A Study on a Walking Companion Robot for Physical and Social Interaction in Gait Training

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Declaration of Authorship

I, Bruno Cesar CAIXETA LEME, declare that this thesis titled, "A Study on a Walking Companion Robot for Physical and Social Interaction in Gait Training" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

"The main difference between artificial and human intelligence is that the human knows what he/she does not know"

Kenji Suzuki

Abstract

In this work, we investigated some aspects of physical and social interactions involved when humans are walking with a companion. We then proposed two Walking Companion Robots to support participants in the scenarios of side-by-side walking with light touch assistance, and of body-weight supported walking for individuals with gait impairment. Besides, we explored alternative modalities for verbal communication, such as haptic feedback and gestural communication, which can be used to assist participants during walking. To improve our design, we reviewed the literature for the common problems faced by different groups of people with gait disabilities. Additionally, we conducted preliminary experiments and video analysis with participants to evaluate features which could be used in our robotic device.

Pilot studies were carried out with healthy participants, where we could confirm the feasibility of our proposed adaptive control to accompany people in both scenarios. In the case of side-by-side walking, participants could guide the robot by using their interpersonal distance. Furthermore, the robot was able to draw their attention and influence their decision by using gestural and haptic feedback. In the scenario where the robot physically supports participants, we verified that the platform could decrease the platform-participant oscillation while our anthropomorphic robot could influence their head orientation. Lastly, considering the multidisciplinarity involved in walking, we explore the taxonomy, called Walking Companion Robot, to better understand the need of people during walking. In this, we dose physical assistance and social interaction aiming to improve the acceptance of people to use the robot and how the robot can influence participants during walking.

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List of Abbreviations

CNS	**C**entral **N**ervous **S**ystem
COBOT	**Co**llaborative ro**BOT**
DOF	**D**egree **o**f **F**reedom
HLGD	**H**igher-**L**evel **G**ait **D**isorder
HRI	**H**uman-**R**obot **I**nteraction
HAL	**H**ybrid **A**ssistive **L**imb
IMU	**I**nertial **M**easurement **U**nit
LRF	**L**aser **R**ange **F**inder
MOCAP	**MO**tion **CAP**ture (system)
SAR	**S**ocially **A**ssistive **R**obotics
SCI	**S**pinal **C**ord **I**njury
WHO	**W**orld **H**ealthy **O**rganization

This work is dedicated to my mother, Rosária Caixeta, and my father, Orlando Leme, who valued the importance of formal education and did their very best to support my aspirations. I offer them all my love and admiration.

Chapter 1

Introduction

By analyzing the interaction between objects, humans are capable of estimating their behaviors and forecast events. It allows us to extract meaning from our surroundings and apply it in our favor in new situations. Interaction can be defined as a relation between two or more objects in which they influence one another. We are continually interacting with the environment in different manners. Our body, for instance, responds to changes in the weather by using sweat glands to regulate internal temperature. In the same manner, our vestibular system gives us a sense of gravity, which allows us to adjust our limbs to stand still.

1.1 Human Gait

During gait, a cascade of physical interactions allows us to displace our center of mass, resulting in movement. Walking is a complex task that involves the synergy of muscles for joint movement. It is performed by reading sensory information such as the one provided by the inner ear and proprioceptor feedback to efficiently move the center of mass. Besides locomotion, the complexity in bipedal walking plays an essential role in adapting to the environment [1]. During walking, for instance, our Central Nervous System (CNS) controls the body in the intended direction while maintaining balance [2]. Moreover, to avoid incongruent information, it can combine different sensory modalities, providing more robust information about the environment and minimizing instabilities [3, 4].

Some groups of people are more prone to suffer gait disorders. It is a common problem among elderly individuals and those with neuromusculoskeletal disorders [1]. A study with 142 subjects over 88 years old, for instance, discovered that 82 percent of them claimed some gait abnormality [5]. Gait impairment can be caused by neurodegenerative diseases such as ataxia and negatively influence individuals in different aspects [6]. When committing the cerebellum (Cerebellar Ataxia), it can compromise the motor coordination of limbs during the movements (Dyssynergia) [7, 8]; and decrease the accuracy of voluntary movements (Dysmetria) [9]. Although cerebellar ataxia does not stop individuals from walking, it decreases the precision of their movements, influencing foot trajectory, and balance [10]. Vestibular ataxia is related to problems in the inner ear and can influence the balance, causing dizziness and vertigo [11]; Finally, Sensory Ataxia is related to damage in the nerves from the spinal cord and its ramification [6].

Locomotion problems have a critical effect on the quality of life of individuals. The reduced mobility caused by impairments can compromise their feeling of independence [1, 12]. Gait disabilities can be classified into three main groups: Balance (which includes sensory information); motor (which includes muscular strength); and joint or skeletal problems [13]. The lack of postural control negatively influences balance and result in falls, which can cause fractures and head trauma [1]. Balance is generally compromised with the reduction of sensory information [4]. It is also one of the leading causes of falls for elderly individuals [14].

There seems to be an intimate relationship between gait impairment and depression. On the one hand, authors suggest that psychosocial factors, such as depression and phobias, may prevent individuals from performing outdoor activities [15, 16]. In the long term, it may decrease their motor capability, which may result in gait disorder [17]. On the other hand, studies with older adults, for instance, shows that gait impairment can prevent people from activities, resulting in less social interaction and contributing to depressive symptoms [18].

1.1.1 Walking Training

Physical exercise is a common recommendation for keeping mental and physical healthy [19]. It can decrease the symptoms of depression [20], alleviate chronic pain [21], prevent coronary heart diseases [22] among others. For those unable to get involved in high-intensity physical activities, regular light-weight exercises are recommended. Studies show the benefits of light-weight exercise to control hypertension [23], improve muscular strength [24], and increase balance [17]. On the other hand, for individuals suffering from poor balance and/or insufficient muscular strength, professional care is demanded. In this case, the therapist can evaluate the condition of the patient and employ devices to handicap their limitation during training.

Assistive Devices

When used correctly, walking assistive devices can improve mobility and, consequently, physical and mental condition [17]. Mobility devices are the most popular type of assistive device [25]. Examples of conventional non-autonomous devices used for walking include canes, crutches, walkers, harnesses, among others. The use of each will depend on the evaluation of the therapist, which will take into consideration factors such as the ability of the person to maintain balance and muscular strength.

- Canes are the most common devices used to assist gait. They can support up to 25 percent of the user's body-weight [13] and can be used for individuals with low sensory acuity or coordination deficits[13, 26]. Their main advantage is to help patients to stabilize gait by giving an extra supporting point to the ground [27];

- Crutches are employed in cases where users can handle their balance, but demand complete unload or movement support for one side of the limb. It is commonly used for individuals with lower-limb injury with preserved cognitive capability;

- Walkers are used as an auxiliary aid for locomotion for individuals with uncompromised motor coordination. They can unload up to 50 percent of the user's body-weight. Thus, They allows more stable support during gait, which can collaborate to maintain balance;

- Harnesses are employed to sustain gait on individuals when they have severe instability in their balance or cannot handle their body-weight. Harnesses can support up to 100 percent of the body-weight and can be used both on overground and treadmill training.

With the increasing demand for rehabilitation care, a new frontier has emerged, which combines traditional rehabilitation with technological aids. These new devices are aimed to minimize the barriers suffered by individuals during regular rehabilitation sessions and can be used to personalize their care. Many robotics devices have been proposed to assisting patients during training. Examples can be mentioned as robotic suits for supporting lower limb movement [28], devices for wrist rehabilitation [29, 30], and for arms training [31], among others. Other researchers focus on technologies to augment people during exercise. These technologies can provide extra information to complement their handicapped senses or offer a virtual environment where participants can practice. Works as the ones done by Sloot et al.[32] and by Song et al. [33], for instance, verify the efficacy of using virtual reality to assist patients during walking training. Some other studies attempt to minimize the workload faced by caregiver personnel. It includes experiments applying robots to coach participants during exercise as in [34, 35], or robots able to socially support with participants [36]. In both scenarios, the prevailing idea is not to replace therapists' expertise, but instead to serve as a tool able to optimize their work. Moreover, these robotics devices can decrease the physical work performed by therapists during treatment, allowing them to focus on the patients' care.

Social Support

During walking exercises, people are immersed in many cognitive challenges [37]. Participants have to decide their trajectory, avoid different obstacles, maintain balance, among others. Moreover, walking is an excellent manner to interact with others, collaborating with their mental health [38]. The physical and social environment has a strong influence on individuals for physical activity [39]. The perception of individuals toward the task and their commitment are essential factors during exercises. Commitment can be defined as the engagement of people in a specific activity over time. In sports, it helps to maintain the motivation of participants to continue at their best, even in unfavorable situations [40]. Several studies attempt to increase the motivation of individuals to change habits and avoid sedentarism. To stimulate older adults to initiate and keep exercising, Phillips et al. [41] suggest activities where the elderly can maintain social interaction. Additionally, it is suggested for participants more information about their progress and details about the activity they are performing. Other studies check the influence of pets on increasing individuals' commitment. Motooka et al. [42] found increased parasympathetic neural activity in the elderly when walking with a dog. Similarly, McNicholas and Collis [43], in their experiments, claim the benefit of dogs as a tool to promote social interaction. Johnson and Meadows [44], suggest in their studies the commitment of people to maintain walking activities even with borrowed dogs.

An increasing number of studies consider the improvement of patients during rehabilitation as a combination of many disciplines. Trabacca et al. [45], for instance, study the rehabilitation of patients with cerebral palsy taking into consideration a multidisciplinary perspective. Schiltenwolf et al. [46], compare the treatment of patients with low back pain with biomedical and biopsychosocial therapy. Their results indicate the benefits of patients submitted to psychotherapy, especially in the early stages, over to those only with conventional therapy. In this new perspective, the rehabilitation sessions can provide more than mechanical support, taking into consideration their personal limitations and psychosocial aspects.

Therapists have a central role during rehabilitation. They are responsible for making the bridge between the individual's well-being and his/her necessary treatment. The tasks involve not only monitoring their gait conditions but also in motivating them to keep exercising throughout the sessions. On the other hand, It can sometimes be too demanding for caregivers to support patients physically and emotionally. Some works report the burden faced by caregivers during rehabilitation [47, 48]. Vicent et al. [47], relate some of their burden as the poor locomotion function and symptoms of depression in stroke patients. Besides caregivers, therapists also have to care about many aspects throughout sessions, such as supporting the patients to perform mechanical work and keep them engaged to maintain training.

1.2 Collaborative Robots

To a better symbiosis, robots have to be endowed with mechanisms to improve their collaboration with humans. Inside the field of Human-Robot Interaction (HRI), researches covering Collaborative Robots (COBOT) have vastly evolved in the last decades to improve the co-ordination of robots to work along-side with human partners. Such as humans work with other humans, a robot to share a common task has to be aware of its peers' movement by anticipating their intended behavior and proactively adapting to changes in the environment [49]. It has a critical point since anticipation involves the close observation of its partner's intention and also the general understanding of the performed task. Many works aim to predict human intention through different gestural cues and sensory modalities. Wakita et al. [50], for example, use force sensors to estimate the intended direction of participants during walking. Gaze is usually a popular method used to estimate users' intention. It is used by [51] to infer user's intention and proactively control the robot's movement.

1.2.1 Socially Assistive Robots

Along with physical support, there is also a crescent demand for robots able to interact in a more human-like manner. The field of Socially Assistive Robots (SAR) intends to help people with social assistance, allowing them to interact and maintain their cognitive skills [52]. The term was first coined by Breazeal et al. [53] to classify robots that use social cues and communication modalities in order to facilitate interaction with humans. Different from conventional assistive robots, SARs are used to interact with humans socially without providing physical support.

There are many studies considering the use of SARs in different domains. Researches, as carried by Shibata with his seal-like therapeutic robot Paro [54], focus on the effectiveness of robots to provide companionship and decrease the level of stress. The robot is mainly targeted at the elderly and has different sensors to interact with people. The study done by Takayanagi et al. [55] using Paro, suggests its efficacy to improve users' mood in case of dementia. Moreover, Mataric et al. [56], analyzed the therapeutic impacts of their robot in the post-stroke rehabilitation scenario. The focus was on the intrinsic motivation of patients, their perception, and their responsibility for the robot's instructions during training.

1.3 Research Purpose

Several works consider the use of robots to provide physical support to humans in different scenarios. However, most of those do not take into consideration the social aspects demanded by patients during walk training. Similarly, the same statement can be argued for the field of socially assistive robotics. Since its conception, SARs are supposed to assist people strictly by social means, without the use of physical support. This work permeates in the combination of physical and social interaction and its importance for an autonomous walking companion robot.

Different from walking alone, walking with (or assisted by) a partner introduces a new gamma of interactions that demands investigation. It involves providing different levels of physical support while taking into account the social interactions that may affect people during walking. This social interaction can include joint attention, gestural signaling, personal area, head orientation, among others. Moreover, it is essential to understand better the dosage between physical support and social interaction that individuals with different gait difficulties may need during walking training. Yet, a common baseline should be defined, linking the similar needs that these different groups may share regarding their physical and social support.

1.4 Thesis Outline

This work is divided as follows:

Chapter 2, we revise the literature regarding the challenges faced by individuals during walking training. We explore the limitations, assistive devices available, treatment, and the robotic devices used to their support. Besides the physical support, this chapter also deals with the social aspects involved during walking and its influence during training. After we discuss the dosage of physical and social interaction and the social dynamics involved during walking.

Chapter 3, we propose a control strategy of a robot to assist people while walking side-by-side with light touch contact. Also, we evaluate an alternative approach for verbal communication with gestural communication and haptic feedback.

Chapter 4, we propose an autonomous robotic platform to accompany participants while providing body-weight support. We then examined the social dynamics involved during walking and propose a socially assistive robot that influenced their head orientation.

Chapter 5, we discuss the results from both experiments and compare it to the requirements proposed in chapter 2.

Chapter 6, we conclude the work and present future directions.

Chapter 2

Related Works

2.1 Walking challenges for elderly people

The number of older adults with gait impairment is estimated at around 10 percent in individuals aged between 60 to 69 years and increases six times when they age over 80 years [12]. From those, approximately 15 percent suffer from Higher-Level Gait Disorder (HLGD). HLGD is a term used to describe severe gait disorders that occur even with the sensory system responsible for balance preserved (e.g., vestibular, vision, proprioception) [57]. For some other authors, this terminology is used to cover an umbrella of gait impairment with no specific cause involved [58–60]. The common symptoms include slow gait, compromised balance, impaired gait initiation, among others [60]. Patients with HLGD have an extreme fear of falling and resilience to walk. Also, similarly to Parkinson's disease, patients can present abrupt freezing of movement, which compromises the completion of the gait cycle [61, 62]. It results in instability in the displacement of the center of mass, which may result in falls.

Other problems can affect older adults to walk. Memory loss, for instance, can cause spatial disorientation and resilience to walk. Seniors are also more prone to falls since their reflexes may get slower with age. Furthermore, decreased visual and auditory acuity may expose them to other risks of accidents. Chamberlin et al. [18], relates the fear of falling in elderly persons to negative influences on their gait parameters such as gait speed, stride length and width, and double limb supporting time.

Walking exercise is usually indicated for the elderly as a manner to maintain/improve their physical condition [63]. Among the benefits, it can be highlighted the help to control diabetes, improve blood circulation, and maintain muscular tenacity [64, 65]. Additionally, when walking, people are involved in cognitive tasks such as motor control and obstacle avoidance. It can contribute to their mental health, decreasing the risks of neurodegenerative diseases such as Alzheimer's, Parkinson's disease, and others.

Motivating the elderly to initiate and maintain physical activity is a challenging task [41, 66]. Discomfort or pain can prevent them from engaging in physical activity [67, 68]. Also, the gradual decline in cognitive skills may turn their movement less precise, demanding extra effort even to perform simple tasks. Isolation and depression are pointed out as critical factors that make seniors resilient to abandon sedentary life-style [69, 70]. It is estimated than more than four-fifth of elderly individuals with Parkinson's disease have some level of depression [71].

Although necessary, assisting the elderly have some limitations. Firstly, even with some degree of illness, most individuals are not hospitalized and do not have any support to start exercising. Secondly, some seniors understand that losing social interaction and outside activities are part of the process of aging and do not look for professional care when the initial symptoms appear [72]. Even so, some simple interventions can minimize the barriers faced by the elderly to walk. Canes, for instance, are suggested to increase balance and reduce their feeling of falling. Moreover, hand in hand walking can increase proprioceptive information while increasing the sense of security [73].

2.1.1 Light-Weight Support

A light-weight bearing can have positive effects on gait for people with impaired balance. The somatosensory stimulation, for instance, can increase spatial orientation and posture stabilization [74, 75]. Studies as the ones done by [74] and [75], demonstrated that light fingertip touch can contribute to postural stabilization. Additionally, Balash et al. [73], conducted studies to verify the influence of light-touch support in individuals with HLDG. They analyzed the fear of falling and gait characteristics of participants in three conditions. Using a walker; Hand-holding walking with the physical therapist; guarded (walking with the therapist side-by-side to increase confidence). Their results showed that hand-holding not only decreased the feeling of falling and improved their confidence but also collaborated with their gait parameters such as gait speed and swing time. Finally, these studies suggest that the balance given by canes may result not only on the extra support point but also because it can provide an additional sensory reference [74].

2.2 Walking Challenges During Neurorehabilitation

The World Health Organization (WHO) estimates that about 15 percent of the word-wide population have some level of disability[76]. From those, half of them have some gait impairment. Most individuals with compromised motor control usually suffer from diseases such as Arthritis, strokes, traumatic brain injury, or spinal cord injury [77].

Spinal Cord Injury (SCI) is defined as a partial or total interruption in the communication between the brain and the limbs caused by damage in the nerves of the spinal cord. Another report from the World Health Organization estimates up to 80 cases of Spinal Cord Injury per million people each year worldwide [76]. From those, traumas such as car accidents and sports represent 90 percent of all SCI [78]. It can profoundly affect the quality of life of individuals and is a common cause of immobility.

Cerebral Vascular accidents, also known as strokes, is caused by an interruption in the blood flow in some part of the brain. It can be caused either by an obstruction(ischemia)[79] or a rupture (hemorrhage) in the artery. It is the second leading cause of death and affects 13.7 millions of people each year [79, 80]. More than 50 percent of stroke survivors get severe gait impairment [81, 82], and around 70 percent of them will be unable to walk half year after the accident[83]. Hemiplegia is a typical impairment in stroke [84]. It is defined as the paralysis in the movement of one side of the body, which influences gait performance [85].

Walking impairment has a devastating effect on the quality of life of individuals, generally resulting in confinement and stress [86, 87]. Studies agree that early intervention is the best key for neurorehabilitation [88, 89]. Stinear et al. [90], for instance, suggest the motor rehabilitation in stroke survivors, when started early, can improve the recovery process and reduce functional disability.

2.2.1 Body-Weight Support Device

For individuals with walking disabilities, regain locomotion may represent a considerable improvement in their quality of life [12]. Due to insufficient control of their limbs, it is usually necessary body-weight support devices (BWS) to attenuate their load and prevent them from falls [91]. During rehabilitation, patients are exposed to overground or treadmill training to recovery balance control and muscular strength. Although there is no consensus on the most effective method, some studies suggest the advantages of overground training. Gama et al. [92], for instance, highlights the better improvement in the step-length of patients performing overground training over treadmill training. Warabi et al. [93], observe that the feet of patients are pulled back in treadmill training as soon as they touch the belt, which may compromise muscular activity. In this sense, since patients are "relearning" how to walk, they should deal with all the phases of the gait cycle. Finally, as mentioned by Mignardot et al. [94], treadmill training imposes a fixed gait speed for patients. It can be hard for them to follow since their coordination is compromised. Figure 2.1 gives an overview of the overground walk rehabilitation treatment.

2.3 Optic Flow

Walking is sensed and controlled by merging visual, vestibular, and proprioceptive information [95]. Optic flow can be defined as the capability of the human brain to extract motion features from visual information and use it to control gait [96]. Optic flow is a necessary component to control walking speed and balance [32]. Studies showed changes in the modulation of extensor and flexor muscles when different optic flow patterns were presented during a balancing task [97]. Considering heading direction, the influence of optic flow is still debatable. Warren et al. [98], support its role for controlling direction. On the other hand, Rushton et al. [99], argue that the

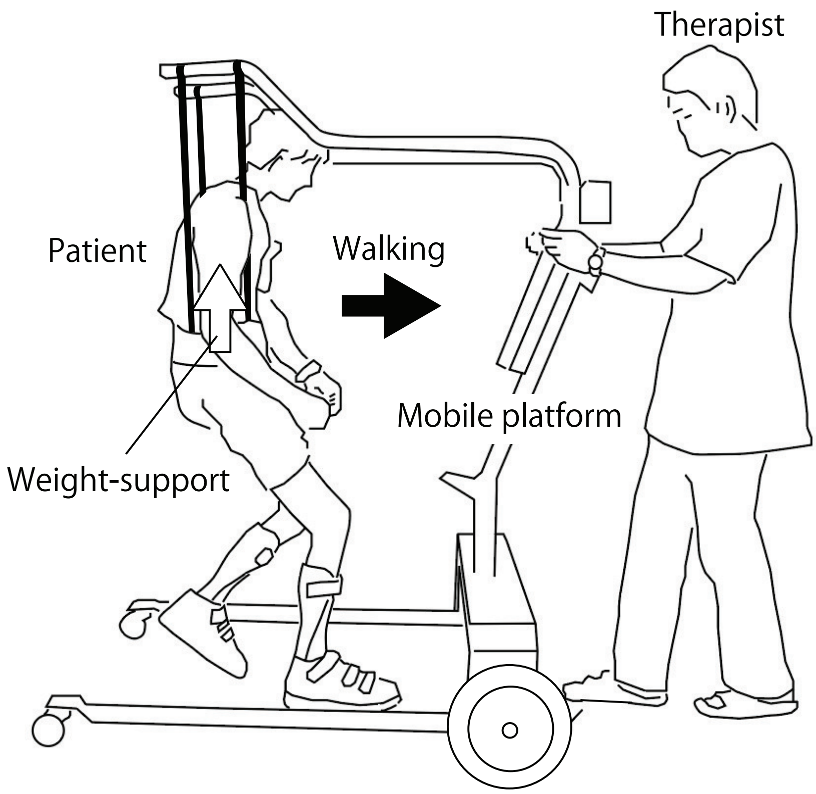

FIGURE 2.1: Overview of overground walk rehabilitation treatment

heading control is maintained by fixing angles of target and obstacles in relation to the person.

Stroke survivors usually present disturbed eye movement and have difficulty to control their gait [100]. For rehabilitation, it is noticed that participants in treadmill training are less exposed to optic flow [101]. It may represent an extra challenge for walking, especially for individuals with other senses damaged. Besides, incongruent information from different senses (visual and proprioceptive, for instance) can result in misinterpretation and cause disorientation in individuals. Researches carried by Lamontagne et al. [102], for instance, used optic flow to influence the perception of stroke individuals and modify their gait patterns.

2.4 Robotic Therapy

Efforts have been addressed for robotic tools to assist individuals during gait training. The commercially available Hybrid Assistive

Limb - HAL (Cyberdyne, Ibaraki, Japan), for instance, is an exoskeleton that supports patients with lower limb disabilities during walking rehabilitation. Electrodes connected in the patients' muscles read the intended movement's signals and transform them into joint movement. Additionally, Lee et al. [103], designed an autonomous walker to support elderly patients during walking. For gait rehabilitation, Mignardot et al. [94], proposed an autonomous body-weight support structure to provide physical assistance to people with gravity compensation. Some other studies explored SARs as an exercise trainer for seniors [34, 35, 104]. Matsusaka et al. [35], use a small size full-body robot called TAIZO to demonstrate physical exercises in collaboration with a human trainer. It can recognize voice command and also has a keypad for the selection of the desired performance. Gorer et al. [104] use a Microsoft Kinect to detect the position of the participant and the commercially available robot NAO (Aldebaran-Robotics, Softbank) to suggest corrections in their pose by mimicking the movement and emitting voice command. Fasola and Mataric [34], used a camera to extract the participants' position and designed an upper torso robot to show movement. They used voice commands to interact with participants and a Wiimote remote control (Nintendo, Japan) to receive responses such as yes or no. In the three scenarios, the authors reported positive feedback from participants and argued the acceptance of elderly individuals to SAR exercises.

2.5 Design Consideration

2.5.1 Dosing Physical and Social Assistance

In the same manner that a therapist needs to dose the treatment and select the equipment that his/her patients may need during rehabilitation, the design of a walking companion robot has to take into account some consideration. It is essential during design to observe the common point, and also the specificities that groups with limited mobility may encounter. For this, it is essential to consider walking not only as of the movement of the limbs but rather as a combination of physical, neurological, and psychosocial capability. In the last decades, scientists have made remarkable progress in technologies to attenuate the limitation of individuals with walking impairment. It can be mentioned exoskeletons to promote voluntary movement of people with neurological diseases; assistive devices for ambulation, such as autonomous walkers and wheelchairs; social robots to motivate people to exercise; intelligent body-weight support devices, among others. On the other hand, to the best knowledge of the author, studies regarding the interdisciplinary between these topics are still limited.

Studies indicate the benefits of considering social and psychological factors during rehabilitation. Trabacca et al. [45], for example, proposed a multidisciplinary study in the rehabilitation of patients with cerebral palsy, aiming at the improvement of their care in the long-term. Schiltenwolf et al. [46], compared conventional biomedical with biopsychosocial therapy when applied to the treatment of patients with low back pain. Their results indicate the benefits of patients submitted to psychotherapy, especially in the early stages, over to those with only conventional therapy.

The amount of physical support and social assistance provided during walking training highly depend on the clinical situation of the individuals. In the case of older adults without severe impairment, for instance, most literature suggests sociological limitation as their main burden to engage in activities. Even so, for some of the elder, low physical support (as provided by canes and walkers) could be beneficial. Firstly, it can overcome some sensory decrease that, even not completely compromising the gait, can turn their walk more demanding. Secondly, by providing extra support, it can increase the safety of participants contributing to their confidence during walking. A robot to accompany individuals during walking, besides collecting gait data that can be used to evaluate their condition and monitor their progress, can be used to motivate them to exercise.

Therapists are responsible for choosing the appropriate rehabilitation strategy and the assistive devices that will suits their patients' necessity best. They also constantly interact and motivate patients throughout sessions. On the other hand, the absence of a companion in the initial stage of impairment or the limited time of therapists may influence the perception of individuals. Most literature argues the prevalence of sociological problems such as loneliness and depression in individuals with gait disorder. We believe that by providing a manner to promote their intended gait autonomously can contribute to their emotional condition. It is inevitable to notice that patients in neurorehabilitation are critically dependent on their therapist and caregivers for the most basics things. A robot able to adapt to personal walking preferences such as gait speed may contribute to their feeling of independence. Moreover, a social robot could be useful in a complementary extent. As in the case of older adults, it could provide a sense of presence, which may increase their motivation to walk.

2.5.2 Clarifying Social Dynamics During Walking

Analyzing the physical interactions during walking can give us cues about some social dynamics. We need to study the social interaction of individuals with their peers and the components, which can turn this interaction more harmonious. The response of humans toward a mechanical device during walking may not be the same as with another human. Also, we need to detect aspects that are important to a given task in order to endow robots with better adaptability. These aspects involve individuals' interpersonal space during walking, joint attention, social signaling, and others.

Proxemics

Walking data is a valuable resource which can be used to check whether users are accurately exercising and measure their improvement. Also, this information, combined with video recording and motion data, can be useful to clarify some mechanisms of social interaction. Regarding the proxemics, for instance, humans tend to maintain social distances from others during walking [105]. On the other hand, it is still unclear whether humans would consider robots invading their personal distances in the same manner we consider for other humans. Furthermore, during gait rehabilitation, the interaction between the patients and the therapist is influenced by the walking harness. In this case, instead of walking side-by-side, the therapist usually is on their front or back to pull/push the device. Since the therapist is assisting their movement, it is inevitable for them to exchange forces. Walking with a harness is a peculiar scenario, and more studies regarding their interaction have to be addressed.

Head orientation

Participants should be able to observe as much as possible the environment around them. It can contribute to maintaining social interaction, which may avoid symptoms of depression. Besides, it is essential to influence participants to keep an upright posture without interfering in their intended gaze direction. It can stimulate them to exercise optic flow during walking and increase their awareness of the environment. Moreover, optic flow, combined with a better posture, can enhance their gait parameters. Finally, influencing head orientation by direct command or placing a fixed target may be unsafe for participants. It can block visual information and requires them to concentrate on a new task, instead of caring about their gait, which can lead to falls.

Challenging

Both social and physical interactions have to be stimulating for patients to keep motivation. If the task is too simple and constant, participants may get bored and resilient to the task. On the other extreme, participants may feel difficulties in completing the exercise and feel unmotivated to continue. In a normal rehabilitation session, therapists can use their experience and subjectively doze the amount of challenge each patient can endure. It can involve forcing them to walk more or at an increased speed, increasing the challenge. On the other hand, they can also minimize the challenge by helping patients to walk in a critical part of the gait attenuating the limitation.

The motivation of individuals to walk can be increased even with a non-human partner [44]. In the case of a robotic device, related works suggest that the feeling of an entity can contribute to increasing motivation. In this work, we consider the shape of the robot and its behaviors intended to maximize this perception. Finally, a robot with gait measurement capability can provide real-time information about their progress. It can go in accordance with Phillips et al. [41], which argues that elderly participants can be motivated if they get involved in the exercise, receiving feedback on their progress.

Chapter 3

Side-by-Side Walking With Low Physical Support

In this study, we investigated the capability of our robot to estimate its users' intended direction and maintain side-by-side walking using its peer's relative distance. Also, we attempt to shed some light on how participants interact with the robot regarding their walking preferences and non-verbal communication. The experiment was performed to evaluate if the robot can accompany participants with different gait strategies, and if hand-holding during walking would maintain the commitment of participants toward the robot. Additionally, we want to clarify the perception of participants from non-verbal gestural communication and haptic feedback emitted by the robot. By gestural communication, the robot tries to influence participants' decisions using head direction to indicate the desired path. In the haptic feedback, the robot offers resistance to locomote, which can be felt by participants. It is used to request participants' attention before the robot starts gesturing.

3.1 Implementation

An anthropomorphic upper torso robot, developed at the University of Tsukuba, was used as our start point. It has a total of 6-DOF and can express simple gestures that may evoke the user's attention. The decision for this robot is explained once that robots with higher anthropomorphic appearance may create frustration in users if not able to reproduce its behaviors accordingly [106, 107].

A mobile platform was used for locomotion (MegaRover, Vstone Inc., Japan). It has a large and heavy structure, which implies better stability for the robot. An aluminum structure was developed,

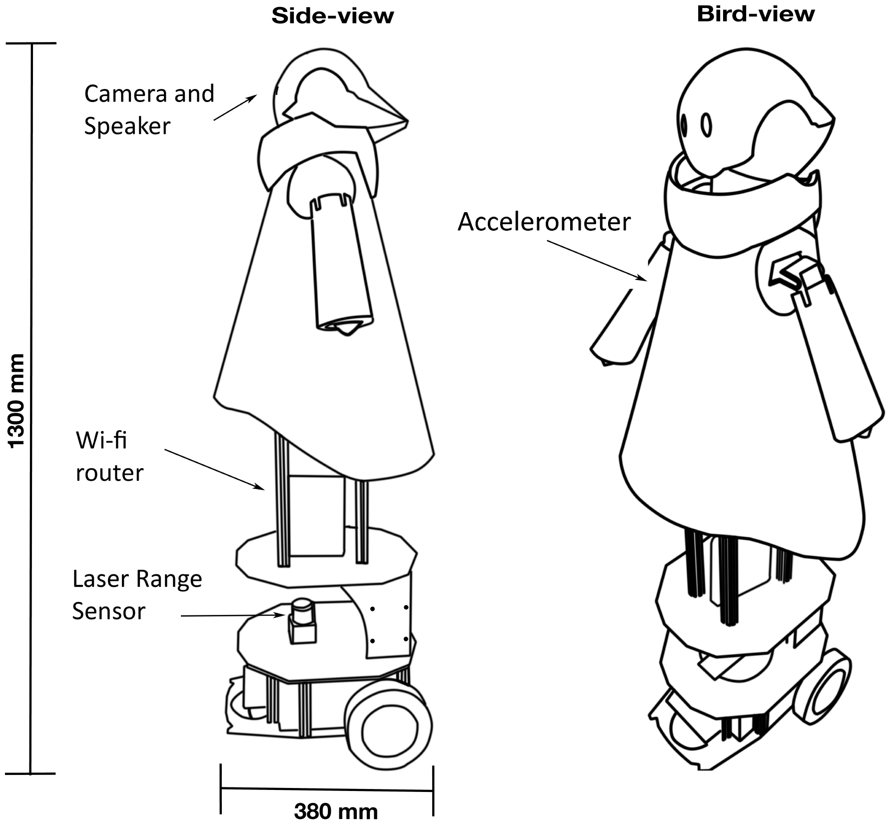

FIGURE 3.1: General view of the robot with its main components

linking the mobile platform to the anthropomorphic robot. A Laser Range-Finger (UST-10LX, Hokuyo, Japan) was installed 200mm from the ground and is responsible for getting gait information. It has a maximum range of 10m and 270 degrees of scanning with an angular resolution of 0.25 degrees.

The robot is controlled using an ARM 32-bits microcontroller. It is responsible for controlling the base's wheels, RGB LEDs, servo motors, analogic sensors such as the accelerometers, and communicate with the server through Ethernet. A wireless router is used to merge the information from the Laser Range-Finder, microcontroller, and communicate with the server. The server is responsible for the control strategy and to store the gait data. The microcontroller is programmed in C++ while on the server-side was used Python. Figure 3.1 shows the general view of the robot and its components.

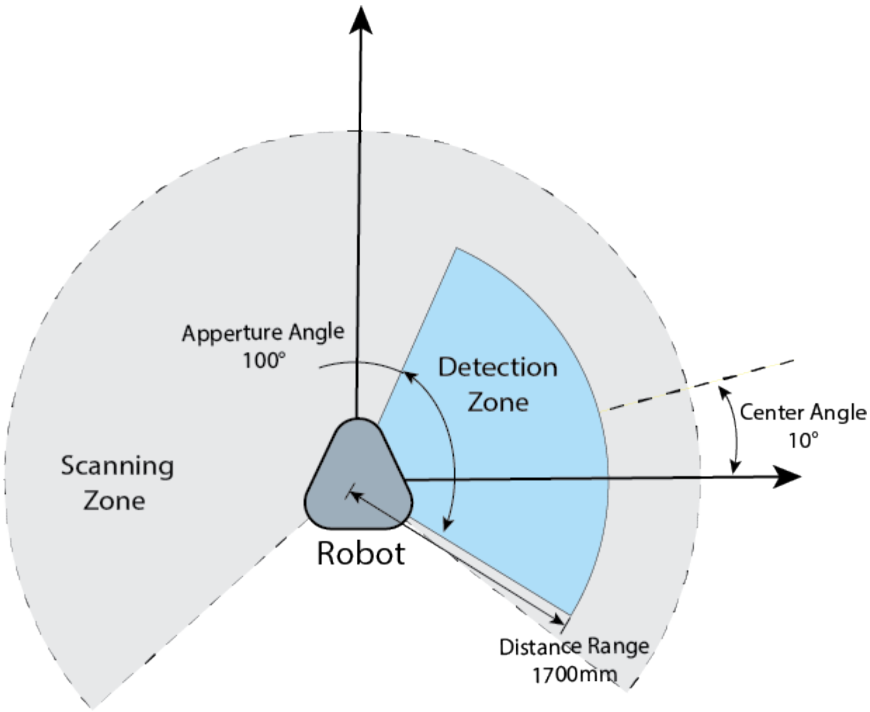

FIGURE 3.2: Laser Range Finder detection mode. Gray area represents the total scanning zone. Blue area represents the person detection zone

3.2 Control Strategy

Two methods can be used to control the robot. In the first, the operator remotely controls the robot using a 3d mouse (Space Navigator, 3dconnexion). In the second method, the robot autonomously follows participants by using the information provided by the Laser Range-Finder to maintain relative distance.

An algorithm was developed to filter the sensor data and avoid the detection of other objects. It starts with an initial Region Of Interest (ROI), which is defined on the right side of the robot. When the user walks, the polar coordinate from the LRF sensor, where the values are greater than zero, is retrieved and represents the user's position. This value also is used to define the next ROI. By constantly redefining the ROI, the algorithm can keep track of the user while ignoring obstacles in other regions. Figure 3.2 shows the Laser Range Finder detection mode.

The robot maintains the lateral distance from participants while accompanying them longitudinally. A previously defined "desired walking distance" represents the average distance side-by-side that the robot and the human should walk. If the human gets closer or

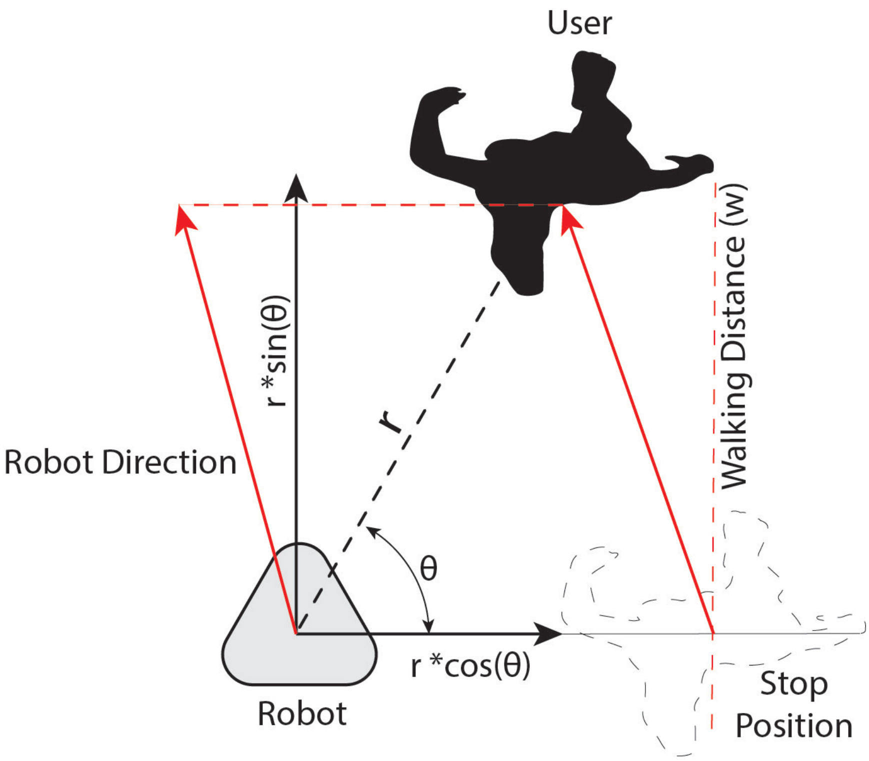

FIGURE 3.3: Human-robot distance and its components used to control the robot.

farther to this distance, the robot will correct its direction proportionally to maintain the interpersonal distance. During the development of the robot, the value of the walking distance was empirically defined and set to 600mm. Sorokowska et al. [105], in their work about preferred interpersonal distance, define distances between 460mm to 1220mm as the area maintained with closer persons (authors refer to this area as "personal distance").

It is used the distance and angle of the robot-user to control the movement of the robot. As output, we need to send the necessary speed in each wheel that the robot should move. The microcontroller in the robot is responsible for receiving and converting the speed values in PWM pulses, and an H-bridge is used to control the wheels. Figure 3.3 illustrates the human-robot distance and the components used to control the robot. The speed that the robot should move can be defined by using the following formula:

$$v = \frac{r \sin \theta}{F_v} \tag{3.1}$$

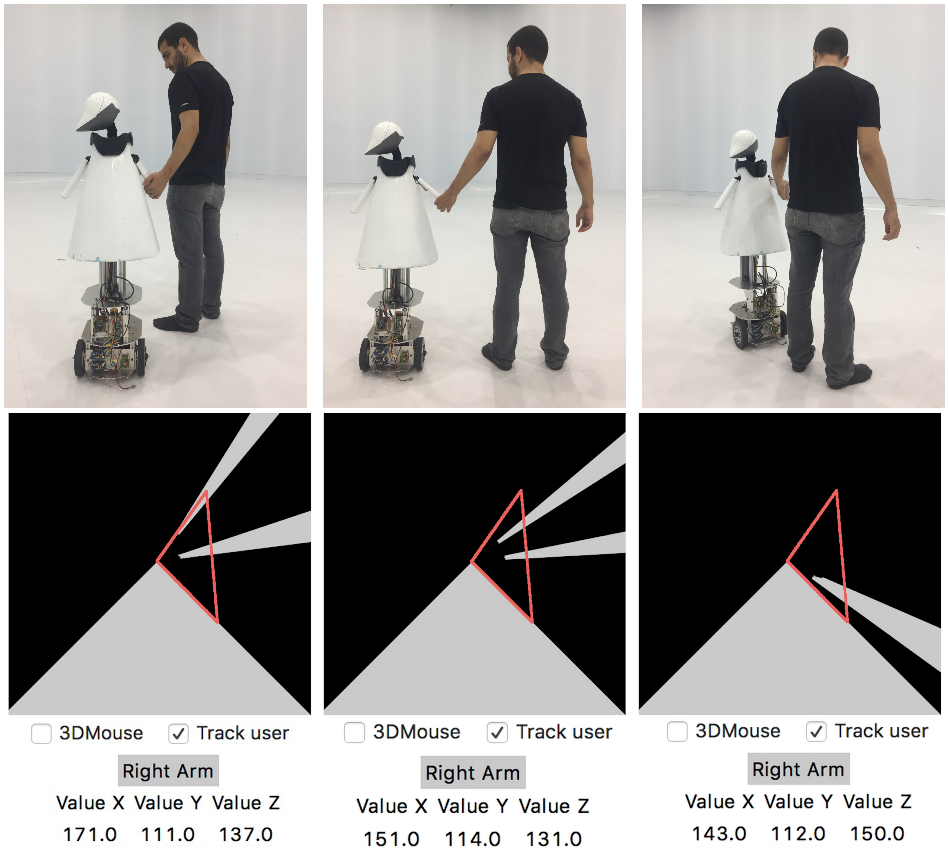

FIGURE 3.4:
Upper part: Example on how the robot is controlled during: turning left, going straight, and turning right.
Lower part: Part of the GUI with scanning area.
Source: adapted from [108]

Where r and θ are respectively the distance and angle where the user is related to the robot, and F_{acl} is a constant that influences the velocity. This value was empirically defined during development. It depends on the characteristics of the device, such as motor ratio, RPM, and diameter of the wheel. The direction of the robot (ϕ) can be calculated by using the following formula:

$$\phi = \frac{D_{wd} - r\cos\theta}{D_{wd}} \tag{3.2}$$

Where D_{wd} is the desired interpersonal walking distance side-by-side between the human and the robot. This value represents how close or far the user moved from the desired distance. Finally, to

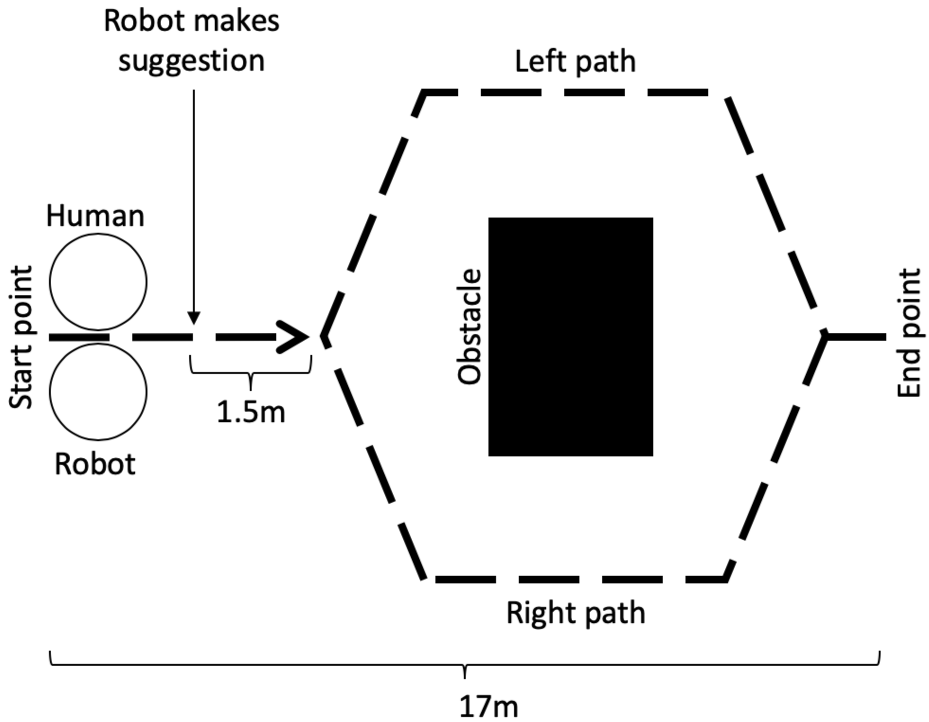

FIGURE 3.5: Proposed circuit for experiment.
Source: adapted from [108].

control the intensity of each motor, the following formula is used:

$$\begin{aligned} m_{right} &= v * (1 + \phi) \\ m_{left} &= v * (1 - \phi) \end{aligned} \tag{3.3}$$

Figure 3.4 shows the proposed device and illustrates how it can be controlled to turn left, go straight, and turn right.

3.3 Experimental evaluation

The task consists of participants walking side-by-side with the companion robot in a predetermined path. Participants were instructed to walk naturally, leading the robot throughout the path by holding its hand. By walk naturally, we informed that users were free to walk according to their gait style. It means that participants could decide how to guide the robot to turn and decide the speed. No further information was given, such as how the robot works or how to control it. Participants were allowed to practice with the robot for 1min before starting the experiment.

During the experiment, an obstacle in the middle of the path forces participants to take a route around it. One and a half meters before the obstacle, participants have to decide between turn left or right. Before it, the robot performs four types of behaviors that are remotely selected at each turn. Ten participants joined in the experiment with a mean age of 25 years old. Each of them performed the experiment four times randomly. Figure 3.5 shows an overview of the path.

The robot transmits its intended direction by using head movement and haptic feedback. Also, we checked whether the robot could attract attention by maintaining head gaze to its users. When the robot has to emit suggestions, it stops looking at the user and starts head gazing the intended path. Before the obstacle, the robot tries to suggest a direction to the participant by using one of the following behaviors: a) the robot suggests the direction by moving the head left or right. b) the robot suggests the direction by moving the head left or right while decreasing its speed until it stops. These behaviors are replicated for the conditions where the robot maintain head-to-head orientation with the participant and in the condition where the robot's head is continuously faced forward. Figure 3.6 illustrates the combination of behaviors emitted by the robot before participants decide the path to go.

During the task, information regarding the position of participants in relation to the robot was recorded. Also, two video cameras were placed to register the task and after verify whether participants perform visual contact with the robot. The positions of the cameras are as following: One camera was placed in the longitudinal axis of the experiment (Front camera), and the other was placed in the lateral axis (Lateral camera).

3.4 Results

The proposed robot was able to accompany all participants throughout the experiment. Also, it could adjust its speed while maintaining the predefined interpersonal distance. Different walk strategies were observed during the experiment. It was important once we could

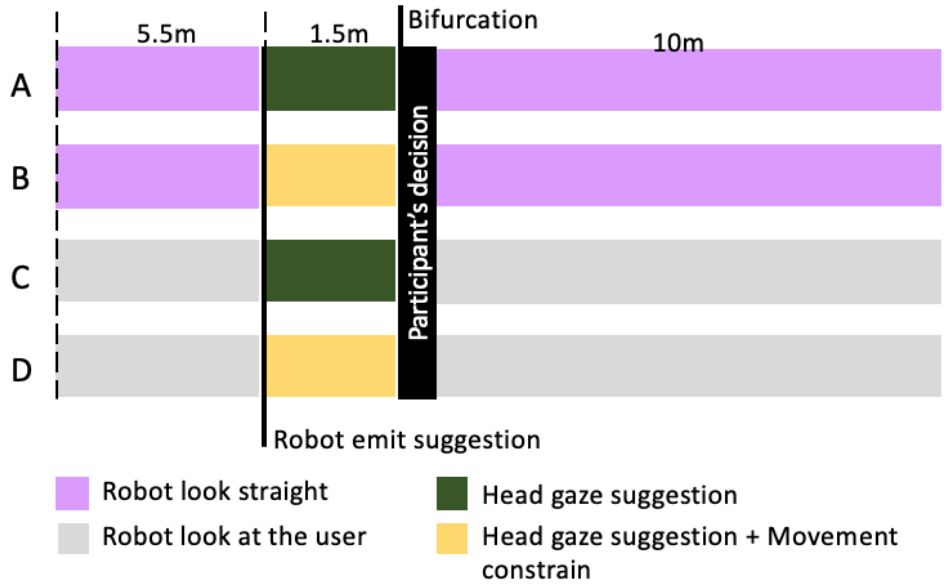

FIGURE 3.6: Overview of the experiment and the combination of behaviors emitted by the robot before participants decide the path to go.

verify the response of the robot in each different scenario. Some participants, for instance, walked faster and were indifferent to the robot while others took more caution and walked slowly. Another peculiar point was the decision on the trajectory to make curves. Some participants strictly followed the lined path making sharper curves while others took only into consideration the general idea and decided for a more smooth path. Figure 3.7 shows the relative human-robot distance and the standard deviation during the task.

Analyzing the recorded videos, more than 70 percent of participants looked at the robot before making the decision, which may suggest their willingness for guidance. Also, most participants decided to take the same direction as the one suggested by the robot. The highest convergence was found in condition D, where the robot

TABLE 3.1: Percentage or participants who looked to the robot and those who recognized its suggestion in the four conditions. Information quoted from [108]

Conditions	Look to the robot	Recognized the suggestion
A	70%	70%
B	70%	70%
C	80%	60%
D	80%	80%

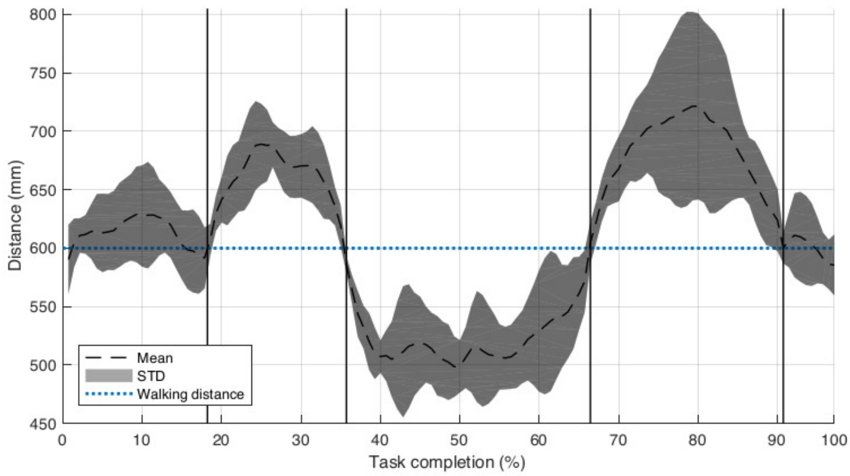

FIGURE 3.7: Relative human-robot distance when walking side-by-side when selecting the right path.

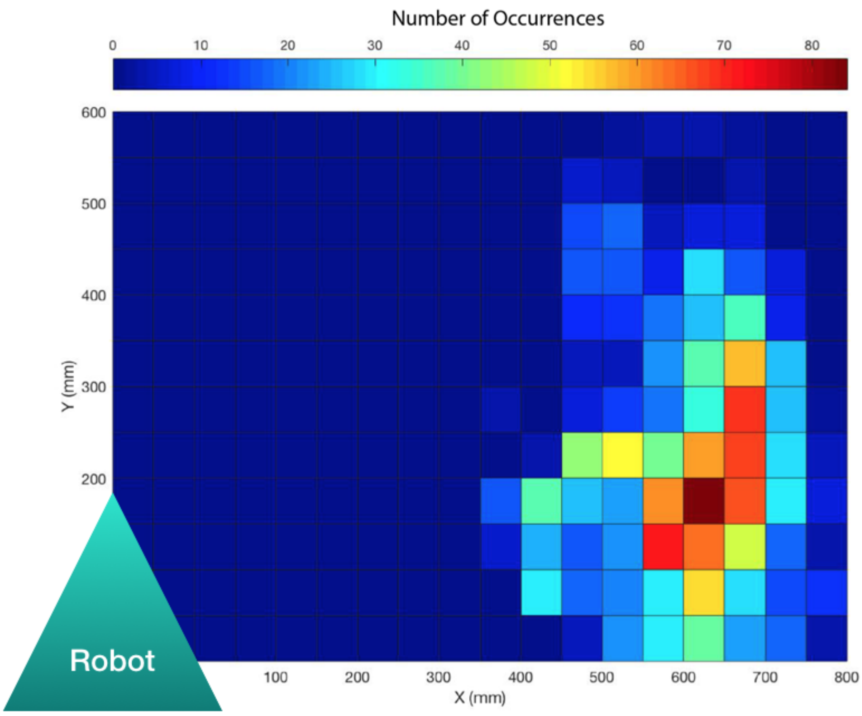

FIGURE 3.8: Heat-map with the human-robot relative position

looks at the user during walking and before making the suggestion emits a haptic feedback to participants. Percentage of participants who looked to the robot and those who recognized its suggestion are shown in Table 3.1.

Chapter 4

A Socially Assistive Mobile Platform for Weight-Support in Gait Training

We developed and experimented a robotic platform to autonomously accompany users during walk training while supporting part of their body-weight. We seek for physical and social interactions which may reflect on the overall perception of participants during training.

4.1 Design Consideration

Different from the investigation done in Chapter 3, in this scenario most participants during gait training require a high level of physical support to exercise. Moreover, their movement are conditioned to the help of therapist and caregivers resulting in less independence.

To better understand the needs of patients with lower limb disabilities during walk training, in special those which may influence their motivation, it was necessary to observe how the treatment occurs. We analyzed the movement of a post-stroke patient using a Body-Weight Support (BWS) device in a gait rehabilitation session (Male, age:60s). In the triad patient-platform-therapist, it was observed the following points:

- Patient-therapist: The head orientation of the therapist and the participants during walking;
- Therapist-platform: How the therapist controls the speed of the platform;
- Patient-Platform: The oscillation in the distance between the patient and the platform.

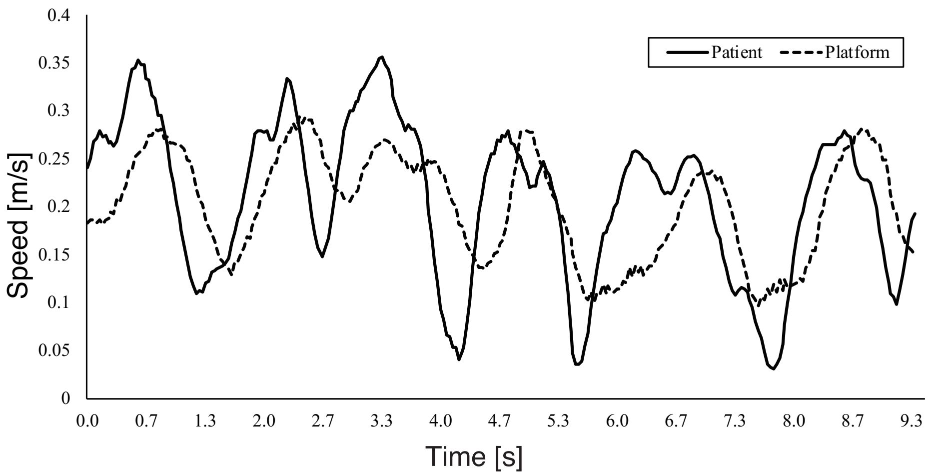

FIGURE 4.1: Speed variation of a patient and the BWS device during a gait rehabilitation session

From the video analysis, it could be noticed that both patient and therapist are mostly looking down during walking. This factor deserves consideration since head orientation can influence posture and, as a consequence, gait. Moreover, it could be observed a delayed response in the speed of the platform in relation to the patient. Once patients' are hanged in the harness by belts, it may force them to a speed decided by the therapist. Finally, a phase delay between the participant-platform speed was observed. It may create horizontal forces, resulting in discomfort and negatively influencing gait. Figure 4.1 illustrates the speed variation (oscillation) of the patient and the BWS device.

People during walking use optic flow to extract motion clues from visual information. To allow participants to interact with their surroundings, instead of forcing them to look at a specific place by using voice command, it is proposed non-verbal communication to attract their attention and change their head orientation. This attempt for attention may be influenced by the priorities of the participant, which can be busy with other task and give to the gestural signaling a second priority.

4.1.1 Physical interaction

The perceived feeling of participants toward the activity, such as comfort and independence, may affect their overall motivation to the activity. In this sense, the physical aspects of our investigation regard on how participants interact with the platform and therapist during walking. Instead of a robotic system to provide social interaction, we propose to facilitate social interaction by minimizing the barriers faced by participants in need of walking support. Thus, we try to reduce the reliance of participants on the therapist to control the platform. For this, the platform is endowed with a LIDAR sensor to extract participants' feet position and estimate their intended moment. It would allow more active control of the platform, which can increase the feeling of independence of participants. Moreover, since participants are hanged to the platform, its oscillations can be transmitted to them, generating discomfort. The faster response of the platform may decrease this oscillation, contributing to reduce horizontal forces acting on the patient.

During a conventional rehabilitation session, gait information is mostly acquired by using motion capture systems (MOCAP). It offers a great amount of information by markers placed into patients' joints. On the other hand, the time consumption for setting up the device to get basic gait information turns this application unfeasible. In this sense, our device can facilitate this process by capturing some gait information such as step-length, step-width, and cadence in a ready-to-go fashion. This information can be used by the therapist to maintain the history of patients during the sessions.

4.1.2 Social interaction

Once the therapist does not have to pull the harness, it may create a lack for participants which may influence their overall perception about the task. Thus, besides the physical interaction, a socially assistive robot is used during training [109]. We analyze how it can influence participants regarding their perceived feeling of stress, motivation, and comfort.

It was observed in a preliminary test that participants tended to look down during walking. This behavior is undesirable once the head orientation can influence the center of mass and as a consequence affect postural control [110, 111]. During experiments, we analyze the influences of our autonomous platform on the head orientation of participants. Also, we verify whether our social robot

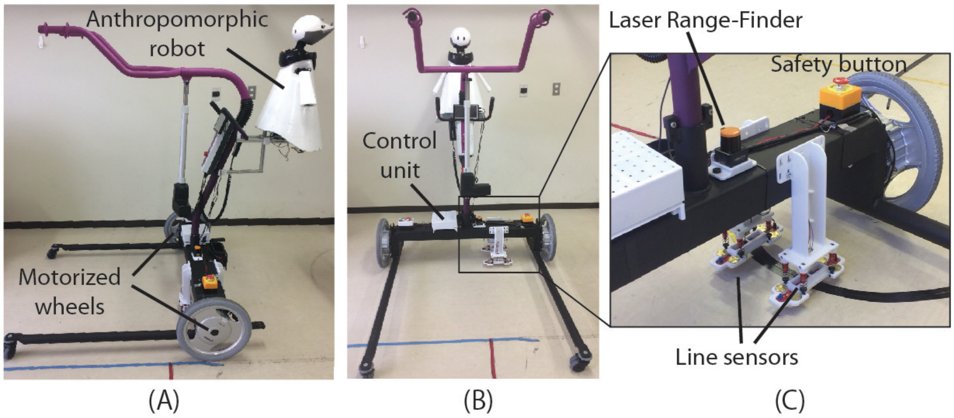

FIGURE 4.2: Overview of our proposed architecture. (A) Lateral view indicating the position of the anthropomorphic robot and the motorized platform, (B) Front view, (C) Sensor attachments

can draw the participants' attention in this scenario and mitigate this behavior.

4.2 Implementation

An over-ground walk training harness (Ropox All-In-One System, Naestved, Denmark) was used to provide Body-Weight Support. An electric power-assist unit for wheelchair (Yamaha JoyUnit X, Shizuoka, Japan) was placed in the position of the platform's front wheels. To acquire the users' gait information a Laser Ranger Finder (Hokuyo) was installed above 100mm from the ground.

Black lines were placed on the floor to define the trajectory of the robot. The area where the user will actuate has 10m long and is called "operational area". After this, there are semicircles in each extremity which guide the robot back to the operational area. Right-sided markers were placed at the ending of each operation area indicating the finish of the track. After reading this marker, the robot slow-down and operates at a constant speed until it reads the left-sided markers, which indicates the beginning of the next operation area.

To detect the path, two arrays of infrared sensors (16 I.R. sensors each) are used. They are positioned 200mm apart from each other 10mm above the ground. By using two sensors, it is possible to acquire the robot position and its rotation in relation to the line. A microcontroller communicates with the wheels by using CAN-BUS and

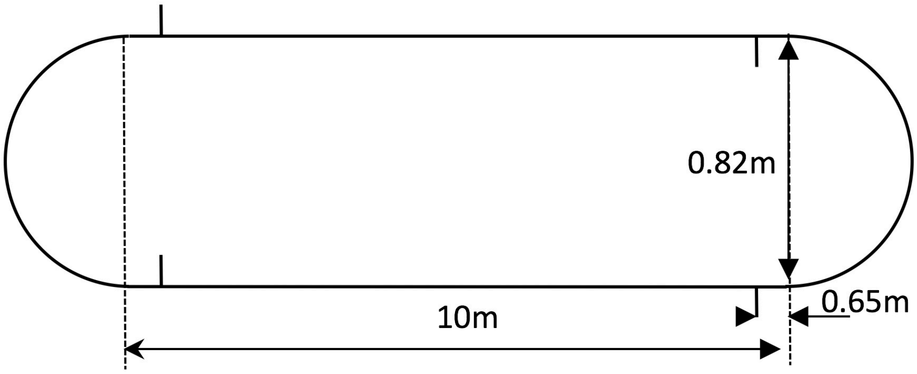

FIGURE 4.3: Proposed circuit with marks to switch control mode

with the line sensors by using I2C. A Raspberry Pi is used to merge the sensory information and send the commands to the wheels. For safety, two safety buttons were included at each side of the platform.

Our anthropomorphic robot was installed in the position occupied by the therapist's head and torso when pulling the harness. It is controlled using a Raspberry Pi 3 that receives the instructions given either by a remote server or by the robotic platform through UDP protocol. The robot has an internal power supply and communicates with the platform and the server through wi-fi. Figure 4.2 shows an overview of the proposed architecture.

4.3 Control

Different from our previous experiment, where participants walk side-by-side with the robot, in this participants are within the rectangular harness' area. It eliminates the necessity for differentiating participants from other objects. The detection starts by transforming the Polar coordinates to Cartesian and then discarding all elements outside the Region Of Interest (ROI). In the Cartesian frame, X is defined as the longitudinal axis in the direction of walking and Y as the lateral axis. Two arrays $X_p = \{X_0 , ... , X_n\}$ and $Y_p = \{Y_0 , ... , Y_n\}$ are generated, where (X_p , Y_p) represents the value of (X , Y) in the position p, and n represents the number of elements in our ROI. Since only feet are expected in the controlled zone, all other elements inside the array should be zero. Equation 4.1 is used to calculate the median (m) where the array can be splinted in both feet.

$$m = median(P : Y > 0) \tag{4.1}$$

Finally, the median of the elements in which Y is greater than 0 is calculated again for each array to locate the position of each leg. The line array sensors were configured to represent a number ranging from -1 (line in the leftmost position) to +1 (line in the rightmost position). In case of no line detected the sensors send an error code shutting the system down. The Eqs. 4.2 and 4.3 are used to calculate the position (p) and rotation (r) of the platform in relation to the line:

$$p = (s_{rear} + s_{front})/2 \tag{4.2}$$

$$r = (s_{rear} - s_{front})/2 \tag{4.3}$$

where s_{rear} and s_{front} are the rear and front sensors. A reference line, which is parallel to the lateral axis determines the intended movement of the participant. If the participant crosses the line with his/her leg, getting closer to the sensor, this invaded distance (d) is used to control the intensity of the movement. This control policy of the platform realizes the voluntary forward movement of the lifted patient, in accordance with his/her voluntary leg swinging.

The value of s_{rear} is used to decide the control strategy. When its value is bigger than 0, it means that the right motor should decrease speed and equation (4.4) is used. On the contrary, equation (4.5) is used to decrease the speed of the left motor.

$$\left.\begin{aligned} m_{right} &= d(K_p(1-p) - (K_r * r)) \\ m_{left} &= d \end{aligned}\right\} \quad \text{if } s_{rear} \geq 0 \tag{4.4}$$

$$\left.\begin{aligned} m_{right} &= d \\ m_{left} &= d(K_p(p) + (K_r * r)) \end{aligned}\right\} \quad \text{if } s_{rear} < 0 \tag{4.5}$$

where m_{right} and m_{left} are the control inputs to the right and left motors, and K_p and K_r are constants which were empirically defined during tests. There are two possible values for each of the constants which are commuted when the infrared sensors detect a flag. In the case of "operation mode", which means that the platform is going on a straight line where the participant controls the speed, the constants are set to perform minor adjustments. In "slow mode", where the platform has to turn back until the next "operation mode", the constants are set higher to follow the curve.

4.4 Experimental evaluation

A pilot experiment was conducted with healthy subjects to check the feasibility of the proposed platform. Three experimental conditions were considered for evaluation. In the first, the therapist guides the participants as in a normal rehabilitation session. In the second condition, our autonomous platform moves according to the desired speed of the users. The only information given was that they could walk freely by choosing their desired speed. In the third condition, participants walked with the autonomous platform, such as in condition 2, but in the place originally occupied by the therapist, our socially assistive robot was placed. Its behaviors were remotely selected by a programmer when participants were looking disperse.

During the experiment, gait information from participants was recorded by using the LRF. Also, a motion capture system was used (VICON MX System with 16 T20S Cameras, Vicon, Oxford, UK) with markers in the legs and head of participants, the platform and the robot's head. This information was used to compute the head orientation of participants in relation to the robot's head and the speed oscillation in the three scenarios. All the experiments were recorded using two fixed cameras. One in the longitudinal axis of the experiment (Front camera), and another in the lateral axis (Lateral camera).

A 7-points Liker scale[112] was used at the end of each condition to assess the perceived feeling of participants. The questions were regarded to the users' comfort during the experiment; the perceived difficulty operating the robotic platform; stress; and their evaluation about the robot's speed and interaction.

4.5 Results

The proposed device could accompany all participants during the experiment. By using the MOCAP data, we analyzed the oscillation between the platform and the participant in the three conditions. In

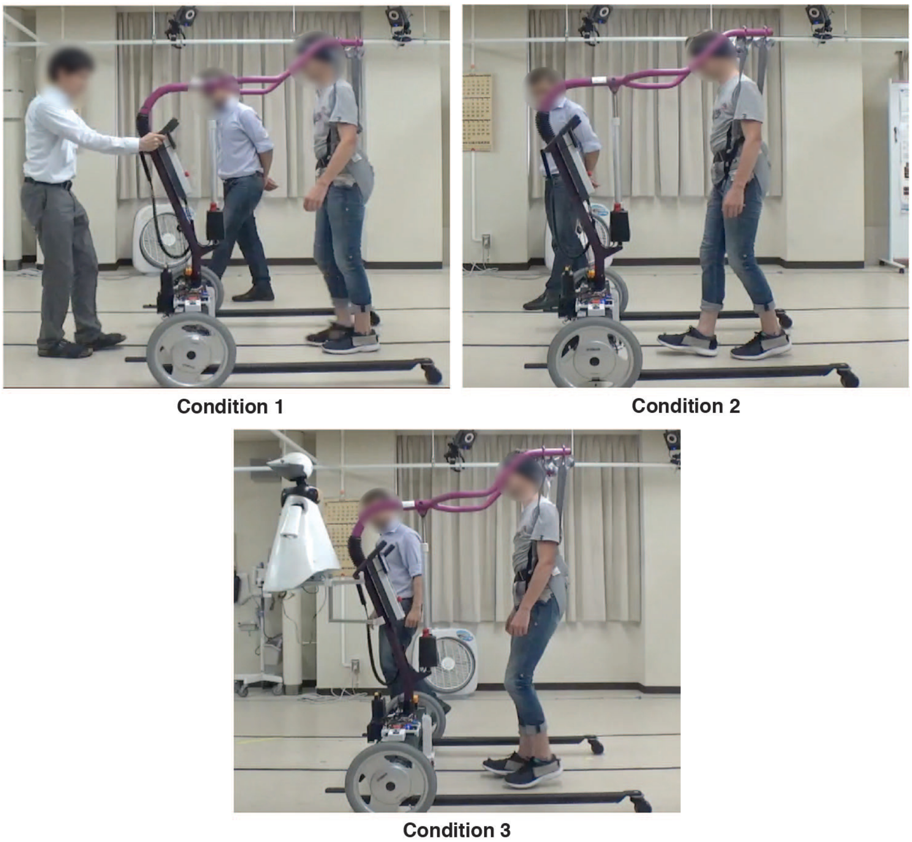

FIGURE 4.4: Participant performing the experiment with: Condition 1) the therapist; Condition 2) the autonomous platform; and Condition 3) the social robot

condition 1 (with the therapist), it was noticed more oscillation of the platform than in conditions 2 and 3 (both with our autonomous platform). Furthermore, in the condition with the autonomous platform, it was noticed a peaks in the speed of the platform, which suggests resistance of the platform to stop the movement. Figure 4.5 shows the speed variation of a participant-platform in the three conditions. Since conditions 2 and condition 3 represents the same control strategy, we compared the oscillations by calculating the envelope of the platform-participant distance in condition1 (with the therapist) and condition 2 (with the autonomous platform) for all the participants. Figure 4.6 shows the envelope for a given participants in the condition with the therapist and the autonomous platform.

The mean of the envelope of all participants was calculated. It can be seen lower amplitude in distance in four of five participants in condition 2 when compared to condition 1. Figure 4.7 shows the average of the envelope for all participants.

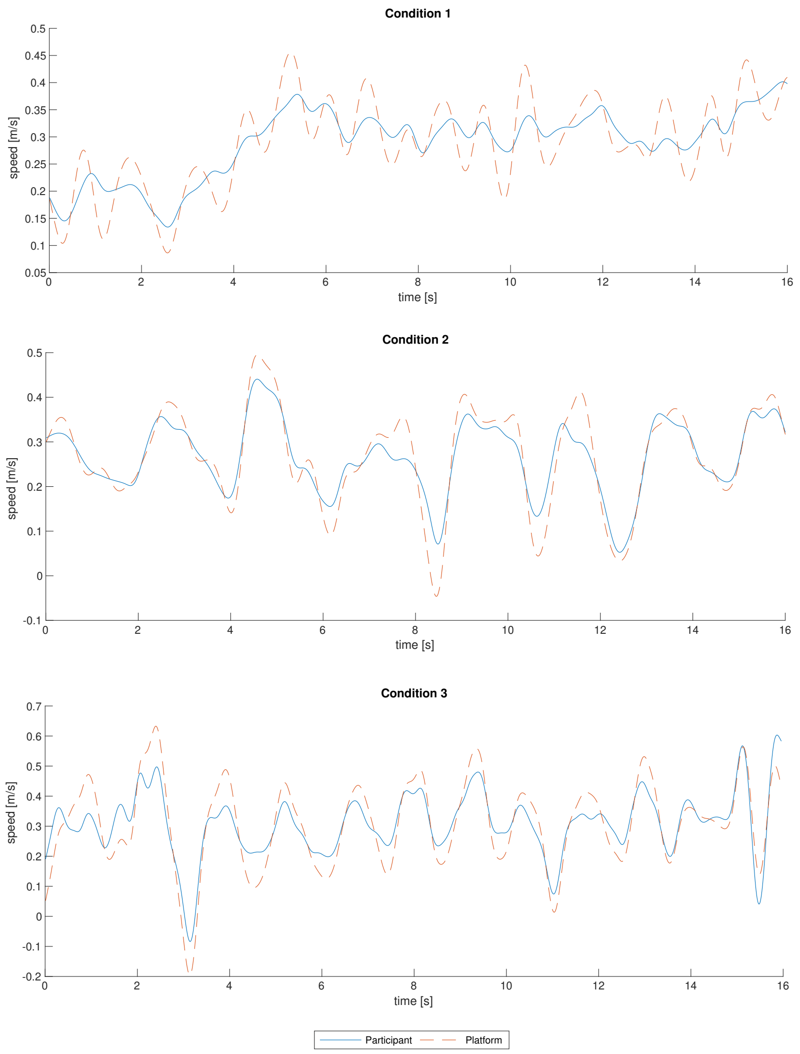

FIGURE 4.5: Participant-platform speed in the three conditions (1) with the therapist, (2) with the autonomous platform, (3) with the autonomous platform and social robot

Although different speeds were observed in condition 1, speed was slower in condition 2 (C1: $0.48^{\pm 0.22}$m/s C2: $0.34^{\pm 0.14}$m/s). In condition 3, some participants increased speed while some decreased when compared to condition 2. It was noticed also different step-length and cadence of participants in all the conditions. Figure 4.8 shows the gait pattern of participants in the experiments.

During walking with the social robot (condition 3), the pitch angle of the participants' head stayed slightly higher than in the first and second conditions. Moreover, when walking only with the platform (condition 2), it was noticed that participants looked more often

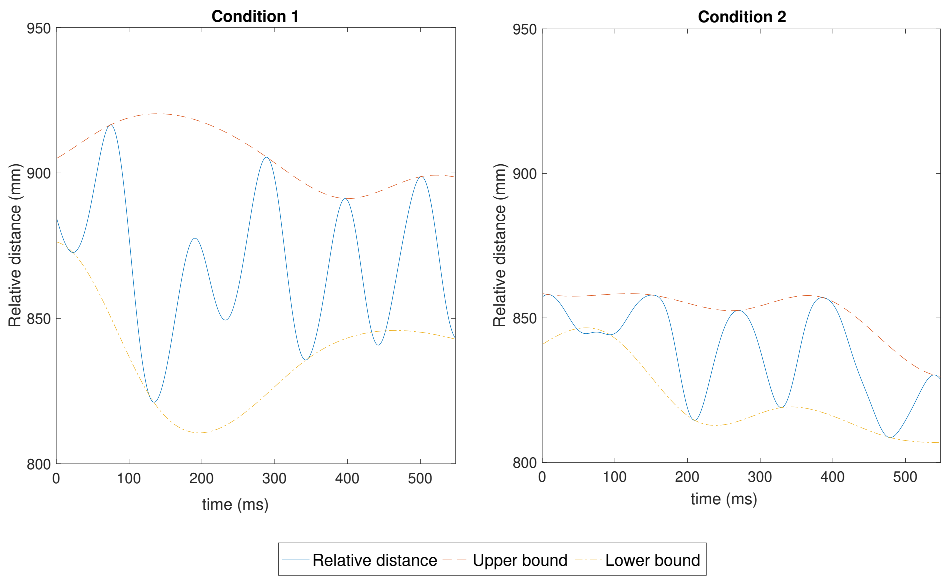

FIGURE 4.6: Envelope of the distance between the platform and a participant in condition 1 (with the therapist and condition 2 (with the autonomous platform).

to their feet, resulting in a lower average. Figure 4.9 illustrates the average head orientation during the experiments.

Questionnaires were applied to participants and the results were used as feedback for further design improvement (Table 4.1). In the conditions with the social robot, assessment from questionnaires indicate slight improvement in the the participants' feeling of comfort (C1: $4.7^{\pm 1.4}$, C2: $4.7^{\pm 1.5}$, C3: $5.2^{\pm 0.7}$), independence (C1: $2.8^{\pm 1.6}$, C2: $3.7^{\pm 1.4}$, C3: $4.7^{\pm 1.5}$) and motivation (C1: $4.7^{\pm 2}$, C2: $3.8^{\pm 1.8}$, C3: $5.8^{\pm 1.2}$). Moreover, comparing the robotic platform with and without the social agent, stress (C1: $2.8^{\pm 1.8}$, C2: $3.8^{\pm 2}$, C3: $2.7^{\pm 0.7}$) and nervousness (C1: $2.7^{\pm 1.5}$, C2: $2.8^{\pm 1.5}$, C3: $2^{\pm 0.6}$) were higher in the condition only with the robotic platform.

4.6 Considerations

We proposed the design of a robotic platform to assist therapists by physically and socially supporting patients during gait training. The study took into consideration the feasibility of a robotic system to accompany patients during gait rehabilitation treatment, adapting to the patients' proxemics in the same manner that the therapist does. Besides, by introducing a social robot, we examined the potential of

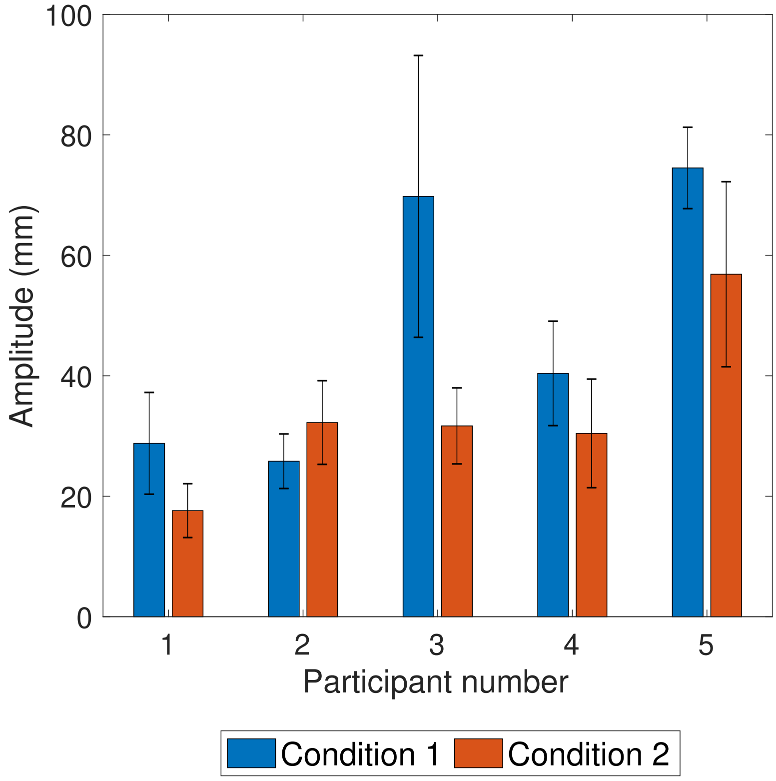

FIGURE 4.7: Average in amplitude of the participant-platform distance variation in conditions with the therapist and with the autonomous platform

an anthropomorphic entity to increase the perceived feeling of motivation and influence head orientation during walk training.

For the gait pattern, the higher speed of participants noticed in condition 1 may be explained as an influence of the therapist in the task. We suspect that the decision on the speed was not only done by the participant but rather by a turn-taking between the participant and the therapist. Even though the therapist was instructed to pull the device in accordance with the participants' gait, it was inevitable for the therapist to interpret and estimate the intended speed of the participants. Even for healthy subjects, having about 50 percent of the weight supported by the device and being constrained by the slings, it was difficult for them to move the center of mass in the moment of full step-length. In this sense, the true intended speed of the participants can not be defined, and hence interpretation comes into play. The therapist is actually facing a challenging exercise of pulling 50 percent of the weight of a participant and the device while

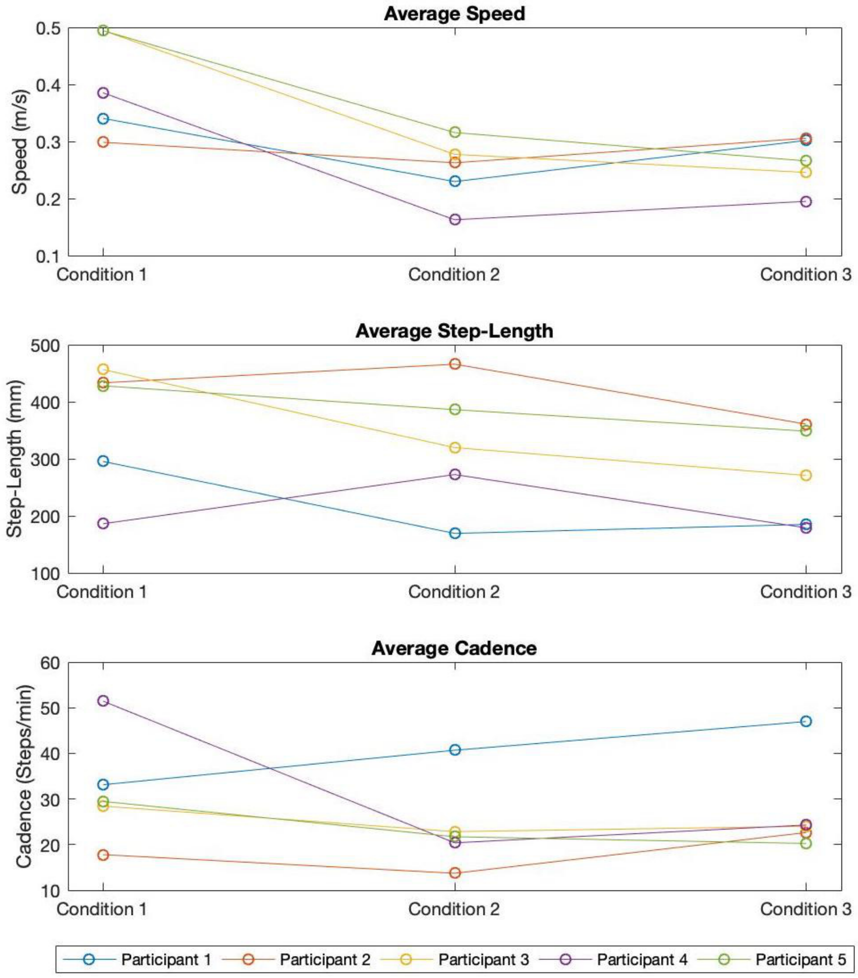

FIGURE 4.8: Walking speed, step-length and cadence of participants in the three conditions

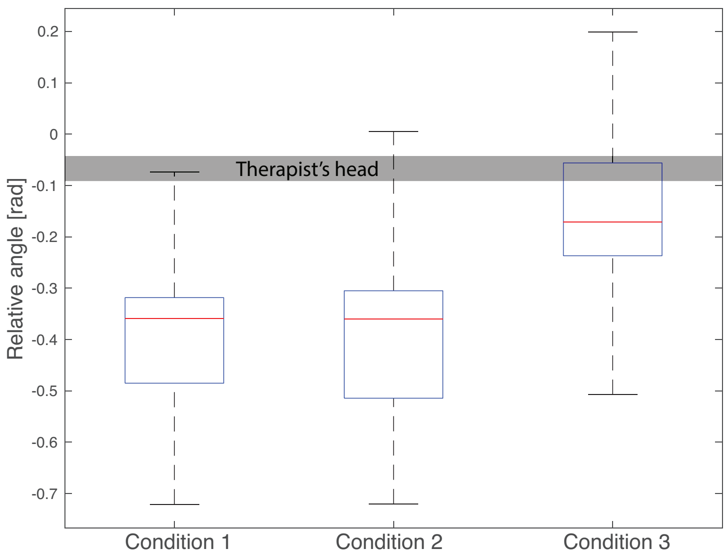

FIGURE 4.9: Average of the head orientation of participants in the pitch angle

estimating the intended speed, which may make the therapist dictate the speed instead of the participant at some instances. During experiments, the participants were told to walk freely, which may explain the lower speed in the second and third conditions.

TABLE 4.1: Results from questionnaire concerning the introspection of participants about the activity.

Question	Therapist (Condition 1)	Autonomous Harness (Condition 2)	Autonomous Harness + Social Robot (Condition 3)
It was feeling comfortable during the experiment	$4.7^{\pm 1.4}$	$4.7^{\pm 1.5}$	$5.2^{\pm 0.7}$
I felt pressure or resistance for walking faster/slower	$4.2^{\pm 1.2}$	$4.7^{\pm 2.2}$	$4.0^{\pm 1.7}$
The task was stressful	$2.8^{\pm 1.8}$	$3.8^{\pm 2.0}$	$2.7^{\pm 0.8}$
I was feeling nervous	$2.2^{\pm 1.5}$	$2.8^{\pm 1.8}$	$2.0^{\pm 0.6}$
I felt independent to walk, even being supported by the harness	$2.8^{\pm 1.6}$	$3.7^{\pm 1.4}$	$4.7^{\pm 1.5}$
I was motivated to walk	$4.7^{\pm 2.0}$	$3.8^{\pm 1.8}$	$5.8^{\pm 1.2}$
The task was hard to follow	$2.5^{\pm 1.8}$	$4.0^{\pm 2.0}$	$2.8^{\pm 1.3}$

*Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree)

Chapter 5

Discussion

By conducting experiments with different groups of individuals with limited mobility, it was possible to extract the similarities regarding their need for a walking companion. In study A, although their major burden be the social interaction, a robot to be employed for this purpose has to be endowed with mechanisms to provide light physical support and cognitive assistance. Also, it is important a robot not only responsible but instead able to proactively support them if necessary. In this collaborative scenario, the behaviors emitted by the robot have to be not too appealing– which may distract its users leading to risks, neither too soft putting its user in danger for not understanding the alert.

5.1 Control Strategy

In both experiments, our Walking Companion Robot could accompany participants during training without the need for technical intervention. In study A, due to the complexity of an open environment, we considered a passive (adaptive) companion robot. During experiments, we could verify that the exchange of the robot from a passive to an active mode could elucidate the attention of users. This haptic feedback can be used to draw its user's attention in case of any situation during walking. In study B, since rehabilitation sessions are generally performed inside hospitals, the variables during locomotion could be partially controlled.

The human-robot distance is used to control the speed of the robot in both studies. In the case of study A, the acceleration/deceleration was defined smother. We believe that it can allow better comfort for users when dealing with the robot. Also, since humans also take time to stop gait, we consider it should sound natural to participants. On the other hand, in study B, the user is attached to the robotic harness by cables, and the delayed response of the robot would result in undesired movement to the participant. In this case, our robotic platform is more responsive to the intentional movement of users in order to avoid oscillations. By comparing the MOCAP data collected during experiments of participants walking in the condition with our platform and with the therapist, we could observe that the platform was more responsive in the intended movement of the participants. It is important to notice that the oscillation in the platform may create horizontal forces on the user, which may influence their balance and also compromise the feeling of comfort.

5.2 Motivating Through Physical Interaction

In chapter 2, we highlighted the benefits of pets to motivate individuals to walk. Similarly, a robot able to socially interact with its users may also be beneficial to motivate them to walk. We believe that our robot can motivate individuals to exercise not only by using social interaction but also by providing physical support. In study A, for instance, besides the social robot to accompany people during walking, the light-touch offered by the robot may contribute to balance and even to minimize the fear of falling in the elderly. In study B, the platform is intended to assist the voluntary leg movement into locomotion by displacing the COM. This can contribute to the feeling of independence of participants with neurodegenerative diseases that rely on therapists and caregivers to assist them in their movement.

5.3 Social Interaction

Different modalities were explored instead of verbal communication. The first reason to avoid verbal communication is that voice commands may require higher cognitive load from participants, which may compromise their task. Moreover, we avoided direct command once it may force participants to look at a specific place, compromising their gaze orientation and optic flow. We focused on two modalities for non-verbal communication, haptic and gestural communication. In study A, the robot suggests the intended direction by head movement. Since individuals walking side-by-side do not have to keep looking to their partner, we included light haptic signal that is done by the robot when offering resistance to move. On the other hand in study B, since the robot is fixed in front of the participant, we only used gestural communication to call users' attention.

It could be noticed during video analysis with patients that some of them were looking down during the session. Although we could not clarify the reasons for this to happen, he hypothesize some reasons. Firstly, patients may look down to avoid gaze contact with the therapist that is pulling the harness in their front. In most cultures gaze contact is embarrassing for people, in special for long period of time. Secondly, since the therapist has to look down to monitor the feet position of patients to control the platform, it may generate a situation of joint attention. Lastly, neurorehabilitation has a high demands on patients to relearn how to move the limbs properly. During this process, participants may look to their feet due to the complexity of the movement.

In study B, the anthropomorphic robot was used to draw individuals attention and affect their overall head orientation. The decision for using an anthropomorphic robot instead of a display comes from authors such as Fasola et al. [34], which argues that users are more responsive to a robotic entity instead of a virtual agent. We also avoided explicit command for participants to look up, since it could influence on participants freedom to look around and have optic flow.

Chapter 6

Conclusion

We conducted experiments to verify the dynamics involved in individuals when walking along with a partner. For this, we proposed two Walking Companion Robots to support participants in the scenario of side-by-side walking with light touch assistance, and of body-weight supported walking for individuals with gait impairment. We could confirm that our control strategy, which uses the feet position of its users to estimate their intended movement, could be used to accompany participants in both scenarios. Furthermore, we proposed an effective manner to collect gait data in real-time, which can be used by therapists to evaluate the progress of the treatment. To assist participants during walking, we proposed gestural communication and haptic feedback, which can be used to draw users' attention and transmit simple information. We believe that different modalities of communication can complement verbal communication and turn the social interaction more pleasant for participants.

By analyzing participants' data when walking in different scenarios, we could clarify some social dynamics involved during the interactions. During the study with body-weight supported walking, for instance, we could attenuate the low head orientation with a social robot that could influence participants' attention. Also, the oscillations verified during the human-platform-therapist interactions could give us some insights on how therapists move the platform when guiding participants. It could be used to improve our control strategy to adapt better to participants' speed and decrease the overall oscillation.

6.1 Contribution of this Work

By clarifying some of the social dynamics of individuals during walking with a partner, this work may contribute to developing walking companion robots able to reproduce behaviors that seem more compatible with a real human companion. Also, we proposed in this work the combination of physical support and social interaction to assist individuals during gait training. This combined approach may be useful to increase the acceptance of users to interact with a robot during exercises.

We performed many experiments to estimate the users' intended movement by using their feet position in the scenarios of side-by-side and frontal walking. Finally, we proposed an adaptive control strategy that can be used for a robot to locomote along with people as a walking companion.

6.2 Future Directions

6.2.1 Improving Intention Estimation

A robot to collaborate with humans needs to rely on intentional cues to advance its behavior. Thus, early estimation of users' intended movement can result in more precision in the collaboration. Estimating humans' intention is done by observing their initial actions in a given context. The precision of estimation can be increased if different modalities are considered. During gait rehabilitation, patients are usually hanged to a walking harness to unload their body weight. We propose a method to estimate the intended movement of users by monitoring the distribution of their body load when supported by the harness device. For this, load-cells can used to monitor their center of mass and indicate accelerations that may suggest their desired direction. Finally, load distribution can be combined with feet position to provide more assertive estimation.

6.2.2 Challenging participants during exercise

Therapists have to dose the comfort of their patients with the progress of the treatment. If the exercise is too light, patients may take longer to recover and feel unmotivated. On the other hand, if over challenged, patients may feel pressure and abandon the therapy. The amount of challenge seems to be subjectively selected by therapist based on their experience and the progress of the patients. In this study, we propose a control strategy that includes challenging behaviors during walking treatment. For this, our robot can be used to collect gait data, which can track the progress of patients throughout the sessions. Moreover, it can also be used with other sensors to monitor the interaction of the therapist with patients to clarify the mechanisms that therapists use to influence participants.

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