable
Keun-Tae, Kim Mr.			No	Other Research Personnel	Yes	Not Applicable
No-Sang, Kwak Mr.			No	Other Research Personnel	Yes	Not Applicable
Grassi, Sara Dr.			Yes	Other Research Personnel	No	Not Applicable
Perroud, Laetitia Dr.			Yes	Other Research Personnel	No	Not Applicable
Goodall, Brian Mr.			No	Other Research Personnel	Yes	Not Applicable

Revision application data for application Id: 4838

Question	Answer
1) Revision Description (check all that are appropriate)	Revision to currently approved protocol
2) Risk Involve:(Check One)	This revision does not increase risks to participants enrolled in this study. (For students, signature of faculty sponsor is required.)
3) Describe the proposed revision. If applicable, include a scientific justification for the revision (for example, changes in the study population).	This revision is to amend the protocol without increasing risks to any participants. As this is the first clinical investigation of the use of H2 in gait training for stroke-survivors, we would like to amend the protocol to indicate that the first 10 stroke participants will be recruited in to the study in an open-label design. That is, the first 10 participants with stroke will be assigned to H2 robot-assisted training. This will enable obtaining initial safety and efficacy data for the H2 robot in this population. Subsequently, participants with stroke who are recruited will be assigned to either H2 robot-assisted training or supervised motor practice as previously indicated in the protocol. This revision does not impact the Consent form and Recruitment documents, therefore, these have not been revised. This revision is also to add Brian Goodall, and undergraduate research assistant to this protocol. His CITI completion certificate is uploaded in the Other folder. Additionally, we would like to request an amendment to allow use of existing structural MRI scan images of participants to create 3-D models of their brains (these could be obtained via accessing the medical records of the patients if scans are available). Medical records of participants are accessed with patient's consent in accordance with HIPPA. This will help perform source localization analysis to estimate the neural regions contributing to EEG activity that is recorded. This will not increase any risk to participants or compromise subject confidentiality. The Consent form has been amended to request patient permission to access existing structural MRI scans.

Project Review Summary Data for Application ID: 4838

Question	Answer
	This research study will investigate the use of smart lower limb robotic exoskeleton (developed by the CSIC, Spain) in rehabilitation after stroke. It will compare robotic-assisted rehabilitation with standard of care

4) State the specific research hypotheses or questions to be addressed in this study	(conventional physical rehabilitation). Additionally, it will also examine the use of noninvasive scalp electroencephalography (EEG) to learn specific brain wave patterns associated with learning to walk on the powered lower limb exoskeleton. The findings will be used to understand human-robot interaction and to design smart orthotic devices that can be controlled by thought activity and assist those that have lost all or part of their walking abilities.
5) What is the importance/significance of the knowledge that may result?	Stroke is the leading cause of neurological disability in the United States (Wolf et al., 1999) and accounts for the poor physical health and the social dysfunction evident in survivors (Velliste et al., 2008). Gait impairment is a large contributor to long-term disability and ambulatory function in daily living (Mauritz, 2002). Many patients, however, lose the ability to walk independently, and furthermore, a large proportion do not regain their normal walking speeds following a stroke (Pennycott et al., 2012). Physical rehabilitation tends to remain the mainstay in long-term stroke treatment to regain functional independence. In this regard, therapeutic approaches as well as underlying theoretical models to stroke physical therapy are diverse. More recently, body-weight supported robot-assisted treadmill training has been shown to lead to better functional outcomes (Hesse et al., 2001; Wemer et al., 2002; Pohl et al., 2007). However, the limitation of these devices is that they are largely restricted to the clinical or research setting owing to their size and therefore are less amenable to training with other functional tasks such as sitting, climbing stairs etc. Therefore, newer robotic-aided therapeutic tools include ¿wearable¿ lower-limb robotic exoskeletons, which allow for the user to be augmented by mechanically actuated lower limb joints that can either completely or partially assist movements of the lower limb segments depending on the patient needs. The H2 exoskeleton (developed by Technaid S.L., Spain) is an example of one such system that has hip, knee and ankle joints actuated for both lower limbs. These devices are very new, and therefore, systematic investigations of therapeutic benefits of these devices are lacking in the field. Further, the nature of adaptive plasticity in the brain and peripheral neuro-muscular system triggered by wearing and training such exoskeletons is unknown. In this exploratory research study, we aim to compare robotic-assisted rehabilitation using the H2 exoskeleton with standard of care (conventional physical rehabilitation) particularly in terms of functional recovery. Additionally, this study will also examine brain plasticity associated with robotic-assisted training using non-invasive scalp electroencephalography (EEG) and changes in lower limb muscle activity during robotic-assisted training using non-invasive skin surface electromyography (EMG). Taken together, the findings from this research will be used to understand human-robot interaction and to design smart orthotic devices that can be controlled directly by brain activity and assist those that have lost all or part of their walking abilities due to neurological disease or injury. Moreover, this study will systematically track neuroplasticity associated with functional recovery after stroke, which will help determine optimal windows for treatment that would maximize therapeutic benefit. Lastly, it will also help characterize markers of learning to use these new devices, which will be important in the clinical setting for modifying and adapting rehabilitation protocols to suit changing needs of the patient (user).

6) Type of Subject Population (check all that are appropriate)	Adults,Elderly (65yrs and above)
6.01) Expected maximum number of participants	50 adults (males & females) with hemiparesis caused by stroke, 10 healthy able-bodied adults (males & females), leading to a total of 60 participants who will be enrolled. This number also accounts for potential attrition/drop-outs.
6.02) Age of proposed subject(s) (check all that apply)	Adults (18yrs-64yrs),Elderly Adults (65yrs and above)
6.03) Inclusion Criteria:	The participants in these studies will be males and females aged between 18 and 75 years: a) healthy able-bodied adults; b) individuals with unilateral stroke resulting in hemiplegia or hemiparesis. Inclusion criteria for participants with stroke are as follows: - Sub-acute or chronic stroke i.e., interval of at least 3 months or interval of at least 6 months from stroke to time of enrollment, respectively; - Cognitive ability to assimilate and participate actively in the treatment protocol (Mini Mental State Examination score > 24 points, out of a total 30 indicating normal cognitive ability) and Ranchos Los Amigos Level of Cognitive Functioning >= VI (with stage VIII being highest level of cognitive functions); - Rankin scale scores 2-4 (Mild-Moderate functional disability post-stroke); - Modified Ashworth Scale of Spasticity score <= 2 (ranges from 0-4 with 4 reflecting maximum spasticity); The height range of all the participants will be between 5'1" (1.55 m) and 6'2" (1.9 m) with maximum weight 220 lbs (100 Kg). Additional inclusion criteria are: have no skin integrity issues; sufficient passive range of motion at the hip (at least 90 deg flexion, 15-20 deg extension), knee (90 deg flexion, complete extension) and ankle (15 deg dorsiflexion, 15 deg plantarflexion); and have no contraindications to standing or walking.
6.04) Exclusion Criteria:	For healthy able-bodied subjects: History of neurological, neuromuscular or physical disability. Determination will be based on a telephone screening interview performed by the PI or his research staff. For individuals with stroke, the exclusion criteria are: severe cognitive and/or visual deficit; hemi-neglect; severe sensory deficit; joint contractures of any extremity that limits normal range of motion during ambulation with assistive devices; skin lesions that may hinder or prevent the application of exoskeleton; uncontrolled angina; severe chronic obstructive pulmonary disease; other medical contraindications; any medical co-morbidities that would prevent standard rehabilitation. Determination will be based on clinical examination by our clinical research collaborators at TIRR Memorial Hermann Hospital (Dr. Gerard Francisco or his appointed staff), Texas Medical Center, Houston.
6.05) Justification:	Stroke can lead to paresis or paralysis which induces significant gait abnormalities and consequent functional limitations. Therefore, this clinical population will likely greatly benefit from robotic-assisted rehabilitation. Additionally, individuals with both sub-acute and chronic stroke are included because it is unknown at what time point the robotic devices would have the maximal therapeutic effect. The inclusion and exclusion criteria reflect the participants who will have moderate levels of impairment and can adhere to the rehabilitation protocol with the exoskeleton. The height and weight inclusion criteria reflects the minimum and maximum heights and the maximum weight of a subject that the exoskeleton can assist in transporting. The age, health, and weight criteria are not due to safety issues but rather study design/goals or device limitations. The criterion of age is used to avoid

	potential confounds due to motor development or degraded movement, and cognitive function in advanced age.
6.06) Determination:	The first contact with most potential subjects will be through the participant telephoning our 12-hour phone number. The study personnel will answer queries from the participant about the nature of the study. Study personnel will request permission from the potential participant to collect data that will be part of the telephone-screening interview. The telephone-screening interview will include a) demographic data; b) basic physical status; c) basic neurological history. The initial telephone screening process will improve the efficiency of the study since it reduces the likelihood of unsuitable participants (i.e., participants meeting exclusion criteria) having to undergo a full screening before being excluded. Healthy participants who pass the telephone screening will be asked to provide their names, telephone numbers, addresses/emails to be contacted to be scheduled for the experiment and to mail/email them a copy of the Consent Form for their review prior to their initial experimental visit. In the case of potential participants with stroke, the informed consent process will begin for those participants who have been determined to meet the inclusion criteria via telephone screening or in-person screening at The Institute for Rehabilitation Research (TIRR) (by Dr. Gerard Francisco). After the potential participant's signed consent has been provided, further evaluations for eligibility will be performed by Dr. Francisco (e.g., there are several medical and physical exclusion criteria). Those potential participants who meet both the inclusion and exclusion criteria will be given medical clearance and be eligible to enroll into the proposed study. Medically cleared subjects with stroke interested in participating will be asked to contact Dr. Venkatakrishnan (at UH) to set up an appointment for the functional assessment to participate in the study. Dr. Francisco and/or his appointed clinical staff and Dr. Venkatakrishnan, a physical therapist, would answer queries from the potential participant about the nature of the study.
7) If this study proposes to include children, this inclusion must meet one of the following criterion for risk/benefits assessment according to the federal regulations (45 CFR 46, subpart D). Check the appropriate box:	
8) If the research involves any of the following, check all that are appropriate:	Clinical Studies
9) Location(s) of Research Activities:	UH campus,Other (Explain) :TIRR Memorial Hermann hospital facilities (pending approval from TIRR Memorial Hermann).
10) Informed Consent of Subjects: Your study protocol must clearly address one of the following areas:	Informed Consent. Signed informed consent is the default. A model consent is available on the CPHS website and should be used as a basis for developing your informed consent document. If applicable, the proposed consent must be included with the application. (http://www.research.uh.edu/PCC/CPHS/Informed.html) ATTACH COPY OF PROPOSED CONSENT DOCUMENT

Research Protocol Data for Application ID: 4838

Question	Answer
	This study will comprise a simple parallel study design. Individuals with stroke will randomly assigned (subsequent to the first 10) to receive either

11) Describe the research study design. (Describe the research methods to be employed and the variables to be studied. Include a description of the data collection techniques and/or the statistical methods to be employed.)	"Supervised motor practice" or "Robotic-assisted rehabilitation". The experimental treatments/interventions will be administered in addition to any other medical/physical therapeutic treatments that stroke participants already receive (if at all). However, as this is the first clinical investigation of the use of H2 in gait training for stroke-survivors, the first 10 stroke participants will be recruited in to the study in an open-label design. They will all be assigned to H2 robot-assisted training. "Supervised motor practice" will comprise of simple motor tasks/exercises (e.g., squat, forward/backward lunge, walk initiation, sit-to-stand, stepping on a stool/pedestal etc.) that are part of a conventional physical rehabilitation regimen which participants will perform for a duration of 1-2 hours per session for a total of 3 sessions/week for 4 weeks under the supervision of Dr. Venkatakrishnan, a physical therapist. This group will serve as a Control group for the experimental robotic rehabilitation group by controlling for motor practice as an extraneous variable. "Robotic-assisted rehabilitation" protocol: On the day of testing, eligible participants (that meet both the inclusion and exclusion criteria) and that have given Informed consent, will be fitted with an electroencephalography (EEG) electrode cap (similar to a swim cap). The purpose of the EEG cap is to record electrical brain activity from up to 64 locations spaced through the scalp. Participants will also have recording of electromyography in the lower limbs i.e., sensors will be placed on the skin of the legs and thighs (4 on each leg) to non-invasively record muscle activity during walking. Additional sensors i.e., goniometers will be placed on the skin to non-invasively record joint angles of the hip, knee and ankle on each leg. These will be attached to the skin using hypoallergenic tape. Then, participants will also be comfortably fitted to a powered robotic exoskeleton (CSIC Techniad S.L.'s H2 exoskeleton). The ankle, knees and hips will be supported within the device by a series of leg braces, straps and harness. The fitting procedure entails making adjustments to the device to ensure it fits the user's body shape and size, i.e., that the lower limb joints are well aligned with the exoskeleton's articulations and comfort is assured. This process needs to be completed so that the user can safely wear the device. Participants will be asked to perform activities such as sitting and standing, walking forward, turn left or right and stop with the exoskeleton. In addition, participants may also be asked to perform movements that are part of a standard physical rehabilitation regimen e.g., squatting, lunging forward, stepping on a 7-8" stool/pedestal etc. They may also be asked to imagine performing walking movements. In order to study functional improvements associated with training to use the exoskeleton, participants will likely be asked to come in for about 3 sessions per week, each lasting for a maximum of 3 hours, for 4 weeks. Dr. Venkatakrishnan, and/or clinical personnel at TIRR will supervise all training sessions and constantly monitor participants for safety and comfort and adjust the protocol as necessary to suit participant needs and safety. In the case of healthy able-bodied individuals, participants will perform movements with the robotic exoskeleton in a manner similar to the "Robotic-assisted rehabilitation" protocol, which will elucidate mechanisms by which the human body learns and adapts to the H2 robotic exoskeleton. Healthy adults will not participate in "Intervention" sessions. They will be invited for a maximum of 5 sessions over 4 weeks. The data collected from healthy adults will inform about human-H2 interactions in the absence of any neurological lesion.

12) Describe each task subjects will be asked to perform.	Stroke participants will be asked to perform activities such as sitting and standing, walking forward, turn left or right and stop with the exoskeleton. In addition, participants may also be asked to perform movements that are part of a standard physical rehabilitation regimen e.g., squatting, lunging forward, stepping on a 7-8" stool/pedestal, sit-to-stand etc. They will also be asked to imagine performing walking movements. Healthy individuals will also be asked to perform the same tasks as stroke subjects.
13) Describe how potential subjects will be identified and recruited? (Attach a script or outline of all information that will be provided to potential subjects. Include a copy of all written solicitation, recruitment ad, and/or outline for oral presentation.)	Recruitment will take place through flyers (see attached) posted at the University of Houston and the Greater Houston Metropolitan area, newspapers, email, and targeted recruitment (for participants with stroke) at the TIRR Memorial Hermann hospital (through Dr. Gerard Francisco, who is participating in this research, is the chair of physical medicine & rehabilitation at TIRR and will recruit interested potential participants). We intend to use list-serves, the PI website and electronic bulletin boards to announce the proposed study. People interested in participating, can phone or email back for further information. The recruitment ad, including the provided statement above, will be emailed it to prospective participants. The email which will also be used to send a copy of the Consent Form for those participants that qualify for the study Recruitment ad, is attached. Interested stroke participants who contact the research team through a recruitment ad will be referred to Dr. Francisco for pre-screening to obtain medical clearance to determine eligibility. Participants recruited through targeted recruitment at TIRR will be pre-screened similarly by Dr. Francisco. The informed consent process will begin for those stroke participants who have been determined to meet the inclusion criteria. After the potential participant's signed consent has been provided, further evaluations for eligibility will be performed (e.g., there are several medical and physical exclusion criteria). Those potential participants who meet both the inclusion and exclusion criteria will be eligible to enroll into the proposed study. Medically cleared stroke subjects who are interested in participating will be asked to contact Dr. Venkatakrishnan (at UH) to set up an appointment for the intial functional assessment to participate in the study. Healthy adults who are interested will be invited to participate in the first experimental session wherein they will be consented (see response to Q. 14).
14) Describe the process for obtaining informed consent and/or assent. How will investigators ensure that each subjects participation will be voluntary (i.e., free of direct or implied coercion)?	For healthy adults, on the day of the first study session, there will be a consent document discussion and any questions will be answered by Dr. Contreras-Vidal (PI) or Dr. Venkatakrishnan (Co-I) prior to signature. For stroke subjects, the consenting process will occur at the time of clinical evaluation for inclusion by Dr. Francisco (participants will be mailed/emailed a copy of the Consent Form for their review prior to arrival to the first study session). Participants will be provided with the study information, study rationale, risks, potential benefits, and the role of the IRB. Participants will be weighed using a digital scale and measured using a measuring tape (head circumference and lower limb segmental lengths). All participants will be asked to complete and sign the Informed Consent form in writing. By signing the form, subjects will attest they are between 18-75 years of age, understand the experimental details and voluntarily wish to participate in the study. The consent form will be dated and countersigned by the PI or the Co-I, and one signed copy will be provided to the participant.
	We will use telephone to administer the telephone screening instrument. The

15) Briefly describe each measurement instrument to be used in this study (e.g., questionnaires, surveys, tests, interview questions, observational procedures, or other instruments) AND attach to the application a copy of each (appropriately labeled and collated). If any are omitted, please explain.	following measurements will be conducted at the Laboratory for Noninvasive Brain-Machine Interface Systems at the University of Houston or at the designated space in a rehabilitation gym at the TIRR Memorial Hermann: - A digital weighing scale and a measuring tape will be used to weight the subject as well as the length of his/her legs. - The EEG system is a noninvasive electrophysiological measurement instrument that measures brain waves outside the scalp. - The EMG system is a noninvasive electrophysiological measurement instrument that measures surface muscular activity. - Goniometry is a noninvasive measurement instrument to record joint angles during movement such as walking using angular sensors placed on the skin near a joint e.g., hip, knee and ankle. - The robotic exoskeleton (H2) is a wearable powered robot that can assist in transporting (carrying) a person and which can be controlled either through its on-board computer/smart phone application/personal computer operated by the study personnel. The exoskeleton provides information about lower limb movements, specifically movements of the various joints. - Functional assessments in individuals with stroke will be performed before and after training. It will inlcude the following (see attached appendices): 1. NIH Stroke Scale 2. Modified Rankin Scale 3. Modified Ashworth scale for spasticity 4. Barthel Index 5. Berg Balance Scale 6. Fugl-Meyer Assessment 7. 6-minute walk test 8. Timed Up and Go Test 9. Functional Gait Assessment Additionally, for every session, participant's physical comfort will be monitored for documentation of safety. Pain, discomfort, fatigue will be assessed at the start and end of each experimental session on a 11-point visual analogue scale ranging from 0 (none) to 10 (worst). The progress note will also document experimental session details (e.g., task performed, date, time etc.). This progress note will include the coded-name for each participant. All assessments will be conducted in a quiet, enclosed room in order to maintain patient privacy.
16) Describe the setting and mode for administering any materials listed in question 15 (e.g., telephone, one-on-one, group). Include the duration, intervals of administration, and amount of time required for each survey/procedure. Also describe how you plan to maintain privacy and confidentiality during the administration.	Telephone: The interview will take 5-10 minutes. Other measurement instruments, such as the EEG, EMG, goniometry and motion capture via the robotic exoskeleton, will be administered at the Laboratory for Noninvasive Brain Machine Interface Systems at the University of Houston or at TIRR Memorial Hermann hospital. The clinical evaluation, in the case of prospective participants with stroke, according to the inclusion/exclusion criteria to be performed by Dr. Francisco or his appointed staff will take 30-60 minutes. In addition, Dr. Venkatakrishnan will perform functional assessments (see attached Appendices) to quantify motor impairment in individuals with stroke in order to assess participant response to training with exoskeleton, which will take additional 60-90 minutes and will be performed at 4 time points i.e., once before, and 3 times after training. Other measurement instruments, such as the weighing scale, measuring tape, EEG, and motion capture via the robotic exoskeleton, will be administered at the Laboratory for Noninvasive Brain-Machine Interface Systems at the University of Houston or at TIRR Memorial Hermann hospital. All these interactions/assessments will take place in quiet, private setting (curtained area/side room), wherein every effort will be made to protect participant's privacy.
	Stroke participants: For each session, a maximum of 3 hours are needed to collect data. Participants will be recruited to perform 3 sessions per week for 4 weeks. The total time commitment is 36 hours for the training program. The

17) Approximately how much time will be required of each subject? Provide both a total time commitment as well as a time commitment for each visit/session.	initial clinical evaluation for inclusion/exclusion to participate in the study will take an additional 1/2 to 1 hr and functional assessments will take 1-2 hours for the individuals with stroke (8 hours total for 4 sessions). Therefore, each participant's maximal time commitment would be 45 hours. Healthy individuals: Each study session will last a maximum of 3 hours. Healthy participants will be invited for up to 5 sessions in total, therefore, total study time commitment would be maximum of 15 hours.
18) Will Subjects experience any possible risks involved with participation in this project?	
18.01) Risk of Physical Discomfort or Harm	Yes: :The procedures described above are widely used in research and are not known to be physically harmful to the participant. There are no known long-term effects associated with the tasks or events experienced during this study. The procedures of this study involve minimal risk and are non-invasive. It is possible that subjects may experience some discomfort and slight sensations and skin irritation when fitted with the EEG cap. To minimize discomfort, participant will be questioned and cap will be adjusted for maximal comfort. It is also possible that they may show fatigue and/or muscle soreness from walking with the H2 exoskeleton. There is a minimal risk of falling during walking with the exoskeleton. To minimize this risk, participants with stroke will walk with a walker while being supervised by Dr. Venkatakrishnan, who is a physical therapist and/or clinical personnel at TIRR. She will also be assisted by two research assistants, one at each side of the subject to hold him/her if necessary. The H2 exoskeleton device is designed with hardware and software safety features that minimize the risk of injury due to the use of the robot. A series of automatic motion stop features are implemented to limit movement to a set of safe boundaries. The exoskeleton cannot move outside of the normal range of motion of the individual user. There is some risk of minor injury due to rubbing while using the robot as well as while entering or exiting the robot. There is also a risk of pressure sores where the exoskeleton is attached to the user. We will assist the subjects in entering and exiting the robot and apply padding to the robot where necessary to prevent rubbing. Breaks will be taken if subjects become tired. Dr. Venkatakrishnan will constantly monitor participants for their comfort, fatigue levels. Subjects are also free to call a break or end the experimental session for any reason without penalty. The risks of persons using H2 exoskeleton will be mitigated by existing device safety features and standard procedures for device preparation and use. These include: 1) Ensuring correct alignment of the user's joint positions with the device centers of rotation by correct size adjustment of the device. These adjustments will be carried out by lab personnel trained by Technaid S.L. and/or CSIC, the manufacturers of H2 exoskeleton. The device is prevented from exceeding the users normal physiological range of motion by the same extensive mechanical, electronic, and software safety features as apply to all uses of the device. 2) Able-bodied users might tend to try balancing more during device movements, which may be counter to what the device is trying to do, potentially affecting stability. To minimize this risk, all users will learn normal device movement patterns. Since healthy, able-bodied individuals will not be using a walker, we will have 2 spotters/research assistants to minimize risk of falling.

18.02) Risk of Psychological Harm (including stress/discomfort)	No:
18.03) Risk of Legal Actions (such as criminal prosecution or civil sanctions)	No:
18.04) Risk of Harm to Social Status (such as loss of friendship)	No:
18.05) Risk of Harm to Employment Status	No:
18.06) Other Risks	No:
19) Does the research involve any of these possible risks or harms to subjects? Check all that apply.	
20) What benefits, if any, can the subject expect from their participation?	While able-bodied individuals will not directly benefit from participation, their participation may help elucidate how the brain and body adapts to the use of an assistive device (H2 exoskeleton). In the case of individuals with stroke, we expect that they should have improved sensory-motor functions, and possibly improved independence in functional activities of daily living such as walking etc.
21) What inducements or rewards (e.g., financial compensation, extra credit, and other incentives), if any, will be offered to potential subjects for their participation?	Upon completion of each experimental session, subjects will receive $20 (either as cash or gift cards for departmental stores such as Target, Walmart etc.) as compensation for their time, for a total possible compensation of $320 for stroke participants (if 16 experimental sessions are completed) OR $100 for healthy participants (if 5 sessions are completed). Compensation will be prorated based on the number of sessions completed if participants do not complete the entire study. Moreover, parking in one of the reserved parking spots in the Department of Electrical and Computer Engineering, will be provided free of charge for sessions performed at the University of Houston campus. [Note: There is no compensation for the initial clinical evaluation for inclusion/exclusion criteria by Dr. Francisco and/or his appointed staff.]

Research Data for Application ID: 4838

Question	Answer
22) Will you record any direct identifiers, names, social security numbers, addresses, telephone numbers, patient or student ID numbers, etc.?	Yes: :During the initial telephone screening, the participant's name and telephone number will be recorded on a cover sheet. This information will be used to contact the participant for scheduling the study session. The cover sheets of participants who do not qualify for the study will be immediately destroyed. A code number (i.e. 123) will be assigned for each participant who qualifies for the study and their personal information will be destroyed right after they finish the testing session.
23) Will you retain a link between study code numbers and direct identifiers after the data collection is complete?	No:
24) Will anyone outside the research team have access to the links or identifiers?	No:
25) Where, how long, and in what format (such as paper, digital or electronic media, video, audio or photographic) will data be kept? In addition, describe what security provisions will be taken to	All data will be stored on DVDs or secured hard drives for at least three years, and possibly as long as ten years after completion of the study.

protect these data (password protection, encryption, etc.). [Note: University of Houston policy on data retention requires that research data be maintained for a minimum of 3 years after completion of the project. All research data collected during this project is subject to the University of Houston data retention policy found at http://www.research.uh.edu/Home/Division-of-Research/Research-Services/Research-Policies/Access-to-and-Retention-of-Research-Data.aspx]	Audio/video will only be obtained if the participant provides his/her consent in the Informed Consent Form to use such video for presentation purposes (if approval is not given by the participant, no audio/video will be recorded). If approved audio/video is recorded, the data will be stored in DVDs and locked in the PI's or Co-I's office, and will not contain identifiable data (W310 or E413, Engineering Bldg 2, UH). All progress notes and functional assessment documents will include the participant's coded name i.e., not contain identifiable information and will be stored separately from consent forms (i.e., de-linked data).

Appendix B

Consent Form

In the next pages is presented the consent form document that all participants signed before enrolling on the experiments. The consent form explicit all the rights of subjects participating on the study. All subjects taken part on this study did it voluntary and they were allowed to refuse their participation at any time without any penalty or loss of benefits to which they were otherwise entitled. Every effort is made to maintain the confidentiality of any subject's participation. All names are kept confidential and they are replaced by a code number to appear on all written materials.

UNIVERSITY of HOUSTON
A CARNEGIE-DESIGNATED TIER ONE PUBLIC RESEARCH UNIVERSITY

UNIVERSITY OF HOUSTON
CONSENT TO PARTICIPATE IN RESEARCH

PROJECT TITLE: **Human-machine system for the H2 lower limb Exoskeleton**

You are being invited to take part in a research project conducted by Professor Jose L. Contreras-Vidal from the Department of Electrical and Computer Engineering at the University of Houston.

NON-PARTICIPATION STATEMENT
Taking part in the research project is voluntary and you may refuse to take part or withdraw at any time without penalty or loss of benefits to which you are otherwise entitled. You may also refuse to answer any research-related questions that make you uncomfortable.

PURPOSE OF THE STUDY
This research study will investigate the use of smart lower limb robotic exoskeleton (H2) in rehabilitation after stroke. It will also examine the use of noninvasive scalp electroencephalography (EEG) to learn specific brain wave patterns associated with learning to walk on the powered lower limb exoskeleton and study the differences between individuals with stroke and able-bodied individuals.

These findings will be used to understand human-robot interaction and to design smart orthotic devices that can be controlled by thought activity and assist those that have lost all or part of their walking abilities. This research study will last for approximately 1 year.

If you are an individual with stroke, you may be invited to participate in training sessions with the H2 exoskeleton i.e., 3 visits per week for 4 weeks. In addition, you may be invited for 4 additional sessions for other tests of movement before and after training, constituting a total of about 16 sessions/visits (including the training sessions).

If you are an able-bodied individual, then you will be invited to participate in up to 5 sessions over 4 weeks.

PROCEDURES
A total of 60 subjects at 2 locations (Laboratory for Non-invasive Brain Machine Interface systems, University of Houston and TIRR Memorial Hermann Hospital) will be invited to take part in this project. You will be one of approximately 60 subjects invited to take part in this study.
If you are an individual with stroke, and have passed a pre-screening for potential eligibility to participate in this study, you will be undergo further evaluations for eligibility as there are several medical and physical inclusion and exclusion criteria that must be met before enrolling in this study. This screening will be performed by Gerard Francisco, M.D.

Screening Procedure: Medical screening for eligibility to participate in this study (for individuals with stroke only) will be performed to ensure you meet both the inclusion and exclusion criteria for the study.
Screening outcome: ☐ Eligible ☐ Non Eligible. You cannot enroll in this study.
(To be filled by physician)

Physician: **Gerard Francisco, M.D.** Signature of Physician: _____

If you are eligible for this study, you will be asked to perform the following procedures at the Laboratory for Non-invasive Brain-Machine Interface Systems, room E413, Engineering Building II at the University of Houston or at TIRR Memorial Hermann Hospital.

Procedure 1: Baseline Assessments and Preparation

1. Your weight and height will be recorded, and measurements of your leg length will be taken for the purpose of adjusting the H2 exoskeleton to best align with your body. You will have the opportunity to see the exoskeleton device and the EEG cap before signing this consent form.
2. If you are an individual with stroke, you will be asked to perform some tasks to assess your leg functions and walking etc. This will involve simple tasks such as moving your leg in different positions, walking on the ground, stepping over obstacles, getting up from a chair etc. These tests will be performed at the beginning of the study, and then again 2-3 times after the 4 week training period.
3. You will also be asked to provide information about your medications. If you are an individual with stroke, you may also be given a medication diary to document all changes in type and dosage of the medication you have been using throughout the duration of the study. This will allow us to differentiate a potential effect of a change in dosage or type of medication on movement recovery while training with the H2 exoskeleton.
4. Next, your head size will be measured with a measuring tape and then you will have your head fitted with an electroencephalographic (EEG) cap (similar to a swim cap) of an appropriate size. This will measure non-invasively the activity of your brain.
5. Next, additional electromyographic (EMG) sensors will be attached to the skin on your legs to measure the muscle activity of your legs non-invasively. This will help differentiate between the work done by your muscles in comparison to the robot when you move your legs. Similarly, goniometric sensors will be attached to your skin to record the amount of movement in your leg joints (joint angles of hips, knees, ankles). This measurement is known as Goniometry.
6. You will then be fitted with the H2, powered robotic exoskeleton in a seated position and your ankle, knees and hips will be supported within the device by a series of leg braces, straps and harness. The fitting procedure entails making adjustments to the device to ensure it fits your body shape and size, i.e., that your lower limb joints are well aligned with the H2's articulations and comfort is assured. This process needs to be completed so that you can safely wear the device.

Procedure 2: Familiarization with the H2 and Training

1. H2 Familiarization: To familiarize you with the H2 robotic exoskeleton, the research staff member will use a personal computer or mobile phone application to control movement of the H2, such as standing-up, walking forward, and turning left or right, stopping, or sitting up. During this part of the testing session, you will have an opportunity to learn and feel how your body moves with H2 exoskeleton. You will be provided with a walker for added stability, while moving with the H2.
2. Training: If you are an individual with stroke who is participating in the 4 week training program, you will be fitted with the EEG cap and H2 exoskeleton based on your previous measurements at each training visit. Then, you will perform various exercises/movements as part of the training program, similar to your physical therapy sessions (e.g., getting up from a chair, squatting, walking on the ground, navigating around obstacles while walking, stepping on a stool etc.). The training will consist of 3 sessions per week for 2-3 hours each, for 4 weeks. Your total time commitment will be up to 36 hours for training. Additionally, the initial clinical evaluation for

inclusion/exclusion to participate in the study will take an additional 1/2 to 1 hour and functional assessments will take 1-2 hours. We will accommodate any requests for participation before or after normal business (9-5) hours.

If you are an able-bodied individual, then you will be invited for up to 5 sessions over 4 weeks. You will perform various exercises/movements, which will mimic physical therapy treatments for individuals with stroke (e.g., getting up from a chair, squatting, walking on the ground, navigating around obstacles while walking, stepping on a stool etc.). Your total time commitment will be up to 15 hours (3 hours per session). We will accommodate any requests for participation before or after normal business (9-5) hours.

CONFIDENTIALITY

Every effort will be made to maintain the confidentiality of your participation in this project. Each subject's name will be paired with a code number by the principal investigator. This code number will appear on all written materials. The list pairing the subject's name to the assigned code number will be kept separate from all research materials and will be available only to the principal investigator. Confidentiality will be maintained within legal limits.

RISKS/DISCOMFORTS

The procedures described above are widely used in research and are not known to be physically harmful to you. There are no known long-term effects associated with the tasks or events experienced during this study. The procedures of this study involve minimal risk and are noninvasive.

EEG: The EEG procedures are widely used in research and are not known to be physically harmful. There are no known long-term effects associated with the tasks or events experienced during EEG procedures. Subjects may experience a slight discomfort and slight sensations and skin irritation when fitted with the EEG cap.

EMG and Goniometry: The EMG and Goniometry system are not known to be physically harmful. They will only require attachment of sensors with adhesive tape on your skin, which may cause minor skin irritations.

Robotic training with the H2: It is possible that you may show fatigue and/or muscle soreness from walking with H2. There is a minimal risk of falling during walking with H2. To minimize this risk, you will be provided with a walker to use while walking and two research assistants will always be by your side to hold you if necessary. The H2 device is designed with hardware and software safety features that minimize the risk of injury due to the use of the robot. A series of automatic motion stop features are implemented to limit movement to a set of safe boundaries. The exoskeleton cannot move outside of the normal range of motion of the individual user. There is some risk of minor injury due to rubbing while using the robot as well as while entering or exiting the robot. There is also a risk of pressure sores where the exoskeleton is attached to the user. We will assist you in entering and exiting the robotic exoskeleton and apply padding to the exoskeleton where necessary to prevent rubbing. Breaks will be taken if and when you become tired. You are also free to call a break or end the experimental session for any reason without penalty.

BENEFITS

Your ability to move your legs, stand, walk, and/or independence in functional activities of daily living may improve as a result of the training (if you are an individual with stroke), but this is not certain, and there may not be any direct benefit to you. Nevertheless even if you will not directly benefit from participation, your participation may help investigators better understand how the brain and body

adapts to the use of an assistive device (H2 exoskeleton). Society may benefit by having a more cost-effective way to provide therapy.

ALTERNATIVES
Participation in this project is voluntary and the only alternative to this project is non-participation.

INCENTIVES/REMUNERATION
Upon completion of each experimental session, you will receive $20 as compensation for your time. You are free to withdraw from any session at any time without penalty and still be compensated with $20 for that session. If you are an individual with stroke, the total compensation will depend upon the number of sessions you participate in and could be a maximum of $320 ($20 per session x 16 visits). If you are an able-bodied individual, the total compensation will depend upon the number of sessions you participate in and could be a maximum of $100 ($20 per session x 5 visits). Compensation will be provided either as cash or gift cards for departmental stores (e.g., Target, Walmart, etc). The total compensation will be prorated if you do not complete the entire study. Free parking will be provided in one of two parking spots reserved by the Department of Electrical and Computer Engineering for sessions conducted at the University of Houston.

PUBLICATION STATEMENT
The results of this study may be published in scientific journals, professional publications, or educational presentations; however, no individual subject will be identified.

AGREEMENT FOR THE USE OF AUDIO/VIDEO TAPES
If you consent to take part in this study, please indicate whether you agree to be audio/video taped during the study by checking the appropriate box below. If you agree, please also indicate whether the audio/video tapes can be used for publication/presentations.

☐ I agree to be audio/video taped during the interview.
- ☐ I agree that the audio/ video tape(s) can be used in publication/presentations.
- ☐ I do not agree that the audio/ video tape(s) can be used in publication/presentations.

☐ I do not agree to be audio/video taped during the interview.
You will still be able to participate in the study even if you refuse to be audio/video taped.

YOUR HEALTH INFORMATION
We may be collecting health information that could be linked to you (protected health information). This protected health information might have your name, address, social security number or something else that identifies you attached to it. Federal law wants us to get your permission to use your protected health information for this study. Your signature on this form means that you give us permission to use your protected health information for this research study.

For this research study we will be accessing your TIRR Memorial Hermann/University of Texas Health Center medical record and collecting portions of this data to include information about the brain injury you experienced at the time of stroke. We will also review your medication records to make sure they don't interfere with your involvement in this research study. Also, we would like to access your MRI brain scans for data analysis if available, please check the box below if you authorize us to do so:
☐ I consent and approve the release of my most recent structural MRI scans (if any) for this study.

This authorization to release your protected health information is valid until you finish your participation in this study. The period of your participation in this research study is expected to be less than three months. We will not access your protected health information after you complete the study. Once the study is completed and there is no longer a need for your identifiable information, it will be destroyed.

If you decide to take part in the study, your protected health information will not be given out except as allowed by law or as described in this form. Everyone working with your protected health information will work to keep this information private. The results of the data from the study may be published. However, you will not be identified by name. People who give medical care and ensure quality from the institutions where the research is being done, the sponsor(s) listed in the sections above, representatives of the sponsor, and regulatory agencies such as the U.S. Department of Health and Human Services will be allowed to look at sections of your medical and research records related to this study. Because of the need for the investigator and study staff to release information to these parties, complete privacy cannot be guaranteed. The people listed above will be able to access your information for as long as they need to, even after the study is completed.

If you decide to stop taking part in the study or if you are removed from the study, you may decide that you no longer allow protected health information that identifies you to be used in this research study. Contact the study staff to tell them of this decision, and they will give you an address so that you can inform the investigator in writing. The investigator will honor your decision unless not being able to use your identifiable health information would affect the safety or quality of the research study.

Your signature below indicates that you have read the above and authorize the staff of TIRR Memorial Hermann/University of Texas Health Center medical record to disclose such information referenced above. You have the right to withdraw this authorization in writing at any time, except to the extent that action has been taken during the period of authorization. You have also been informed that when this information is used or disclosed in accordance with this authorization, it may be subject to re-disclosure by the researcher and may no longer be protected.

The Principal investigator, Prof. Jose L. Contreras-Vidal, or Co-Investigator, Dr. Anusha Venkatakrishnan will try to answer all of your questions. If you have questions or concerns at any time, or if you need to report an injury related to the research, you may speak with a member of the study staff. If you have questions or concerns at any time, or if you need to report an injury related to the research, you may speak with a member of the study staff: **Dr. Jose L. Contreras-Vidal**; email: jlcontreras-vidal@uh.edu; phone number: 713-743-4429 or **Dr. Anusha Venkatakrishnan**; email: avenkatakrishnan@uh.edu; phone number: 713-743-0796.

Members of the Institutional Review Board for University at Houston can also answer your questions and concerns about your rights as a research subject. The IRB office number is 713-743-9204. Call the IRB office if you would like to speak to a person independent of the investigator and research staff for complaints about the research, if you cannot reach the research staff, or if you wish to talk to someone other than the research staff.

CIRCUMSTANCES FOR DISMISSAL FROM PROJECT

Your participation in this project may be terminated by the principal investigator:

- if the principal investigator determines that staying in the project is harmful to your health or is not in your best interest

PARTICIPANT RIGHTS

1. I understand that informed consent is required of all persons participating in this project.

2. I have been told that I may refuse to participate or to stop my participation in this project at any time before or during the project. I may also refuse to answer any question.

3. Any risks and/or discomforts have been explained to me, as have any potential benefits.

4. I understand the protections in place to safeguard any personally identifiable information related to my participation.

5. I understand that, if I have any questions, I may contact **Professor Jose L. Contreras-Vidal** at **713-743-4429** or **Dr. Anusha Venkatakrishnan** at **713-743-0796**. I may also contact **Dr. Gerard Francisco**, at **713-797-5282**.

6. **Any questions regarding my rights as a research subject may be addressed to the University of Houston Committee for the Protection of Human Subjects (713-743-9204). All research projects that are carried out by Investigators at the University of Houston are governed be requirements of the University and the federal government**.

SIGNATURES

I have read (or have had read to me) the contents of this consent form and have been encouraged to ask questions. I have received answers to my questions to my satisfaction. I give my consent to participate in this study, and have been provided with a copy of this form for my records and in case I have questions as the research progresses.

Study Participant (print name): _____

Signature of Study Participant: _____

Date: _____

I have read this form to the subject and/or the subject has read this form. An explanation of the research was provided and questions from the subject were solicited and answered to the subject's satisfaction. In my judgment, the subject has demonstrated comprehension of the information.

Principal Investigator/Co-Investigator: _____
(Print name and title)

Signature of Principal Investigator/Co-Investigator: _____

Date: _____

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