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Human–Robot Interaction Analysis for a Smart Walker for Elderly: The ACANTO Interactive Guidance System

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Abstract
The present study aims to investigate the interaction between older adults and a robotic walker named *FriWalk*, which has the capability to act as a navigation support and to guide the user through indoor environments along a planned path. To this purpose, we developed a guidance system named *Simulated Passivity*, which leaves the responsibility of the locomotion to the user, both to increase the mobility of elder users and to enhance their perception of control over the robot. Moreover, the robotic walker can be integrated with a tablet and graphical user interface (GUI) which provides visual indications to the user on the path to follow. Since the *FriWalk* and *Simulated Passivity* were developed to suit the needs of users with different deficits, we conducted a human–robot interaction experiment, complemented with direct interviews of the participants. The goals of the present work were to observe the relation between elders (with and without visual impairments) and the robot in completing a path (with and without the support of the GUI), and to collect the impressions about of the older adult participants about the interaction. Our results show an overall positive impression of the *FriWalk* and an evident flexibility and adaptability of its guidance system across different categories of users (e.g., with or without visual impairments). In the paper, we discuss the implications of these findings on service social robotics.

Keywords Robotic walker · Assistive robotics · Human–robot interaction · Perception of robots · Social service robotics

1 Introduction

One of the main global societal challenge of our times is related to population ageing: by year 2050 the population of 60 + years will be larger than the population aged between 10–24 years (2.1 billion versus 2.0 billion). It is estimated that in the most developed regions of the world, such as the USA, the EU, Japan and Australia, the people with 65 + years will soon exceed the 20% of their entire population [32]. It is generally agreed that senior citizens have to face a significant decline in their physical and cognitive abilities. In the vast literature documenting this fact, we can cite the slowdown of reflexes observed by Langan et al. [25] and the reduction of muscle tone [22]. In this scenario, service robots have become an increasingly popular solution to mitigate physical decline and address a number of cognitive problems of older adults [16,23].

Generally speaking effective ways to tackle age related physical deficit has been in the focus of recent robotic research. For example, some mobility service robots were specifically developed to assist visually impaired people in walking [35,38,43]. Despite the evident importance of these results, focusing only on visual deficit could be insufficient. A research conducted on 3000 US people aged 57 and 85 years, showed that 94% of the sample had problems with at least one of the five senses (taste, smell, hearing, viewing or touch), 40% with two senses, and 28% with three or more senses [39]. Moreover, the 2015 report of the Italian Institute of Statistics on elders in Italy and in the European Union [21], highlighted an important gap between 65 and 80 years old Italians, showing an exponentially increase of percentage of older adults with severe difficulties in viewing and hearing (from 5.1% for 65 y.o., to 29.5% for 80 y.o.). These results show that

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physical and cognitive deficits are not uniform within the elder population. For these reasons, flexible solutions that can effectively deal with an heterogenous population of older adults are an important research priority. Another important challenge is represented by the reluctance and the difficult adaptation of senior users toward the adoption of new technologies [9]. A correct understanding of elders' feelings and of their perception of the advantages and the disadvantages of new technological products is key to their effective application [42]. As a consequence, the development of assistive service robots for older adults must be tightly linked to a correct understanding of their requirements. In this context, user-centred approaches come to rescue as they allow the developer to effectively capture the users' needs, and, in the mean time, to show and explain the potential of the proposed technologies in order to facilitate their acceptance [18]. This point becomes even more crucial when the development embrace other players, such as other users of the technology (both elderly and caregivers) and/or service providers (elder centres, hospital, social services, charities, etc.) [10].

The ACANTO project [1] aims at the design of an assistive robotic walker for seniors, named *FriWalk*, taking into account all these requirements. The *FriWalk* has several sensing and reasoning abilities but one of the most important is the capability to act as a navigation aid [33,34] and to guide the user through indoor environments [3,5,6] along a planned path that satisfies his/her requirements [8,37]. The device is developed as a navigation support rather than an autonomous assistive vehicle. The *FriWalk* was created with the intention to give the user a perception of freedom and control over the robot and the environment, reserving the active intervention of the walker only when the user makes choices that could endanger her/his safety or undermine her/his sense of confidence. Perfectly aligned with this vision is the guidance system, named *Simulated Passivity* [2], adopted in the *FriWalk* and inspired to the paradigm of passive robots [13]. Passive robots offer their support to users leaving them the ultimate responsibility of the motion. Contrary to passive robots, *FriWalk* can recognise user's motion and adapt to him/her through the physical interaction, without requiring direct individual's input (through joystick [29], force sensors [14,26,45], turn buttons and voice commands/navigator support [24], etc.). The idea is to alternate phases in which the *FriWalk* remains totally passive observing and measuring the user's desired speed, to other phases in which the angular velocity is altered to make turns, without changing the forward speed. The impression is that of a passive system even if the system uses the electric motors on the wheels, hence the name *Simulated Passivity*. The motion of the *FriWalk* during the turns is developed to be perceived as a very gentle mechanical stimulation. The navigation system is complemented by a graphical user interface (GUI), which provides indications on the direction suggested by the robot and clarifies to the user the reason of a mechanical intervention. The orchestration of the *Simulated Passivity* mechanical guidance and the visual GUI in the navigation support is specifically conceived to address the aforementioned variability of the elder population in capabilities and deficits. Very autonomous users could anticipate the intervention of the mechanical system by looking at the GUI in the proximity of path selection points (e.g., intersections between different roads), whilst the users more reliant on the system could use the GUI to better understand how the system actually behaves. The previous published literature on the *FriWalk* covers the technical aspects of the guidance solutions available on the robotic platform showing their effectiveness and the technological feasibility of the solutions adopted. In this paper we focus on the users. Our goal is to carry out a scientifically founded study on how the users interact with the device and on the level of acceptability of the guidance system. A specific theme we focused on is if the device can accommodate for the needs of a varied population: some of our users have an intact eyesight, while others have severe visual impairments. Finally, we aimed to understand the possible impact of the presence of a GUI combined with the mechanical guidance. To explore our different scientific hypotheses, we have set up human–robot interaction (HRI) experiments. The users were required to follow a difficult path with the presence of obstacles along the trajectory relying on the *FriWalk* mechanical guidance. All the participants of the study were interviewed at the end of the experiments in order to collect their impressions of the *FriWalk* and the experienced interaction.

The paper is organised as follows. In Sect. 2 a description of the *FriWalk*, including the *Simulated Passivity* guidance and the path following task, and its components that are relevant for this paper are given. Section 3 presents the methodology, describing the hypothesis and the research question, the experimental setting, the graphical user interface, the group of older adults who participated in the HRI study, the experimental procedure and the dependent measures. Section 4 analyses the results, while Sect. 5 discusses their implications and possible future research direction. Finally, Sect. 6 draws the conclusion of the paper.

2 System Overview

The robotic platform *FriWalk* is depicted in Fig. 1. In the embodiment considered for the present study, the *FriWalk* is a commercial walker (a walker 12er navy of Trionic[1]), on which we applied brushless motors on the rear wheels, and an electronic box containing both the batteries and the computing power. The device has four air-pressure tires of

[1] https://www.trionic.uk/en/rollator-walker-12er-c-15/.

Fig. 1 Picture of the *FriWalk* prototype. The red circle emphasises the location of the webcam for QR-code detection, while the red squares indicate the mounting point of the encoders and the brushless motors. (Color figure online)

Fig. 2 An example of the GUI used for the test

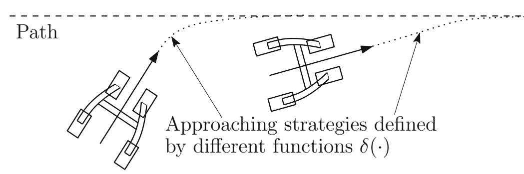

Fig. 3 Examples of approaching directions

31 cm in diameter, with grip height of 76–96 cm and body height of 152–192 cm.

In order to solve the localisation problem with a given target uncertainty, the rear wheels host incremental encoders (marked with the red square in Fig. 1), which were used in combination with a camera (a low resolution and high sampling rate webcam, placed on the walker in the position marked with a red circle in Fig. 1) pointing forward and downwards to detect the QR codes placed on the ground [27,28,33].

2.1 Graphical User Interface

To provide to the participants a visual hint on the direction to follow, a Samsung Galaxy Tab S2[2] is positioned at the right of the walker seat place. The tablet shows a GUI with a green arrow of (8 cm height and 3 thick) on a white background, shown in Fig. 2. The green arrow icon, rotating on the screen to suggest the direction to follow for the planned path, has been selected for its simplicity and its capacity to give intuitive feedback to the user. The direction to follow is computed according to the distance and the orientation that the user has with respect to the planned path as a parametric function, inspired by robot control algorithms in the literature [3,41,43]. In particular, we use the function

$$\delta(l) = -\alpha \tanh(l), \quad (1)$$

where l is the distance of the *FriWalk* from the closest point on the planned path and α a tuning parameter, whose main purpose is depicted in Fig. 3 for two different choices of α. The attitude error, that is the desired orientation towards the path, to be shown showed in the GUI Fig. 2, is given by

$$e_\theta = \theta - \theta_d - \delta(l), \quad (2)$$

where θ is the actual user orientation, θ_d is the local orientation of the path computed on the closest point to the robot, and δ is the approaching angle (1).

2.2 Simulated Passivity Guidance and the Path Following Task

The *FriWalk* guidance system was created to help seniors in their navigation to reach a specific goal in an unfamiliar environment. To assist older adults in this activity, we adopted *Simulated Passivity* as a guidance solution, whose main purpose is to maximise the perception of control of the user and, therefore, facilitate its acceptance. A detailed description of the control algorithm can be found in [2], here summarised for completeness.

The main idea of *Simulated Passivity* is to share the authority of the control with the user, with the motors being activated only when actually needed. To this end, two different control states are defined, namely *User in control* and *Robot in control*. In *User in control* mode, the authority belongs to the user: the motors are not active, hence the *FriWalk* is totally passive and behaves like a standard walker. In this modality, the robot estimates the user walking speed in order to adapt to her/his velocity during the *Robot in control* mode. In the latter state, the authority on the walker motion is shifted to the robot, which operates on the rear motors. Specifically, when the robot is in control, the *Fri-*

2 https://www.samsung.com/global/galaxy/galaxy-tab-s2/.

Walk actively controls the rear motor angular velocities and, hence, steers the vehicle towards the desired direction, but it maintains as much as possible the forward velocity equal to the one estimated during the *User in control* phase.

More formally, the *FriWalk* is modelled as a unicycle like robot, having differential kinematics

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} v\cos\theta \\ v\sin\theta \\ \omega \end{bmatrix}, \tag{3}$$

where the coordinates $[x, y]$ define the position of the vehicle reference point, i.e. the mid point of the rear axle, with respect to a fixed world frame $\langle W \rangle$ and θ the orientation of the vehicle with respect to $\langle W \rangle$. The vehicle linear and angular velocities are denoted by v and ω, respectively. Under the hypothesis of pure wheel rolling motion, the vehicle velocities v and ω are linked to angular velocities of the rear wheels by

$$v = \frac{r(\omega_R + \omega_L)}{2}, \quad \omega = \frac{r(\omega_R - \omega_L)}{d}, \tag{4}$$

where ω_L and ω_R are the angular velocities of the left and right wheels, respectively, r is the wheel radius and d is the length of the rear axle. As a consequence, by properly controlling ω_L and ω_R it is possible to fully control both forward and angular velocities and determine the future position of the robot.

The main problem to face when the authority switches to *Robot in control* mode is that the user may feel to be pushed or pulled, which may generate loss of balance and hence falls. To avoid this problem, the controller uses the user velocity estimated in *User in control* mode (that are denoted as v_{user} and ω_{user} for the linear and angular user velocities, respectively) and then apply a correction to smoothly steer the walker towards the desired direction at the same user pace (called *velocity projection*) or slightly slow down the walker if a large direction correction is needed (called *braking actuation*). The choice between this two control strategies, generating the controlled walker velocities $v^\star$ and $\omega^\star$, is based only on the estimated velocity and tailored on the user need with a threshold parameter [2]. Notice that using this paradigm, the robot does not autonomously drive towards the final destination, but adapts to the thrust generated by the user by estimating its current velocity v_{user} and ω_{user} and continuously alternating the two modalities *User in control* and *Robot in control*.

To clarify this behaviour, we summarise here the mechanism that switches between *User in control* and *Robot in control* modes. The *Robot in control* mode occur only when the user overcomes a certain attitude error threshold, which has been set in this work to 15°. The authority is then shifted to the robot until this error is reduced to below another threshold, here set to 8°, or after 2 s. Once one of these two threshold

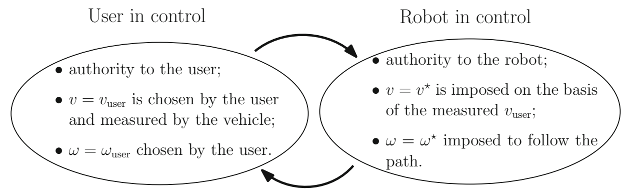

Fig. 4 Authority sharing mechanism for *Simulated Passivity* guidance as described in [2]

is reached, the authority is given back to the user (i.e. *User in control* mode) for at least 0.8 s, when the attitude error is checked again against the threshold. This mechanism is depicted in Fig. 4 and formally modelled as a hybrid system in [2]. It has to be noted that all these thresholds and parameters have been set based on trials we have carried out with another group of users. Albeit those parameters can be adapted to the needs of each older adult, they have been fixed to the same values to concentrate the analysis on the presence of the GUI.

The *Simulated Passivity* guidance was used during the human–robot interaction along the path following task with the *FriWalk* within the chosen environment. To properly represent the path following problem, let s be the curvilinear abscissa of the robot reference point on the path (i.e. a Frenet frame), θ_d the desired orientation of the vehicle as in (2), and let $[l_x, l_y]$ be the coordinates of the vehicle reference point O_m in the Frenet frame. Define the vehicle orientation error as $\tilde{\theta} = \theta - \theta_d$. Using this new set of coordinates $[l_x, l_y, \tilde{\theta}]$, the differential kinematics of the vehicle (3) can be rewritten as

$$\begin{cases} \dot{l}_x &= -\dot{s}(1 - c(s)l_y) + v\cos\tilde{\theta}, \\ \dot{l}_y &= -c(s)\,\dot{s}\,l_x + v\sin\tilde{\theta}, \\ \dot{\tilde{\theta}} &= \omega - c(s)\dot{s}, \end{cases} \tag{5}$$

where $c(s) = \frac{\mathrm{d}\theta_d}{\mathrm{d}s}(s)$ is the path curvature and the velocity $\dot{s}$ of the Frenet frame is an auxiliary control input. Using the coordinates $[l_x, l_y, \tilde{\theta}]$, the path following problem is considered solved if

$$\lim_{t\to+\infty} |l_x(t)| \le l_\infty, \quad \lim_{t\to+\infty} |l_y(t)| \le l_\infty, \quad \lim_{t\to+\infty} |\tilde{\theta}(t)| \le \tilde{\theta}_\infty, \tag{6}$$

where t denotes the time, and $l_\infty > 0$ and $\tilde{\theta}_\infty > 0$ are positive arbitrary tolerated errors.

3 Method

In this section we will present the adopted methodology, i.e. the definition of the experimental design and hypotheses, the selected participants and the procedure. Following the

Ethics policy of the ACANTO project, the experiment design was submitted to the Ethical Committee of the University of Trento and received approval in all its different aspects prior to its execution. In the rest of this paper we denote with M the mean and with SD the standard deviation.

3.1 Experimental Design and Hypotheses

A between-subjects experimental design with 2 conditions (*Tablet* vs. *No Tablet*) was developed. Participants in *Tablet* condition could rely on the support of a graphical user interface to understand the path to follow, whereas participants in *No Tablet* condition referred uniquely on the *Simulated Passivity* guidance to complete the task with the robot. Moreover, participants with visual impairments were observed as a separate group in order to understand possible differences in interacting with the *FriWalk* due to vision deficits. As *Simulated Passivity* was developed with the aim of adapting and guiding elders with different problems and characteristics, we expected most of the participants completing correctly the path following task (H1) with no significant difference between participants in *Tablet* versus *No Tablet* condition (H2). Nor did we expect that the presence or absence of visual impairment could play any role in completing the path with the *FriWalk* (H3). However, as the user interface helped in understanding the expected direction of motion of the *FriWalk*, we hypothesised that participants with intact eyesight in *Tablet* condition would show a better impression toward the *FriWalk* and a higher interaction acceptance in comparison with the *No Tablet* condition (H4).

3.2 Experimental Setting

The experiment was conducted at the University of Trento's Lab at Business Innovation Centre (BIC) of Pergine Valsugana (Trento, Italy). The lab was divided in several environments with different functions.

The main environment is described in Fig. 5 and was composed of a rectangular open space of 77 square meters (7 m long and 11 m wide), designed path following experiments with the *FriWalk*. On the floor of the open space, a series of QR code printed on A4 papers were positioned at the distance of 1.5 m from each other for the *FriWalk* localisation following [33]. Within the open space, three tables (2 × 1 m) were positioned with the function of obstacles (represented in Fig. 5 with three rectangles). Since the robot was programmed to follow a specific route, the presence of physical obstacles was not relevant from the *FriWalk* perspective, but it gave the participants the impression that the robot was actively avoiding those specific objects, as in a real scenario. 6 ELP cameras with HD resolution and 30 fps were used to record the interaction between the elder participant and the *FriWalk*. The cameras were linked through wireless to the recording system and synchronised. To cover all the area designed for the path following task, 4 cameras were located at the corners and 2 cameras were positioned in the middle of the longer sides of the rectangular open space (represented in Fig. 5 with 6 black squares).

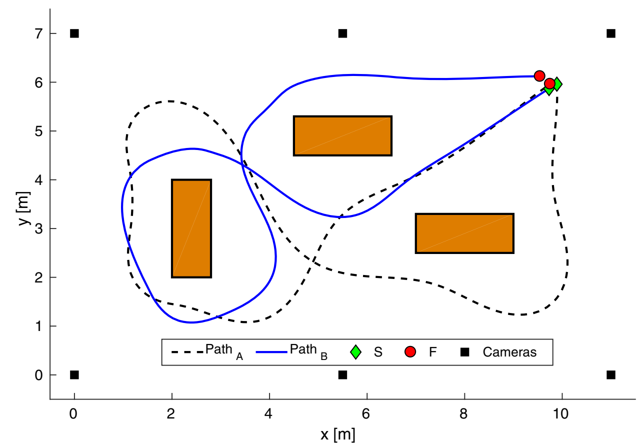

Fig. 5 Experimental set-up for the path following task. The lines (dashed and solid) show the two desired paths used in the experiments. The rectangles represent the three tables used as obstacles. The black squares indicate the position of the six cameras used to record the human–robot interaction. The green diamond 'S' identifies the path starting position, while the red circle 'F' its ending position (path finish). (Color figure online)

A second environment within the lab was the room for the interviews. In this room, a table and two chairs were located. A Reflex camera (Pentax®K3) positioned on the table was used to record the interviews. Finally, a waiting space between the open space and the interview room was created. In this environment, participants were welcomed and waited their turn for the experiment with the *FriWalk* and for the interview. A series of chairs and a table with snacks and drinks were located in the waiting space to ensure comfort to the elders.

3.3 Participants

39 participants came to the BIC of Pergine Valsugana to participate to the study. However, since some of them decided at the last moment to not participate or they interrupted the experiment before completion, the final sample consisted of 29 participants (11 males and 18 females), ranging from 66 to 96 years old ($M = 84.27$, $SD = 7.35$). 27 participants reported to daily use a support device for walking, and specifically 24 used a walker (82.8%), 2 participants used a walking or tripod stick (6.9%) and other 2 declared to move with a wheelchair (6.9%). 8 participants (27.6% of the sample) reported to have a serious visual impairment and they all completed the experiment in *No Tablet* condition only.

3.4 Procedure

To recruit participants, we contacted 7 elder centres of Trento Province, presenting the ACANTO project and its objectives to the responsible, doctors and professionals caregivers of the different centres. After the detailed explanation of the aim of the present study, we asked them to conduct a pre-screening of the possible guests who could participate. Specifically, we asked for elder people who presented no significant cognitive problems, at least a minimum difficulty in walking and willingness to participate in the experiment. To better organise the study, we also asked the representatives of the centres to indicate which persons had a serious visual impairment. To respect the principles of ethical research with the elder population, we referred to the procedure described by Walsh [44]: some weeks before the experiment, we met the selected guests of each centre to discuss the study and its objectives, leaving them the informed consent and the documents related to the use of personal data and their privacy rights. We invited the potential participants to consult also with their relatives, with the representatives of the centres and to recontact us if any further explanation about the study was needed. Participants in couples were accompanied by caregivers from the elder centres to the BIC where the lab of the University of Trento was located. Once they arrived at the lab, they were welcomed by the first experimenter who reminded them of their rights as participants and explained again the purpose of the study. After they renewed their intention to participate, a second experimenter led one participant at a time to the rectangular open space and explained him/her the features of the *Simulated Passivity* guidance, how the *FriWalk* provided cues on the path to follow and what he/she had to do with it. After that, to take confidence with the robotic walker, the participant was invited to complete a first trial path accompanied by a second experimenter. Then, participants were randomly assigned to one of the two experimental paths (showed in Fig. 5), which were different from the first trial path. They were invited to complete autonomously the path with the *FriWalk*, although they could stop and interrupt the task and/or ask for the experimenter support at any time. Since the guidance function of the *FriWalk* shows its real utility when the user has to move in unfamiliar environments or when he/she does not know (or remember) the route to reach a specific goal, participants did not receive any upfront information about the experimental path they had to complete. This obliged them to totally rely on the robotic walker *Simulated Passivity* guidance and, when in *Tablet* condition, on the information provided by the GUI. After the path following task was completed, the participant was asked to move to another room where a third experimenter conducted the interview to collect the impressions on the *FriWalk* and the interaction with it.

We structured the procedure of the experiment in order to avoid that participants could talk to each other and influence their impressions on the *FriWalk*, and their performance with it: when a participant was completing the path following task, the other was interviewed by the third experimenter and vice-versa. When both participants completed the experiment and the interview, they were debriefed, thanked and dismissed.

3.5 Dependent Measures

We used both a quantitative and a qualitative approach to observe the interaction between the elder participants and the *FriWalk* and to collect their impressions.

3.5.1 Video Analysis of the Interaction with the *FriWalk*

The videos of the interaction between the elder participants and the *FriWalk* were analysed using the video analysis software BORIS [12] which allowed observing the frequencies and the length of a series of events occurred during the experiment with the robotic walker. Between all the events considered for the analysis of the interaction, those that showed interesting results for the present study are described below.

Total length and correct completion of the path following task: We first observed if the participants followed correctly the indications provided by the *FriWalk* and completed correctly the path and how much time the task required.

Stop and braking: We considered the number and length of participants' stop and braking during the task, i.e. when the participant stopped or visibly slowed down his/her own speed during the task. Since the *Simulated Passivity* guidance was developed to adapt the speed of the *FriWalk* to the user (as explained in Sect. 2.2), stop and braking were considered as signs of a negative interaction between the users and the walker.

Help requests to the experimenter: We measured the number and the length of participants' requests to be assisted by the experimenter. Specifically, it was explained to participants that during the task they could ask the support of the experimenter or an explanation of the walker behaviour at any moment if they had some difficulties. A higher number of requests and a longer time of support provided by the experimenter are considered as a greater difficulty in interacting with the *FriWalk*.

Potential collision with an obstacle: We observed how much and how long each participant moved in the close proximity of one of the obstacles and risked the collision. As the *FriWalk* was programmed to follow routes which maintained a safe distance from the obstacles, the proximity indicated a misunderstanding in the interaction between the participant and the robotic walker.

3.5.2 Flexible Interview

To collect the impressions on the *FriWalk* and on the effectiveness of the interaction, the approach suggested by Minocha et al. [30] in conducting research with elders was used. In place of questionnaires and structured or semi-structured interviews, we developed the protocol for informal interviews establishing the main areas of interests for our study (defined also in relation to a previous pilot study). Except for the first question on the general impressions of the participant toward the *FriWalk* and the interaction with it, the informal interview was characterised by the absence of a pre-determined order in the questions and by the possibility to adapt the conversation to the issues raised by the participant during the interview. In this way, the discussion with the participants had a flexible strategy and focused on what each participant believed more important. Below the description of the different areas of interest investigated within the flexible interview.

General impression: The first question of the interview aimed to collect the first general impressions of the participants on the *FriWalk* and the quality of the interaction. An example of the question is "What is your general impression on the walker and on the trial you just performed with it? Is there something you particularly liked or disliked?". The question on general impressions was always at the beginning of the flexible interview to understand what were the most important issues with the *FriWalk* interaction, if any. Since participants were invited to freely express their opinions, the content of their response was affected by their own willingness to talk. For example, a single participant could highlight several features of the *FriWalk* and the interaction with it in a single answer. For these reasons, the aim of general impressions question was not to make a comparison between the different areas of interest or the experimental conditions, but to understand what was more relevant for the elder participant.

Control: To investigate possible problems of control over the robot, we developed a series of questions, such as "Did you have the impression you could always control the walker?" or "Did you have the feelings that the walker could be out of control?". The content of the answers was analysed in order to collect dichotomous values and specifically to determine if an individual had or did not have problems in controlling the *FriWalk*. The replies indicating a minimum difficulty in controlling the *FriWalk* were coded as "having problem in controlling the walker" (e.g., "There was a moment when I had the feeling of not controlling the *FriWalk* very well").

Intuitiveness: The ease in using the *FriWalk* was investigated through two different kinds of questions. First, the participants were asked directly if they had some difficulties in understanding the use the robotic walker (e.g., "Was it easy or difficult to understand how to use the walker?"). The answers to this question were analysed and coded in order to obtain dichotomous values, that is if it was "easy" or "not easy" to understand how the *FriWalk* moves. All the responses showing a minimum difficulty were classified as "not easy" (e.g., "it was a little bit hard to understand how the walker moved"). The second type of questions were focused on the suggestions provided by the *FriWalk* to follow the desired path (e.g., "Were the clues on the direction to follow provided by the walker clear?"). Since in the *Tablet* condition these indications were provided both by the GUI and by the *Simulated Passivity*, participants were asked to specify the type of clue that was clear or unclear for them (e.g., "Was the arrow on the screen a clear indication to understand the direction?"). As in the previous case, the answers were analysed and properly coded: "clear indications", "unclear indications" and "it depends on the particular suggestion".

Motion: A series of questions were developed to investigate the impressions on the *FriWalk* motion. In particular, we focused on the perception of possible sudden movements, and abrupt braking (e.g. "How did the walker move? Did you have the impression that the motion was smooth or did it show twitches? Did you feel any abrupt braking?"). The content of the answers on the motion was analysed to create dichotomous values in relation to two labels which described the motion as "jerky" or "smooth". All the participants' responses indicating at least a minimum presence of glitchy movements of the *FriWalk* were classified as "jerky" (e.g., "The walker moved both jerkily and smoothly.").

Adaptability: Three questions were developed to observe the participants' perception of adaptability of the *FriWalk* to their own walking style or if it affected the natural walking style of the participants. The first type of question investigated if they had the impression that the walker adapted to them or the other way around (e.g., "Did the walker adapt well to your movements and specifically to your walking pace?", "Did you have the impression that it was more the walker to adapt to your walking style or the opposite?"). Two labels were created to code the answers: "*FriWalk* adapted to the participant" or "participant adapted to the *FriWalk*". All the answers revealing a minimum adaptation of the senior to the robotic walker were classified as "participant adapted to the *FriWalk*" (e.g., "I had the perception we both [participant and *FriWalk*] adapt to each other"). The second type of questions aimed at investigating the participants' feeling to be blocked, pushed or pulled during the path following task (e.g., "Did you have the sensation to feel blocked, pushed or pulled during the task?"). The answers to the second kind of questions were classified as dichotomous values of "yes" or "no". All the replies indicating a minimum sensation of stoppage or push were coded as "yes" (e.g., "Just a little bit"). Finally, participants were asked if they felt that using the robotic walker was an effort for them (e.g., "Did you feel it was tiring to use the walker?", "Did you have the impression that the walker was heavy or hard?"). Also in this case, answers were coded as "yes" or "no" values and all the replies evidencing at least a minimum effort by the participant were considered as "yes" (e.g., "The walker was hard only in some specific moments").

Characteristics of the participant: In the end, participants were asked some information about them and specifically if they ever had problems in walking and for what reason (e.g., "Do you have any difficulty in walking? Why?"), if they ever used any walking aid (e.g., "Have you ever used any walking support?"). If participants replied affirmatively, they were asked what kind of devices and how long they used them. To distinguish participants who presented severe visual impairments, we asked them if they have problems in viewing the obstacles and the tablet (for those in *Tablet* condition), or if they could clearly see everything during the task. Moreover, we also asked the referents of each elder centre additional information about the visual condition of their guests who participated in the study. Finally, participants were requested to indicate their age, they were thanked for the participation and dismissed.

4 Results

Due to technical problems, it was not possible to analyse the video data of one participant in *Tablet* condition and another participant in *No Tablet* condition. However, their data were considered for the flexible interviews. In this section we denote with F the value of the analysis of the variance and with η^2 the effect size of the analysis of the variance.

4.1 Interaction with the *FriWalk*

Total length and correct completion of the path following task: The video analysis of the interaction with the *FriWalk* revealed that all participants completed the path correctly, meaning that the interaction was overall clear. After that, we run a two ways ANOVA with condition *Tablet* versus *No Tablet* and visual impairment as fixed factors, and the total length of path following task as dependent variable. We found that the time needed to complete the task was affected neither by the experimental condition ($F(2, 27) = 0.011$, $p > 0.915$, $\eta^2 = 0.000$) nor by the visual conditions of the participants ($F(2, 27) = 0.038$, $p > 0.845$, $\eta^2 = 0.002$). The length of the path following task was very similar for participants in *No Tablet* condition with ($M = 48, 73$, $SD = 11.74$) or without ($M = 49.93$, $SD = 10.05$) visual impairments and for participants in *Tablet* condition ($M = 49.36$, $SD = 10.99$).

Stop and braking: Results showed that only 6 participants (22.2%) stopped or braked their walking during the experiment with the *FriWalk*. More precisely, we found 4 participants in the *Tablet* case and 2 in the *No Tablet* case (one with visual impairments and another without). With the exceptions of 2 participants in *Tablet* condition, which stopped or braked three and four times for a total of 11.5 and 36.7 s respectively, all the others slowed their walking for less than 6 s.

Help requests to the experimenter: Video analysis showed that a total of 5 participants (18.5%), 3 participants with visual impairments in *No Tablet* condition and 2 in *Tablet* condition, required the support of the experimenter during the task. With the exception of 2 participants, who showed higher need of support by the experimenter (one participant with visual impairment in *No Tablet* condition requested the help of the experimenter 4 times for a total of 16.1 sand another participant in *Tablet* condition for 5.6 s), the experimenter intervention lasted 2 s or less, showing a high autonomy of elder participants in interacting with the *FriWalk*.

Potential collision with an obstacle: Results of video analysis showed no problem for the potential collision with an obstacle. Only 3 participants (11.1%) risked a collision with the obstacle, which are 2 participants with visual impairments in *No Tablet* condition and 1 in *Tablet* condition. All these events lasted 2 s or less.

4.2 Flexible Interview

The content of flexible interviews was analysed through the approach of direct content analysis described by [20]: responses were examined in relation to the areas of interest created (control, intuitiveness, motion, and adaptability) in order to summarise their content within specific categories. We considered both the valence (positive or negative) of each response and the explanation provided by the participant to better understand their impression on the *FriWalk*. In particular, for the question on the general impression, we observed the frequencies of each area of interest mentioned in participants' responses in order to understand what were the priorities for them in interacting with the *FriWalk* and completing the path with it.

All the other questions were analysed to have specific values, hence we first conducted two chi-square tests to observe

Table 1 General impression results

Label	Tablet	No Tablet	
	No visual impairment $N = 15$	No visual impairment $N = 6$	Visual impairment $N = 8$
General	6 *pos* and 2 *neg*	4 *pos*	3 *pos*
Motion	1 *pos* and 3 *neg*	2 *neg*	1 *pos*
Control	2 *pos* and 2 *neg*	1 *pos*	1 *pos*
Intuitiveness	2 *pos* and 1 *neg*	1 *pos*	2 *pos* and 1 *neg*
Adaptability	2 *neg*	1 *neg*	2 *neg*
Emotion	1 *neg*	1 *neg*	/

We reported the number of times the participants spontaneously talked about one of the areas of interests. Both *Tablet* condition and *No Tablet* conditions are reported and, additionally, distinctions for visual impairments is made explicit. Valence positive (*pos*) or negative (*neg*) of their impressions is indicated

Table 2 Results of Chi-square difference tests between *Tablet* versus *No Tablet* condition considering the different areas of interest

Area of interest	Chi-square	Effect size	Power	Tablet	No Tablet
Control over the *FriWalk*	$\chi^2(1, 29) = 3.03$, $p = 0.082$	0.323	0.501	10 (66.7%) o.o. 15	13 (92.9%) o.o. 14
Intuitiveness	$\chi^2(1, 24) = 0.839$, $p = 0.36$	0.187	0.537	10 (76.9%) o.o. 13	10 (90.9%) o.o. 11
Clear indications	$\chi^2(2, 25) = 2.78$, $p = 0.249$	0.333	0.626	9 (64.3%) o.o. 14	6 (54.5%) o.o. 11
Motion (smoothness)	$\chi^2(1, 25) = 0.103$, $p = 0.748$	0.064	0.760	4 (30.8%) o.o. 13	3 (25%) o.o. 12
FriWalk adapts to user	$\chi^2(1, 23) = 0.006$, $p = 0.94$	0.016	0.940	6 (42.9%) o.o. 14	4 (44.4%) o.o. 9
Feeling Blocked	$\chi^2(2, 28) = 6.028$, $p = 0.049$	0.464	0.583	7 (50.0%) o.o. 14	2 (14.3%) o.o. 14
Effort using the *FriWalk*	$\chi^2(1, 29) = 1.66$, $p = 0.198$	0.239	0.505	5 (33.3%) o.o. 15	8 (57.1%) o.o. 14

In columns **Tablet** and **No Tablet** are reported the number and the frequency of participants who replied affirmatively to the question concerning that area of interest (e.g.: "Did you have the perception you could control the *FriWalk*?", "Did you feel blocked during the interaction with the *FriWalk*?"). "o.o." stands for "out of"

the effect of experimental conditions and visual impairments, and then we described the frequencies of responses to each question to compare participants in *Tablet* versus *No Tablet* condition and participants with or without visual impairments. The results of the following analysis are subsumed in Table 1 (for general impressions), Table 2 (results of the Chi-square difference tests between *Tablet* and *No Tablet* conditions) and Table 3 (results of the Chi-square difference tests between participants with and without visual impairments).

General Impression: The analysis of the content highlighted an overall positive impression of the robotic walker and the interaction with it: we found that 13 participants expressed appreciation stating "It was fine" (6 in *Tablet* condition and 7 in *No Tablet* condition). Only 2 participants in *Tablet* condition expressed a generally negative opinion on the *FriWalk* and on the way the task has been executed (e.g., "I did not like it"). They also explained that the negative impression was related to the "abrupt braking" and to the impression that sometimes "it was stuck and unstable". We found that 6 participants talked about the control issue: 2 in *Tablet* and 2 in *No Tablet* highlighted positive aspects (e.g., "it is beautiful because the walker gently guides he user", "I could easily control the walker"), whereas other 2 in *Tablet* evidenced negative aspects (e.g., "The walker does what it wants and not what I want").

Analysing these data, we observed that the *FriWalk* controlled behaviour may have opposite impressions based on the peculiar user experience. Another important element concerning control is that 1 participant reported she lost the control over the *FriWalk* at the end of the path following task, i.e. "The walker has escaped me. I was scared", and this episode strongly affected the whole perception of the robot. 9 participants talked about the intuitiveness of using the robotic walker. Most of the comments were positive and concerned both the ease in learning to use the *FriWalk* and the clearness of the indications provided (e.g., "The walker is very easy to use", "Indications to go left or right were clear"), but 1 participant in *Tablet* condition and 2 in *No Tablet* conditions (both with visual impairments) highlighted in some cases problems in understanding the *FriWalk* behaviour ("Sometimes the direction to take or the suggestions are not clear", "The walker stops and then it is necessary to understand the direction to continue"). A total of 9 participants (6 in *Tablet* and 3 in *No Tablet* condition) mentioned some motion issues of the robotic walker. 5 participants in *Tablet* condition and 2 participants in *No Tablet* expressed a negative opinion on the motions of the *FriWalk*, highlighting the jerky motion of the robot. Curiously, all these participants showed no visual impairments, and most could also rely on the arrow indications on the tablet during the path following task. 5 participants expressed also a negative opinion on the adaptability of the *FriWalk*, in particular describing it as "heavy" or "hard" to push. The results of the following analysis are subsumed in Table 1.

Control: To observe if the presence of the GUI affected the perception of control, a Chi-square test was conducted. Despite a marginal significant difference between the experimental conditions, $\chi^2(1, 29) = 3.03$, $p = 0.082$, with 5 participants (33.31%) out of 15 in *Tablet* condition and just 1 participant (7.1%) out of 14 in *No Tablet* condition reported some problems in controlling the *FriWalk*, we have to remark that the statistical power for this analysis was quite low (0.501). Moreover, a second Chi-square test to observe the possible influence of visual impairments on the perception of control revealed a marginally significant effect of vision problem, $\chi^2(1, 29) = 2.88$, $p = 0.09$, but even in this case the statistical power was low (0.501).

Intuitiveness: The answers concerning the first question on the intuitiveness of the *FriWalk* showed that for the experimental condition (*Tablet* vs. *No Tablet*) the results of the Chi-square test (($\chi^2(1, 24) = 0.839$, $p = 0.36$) had a low statistical power, whereas it was found that participants' visual impairments did not affect the ease of learning in using the robotic walker ($\chi^2(1, 24) = 0.04$, $p = 0.84$). Most of the participants, regardless of *Tablet* or *No Tablet* condition, reported that it was easy to understand the behaviour of the robotic walker. We found that only 4 participants (17.2%, 3 participants in *Tablet* condition and one participant with visual impairments in *No Tablet* condition) reported having problems in understanding the use of the *FriWalk*. Concerning the clearness of indications, the two Chi-squares tests conducted to observe the effect of experimental condition and visual impairments showed no significant relevance ($\chi^2(2, 25) = 2.78$, $p = 0.249$ and $\chi^2(2, 25) = 1.928$, $p = 0.381$, respectively). Responses of participants showed that for 15 of them (60%) indications were "clear", while for 8 participants were "not clear" (32%). Interestingly, 2 participants in *Tablet* condition (8%), reported that the clearness of the cues depended on the type of indication, with the GUI perceived as clear, whereas the *Simulated Passivity* clues unclear.

Motion: The Chi-squares tests revealed no significant effect of *Tablet* versus *No Tablet* condition ($\chi^2(1, 25) = 0.103$, $p = 0.748$) or of visual impairments ($\chi^2(1, 25) = 0.053$, $p = 0.81$). In particular, results showed that 18 participants (62.1%) perceived the motion of the robotic walker as "jerky": 6 of them with and 12 without visual impairments (among which, 9 in *Tablet* condition and 3 in *No Tablet* condition). Only 7 (24.1%) described the motion of the *FriWalk* as smooth: 2 of them with and 5 of them without vision problems (4 in *Tablet* and one in *No Tablet* condition).

Adaptability: The first question on adaptability aimed at investigating if participants had the sensation that the *FriWalk* adapted to their own motion and speed or the other way around. Two Chi-square tests were conducted to observe the influence of *Tablet* versus *No Tablet* and of the presence of visual impairments, both revealing no significant effects ($\chi^2(1, 23) = 0.006$, $p = 0.94$ and $\chi^2(1, 23) = 0.34$, $p = 0.797$, respectively). Results evidenced that a total of 10 participants (43.5%) had the sensation that the robotic walker adapted to their pace, whereas 13 (56.5%) felt that the participant should adapt. The aim of an additional Chi-square test was to observe the presence of the GUI on the interactions feelings, i.e. to feel blocked, pushed, pulled, showed: despite a significant effect can be observed by the presence or not of the tablet ($\chi^2(2, 28) = 6.028$, $p = 0.049$), a low statistical power (0.58) was related to this result. We further conducted some frequencies exploratory analyses and we found that a total of 16 participants (57.15%, 9 participants in *No Tablet* condition and 7 in *Tablet* condition), declared they did not feel blocked, pushed or pulled during the path following task. Instead, only 3 participants (10.7%, all performing the path following task in *No Tablet* condition) reported to feel "a little bit" blocked, and, finally, a total of 9 participants (32.14%, 2 in *No Tablet* and 7 in *Tablet* condition) had the impression to feel stuck. Visual impairments again showed no significant effect, $\chi^2(2, 28) = 3.534$, $p = 0.171$. Finally, we conducted two Chi-square tests to observe the effect of experimental conditions and visual impairments on the effort perceived by the users. Both tests, showed no significant results ($\chi^2(1, 29) = 1.66$, $p = 0.198$ and $\chi^2(1, 29) = 0.120$, $p = 0.73$, respectively), but the analysis considering the *Tablet* versus *No Tablet* conditions showed a low statistical power (0.504). Results showed that a total of 16 participants (55.2%) reported it was not tiring using the *FriWalk*, whereas other 13 (14.8%) declared the opposite. Moreover, observing the results for participants with visual impairments, we found out that half of them described the walker as "heavy" and "hard", while the other half said they had not made any effort during the tests. These results highlighted that other participants' physical features, more than the presence or absence of the GUI on the tablet or the visual impairments, affect this specific opinion.

Tables 2 and 3 succinctly report the outcomes discussed in this section. The results showed in general not a very high statistical power, which is mainly due to the reduced sample size. However, we want to stress that in user experience and human–robot interaction research involving seniors this is a

Table 3 Results of Chi-square difference tests between participants with and without visual impairments considering the different areas of interest

Area of interest	Chi-square	Effect size	Power	Visual Imp.	No Visual Imp.
Control over the *FriWalk*	$\chi^2(1, 29) = 2.88$, $p = 0.09$	0.315	0.501	8 (100.0%) o.o. 8	15 (71.4%) o.o. 21
Intuitiveness	$\chi^2(1, 24) = 0.04$, $p = 0.841$	0.410	0.978	6 (85.7%) o.o. 7	14 (82.4%) o.o. 17
Clear indications	$\chi^2(2, 25) = 1.928$, $p = 0.381$	0.278	0.658	5 (83.3%) o.o. 6	10 (52.6%) o.o. 19
Motion (smoothness)	$\chi^2(1, 25) = 0.053$, $p = 0.81$	0.046	0.824	2 (25.0%) o.o. 8	5 (29.4%) o.o. 17
FriWalk adapts to user	$\chi^2(1, 23) = 0.34$, $p = 0.797$	0.122	0.622	2 (33.3%) o.o. 6	8 (47.1%) o.o. 17
Feel blocked	$\chi^2(2, 28) = 3.534$, $p = 0.171$	0.355	0.611	1 (12.5%) o.o. 8	8 (40.0%) o.o. 20
Effort using the *FriWalk*	$\chi^2(1, 29) = 0.120$, $p = 0.73$	0.064	0.745	4 (50.0%) o.o. 8	9 (42.9%) o.o. 21

In columns **Visual Imp.**, **No Visual Imp.** are reported the number and the frequency of participants who replied affirmatively to the question concerning that area of interest, as in Table 2. "o.o." stands for "out of"

common limitation (e.g. 30 users in [17], 6 in [31], and 31 in [36]).

5 Discussion

In the present study, we aimed at observing the interaction with the robotic walker *FriWalk*, whose main purpose is to guide senior participants along a predefined path. The chosen *FriWalk* guidance system, named *Simulated Passivity* [2], has been developed considering the paradigm of passive robots [13] with the idea of authority sharing [3], hence it shares with the user the responsibility for the locomotion. The effect of a GUI has been also investigated, which plays the role of standard navigator. Participants were asked to complete an unknown predefined path following the cues provided by the robotic walker (in both *Tablet* and *No Tablet* conditions) and they were interviewed to collect their impressions. Results of video analysis on human–robot interaction showed that all participants completed correctly the path following task (confirming H1) irrespective of the presence of the visual GUI (confirming H2). Similarly, the task completion was not affected by the visual impairments of the participants (confirming H3). Only a small percentage of participants stopped or braked during the path following task, requested the support of the experimenter during the interaction with the *FriWalk* and showed problems related to potential collisions with the obstacles. Thus, the outcomes confirmed that the *FriWalk* and the *Simulated Passivity* are quite effective and adaptable to elder individuals with different types and measures of deficits. The analysis of the content of the flexible interview showed an overall participants' appreciation of the *FriWalk*. Nevertheless, the questionnaire on the *FriWalk* general impressions highlighted that the most relevant issues, in order of importance, are the intuitiveness (and in particular the indications on its direction), the control over the robot, its motion and its adaptability (see also the summarising Table 1).

We also found no significant differences related to visual impairments for the intuitiveness and the motion of the *FriWalk*, with most of the participants reporting it was easy to learn to use the robotic device and half of them declaring the indications on the direction were clear. However, most of the participants reported they perceived the *FriWalk* movements as "jerky". Marginal differences related to the experimental conditions and the visual impairments of the participants were found for the questions on control over the robot and adaptability. For control, despite the low statistical power of Chi-square test between *Tablet* versus *No Tablet* conditions, a higher percentage of participants having the support of the GUI reported to have some problems in controlling the *FriWalk*. A similar marginal effect with low statistical power was found for visual impaired users, since no one of the participants with severe visual problems declared difficulties in controlling the robotic walker. For adaptability, most of the participants reported the sensation they had to adapt to the robotic walker, although the most of them declared it was not tiring walking with the *FriWalk*. These results highlighted that the weight of the robotic walker is not perceived as excessive by the users, but that it is necessary to improve the adaptability to the user's walking style avoiding abrupt changing of speed especially in the changing of the user in control and robot in control phases. Finally, concerning the question on the sensation of feeling blocked, pushed or pulled by the robotic walker, we did not find an effect of participants' visual impairments nor of the experimental conditions, but it was observed that a higher number of participants in *Tablet* condition than those in *No Tablet* condition reported they felt to be blocked by the *FriWalk* during the completion of the path.

The results of content analysis of flexible interviews evidenced that participants in *No Tablet* condition (and especially those with visual impairments) had a better impression of the *FriWalk* and the interaction with it, thus disconfirming H4.

As a consequence, the results of the present study highlighted that the *FriWalk*, with its *Simulated Passivity* mechanical guidance system, represents a trustworthy device for assisting seniors in walking. Moreover, they showed reliability in guiding both people with or without visual impairments, showing the good adaptability of the assistive device to users with different physical deficits. Furthermore, the general impression is that the *FriWalk* was more appreciated by people with visual difficulties, thus without the possibility of using the GUI. A possible explanation of these differences in perceiving the robotic walker could be related to the additional information provided by the GUI. In fact, participants in *Tablet* condition reported that the direction was already clearly shown by the GUI, so the intervention of the mechanical guidance was perceived as unnecessary and disturbing. Follow these information, we may argue that the *Simulated Passivity* corrections should be milder in presence of the GUI. Nonetheless, we want to highlight two important elements concerning the results of the present study. First, the answer's of participants were recoded through a severe approach (e.g., replies indicating a minimum issue in controlling the *FriWalk* were coded as having problems in controlling the robotic walker). Second, the differences concerning the several areas of interests were only marginally significant, indicating that *Simulated Passivity* can work properly also without the GUI. However, we want to stress that a "positive impression" reported on the robotic-walker system does not automatically imply that a user would actually use it in their daily life. In fact, some of the participants during the interviews spontaneously declared that, even if they liked the *FriWalk*, they would not use it because of the possible stigma in using such a kind of device. This is perfectly aligned with the difference between willingness and intention to use a device, as reported by many authors for healthcare technology [4,19].

Of course, the present research has some limitations. First, we developed the path following task has been carried out within a university lab. Clearly, a controlled environment have effects on the interaction between the elder participants and the *FriWalk*. In particular, we have to highlight that all our lab tests within the ACANTO project, were conducted considering the safety of elder participants as primary concern, and this can have affected both the interactions and the results of the reported experiments. A more ecological approach, despite methodological limitations, certainly allows the collection of more comprehensive information on the interaction [11,40]. Second, the possibility of observing the interaction in a longitudinal way may open to information gathering on possibly unobservable features that are not at disposal in laboratory tests [7,15]. Finally, in the present study, all participants showed no cognitive problems: future studies should include older adults with cognitive problems, as they can show different issues in relating to assistive technological devices [46], with the aim of enlarge the user group that can benefit of the proposed technological solutions.

The results of the present work highlight that the effectiveness of a robotic system is strictly connected to its flexibility. Developing a system which can respond to the most common problematics for elders spread the range of the possible users, as well as the adaptability of the system to the elder users improves their experience and help having a positive relation with the technological device.

6 Conclusion

In the present research, we observed the interaction between elder users and the robotic walker *FriWalk*, developed to guide older adults with walking deficits. The results showed that the robotic device worked properly with or without a GUI which provided indications on the direction to follow, as well as for people with and without visual impairments. The interviews highlighted overall positive impressions of participants, with visually impaired users evaluating slightly better the robot than individuals who could rely also on the graphical user interface to complete the path.

Future research directions comprise the observation of the interaction with the robotic walker through a longitudinal and more ecological approach in real environments, involving elder users with possible cognitive problematics and deficits.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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