A Study on a Socially Assistive Humanoid Robot as a Walking Companion for Elderly Individuals

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Abstract

The purpose of this research involves designing a socially assistive humanoid robot as a walking companion for elderly individuals. Because of the world-wide population ageing phenomenon, several researchers focused on exploring new methods to improve the quality of life of elderly individuals by allowing them to remain independent and healthy to the maximum possible extent. For instance, new walking aids are designed to allow elderly individuals to remain mobile in a safe manner because the importance of walking is well-known. In this study it is hypothesised that the same companion robot provides an assistive and social contribution during the interaction between elderly users by guiding them and, simultaneously, by providing gait monitoring while walking. This study includes a detailed statement of the research problem as well as a literature review of existing studies related to walking companion robots. A user-centred design approach is adopted to report the results of two feasibility studies by using a commercially available humanoid robot known as Pepper developed by Softbank-Aldebaran. A quantitative questionnaire was used to investigate all elements that assess intrinsic motivation in users while performing a given activity. Conversely, basic gait data were acquired through a video analysis to test the capability of the robot to modify the gait of human users. The results in terms of the feedback received from elderly subjects and the literature review improved the design of a new humanoid robot, with less degrees of freedom and a simpler design. In the second part, the new robot's abilities to monitor gait parameters and to express its intent in a mixed-initiative interaction were tested in two distinct experiments. The main contribution of this work is the finding that a robot with a simple design could perform both the functions of following and guiding older participants while walking.

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This work is dedicated to my dad and mum who have been always a constant source of support and encouragement during all my life.

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List of Abbreviations

AAL	**A**mbient **A**ssisted **L**iving
DPI	**D**irect **P**hysical **I**nterface
HRI	**H**uman **R**obot **I**nteraction
IMI	**I**ntrinsic **M**otivation **I**nventory
MAE	**M**ean **A**bsolute **E**rror
SD	**S**tandard **D**eviation

Chapter 1

Introduction

1.1 Background

1.1.1 Elderly Care: New Challenges Ahead

There is a constant increase in the number of individuals over the age of 65. Projections indicate this will approximately correspond to 1.5 billion in 2050 [1]. Consequently, pressure on national pension plans and long-term health care is increasing. Simultaneously, the number of working-age adults available to support elderly individuals is decreasing due to declining birth rates and increased longevity [1]. Health systems of individual governments should be prepared to address the fore-mentioned issues at the earliest.

United Nations' estimates [2] indicate that the most common diseases that affect older women over 60 years correspond to unipolar depressive disorders, hearing loss, back and neck pain, Alzheimer's disease and other dementias, and osteoarthritis. Among older men, the main causes of disability include hearing loss, back and neck pain, falls, chronic obstructive pulmonary disease, and diabetes mellitus [2].

Dementia is an umbrella term that indicates all diseases that are characterised by the progressive impairment of brain functions. Unfortunately, there are no cures for dementia to date. Among the diseases listed above, dementia is considered one of the biggest health concerns in developed countries nowadays, mainly because it is a devastating disease both for the patient himself and for his loved ones, and because it is a new problem that in the past we did not have to deal with.

In the last century, medical treatments for several and different physical illnesses have been found, making life expectancy longer than ever before. However, there is not yet a cure for the cognitive decline that affects some people after a certain age. The worldwide number of persons with dementia in 2000 was estimated at about 25 million, which corresponded to 6.1% of the population over 65 years of age. The number of people affected will double every 20 years to 81-100 million by 2040 [3].

1.1.2 The Benefits of Walking

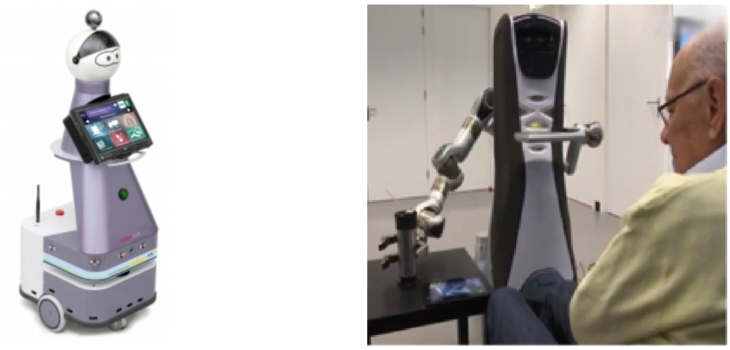
In order to decelerate or even prevent cognitive decline, doctors recommend living a healthy life by following a healthy diet, performing physical exercise, and challenging the brain via social engagement or intellectual stimulations. Thus, it is important to perform any activity that keeps the brain active and improves blood circulation. Specifically, physical exercise is an important part of a healthy lifestyle that increases the sense of wellbeing of an individual. Walking itself is a completely accessible way of physical exercise because it suits all abilities, it is free, it does not require equipment, and it can be performed anywhere. Moreover, walking in an outside environment leads to interaction between an individual and others, and thus it can correspond to a social activity that can improve an individual's mood. There is no definitive evidence from randomised trials although studies continue to explore the potential of walking as a preventive treatment for dementia as well as a disease-modifying treatment [4, 5]. A main question focuses on whether physical activity directly protects an individual from dementia by providing better oxygen supply or instead whether it offers indirect protection by reducing risks, such as hypertension, that impair cognition. In any case, walking must be considered as extremely important for elderly individuals due to its role in modifying the progress of the previously mentioned diseases, *e.g.* diabetes [6], was scientifically proven by extant studies. Moreover, monitoring the right gait parameters during walking (Section 2.4) could aid in measuring balance, and thus prevent falls that are another cause of disability based on United Nations' estimates. Gait and balance disorders increase indeed with age, ?from around 10% between the ages of 60 and 69 years to more than 60% in those over 80 years [7].

1.1.3 Recent Network Robots for Elderly Individuals and Acceptance Issue

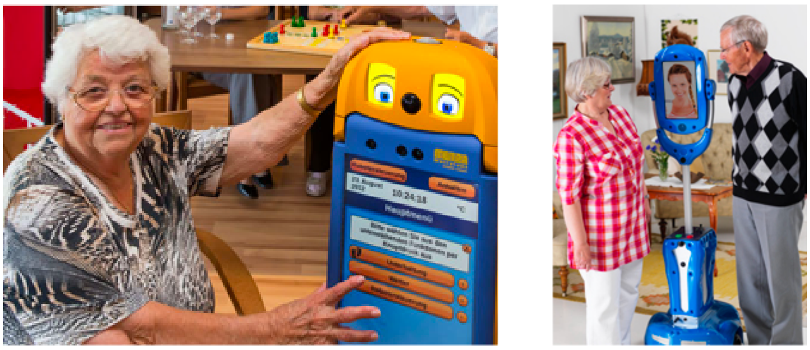
The expected growth in the population of elderly individuals has influenced researchers to design innovative solutions in the field of eldercare including robots. Assistive Human-Robot Interaction involves robots that are designed to aid individuals through physical, social, or cognitive assistance [8].

A newer technology trend involves aiding elderly individuals to remain at home and live independently to the maximum possible extent. Several projects focus on ambient assisted living (AAL) [9] and follow the same basic approach wherein a house becomes a smart environment that is full of sensors that provide services such as indoor user localisation, activity and event recognition, user health status assessment *etc.*, and a service robot is integrated with other types of assistive devices by the cloud [10]. Such robot is an embodied interface of the smart systems for net-living environment. By considering human factors, this robot aims to help people at home or in a nursing home and to contribute to enhancement of quality of life.

The robot in these cases typically corresponds to a wheel based mobile platform with a touch screen for a user interface - *e.g.* Kompai in the Domeo project [11], Care-O-bot in the Accompany Project [12] and ScitosG3 in the Companionable Project [13] - or with a video for telepresence - *e.g.* the Giraff robot in the Excite Project [14]. The shape of the service robot is related to its tasks, *e.g.* to provide telepresence services to enable communication with elderly individuals or with medical staff to perform basic actions such as handling an object or to provide reminders about appointments. Cloud technology is an important solution that must be considered because it makes a robot cheaper and more efficient and provides opportunities to store additional information and to access knowledge provided by other sensors around the house.



(A) Domeo project [11]
(B) Accompany project [12]



(C) Companionable Project [13]
(D) Excite project [14]

FIGURE 1.1: Different service robots in Ambient Assisted Living projects

In a manner similar to any commercial product, the success of a robot mainly depends on the level of acceptability perceived by the users. In the case of the present study, target users correspond to elderly individuals who may be more vulnerable and definitely possess individual necessities that should be addressed. An individual accepts and uses a certain tool if the following requirements are met: the individual possesses a motivation to use it, he/she considers it easy to use, and he/she feels physically and psychologically comfortable using the same. Therefore, it is important to initially understand the motivations of elderly individuals to accept or reject a new technology. Questionnaires are usually used to quantitatively evaluate users' response during experiments. For example, the Almere Model [15] was specifically designed to test the acceptance of socially assistive robots by older adults in a care home and was then successfully used in [16].

1.2 Purpose of this Research

1.2.1 Final Aim and Engineering Problems

Given the reasons specified in the previous sections, the final aim of the current study involves designing a socially assistive humanoid robot as a walking companion for elderly individuals.

The target users correspond to older individuals who can walk by themselves or by using a walking aid, *e.g.* a cane or a walker, and are sufficiently mentally healthy to use a robot. The specific scenario corresponds to the development of a personal robot that can stay at home with a user and convince him/her to go out given the advantages of leaving the house and meeting other individuals outside as described in Section 1.1.1.

This walking companion should provide an assistive and a social contribution during the interaction: it should guide the user and, at the same time, it should monitor his gait (Section 2.4). An encouraging behaviour, based on intrinsic motivation theories (Section 2.2), could ensure that a user understands the importance of walking. An appropriate design allows the same robot to make two contributions to the interaction, namely social and gait assistive contributions (Figure 1.2).

With respect to the guiding function, we have the most challenging problems to solve: first of all, the robot should be able to monitor and track the user in an efficient way and, secondly, we do not know if the robot will be accepted by the target users and if it will be able to successfully modify their gait. In the case of a different interaction between the user and the robot, *i.e.* the robot may follow or guide the user, we have to solve different problems. To design how walking together works is indeed complicated (Section 2.3).

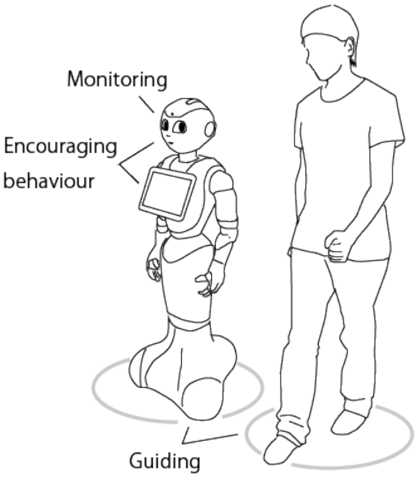


FIGURE 1.2: Potential walking method with a socially assistive humanoid robot. The picture highlights different aspects of the interaction: the same robot guides a user by encouraging him/her to walk more by using its voice and its tablet and simultaneously monitors his/her gait

1.2.2 Research Questions and Hypotheses

A hypothesis with respect to the design is as follows: in the past, physically embodied social robots were designed to exhibit human-like social behaviours to create an interaction as similar as possible to an interaction between two individuals in which a human user knows the rules and knows how to behave. Thus, a human-shaped robot can perform human-like actions, and therefore its gestures can be easily understood and it is accepted if an appropriate behaviour is selected (Section 2.1). A second hypothesis regards the efficacy of intrinsic motivation theories (Section 2.2).

A proper design is definitely required to fulfil the double task of our walking companion robot. An understanding of the needs and expectations of target users' in a specific situation involving walking with a robot improves the design of the robot. A user-centred design approach involves including target users at the beginning of the design process and maximises the acceptability of the system [17]. Therefore, the first step in the current study involved performing two feasibility studies by using a commercially available robot. These results were used in the design of the new walking companion robot. In other two experiments, its ability to monitor the user gait and to trigger his/her behaviour through non-verbal communication were under investigation.

To summarise, the main question we wanted to answer to, which is the novelty of this research, regarded the interaction itself between the user and the robot: will the robot just be able to follow the user or will it be able to guide and modify his/her gait during walking?

1.2.3 Research Outline

In Chapter 2 the past works related to this research are presented and reviewed: Socially Assistive Robots and their non-verbal communication in Section 2.1, persuasive technology in Section 2.2, accompanying robots in Section 2.3 and gait measurements systems in Section 2.4.

In Chapter 3 the requirements and methodology of designing a HRI while walking together is explained.

In Chapter 4 the two humanoid robots used in this research are shown: in the feasibility studies a commercially available robot was used (Section 4.1), a new walking companion robot was then designed and tested (Section 4.2).

Chapter 5 presents the methodology and the results of the feasibility studies, the first one with younger participants (Section 5.1) and the second one with older participants (Section 5.2). In order to test the users' acceptance, a intrinsic motivation inventory questionnaire was adapted to our experiment (Section 5.3).

Chapter 6 shows the two experiments with the new designed walking robot: the first one about gait measurement by the robot (Section 6.1) and the second one about robot compliance in an obstacle avoidance scenario (Section 6.2).

Chapter 7 provides a discussion about the results of the feasibility studies (Section 7.1) and of the last two experiments (Section 7.2 and 7.3).

Finally, Chapter 8 summarises the contributions of this work (Section 8.1) and the future directions (Section 8.2).

Chapter 2

Related Works

2.1 Socially Assistive Robots and Non-Verbal Communication

According to the International Federation of Robotics [18], a service robot is 'a robot which operates semi or fully autonomously to perform services useful to the well being of humans and equipment, excluding manufacturing operations'. In the case of elderly users, it could provide three different types of services (Figure 2.1). A healthcare robot could detect falls and send alarms, monitor the location of people, measure vital signs or provide medicine reminders. A chore robot could assist in lifting heavy things, delivering drinks or cleaning. A social robot could provide companionship. Another well-known category includes Socially Assistive Robots, which are designed to help and address social needs through interactions of a specific category of users, like elderly individuals indeed [19]. A very famous example in this category corresponds to Paro, a touch-sensitive seal robot that successfully produced positive effects for dementia patients, such as mood improvement and a calming effect, in several experiments worldwide [20].

Human beings have the capability to communicate and understand intuitively each other's intents from their verbal (speech, vocal prosody *etc.*) and non-verbal actions (eye gaze, facial expression, gestures, proxemics *etc.*). This mutual understanding increases the pleasantness and safety of the interaction during joint tasks. Even

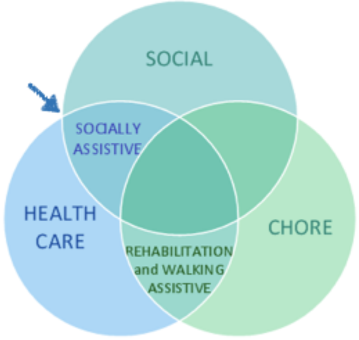


FIGURE 2.1: Service robots for elderly users

(A) Paro robot [20] (B) Palro robot [21]

FIGURE 2.2: Two examples of Socially Assistive Robots

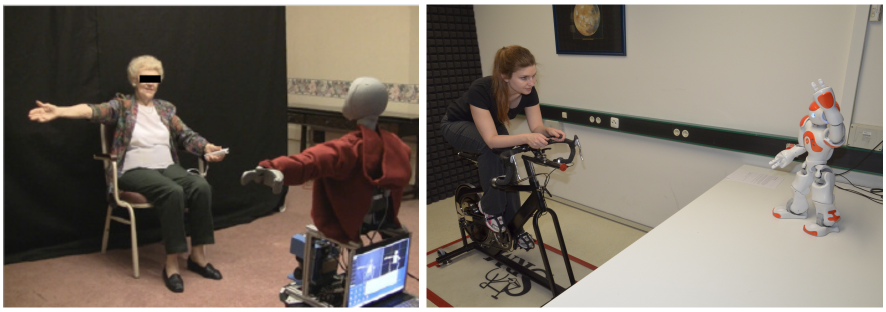
if verbal communication tends to be primary, nonverbal actions can convey mental state, augment verbal communication, or reinforce what is being said. Therefore, anthropomorphic components (head, eyes, arms *etc.*) are sometimes added on companion robots to make their actions similar to the ones humans make, thus more easily understood by the human user. Neuroscience research in the last 15 years suggests that actions of very human-like robots may activate the human mirror neuron system as actions of another human do [22]. Several studies indicated that physically embodied robots offer more engaging, enjoyable, and effective social interactions when compared to those of virtual agents [23].

2.2 Persuasive Technology

Persuasion, or motivation, is a method to increase the will to perform a certain behaviour. Psychologists distinguish between extrinsic and intrinsic motivations [24]. The first one occurs when individuals are motivated to engage in an activity to earn an external reward or avoid punishment. In contrast, the latter one involves performing an activity because it is personally rewarding, *i.e.* given that users find the activity itself enjoyable.

In the case of physical exercises, extant studies indicate that intrinsic motivation corresponds to most effective motivations [25]. Health professionals can better motivate older patients if they clearly explain the instructions and emphasize the importance of exercises. Reinforcement techniques are also suggested, *e.g.* giving positive feedback if the patient succeeds and encouragement if he/she stops, or to showing the current score compared to the point when the goal is reached.

In the early 2000s, Fogg [26] invented a new discipline of persuasive technology to explain the power of technology to change user attitudes and behaviours. Schneider *et al.* [27] showed the results of a long-term experiment on indoor cycling training with healthy subjects and in two different conditions: in a case they were instructed



(A) Fasola *et al.* [28] (B) Schneider *et al.* [27]

FIGURE 2.3: Two experiments where a robot motivated the users to perform a given physical activity

by a humanoid robot, and they were instructed by a display in another case. To the best of the authors' knowledge, Fasola *et al.* [28] performed the only experiment with a robot that was used to motivate older people during physical exercises. An intrinsic motivational strategy was applied following suggestions by psychologists in which a robot provided continuous feedback in real time, *e.g.* praise in the case of success or corrections if needed, and encouragement.

2.3 Accompanying Robots

Recently, there is an increase in studies on robots accompanying individuals. Researchers focused on the human users' social perceptions and level of comfortableness and investigated new methods to solve motion planning and control problems of detecting and following an individual in a static or dynamic environment. Table 2.1 summarises a few studies and shows the different locations of the robot with respect to the human user based on different tasks and scenarios. Side-by-side walks correspond to the most investigated phenomena because they are considered as the most natural type of interaction during walking. In most cases, the robot follows the human user during the interaction. Pandey *et al.* [29] and Leica *et al.* [30] defined this type of interaction as unilateral in contrast with the interaction in which a robot guides a user to a predefined goal that is subsequently defined as bilateral. In the final case, the robot must guide as well as interpret the human partner's behaviour - *e.g.* if the person experiences walking difficulties or does not want to continue following the robot *etc.* - and changes its behaviour based on the same. Physical contact is present if a direct physical interface (DPI) corresponds to the object of study. A DPI is an interface that enables a user to move the robot or influence its behaviour by making contact with its body, thus it must be intuitive, safe and effective [31]. Existing methods include using a 6 axis force/torque [31], reading the servo motors data of the robotic arm in combination with the

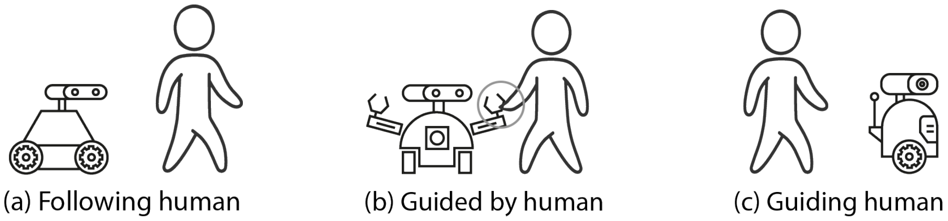


FIGURE 2.4: (**a**) The robot tracks a human user and continues to follow the user (**b**) The human user controls and moves the robot through direct physical contact (**c**) The robot guides and influences the human trajectory towards a goal

laser range sensor data [32], or reading the DC's motor torque which is proportional to its armature current [33]. Figure 2.4 summarises these three cases of interaction type.

When social perceptions are investigated, proxemics rules from human-human interaction studies are typically considered [34]. Proxemics is the study of how humans use and manipulate distances between each other with respect to social and cultural norms and perceptions. Individuals use proxemics signals, such as distance, body stance, hip and shoulder orientation, head poses, and eye gaze, to communicate an interest in initiating, accepting, maintaining, terminating, or avoiding social interactions. All individuals occupy space for themselves and respect the spaces occupied by others. The social-spatial distance varies with respect to the degree of familiarity between interacting humans, by the type of activity, or by the number of interactors. For example, an increase in the distance between strangers increases the comfort. The orientation is another important element that should be considered because most individuals prefer an increased distance with respect to an individual in front of them than with respect to an individual beside them [34]. Several human-robot interaction trials were performed to investigate the effect of combinations of various factors, such as robot's appearance and behaviour, or different situations, or human users' age and gender *etc.*, on the relative location and the comfortable distance that an individual allows between himself and a robot [35, 36].

2.4 Gait Measurement Systems

Normal walking appears rhythmical, flowing and with freely swinging legs. When the walking is not like the one just described, we talk about gait and balance disorders which increase with age, from around 10% between the ages of 60 and 69 years to more than 60% in those over 80 years [7].

TABLE 2.1: Extant studies on the specific interaction in which a human and a robot move together

Author	Year	Interaction type	Location with respect to human	Robot shape	Touch	Purpose
Prassler [37]	2002	Following human	Beside	Wheelchair		To follow the human nurse
Jin [38]	2006	Following human	Beside and in front	Mobile base		To detect and follow the human
Gockley [39]	2007	Following human	Behind	Mobile base with screen		To find the more human-like behaviour for the robot
Hoeller [40]	2007	Following human	Behind	Mobile base		To follow a human target in a dynamic environment
Morales [41]	2012	Following human	Beside	Humanoid		To find the more human-like behaviour for the robot
Kobayashi [42]	2012	Following human	Beside and in front	Wheelchair		To follow the human nurse
Ferrer [43]	2013	Following human	Beside	Humanoid		To follow the human in a dynamic environment
Morales [44]	2014	Following human	Beside	Humanoid		To find the best side-by-side behaviour toward a common goal
Oishi [45]	2016	Following human	Several locations	Mobile base		To change behaviour according to human's activity
Spenko [46]	2006	Guided by human	In front/beside	Smart walker	X	To provide support, guidance and health monitoring
Chen [31]	2010	Guided by human	According to user	Mobile base with robotic arms	X	Direct physical interface to guide the robot
Yamamoto [32]	2013	Guided by human	Beside	Mobile base with robotic arm	X	To study communication during hand-in-hand walk
Dabrowski [33]	2014	Guided by human	Beside	Humanoid	X	Direct physical interface to guide the robot
Kochigami [47]	2015	Guided by human	Beside and in front	Humanoid	X	Direct physical interface to guide the robot
Leica [48]	2017	Guided by human	In front	Mobile base	X	Direct physical interface to guide the robot
Pandey [29]	2009	Guiding human	Beside and in front	Mobile base with robotic arm		To design the most social behaviour for a robot guide
Leica [30]	2015	Guiding human	Beside and in front	Mobile base		To design a bilateral interaction to guide the human user

Several walking aids were designed to physically assist elderly individuals and improve their balance, *e.g.,* walkers and canes, because balance impairment due to age is quite common. An analysis of walking patterns is considered important since gait alterations may reflect a pathology, *i.e.,* neurological or musculoskeletal disorders [49]. With respect to quiet standing, the position or the velocity of the centre of pressure in the anterior-posterior plane is typically calculated. While walking, it is possible to measure several gait parameters in both the anterior-posterior plane and mediolateral plane including step width (the perpendicular distance from a heel/toe to the line of progression of the other heel/toe), step length (the distance from the initial contact point in a foot to the initial contact point in the other foot), cadence (walking rate, *i.e.* the number of steps per minute), and walking speed (the product of step length multiplied by cadence). All the fore-mentioned parameters are related to body sway [50, 51], and thus observing the same can reduce the risk of falls. Falls may cause physical injuries as well as restrict mobility and lead to social isolation, which may result in depression [52].

Typically, these gait parameters are monitored in hospitals by health experts. Force plates and motion capture systems, such as VICON [53], are commonly used with good reliability. However, few observations in a hospital could not insufficient for early detection of pathologies. Furthermore, the systems require large spaces and are expensive. In the case of using markers attached to a patient's body, the placement of inaccurate markers by palpation and markers detection losses are well-known disadvantages of these systems.

Given the fore-mentioned reasons, researchers are increasingly focusing on personal robots as a better solution because the personal robot could stay at home with an elderly individual and could be provided with an inexpensive system to measure gait parameters in a non-invasive manner. Cameras are not sufficiently robust to constantly detect the legs of a user given different clothing and different light conditions. Hence, a few extant experiments successfully detected the legs of human subjects by using a laser range sensor [54, 55].

2.5 Considerations about Past Works

In order to summarise the state of art, it is affirmed that there is an increase in studies that focus on accompanying robots during walking although difficulties persist with respect to the same, *e.g.* to investigate the best social behaviour for the robot and the best navigation and humans detection algorithms. To the best of the author' knowledge, extant studies have not proposed a walking companion robot specifically designed to satisfy the needs of elderly individuals, and thus it is necessary to investigate proxemics preferences in this specific category.

Extant studies proved that robots act as a companion and a motivator to perform physical exercises for elderly individuals, and thus there is a good possibility of designing an effective product that will be accepted by elderly users. In the study, it is proposed that a method to increase the chances of success involves including final users at the beginning of the design process.

Chapter 3

Design Methodology

3.1 Design Requirements

After the review of state of the art, some design requirements for a walking companion robot were pointed out:

- it should be a network robot, following the idea of AAL (Section 1.1.2);
- it should have sensors to provide reinforcement feedback, like a speaker (Section 2.2);
- it should have anthropomorphic components for an interaction that is easier for the human user to understand (Section 2.1);
- it should have sensors to perform the gait analysis of the human user, to effectively monitor balance, detect anomalies and to observe the influence of the robot on the user's gait (Section 2.4);
- it should have a stable mobile base for a safe interaction.

It is expected that a humanoid shape performs better in case of interpersonal communication, *i.e.* verbal language and non-verbal actions such as proxemics and body language. Thus, a humanoid can better communicate its intents to a human partner. However, the question is still what kind of body torques and what is the ideal contingency for a walking companion to be effective and accepted. In the feasibility study, the effects of proxemics were analysed (Section 5); while in the experiment about robot's compliance, some non-verbal actions were under investigation (Section 6.2).

3.2 Decide the Scenario: Guiding or Following?

When two agents walk together, there are many aspects to consider. Walking together is a joint, or a shared, task and a social relationship [56] as well, thus proxemics rules could be taken into consideration. Moreover, walking together with someone is a complicated cognitive

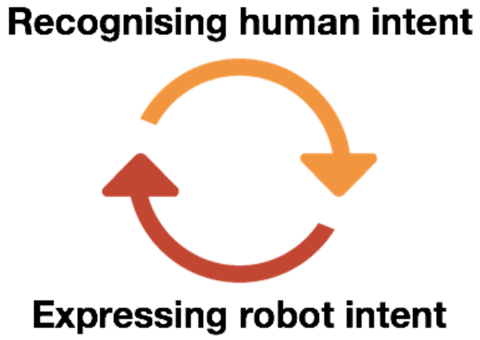


FIGURE 3.1: In a mixed-initiative HRI, the robot has to recognise human intent and express its own intent at the right time

motor task. Each agent has to make decision based on understanding of each other's perspective. Therefore, previous works did focus only on one function while designing the HRI, *i.e.* the robot just follows or, at the opposite, it just guides the human user (Section 2.3).

Nevertheless, robots should offer mutual understanding during joint tasks, like humans do, to increase the pleasantness and safety of the interaction. Figure 3.1 summarise this belief. Based on literature review [57] a mixed-initiative human-robot interaction happens when both the human user and the robot can opportunistically seize the initiative from the other when it is necessary, thus allowing the team member who is the best at the current task to take charge of it. The research questions in this field are mainly two: when one agent - the human or the robot - determines it is better to take initiative from the other agent [58], and how it communicates its initiative-taking. A common task that has been investigated in HRI is the hand-over [59]. However, to the best of the author's knowledge, extant studies have not proposed methods of initiative sharing during walking with a robot. The implemented control system of the new robot is presented in Section 4.2 and tested in Section 6.2.

Chapter 4

System Overview

4.1 The Robotic Platform A

As previously specified, for the first feasibility studies, a commercially available robot was selected because it was necessary to test the reactions of elderly individuals walking for the first time with a robot, to observe the strong points of the current robot and its limitations, to improve the future design, and to verify the effectiveness of the experimental procedures and evaluation methods.

The selected robot was Pepper, the last humanoid designed by Softbank-Aldebaran [60]. Pepper has 17 degrees of freedom. It can perform yaw and pitch rotations with its head. It can perform shoulder pitch and roll, elbow yaw and roll, and wrist yaw rotations with both arms, and it can close and open both hands. It can perform hip roll and pitch, and knee pitch rotations in the lower part of its body. The joints in the head and in the arms are sufficient to suggest the possibility of programming it to perform non-verbal gestures similar to the ones performed by humans (Section 2.1).

With respect to locomotion, Pepper possesses a system of three wheels that is definitely more stable than that with two robotic legs. Its weight approximately corresponds to 28 kg and its height corresponds to 1.20 cm, and thus it is theoretically possible for an individual to walk together with the robot leaning on its shoulder in a comfortable manner (Figure 1.2). Extant studies indicated the efficacy of light touch [61] as well as of interpersonal touch [62] in increasing balance in several experiments and mostly in standing conditions. To the best of the author′ knowledge, the influence of interpersonal touch during gait was only studied by Zivotofsky *et al.* [63] simply to observe synchronisation of gait in the case of two individuals holding hands and walking together. There is a paucity of studies to guarantee the safety of elderly individuals and to effectively enhance balance.

With respect to the motivational task of our walking companion, the design of Pepper design was potentially sufficient for the specified purpose. In addition to the humanoid shape, Pepper includes a speaker, and thus it could provide positive feedback, such as encouragement and verbal praise, to increase a participant's motivation and enjoyment while walking (Section 2.2). Table 4.1 shows examples of

TABLE 4.1: Examples of the utterances of the robot to increase the users' motivation based on intrinsic motivational theories. During the experiment, the robot speaks in Japanese since all the participants are Japanese. The English translation is reported.

During the walk	Try to follow me You are doing great You are walking really well Just few meters until the end
At the destination	Bravo! You completed the path Let's walk together again

the sentences spoken by Pepper during the experiment. Additionally, the robot has a tablet on the chest in which it shows the current score of the user, *e.g.* his velocity, the distance covered on a specific day, the number of steps needed to reach the goal fixed by the doctor for a specific day, and improvements gained since previous walks.

With respect to tracking the human user and monitoring the gait of the user, the cameras in the eyes are definitely not sufficient, and thus it was necessary to include external cameras for the sake of the experiment. A current limitation of mobile service robots corresponds to their inability to detect humans out of their sensing range. Section 1.1.3 specified the advantages of using a smart environment that could provide the robot with information regarding the user's position. This should be considered for a future design as well to integrate the walking companion with a system that successfully monitors a user's gait parameters.

In order to perform the experiment and control the robot in an easier manner, a graphical user interface (GUI) was designed by using the TkInter package in Python [64]. In the control window, each button corresponded to a different behaviour: each behaviour was a combination of motivational utterance (Table 4.1) or and non-verbal gestures, *e.g.* head or arm rotation. The operator could move the robot by using a 3d Mouse (Space Navigator by 3dconnexion [65]) and by looking at the images captured by the robot camera and showed in the control window.

FIGURE 4.1: Gemini: the new designed humanoid walking companion

4.2 The Robotic Platform B

4.2.1 The New Design

We modified a pre-existing robot designed at the University of Tsukuba in 2013, namely Gemini (Figure 4.1). The original version had the head and the arms as the only humanoid features. The shape of the head is very simple, though it is enough to communicate simple social signals: the head has eyes and, at the back, the elongated shape gives immediately the idea of the direction the robot is looking at. Its height was 70 cm and the six servo motors were used only for arms and head movements. The body was made of expanding foam, while the head and the neck were 3d-printed. For our aim, we needed a taller and moving robot, thus we added a 3-wheel mobile base (VStone Mega Rover 1.2) and a metal structure to make it taller (130 cm) and heavier for safety reasons. Inside the head, there are LED lights and a camera with a speaker. A laser range sensor (Hokuyo UST-10LX) is fixed on the mobile base at a height of 20 cm from the ground; some of its specification are the following: a detection range from 0.6m to 10m, a scan angle of 270° and a scan time of 40 Hz. In order to monitor the arm position, we opted for putting inside a triaxial accelerometer (Kxm52 1050). The core of the robot is composed of a micro-controller (ARM Cortex-M3, 32-bits) running at 96mhz. It is responsible for controlling the mobile base, the servo motors, the accelerometers and so forth, and communicate with the server through Ethernet.

Figure 4.2 shows the lateral and the front view. Figure 4.3 gives an overview of the entire system.

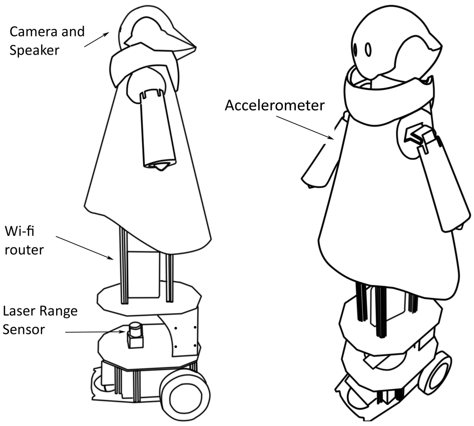


FIGURE 4.2: Lateral and front view of Gemini

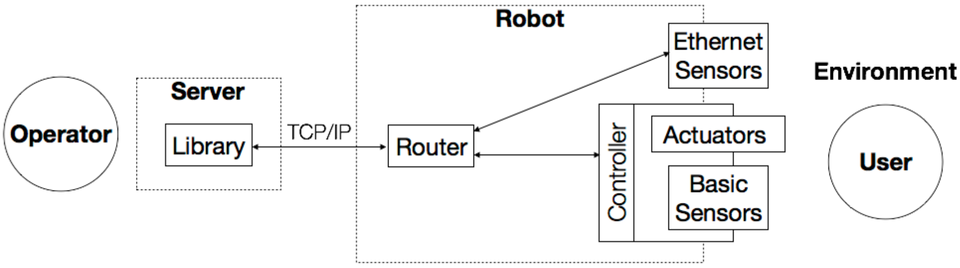


FIGURE 4.3: Gemini as a network robot

Regarding the motion control of the robot, we implemented two methods: the robot could be moved by a human operator through a 3d mouse (Space Navigator by 3dconnexion), or it could be moved according to the user's relative distance and position obtained by the Hokuyo sensor (Figure 4.4). In the latter case, the robot moved in order to keep the user at a desired distance and position inside the red triangle shown in Figure 4.5. If the user gets closer or farther than the desired distance, the robot will try to follow to keep the same value. The speed of the robot can be calculated using the following formula:

$$v = \frac{r\sin(\theta)}{offset} \tag{4.1}$$

Where r and θ are respectively the distance and the angle acquired from the scanner. The direction is instead calculated using the following formula:

$$\phi = \frac{D_{des} - r\cos(\theta)}{D_{des}} \tag{4.2}$$

Where D_{des} is the desired walking distance between the human user and the robot.

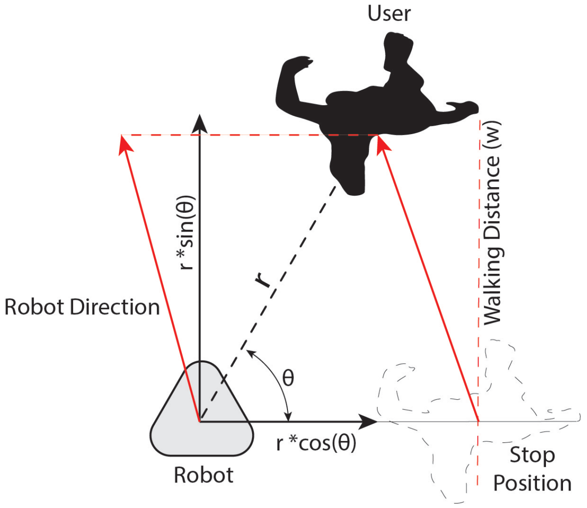


FIGURE 4.4: A simplified explanation of how the robot follows the human user reading the data from the Hokuyo sensor. The robot moves in order to keep the user at a desired distance and position. If the user is in 'stop position', the robot does not move.

TABLE 4.2: Hokuyo UST-10LX specifications

Detection Range	0.06m to 10m, max. 30m
Scan angle	270°
Accuracy	±40mm
Angular Resolution	0.27° (360°/1330)
Scan Time	25 ms/scan (40 Hz)

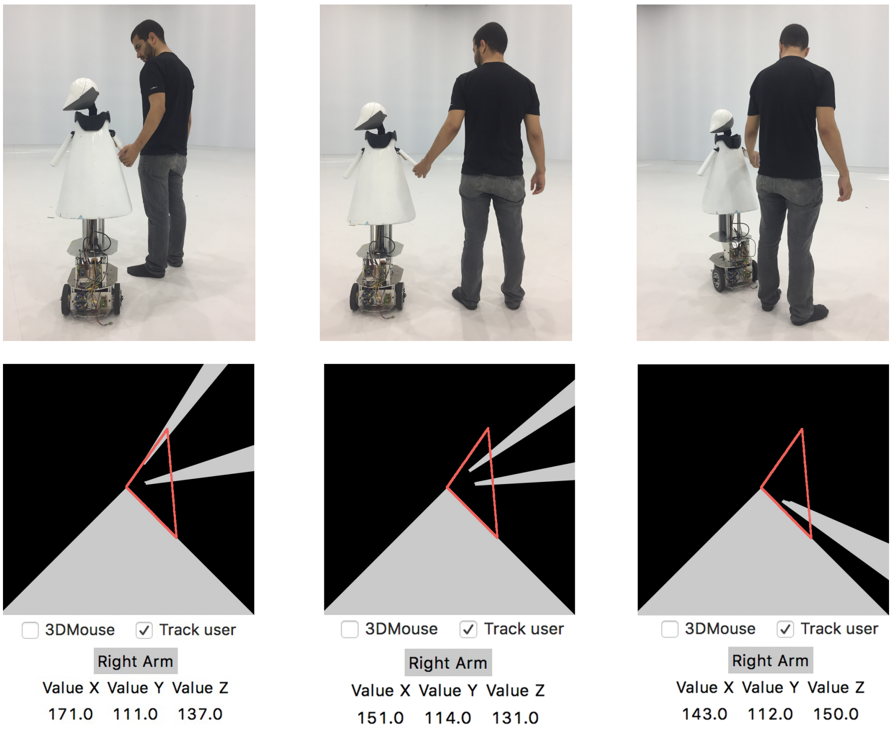
4.2.2 The Gait Measurement System

The aim is to obtain all the gait parameters to monitor body balance by using only the laser range sensor attached at the bottom of our walking companion robot, on the mobile base, with the measurement plane parallel to the ground (Figure 4.6). For this purpose, the Hokuyo UST-10LX [66] was chosen. Table 4.2 shows its specifications.

Since the laser range sensor is at a height of 20 cm from the ground, we are able to detect the legs only at that specific height (Figure 4.6). We need to keep this in mind when we have to calculate step length and step width, which are commonly measured between the feet contact positions on the ground.

The height of the measurement plane should not be too small, otherwise the toes might be detected, instead of the leg, when the foot is off the floor and is performing the step. We think that 20 cm is a good compromise, especially for older users.

The raw data from the sensor contains an array of 1330 distance



☐ 3DMouse ☑ Track user
Right Arm
Value X Value Y Value Z
171.0 111.0 137.0

☐ 3DMouse ☑ Track user
Right Arm
Value X Value Y Value Z
151.0 114.0 131.0

☐ 3DMouse ☑ Track user
Right Arm
Value X Value Y Value Z
143.0 112.0 150.0

FIGURE 4.5: A participant is guiding the robot which moves according to the user's relative distance and position obtained by the laser range sensor. In the first figure the robot turns left, in the second one it goes straight, in the third one it turns right. At the bottom, the arm's accelerometer data are shown.

points expressed in mm, thus the angular resolution is 0.27°, though the scan angle is only 270°. First, the positions of the legs are estimated by finding the points that define their contour in a smaller window of the scanner frame where the legs are supposed to be according to our experimental protocol. This smaller window was chosen for having less computation. Once the legs are detected, the step length can be calculated as the relative distance between the legs respect to the laser range sensor, *i.e.* the vertical distance in the scanner window in case the human user walks with the robot in front of him/her, not side-by-side (Figure 4.6).

It is well-known [55] that human walking consists of a repeated gait cycle: this cycle itself has stance and swing phases and at least one foot is always in contact with the ground, in other words when the left leg is in swing phase, *i.e.* not touching the ground, the right foot is in stance phase, *i.e.* on the floor, and *vice versa*. Therefore in an ideal graph of step length values, where x is the time and y the distance, we expect to find a curve similar to a sinusoid and we expect to find its maxima - and its minima - values when both legs are on the floor and they are going to exchange the phase. Moreover, we expect to find zero values when the swing leg passes close to the stance leg.

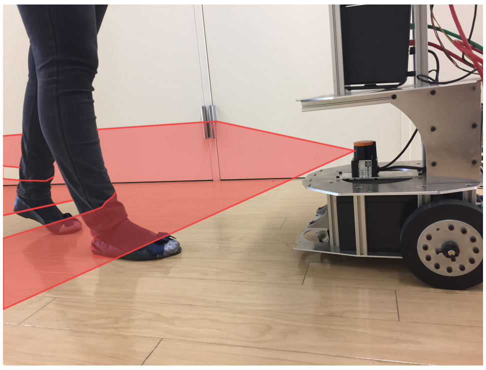


FIGURE 4.6: The laser range sensor is placed 20 cm above the ground and the scanning plane is parallel to the floor, therefore the legs are detected at that specific height

To obtain step width according to the standard definition, we calculated it as the horizontal distance between the legs in the scanner window at the specific time frames when the step length graph has its maximum and minimum peak values, *i.e.* both feet are on the ground. Again, it is the horizontal distance only in the case the human user walks following the robot.

Using only one sensor to extract gait parameters has indeed some challenges. In some time frames the legs might not be correctly detected, *e.g.* when one leg covers the other, thus several past researches have used methods to estimate leg positions in case of missed detection and in case of noise, such as applying a step line model [54] or using a Kalman filter [55].

Chapter 5

Feasibility Experiments

At this starting point, the following steps were necessary:

- to observe the reactions of elderly individuals, *i.e.* if and how they accept a humanoid robot that asks them to walk together;
- to test the effectiveness of the experimental procedure and the instruments selected for evaluation;
- to investigate the strengths and the weaknesses of the current robot, its feasibility as a safe and entertaining walking companion, and to consider improvements based on users' preferences.

5.1 Feasibility Study with Younger Participants

In order to investigate the influence of touch on the interaction, we initially carried out a pilot experiment with younger and healthy subjects. Observing the physical structure of Pepper, we decided that three different behaviours were feasible: (a) without touch, the robot walks in front and beside the human, (b) single touch, they walk side-by-side and the user touches one shoulder of the robot, (c) double touch, Pepper is in front and the subject leans on both shoulders (Figure 5.1). The last two behaviours take into account human-initiated touch, though touching only one shoulder appears to be more comfortable. The option of making Pepper follow the user from behind was discarded because it is considered dangerous, *i.e.* during the walk the elderly individuals should not be distracted by looking behind and they should carefully see where they put their feet.

Eight young participants were asked to interact with the robot and test all the three behaviours, walking for ten meters in a controlled environment. The participants were from seven different nationalities and their ages ranged from 23 to 33. All of them were students, three of them were not engineers, thus they might have different expectations about the robot. The setting did not have slopes or dynamic obstacles. To initially track the human, Pepper currently used its cameras; although it lost the user's position during some behaviours, the success of the interaction was not barred. For this controlled experiment, the speed of the robot was fixed and not related

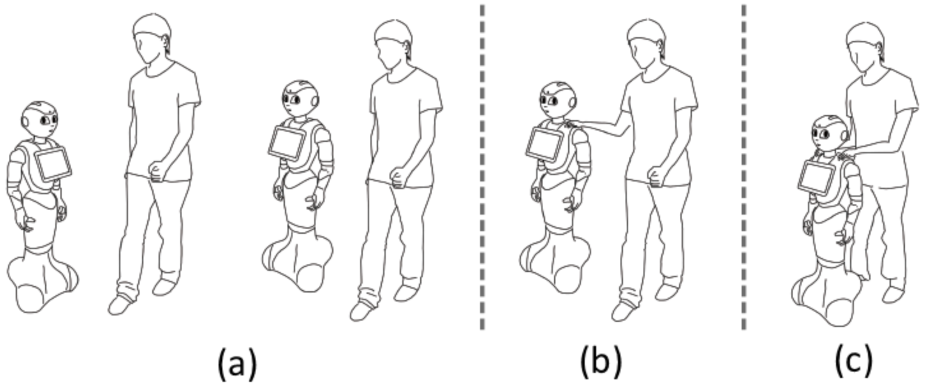


FIGURE 5.1: *The experiment with younger subjects* - The three different behaviours: (a) no touch, (b) single touch and (c) double touch. In (b) the robot walks beside the subject, in (c) it walks in front and in (a) it walks in front and side-by-side

to the human gait. Regarding the behaviour (a), the subject walked side-by-side and behind Pepper as well; the choice of selecting the side was left to him according to his personal preference.

Our main interest in this pilot study regarded people's comfort, in particular in (b) and (c) we wondered if the user trusted enough the robot to walk leaning on it. The Intrinsic Motivation Inventory questionnaire (IMI) fit our purpose (Section 5.3).

5.2 Feasibility Study with Older Participants

The second feasibility study was performed in a care facility for elderly individuals because it includes caregivers who are familiar with the needs of their older patients, and thus useful feedback can be obtained. Additionally, a robot in a nursing home or a hospital is an attractive option because it brings a sense of novelty and enjoyment to the fixed routines of these facilities and works with overworked staff to aid them in completing tasks. In these places, a mobile robot could encourage patients to walk for health benefits or to go to common areas to talk to other individuals.

There were a total of 8 participants (three women among them) aged between 73 to 92 years old. They were cognitively healthy, and they consistently understood and fulfilled the task expected of them. During the preparation phase, the robot and the experimental environment were introduced to the participants. The participants were clearly told that they could walk once without the robot and once with the robot. In the second case, they could choose the preferred position either side-by-side by keeping the robot at their right (1) or their left (5), or behind Pepper by keeping the robot at their front-right (2), at their front (3) or at their front-left (4). Figure 5.2 shows

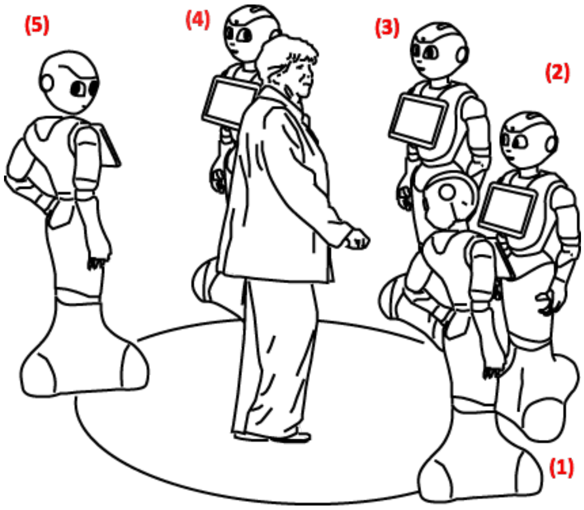


FIGURE 5.2: All the older subjects are asked as to where they prefer walking with the robot: beside the robot in (1) and (5) or behind the robot in (2),(3),(4)

the relative position of the user with respect to the robot. In all five cases, Pepper looked at an individual's eyes. The case of the robot following the user from behind was discarded because it was considered that elderly individuals must always look in front of them while walking due to safety reason. All the subjects signed the informed consent form and agreed to the video recording prior to participating in the experiment.

The actors were asked to walk straight on a PVC roll (1 mm x 1370 mm x 10 m) that was marked in advance with strips of tape at intervals of 50 cm along the length. The PVC roll was selected to easily calibrate videos of the camera that were subsequently analysed by using Dartfish software [67]. The software requires the camera to be perpendicular to the plane of movement and to directly face the object of interest, and thus an assistant carried the camera on a cart beside the walking path during the experiment to obtain step lengths of the participants. Consequently, the cadence and walking speed were also calculated.

A Wizard of Oz approach was preferred due to the hardware limitations of the current robot *i.e.,* its inability to keep tracking the human user's position and measuring the gait data in real time. In the study, the robot moves and speaks based on the actions of elderly individuals. The robot was operated in a smooth manner due to the GUI and the 3d mouse.

5.3 Questionnaire

With respect to the evaluation of the robot performance from a more social viewpoint, *e.g.* to measure the comfortableness of the users

FIGURE 5.3: A male participant follows Pepper

and to investigate their motivations, the Intrinsic Motivation Inventory Questionnaire (IMI) [68] that is commonly used to assess participants' level of motivation during a given activity in an experimental environment was adopted [69]. The quantitative questionnaire was administered to the participants after the end of the experiment.

The general version of the IMI questionnaire includes 7 subscales each of which corresponds to a positive or a negative predictor of intrinsic motivation according to psychologists. There are 6 positive subscales as follows: interest/enjoyment, effort/importance, perceived competence, perceived choice, value/usefulnesss, and relatedness/trust. Only 1 subscale is a negative predictor of intrinsic motivation, and it is related to pressure/tension. Past experiments proved the possibility of using only a few subscales without influencing the results of the others. In each subscale, there are several statements termed as items that should be rated by the participants based on a Likert scale from 1 (not at all true) to 7 (very true). Each subscale score is then calculated by averaging across all the items of the specific subscale. The full version has 45 items, and a few items in the same subscale are very similar although the use of a shorter version is considered reliable [69].

Following the instructions given by the IMI creators, a questionnaire with the following 4 subscales was obtained: enjoyment/interest (E/I), relatedness/trust (R/T), value/usefulness (V/U), and pressure/tension (P/T). For each subscale, 3 items that were randomly ordered in the questionnaire were selected. Additionally, they were modified to fit the specific activity. The final version corresponded to a personalised questionnaire for the experiment without affecting the validity of the original. Nevertheless, Cronbach's alpha test was used to confirm the internal reliability of each subscale. In the case of the older participants, with respect to the E/I, the R/T, the V/U,

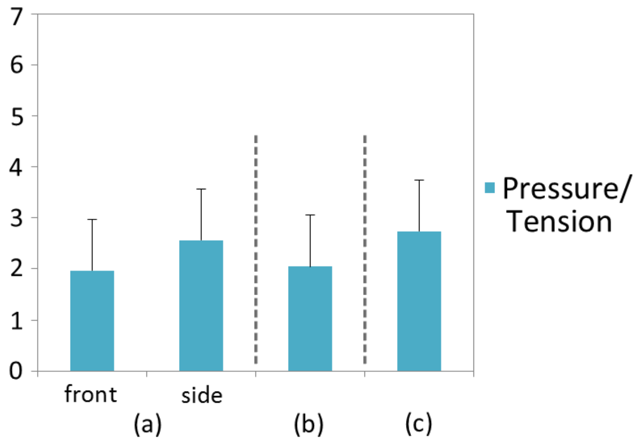


FIGURE 5.4: *The experiment with younger subjects* - Mean values and standard deviations of the negative subscale for the three behaviors (a), (b) and (c)

and the P/T subscales, Cronbach's alpha coefficients corresponded to 0.86, 0.84, 0.87, and 0.84, respectively, and thus the modified questionnaire were considered reliable. Therefore, all the statements were well written and the participants fully comprehended the meaning of each item.

5.4 Results

Figure 5.4 shows the mean values and the standard deviations of the pressure/tension subscale, taken from the IMI questionnaire of the first experiment with younger subjects.

Figure 5.5 shows that all the older participants did not choose to walk beside to Pepper.

Figure 5.6 shows the results of 4 subscales of the IMI questionnaire, in the case of the older participants.

With respect to the assistive task, Table 5.2 lists the walking speeds and the number of steps of each participant with respect to walking without and with Pepper.

TABLE 5.1: This table shows the English version of the modified IMI questionnaire. The participants receive the Japanese version in which the items are presented in a random order and rated from 1 to 7. In the case of the items with (R), the final score is calculated by subtracting the item response from 8

Subscale	Predictor of intrinsic motivation	Item
Enjoyment/Interest	+	I enjoyed walking with the robot very much
		This walk did not hold my attention at all (R)
		I thought this activity was quite enjoyable
Relatedness/Trust	+	I'd like a chance to interact with this robot more often
		I'd really prefer not to interact with this robot in the future (R)
		I don't feel like I could really trust this robot (R)
Value/Usefulness	+	I think using this robot could help me to walk more
		I believe using this robot could be beneficial to me
		I think this is an important activity
Pressure/Tension	-	I did not feel nervous at all while walking with the robot (R)
		I was very relaxed while walking (R)
		I felt pressure while walking

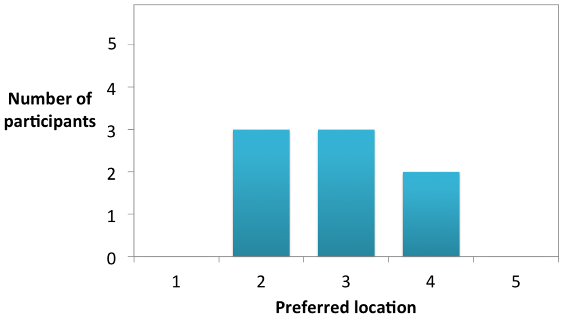


FIGURE 5.5: The figure shows the number of older participants selected each specific location. The preferred location numbers correspond to the ones in Figure 5.2

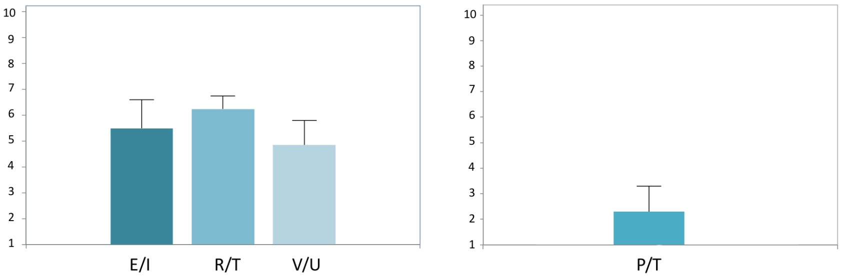


FIGURE 5.6: *The experiment with older subjects* (**a**) Mean values and standard deviations of the three positive subscales in the IMI questionnaire as follows: enjoyment/interest, relatedness/trust, and value/usefulness (**b**) Mean value and standard deviation of the pressure/tension subscale and negative predictor of intrinsic motivation

TABLE 5.2: This table shows the mean step length and walking speed of each participant without and with Pepper. The maximum velocity of the robot is set to a fixed value that is lower than the speed of a user (0.25 m/sec). All the participants follow the robot by slowing down their speeds

Participant	Step length m w/o Pepper	Step length m w Pepper	Walking speed m/sec w/o Pepper	Walking speed m/sec w Pepper
1	0.46	0.35	0.63	0.29
2	0.43	0.20	0.50	0.17
3	0.36	0.23	0.45	0.25
4	0.39	0.23	0.56	0.26
5	0.41	0.26	0.58	0.26
6	0.47	0.35	0.65	0.28
7	0.46	0.34	0.65	0.28
8	0.44	0.21	0.53	0.22

Chapter 6

Mixed-Initiative Interaction Experiments

6.1 Human Gait Measurement by the Robot

6.1.1 The Experimental Procedure

This time we conducted the experiment in the university with younger subjects because we needed to firstly test the accuracy of the laser scanner in monitoring the user gait.

The subjects were three young healthy participants - one woman and two men in their twenties - without any health impairment. Each of them performed the experiment three times. The procedure of the experiment was explained to them in detail before starting.

The actors were asked to walk straight on a PVC roll (1mm x 1370 mm x 10 m), which was previously marked with strips of tape every 50 cm along the length. The presence of this PVC roll was not required for the laser scanner, though it was needed to calibrate the videos of the cameras, which were later analysed using the Dartfish software [67]. Since the software requires the camera to be perpendicular to the plane of movement and to face directly the object being measured, for the AP plane measurements an assistant was carrying the camera on a cart beside the walking path during the experiment, while for the ML plane measurements a second camera was provisionally put at the bottom of the robot.

The legs positions were acquired by the Hokuyo sensor, then the speed of the robot was determined in order to keep the same distance from the participant (50 cm). The robot smoothly moved according to the subject motion and guided him from the start of the experimental walkway to the end maintaining the same distance.

After walking three times following the robot, the participant was thanked for his contribution and the next participant was called to perform the experiment.

The online analysis of the raw data acquired by the Hokuyo sensor had the following steps:

- for having less computation, a smaller triangular window in the scanner frame was extrapolated;

- a filter was applied in order to cut what was far than a certain distance (1.5 m);
- the group of points which constituted the legs were detected in order to define the robot's speed.

In order to obtain gait parameters, an offline analysis of the data was carried out in a second moment:

- a Butterworth 2-order filter was applied to the detected displacement of the legs to reduce uncertainty, noise or overlapping, with a cut-off frequency of 6 Hz;
- step length was calculated as the vertical distance between the two legs in the scanner window;
- minima and maxima values of step length were detected, which correspond to the time frames when both feet are in contact with the ground;
- step width was calculated as the horizontal distance between the two legs in the scanner window at the time frames obtained in the previous step.

Because of the position of the laser range sensor, in our system, we can detect the calf position at 20 cm of height from the ground. In order to obtain the foot contact positions on the floor, adding the geometric parameters of the user's leg and foot was needed.

After the experiment, the video analysis was performed. The software successfully kept tracking of the feet during the walk for all the trials - fortunately, the feet were entirely visible in all the videos - and it measured step length and step width in all the cases.

To summarise, the aim of this experiment was to find out if the steps of our algorithm were sufficient to reduce uncertainty in the determination of the gait phases and to successfully detect the gait parameters of interest.

6.1.2 Results

As previously discussed, we expected to obtain a curve similar to a sinusoid representing the step length variability. Figure 6.1 shows two examples of these data obtained in two different trials with different participants. The curves are positive when the right leg is in swing phase, they are negative when the right leg is in stance phase. The maxima and the minima values were considered as the scan time frames when foot contact on the ground happened. In those scan time frames, step width was calculated as well.

In our experiment all the participants were young and healthy, thus we were not interested in studying their walking pattern. Instead, this time we were more interested in testing the accuracy of

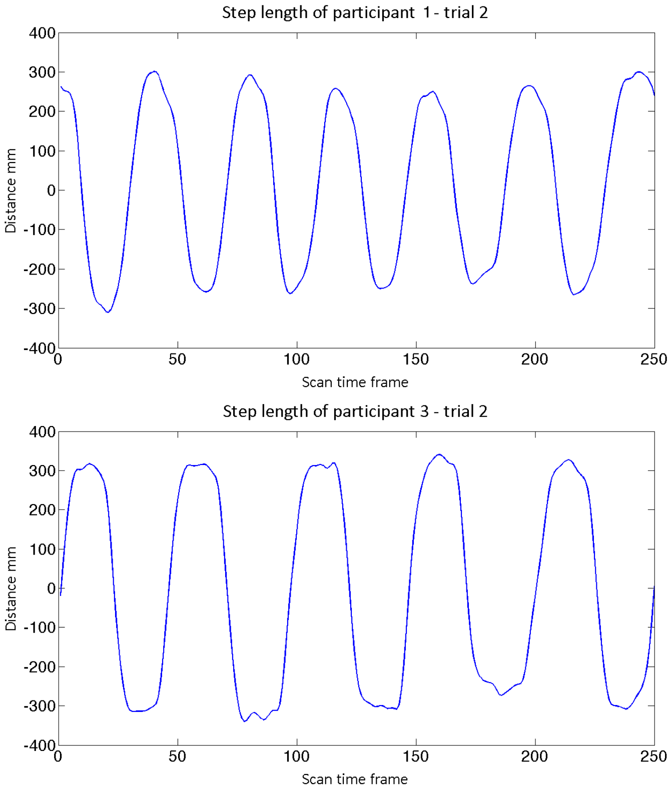


FIGURE 6.1: Examples of the step length values obtained during two trials, after the offline analysis (Section IV). In each figure, ten gait steps were extracted from the straight walk. The curve is positive when the right leg is in swing phase, it is negative when the right leg is in stance phase.

our gait measurement system. Nevertheless, in Figure 6.2 we decided to present the mean value and the standard deviation of step length and step width for each participant, calculated among all the trials, in order to show that our proposed system was tested with participants who had various walking abilities.

As a next step, we considered the data obtained by the video analysis as the ground truth and we used them to calculate measurement accuracy.

Table 6.1 and Table 6.2 display the mean absolute error (MAE) and the standard deviation (SD) of the gait parameters of our interest acquired by the robot, compared with the gait parameters acquired by Dartfish.

Lastly, Table 6.3 shows the detection rate of our walking companion, again compared with the data obtained by video analysis.

TABLE 6.1: Measurement accuracy of step length measured by the laser range sensor compared with video analysis

	MAE [m]	SD [m]
Participant 1	0.020	0.010
Participant 2	0.030	0.013
Participant 3	0.015	0.007

TABLE 6.2: Measurement accuracy of step width measured by the laser range sensor compared with video analysis

	MAE [m]	SD [m]
Participant 1	0.025	0.014
Participant 2	0.033	0.015
Participant 3	0.017	0.009

TABLE 6.3: Results of measurement detection by the laser range sensor compared with video analysis

	Step length	Step width
Detection rate	100% (178/178)	88% (158/178)

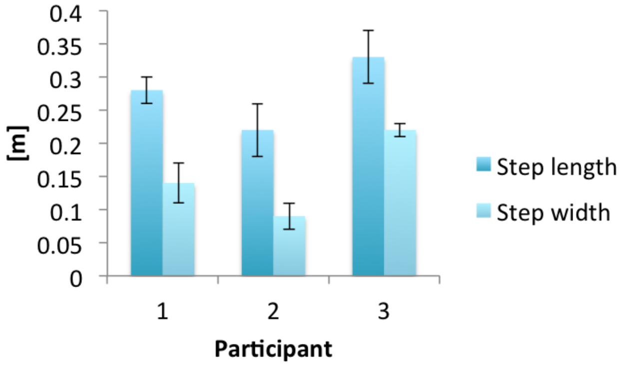


FIGURE 6.2: The mean value and the standard deviation of step length and step width for each participant in all the trials

6.2 Robot Compliant Behaviour in an Obstacle Avoidance Scenario

6.2.1 Hypotheses for an obstacle avoidance scenario

In our proposed mixed initiative strategy, the human user guides the robot most of the time, walking side-by-side and holding its arm. Haptic channel was added because it is a potentially valuable channel of communication and because users felt less pressure beside the robot if touch occurred during the feasibility studies. The switching of control between the human and the robot happens in case of obstacle, because it is common for elderly individuals having vision problems.

Non-verbal behaviours over the voice channel are preferred in our scenario because the environment might be noisy and the elderly individuals could suffer from hearing loss, which is another common disease according to United Nations' estimates.

With respect to initiative exchange during walking, our robot, with its specific design, could potentially read the human's intents from the led arm's position and laser scanner data, while it could potentially show its own intent moving the arms, the head, switching on/off the LED lights using different colours, or changing its speed. For this first experiment, we hypothesise that:

- the robot can understand the human's intent from his/her relative position and distance;
- the robot can show its intent through head gaze and speed change, and the human partner will understand it.

Regarding the first hypothesis, the guidance system had to be evaluated in order to test if the laser scanner data were sufficient or if they had to be combined with the arm's accelerometer data. Our previous tests suggested that guiding the robot by its arm allowed more precise movements - for instance if the robot's arm was pulled to the front position, the robot turned right, in the same way if it was pushed back, the robot turned left - though it was more complicated and it required more practice for the user to successfully control the robot. Conversely, regarding the second hypothesis, we opted for head gaze, which is a common non-verbal behaviour in HRI experiments to show engagement, convey intent, and direct attention [59]. We added speed change as a second independent variable because we supposed the human attention would not have been drawn to the robot head during all the walk. By deliberately modifying the speed of the robot we hoped to draw the user attention to the robot itself, even if this might have decreased the smoothness of the interaction. One aim is to maximise the likelihood that a user will understand the robot?s intent while minimising the cost of the robot's actions [59].

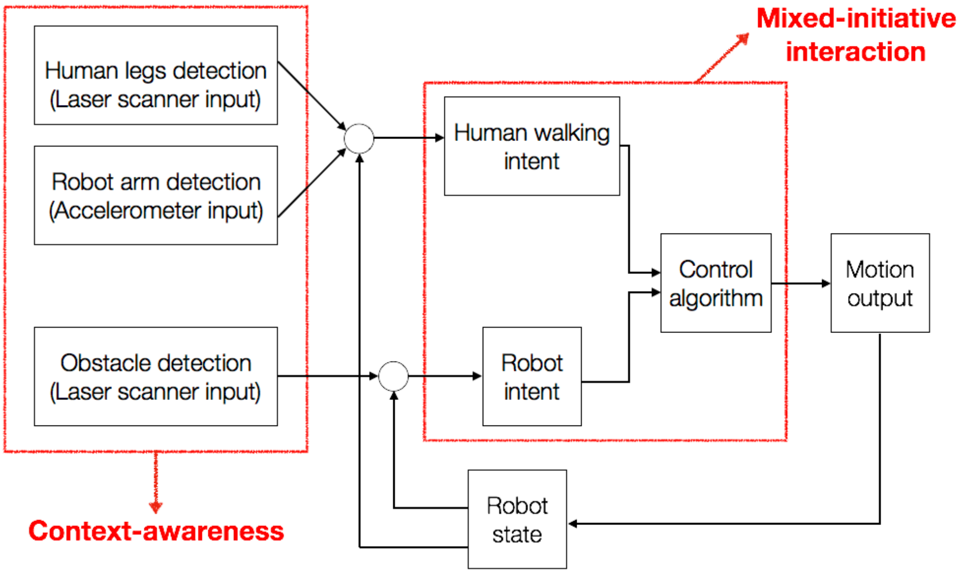


FIGURE 6.3: Control system architecture

6.2.2 The Experimental Procedure

In this experiment, 10 participants - 2 females, with a mean age of 25 - were asked to walk four times with our walking companion, testing all the four robot behaviours - (a), (b), (c), (d) - that are described in Figure 6.4. The order of robot behaviour condition was randomised among the participants to remove the order effect. The experimental space consisted of a straight path of 17 meters with an obstacle placed halfway down the path (Figure 6.4). Before starting the experiment, the participants were instructed to walk leading the robot by its arm along the path. They were told as well that the robot was going to communicate with them through non-verbal behaviours giving suggestions, though they could freely choose how to avoid the obstacle, *i.e.* if turning right or left. After the explanation, the participants had three minutes to learn how to guide the robot. During the experiment the robot was showing different head gazes - looking straight or at the user's face - and speeds, though it always suggested how to avoid the obstacle through head gaze, *i.e.* looking right or left. Moreover, the robot never autonomously moved its arms during this first experiment: they were moved only by the user while guiding the robot along the path. A human operator randomly chose the direction the robot looked at; all the other robot behaviours were autonomous. After each trial, the participants were asked to answer some Likert scale questions from 1 to 7 about the robot - rating features like speed, comfort, and ease of leading. At the end, they were asked to answer some open questions about robot compliance, *e.g.* if the participants noticed and followed the robot's suggestion, and about their ideas to improve the interaction. The experiment was video recorded to count the number of times the participants looked at the robot's face in front of the obstacle.

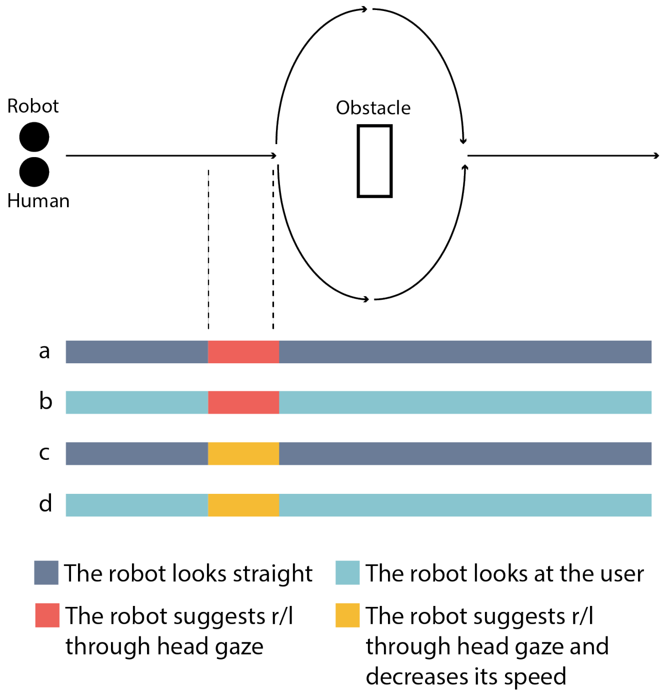


FIGURE 6.4: The experimental path and the four different robot behaviours - a, b, c, d - which were all tested by the participants in a random order.

6.2.3 Results

Likert scale questions were used for the evaluation of the robot design and the guidance system. Figure 6.5 shows mean and standard deviation values calculated for all the participants in each interaction regarding ease of leading the robot, comfort, and satisfaction with the robot's speed. Table 6.4 shows the percentages of participants regarding the robot's ability to show its own intent and compliance.

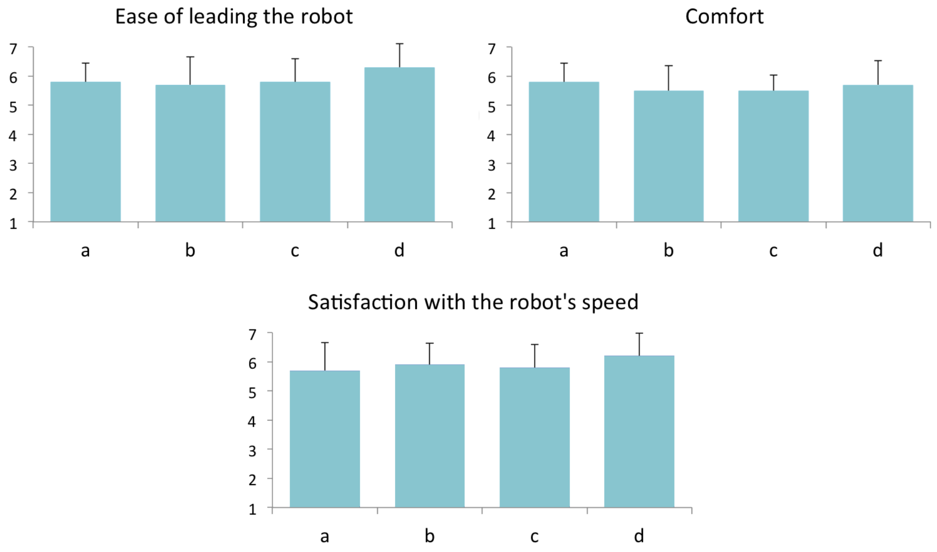


FIGURE 6.5: Results of Likert scale questions about the robot design for all the four robot behaviours - a, b, c, d.

TABLE 6.4: Evaluation of the robot's ability to show its own intent and compliance

	(a) Look straight + head gaze for suggestion	(b) Look at the user + head gaze for suggestion	(c) Look straight + head gaze and speed decrease for suggestion	(d) Look at the user + head gaze and speed decrease for suggestion
Participants who looked at the robot in front of the obstacle (data from video analysis)	70%	80%	70%	80%
Participants who recognised and followed the robot's suggestion (data from questionnaire)	71%	63%	71%	75%

Chapter 7

Discussion

7.1 About Robot Acceptance

In the first feasibility study, with younger participants, using Pepper, we were interested in observing the influence of touch on people's comfort. This pressure/tension subscale is a negative indicator of intrinsic motivation, therefore we have to look at the behaviour that obtained the lowest score. Figure 5.4 shows the mean values and the standard deviations of the pressure/tension subscale, taken from the IMI questionnaire of the first experiment with younger subjects. We can assert that, generally, the participants did not feel nervous during the interactions, since all the mean values and the standard deviations are low. The walk with the robot in front without touch was the outstanding one. This is quite surprising because in this interaction Pepper was looking all the time to the human face and the participants should have felt nervous in our opinion. We assume it did not happen because the participant could freely choose the distance between himself and the robot, a distance where he could feel more at ease, and the robot was not approaching him, which could have been scarier. The behaviour (b) - single touch, side-by-side - obtained a similar result. During the side-by-side walks, Pepper was not looking all the time to the human face, in order to recreate a more natural interaction, as two people walk without constantly looking at each others. The worst behaviour turned out to be (c). This was expected because leaning on both shoulders seemed uncomfortable, due to the low height of the robot. A surprising result is that the pressure changed during the side-by-side scenario if human-initiated touch happened or not: if the subject used Pepper as a walking aid was feeling less tension. Therefore, the possibility of touching the robot during the walk was considered feasible. Since the following-the-robot and the beside-the-robot scenarios had good results, they were both proposed to the older subjects. Finally, the IMI questionnaire showed coherent results to the users' reactions (Cronbach's alpha test), therefore a more complete version was created.

With respect to all the elderly participants, they interacted with a humanoid robot for the first time, and thus additional care was exercised to make them feel safe and comfortable before, during, and after the experiment. It was especially to not exhaust the elderly individuals in the care facility since something new in their routines can exhaust them, and thus they were asked to walk on the experimental path just once without the robot to indicate the possibility of monitoring their walking speed in normal conditions and then to walk once with the robot in a preferred position and for a preferred distance.

With respect to the selection of preferred location as shown in Figure 5.5, all individuals did not select the side-by-side walk. This was considerably unexpected because it was assumed that a side-by-side walk was more natural since this is normally adopted by two individuals when they walk together. The participants appeared to view Pepper more as a guide to follow as opposed to an accompanying companion or a caregiver to walk with. Nevertheless, this corresponded to the first trial with the robot, and trust typically corresponds to something that must be earned. Pepper received a good score on the R/T subscale although it is a score that was given after the experiment and not before. The preference for the position influences future design including the position of the laser range sensor at the bottom of the robot, gait monitoring, the position of a possible handlebar, and interaction behaviour.

Another misconception involved considering the first reaction of elderly individuals to the robot in which they were expected to be significantly mistrustful, fearful, and not confident of the robot's abilities. Although this was true since nobody selected the side-by-side walk, it was not completely true. For example, it was observed that some individuals did not exhibit a sense of danger and walked very close to Pepper touching it without fear while the experiment was performed. Thus, a safer robot should be considered to design a softer robot. The cute design certainly influenced the positive reaction although it was also a disadvantage since Pepper includes details that are so well designed that sometimes the participants expected a lot from the robot even with respect to tasks not implemented in this experiment such as shaking the robot's hand or holding a proper conversation.

With respect to the motivational task, good results were obtained in the IMI questionnaire in all the subscales (Figure 5.6). The IMI questionnaire results indicated that intrinsic motivation theory was efficient for this purpose as suggested by extant studies. Simultaneously, the Cronbach's alpha test proved the reliability of the modified questionnaire. A higher score is obtained if the interaction is personalised according to the user's preferences and characteristics. For example, there is a positive impact on the interaction if the robot recognises the human user, if it remembers the relative distance or the walking speed he prefers, or if it remembers what are his interests and what he likes talking about during the walk *etc.*.

With respect to the gait performance as shown in Table 5.2, it was decided to move the robot at a slower speed when compared to the subject's normal speed to study whether or not the subject could follow and adapt his own speed to the robot's speed. All the subjects could execute the same, and this implied that a walking companion robot successfully maintained or corrected the gait of an elderly individual if an appropriate motivational behaviour is selected. As a reminder, the target users include older individuals without a physical or mental pathology although they may be balance-impaired due to their age.

As a walking companion, the robot guides the subjects, and thus it influences the subject's behaviour. Simultaneously, the robot's behaviour is influenced by the subject, *e.g.* if the subject stops or slows down, then the robot catches him, attempts to get his attention again, and motivates him to maintain the walking pace. In the feasibility study, the robot was controlled by a human operator, and this bilateral interaction in the future will be performed by a control algorithm that elaborates the response from sensors, *e.g.* the response regarding a user's position and gait data.

In this study, the feasibility of the propose concept and the reliability of our evaluation method and experimental protocol were proven. Additionally, useful comments were elicited to improve the design of the future robot. The development of first prototype will definitely require additional long-term trials with additional subjects to validate its effectiveness as a walking companion. Currently, it is possible to investigate other conditions in addition to the relative position, *e.g.* different robot speeds, different distances *etc.*, and to thereby enhance the quality of the experiments.

7.2 About Gait Measurement

We experimented the advantages of using a laser range sensor, *e.g.* it is non-invasive, it can be used with any lighting condition, it does not need calibration *etc.*, and its disadvantages. The main drawback is that only planar information of the leg position at a fixed height could be obtained. Using many laser range sensors at different heights could certainly give more body motion parameters. However, one of our aims is to design an affordable companion robot that can be used by the elderly individuals at home or even in a nursing home. Another disadvantage of using only one sensor is that missed detection of leg position could happen more often, because of noise or because one leg could cover the other one, thus a proper analysis of the data is needed.

In the studies where body sway is investigated, the common procedure is to extrapolate a certain number of steps from the straight walk - the initial and the final steps are usually discarded - and to calculate the mean and the standard deviation of step width and length in all the trials.

Regarding the results, we can confirm that our system could always measure the phase change in the gait - from swing to stance phase and *vice versa* - thus the number of steps. Figure 6.1 displays ten gait steps of two different participants, where each curve minimum and maximum correspond to a new gait step.

Table 6.1 and Table 6.2 show that our system had a good measurement accuracy, compared with video analysis data used as ground truth. Step length value was always successfully calculated (Table 6.3). Step width detection had a lower rate because sometimes part of the leg was outside the window scan area. This can be solved increasing the area of the scanner window where the analysis is carried out, though this means more computational burden. We chose a smaller area because the robot had to do some online computation in order to define his motion speed. For the next experiments, we need to find a better compromise.

In this study, we found out that, if we are interested in detecting only step length and step width, one laser range sensor may be enough, at least during a straight walk, as it was in our experiment. This proposed system may have difficulties because of the narrower steps of the elderly, though we believe it would be able to distinguish the gait pattern even in case of asymmetry. Older people may indeed present abnormal changes in gait due to neurological or musculoskeletal disorders, and asymmetry of motion and timing between left and right side may be one of those changes.

It is interesting to notice that the step length values of our participants were a bit lower than the average values that are usually found in literature - 39 cm for men and 35 cm for women. The reason could be a sort of caution not to go too close, since it was the first time for them to follow a robot, though more probably we should have developed a faster algorithm to detect the leg position, thus changing the robot's speed, or we should have made the robot walk a bit farther from the user.

7.3 About Robot Compliant Behaviour

With respect to the robot design and the guidance system, good results were obtained in all the interactions (Figure 6.5). Gaze type - looking straight in (a) and (c), or looking at the user in (b) and (d) - did not have a significant effect. Surprisingly, the speed decrease was not considered negatively during (c) and (d) behaviour. The score was high in average, and this indicates that our first hypothesis proved to be correct: laser range sensor data could be sufficient in a simple environment like the one we used for our experiment.

With respect to robot compliance (Table 6.4), in this experiment the robot showed its intention moving its head. Since human attention during walking with another human partner is often drawn to the path rather to the other's face, speed change was added as well to address this issue. Similarly to the other results, gaze type did not significantly affect the interaction. Two subjects looked at the robot face, though they did not understand its suggestion. One participant recognised it only in the behaviour (d) - the robot looked at the user and decreased its speed while suggesting. Two participants never looked at the robot because they were extremely focused on the path, though they were told the robot was going to communicate with them through non-verbal behaviours. We hypothesised that a combination of head gaze and speed change could increase both awareness and compliance. This second hypothesis was not supported by the results. The non-verbal behaviours were not sufficient to communicate the robot intention in a walking scenario.

The next step should be investigating the haptic channel, *i.e.* the robot arm touched by the human user for guidance, which can be used by both the user and the robot itself to show intention. As some participants pointed out, they would not mind having the robot pull the arm to suggest an obstacle presence, as a small child does when he wants to lead. The recorded videos and the data collected by the accelerometers would give us some feedback to design this new system.

Other interesting considerations about the robot arm are the facts that 3 participants preferred to put their hand on top of the robot arm, instead of under, while leaning the robot, and that no participant was afraid to break it though it was made of expanding foam.

Chapter 8

Conclusions and Future Directions

The focus of this study involved determining key factors that influence a walking companion robot for elderly individuals, to validate its feasibility and finally to test the new designed robot. The concept of a walking companion evolved from observations of current society problems and the needs of elderly individuals. Section 1 shows the social and economic impact of the ageing population on society in developed countries and how it will worsen based on all projections. An active study aim involves improving the mobility of elderly individuals because the importance of walking for mental and physical health is scientifically established. Section 2 discusses evidence for the feasibility of the proposed concept with respect to state of art studies. It is observed in similar extant studies, and the novelty of the study in socially contributing to gait training is validated. A walking companion for the elderly was validated as a useful tool that should at the very least include effective motivational behaviour, a safe and comfortable interaction with the user, and provide continuous gait analysis. A robot should be accepted by its target users to ensure success, and thus the study opted for a user-centred design and two feasibility studies were performed by using an available humanoid robot. In the second part of this study, the new designed humanoid robot was tested. In particular, its ability to measure the user's gait and to communicate its intents through non-verbal actions were under investigation. With respect to the walking companion robot, the most interesting challenges consisted of increased research in the fields of social robotics as well as human-robot mixed initiative.

8.1 Contribution of this Work

8.1.1 Contribution to Social Robotics

A novel approach of designing a HRI was presented, starting to clearly define the research problem, to include final users since the beginning, and how to understand and evaluate the interaction. A walking companion robot corresponds to an application in a real-world setting, and thus it is necessary to first understand its setting and its future users. A user-centred approach aids in designing a more natural and engaging human-robot interaction. A simplicity design was later chosen for the second robotic platform because the well-designed details of the first one increased extremely the expectations of the participants.

8.1.2 Contribution to Human-Robot Mixed-Initiative

A mixed-initiative approach was adopted after the results of the feasibility study where the robot was able to modify the gait of the participants, thus its guiding function was validated. A safe and natural interaction model was then proposed, taking into consideration practical problems in an everyday scenario and investigating the role of non-verbal actions in guiding behaviour during walking together. The robot was able to communicate its intent through simple social signals, as humans do during shared tasks.

8.2 Future Directions

The initiative exchange between a user and a robot has never been studied in a obstacle avoidance scenario, thus the novelty of our research. We proved that, even though the laser scanner data may be sufficient for guiding the robot, adding a haptic channel is indeed useful, since the robot could not show its intention through only head gaze and speed change even in this first simple experiment. Moreover, in a noisy environment with dynamic obstacles, our leg detection algorithm could be not sufficiently robust, thus it must be tested in future works as well. The next steps of our research involve the investigation of the robot arm as a direct physical interface using the data collected in this experiment. At a later stage, when we find the best non-verbal behaviours for initiative exchange, we plan to study the influence of light touch during walking, *i.e.* if light touch provides physical assistance during walking, monitoring the gait data obtained by the laser range sensor at the bottom of the robot.

It was observed that the elderly individuals were not afraid of the robot once they commenced the experiment even if it was the first time that they interacted with a humanoid, and they could successfully follow the speed of the robot. The introduction of a robot in a nursing home is a good idea, *e.g.* since it could help the overworked staff or bring a sense of refreshment in the facility. Nevertheless, it could be more useful to design a personal robot that can stay at home because elderly individuals typically prefer to remain independent in their homes although it is sometimes not possible due to poor health conditions. The current new trend of smart homes can help them in fulfil their wishes and keep them healthy in their own houses, and this would even result in a reduction of costs with respect to the national health services provided by individual countries. Future internet technologies open new opportunities to provide advanced robotic services since service robots would become cheaper and smarter due to the cooperation of all sensors and devices in a house. In this type of scenario, a walking companion could obtain more data with respect to a user including location, activities, and health measurements *etc.* and send the same to doctors or families and share information obtained from a cloud with elderly individuals. For example, a robot could examine if a user's friends are walking outside in a specific moment and could suggest going out and reaching out to them for a nice talk and walk together.

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