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Robotic Companions in Stroke Therapy: A User Study on the Efficacy of Assistive Robotics among 30 Patients in Neurological Rehabilitation *

S. Meyer. Ch. Fricke

Abstract— **This article summarizes and explains the results of our recently completed German research project ROREAS (Robotic Rehabilitation Assistant for Gait Training of Stroke Patients). The project combines medical, technical and sociological expertise to develop an autonomous robot companion to aid stroke patients' recoveries. The robotic companion aims to bridge the gap between human assisted gait training and independent exercise.**

From the beginning, the project was carried out in the real surroundings of the users – the corridors of a rehabilitation clinic. N=12 stroke patients were included in the technical development and N=30 patients in the evaluation of the robot companion. The robotic platform and HRI (Human-Robot Interaction) have been developed specifically for the particular requirements of this study.

The empirical results show that the majority of robot users accept the mobile robotic companion and would incorporate it into their gait training. Despite severe mobility and/or cognitive handicaps, all patients could easily handle the robot. The robotic assistance motivated patients to leave their room despite difficulties in spatial orientation and ultimately they were able to increase the length of their routes and the duration of their training units.

I. Introduction

In Germany, around 262,000 people suffer from strokes annually; strokes are the most commonly acquired disability for adults [1]. Three months after the incident, around 25% of surviving patients are seriously afflicted with severe limitations to their daily activities, and around 17% show moderate to severe dysfunction [2]. Today, strokes make up a total of 2-5% of health care expenditure [3]. Current forecasts predict that the number of patients will continue to increase due to changing demographics. At the same time, social and individual expectations for rehabilitation are rising. The need for innovative, effective and sustainable therapies to recover mobility and orientation is growing enormously. [4].

Neurological rehabilitation proceeds in three phases: mobilization of the patient from bed to wheelchair; recovery of walking capacities and finally, refining the ability to walk through constant gait training [5]. Types of robotic assistances for stroke patients have so far only been conceived for early stages of rehabilitation, when patients cannot yet stand or walk independently. The most common approaches combine treadmills and exoskeletons to support and relieve patients of their weight. [6, 7, 8, 9, 10]. In later stages of rehabilitation, when patients are able to make their first independent steps, only manual assistances tend to be used, such as walking frames, crutches and tetrapod walking sticks. For this later phase of the rehabilitation, the autonomous robot companion ROREAS (derived from the project acronym) has been designed.

Figure 1. ROREAS accompanying the patient during their gait training in the corridor of the stroke rehabilitation clinic

The project's overreaching aim is to develop a robot companion which will accompany the patient in their daily gait training. It is designed to motivate the patient to train for longer periods, cover greater distances, provide them with more security to walk independently and strengthen their orientation abilities.

Secondly, the project aims to develop a HRI (Human-Robot Interaction) which allows stroke patients, with their respective handicaps, to handle the robot naturally.

The third and final goal is to evaluate the feasibility and user friendliness of the developed robot companion, combining medical parameters, social and ethical requirements as well as technological criteria. Accordingly, the evaluation strategy is threefold: a) to test the technical feasibility of an autonomous gait assistant, b) to evaluate the user-friendliness, patients' acceptance and training motivation and c) to assess the therapeutic impact of robotic gait assistance.

ROREAS belongs to the field of Socially Assistive Robotics, which is defined as the "provision of assistance through social (not physical) interactions with robots". Such a robot uses "noncontact feedback, coaching, and

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S. Meyer, SIBIS Institute for Social Research Berlin, Germany (phone: +49 30 330 072 30; e-mail: sm@sibis-berlin.de)

C. Fricke, SIBIS Institute for Social Research Berlin, Germany (email: cf@sibis-berlin.de)

encouragement to guide a user during the performance of a task" [11]. Socially assistive robots are promising in a number of domains, including skill training, daily life assistance, and physical therapy [12], however to date there is no project known with the same aims as ROREAS [13].

This paper will focus on the social scientific aspects of the study (for technological challenges and test results see [14, 15, 16, 17].) The following questions were raised:

- How can a social robot be designed in a way that the patient will enjoy training with it?
- How can a user interface be designed which can be grasped by stroke patients whose cognitive, tactile and emotional resources are restricted?
- Is the robot-assisted training more or less accepted than training with a physiotherapist or family member?
- Will the robot-assisted training motivate patients to train more frequently than they would when training alone? And do patients cover greater distances than they would without the company of a robot?

II. TRAINING CONCEPT

The starting point of this project was to design a suitable concept for robot-assisted gait training by both medical and social scientific partners [16]. Consequently, the following requirements for the robotic platform and HRI were established:

a) ROREAS should call the patient in their room via telephone to invite them to start their gait training in the corridor. The patient should then answer the call and follow to the corridor.

Figure 2. ROREAS gives the patient a call in their room, inviting them to start their robotic gait training in the clinic corridor

b) ROREAS should initiate the interaction verbally. The robot should greet the patient and prompt them to sit down on a chair next to it.

c) ROREAS should then show the patient a floor plan, displaying the possible training routes. Possible resting points (green dots) and destinations (dining room, nursing station, and elevators) are also indicated (see Figure 3). ROREAS explain the routes and the destinations vocally while simultaneously displaying them on its screens.

d) The patient selects their route and starts the training. The robot must follow in a comfortable and constant distance and navigate the clinic floors largely autonomously [17, 18].

e) ROREAS should indicate the possible resting points (see green signs marked R, on Figure 3) and rest by the patient's side, should they wish to rest. When the patient decides to proceed their training, the robot should follow.

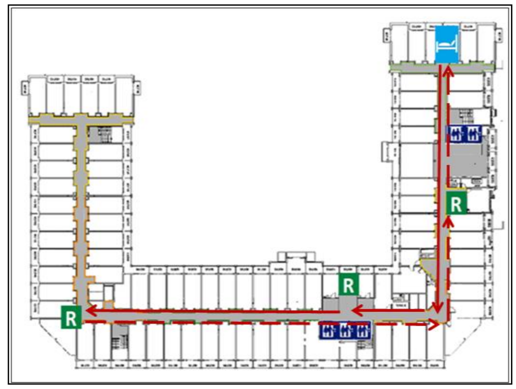

Figure 3. Plan of one floor where the robot-assisted gait training and user studies took place. The blue sign marks the room of test patient (starting point of gait training); R marks the possible resting places; the red line indicates the patient's route

f) The robot should display the floor map and indicate the patient's location as well as the possible routes (straight ahead, back to their room or to the restaurant, see Figure 4) at each resting point.

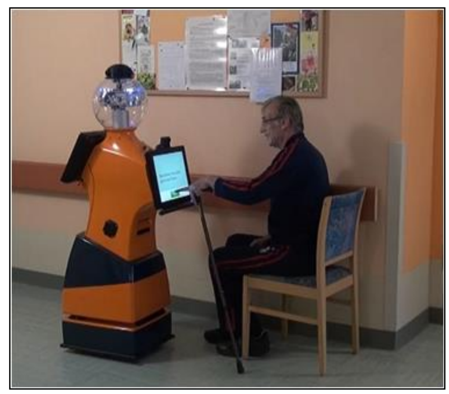

Figure 4. Interaction in front of the patient's room at the end of training

g) The training should always end at the patient's room (see blue sign in Figure 3). The patient should receive feedback from the robot about the distance and duration of their training in order to compare their performance to that of previous trainings. The robot should then ask the patient to rate their physical condition after completing the training. Both pieces of information will serve as input for the next training unit.

III. TECHNICAL DEVELOPMENT: NAVIGATION, PERSON DETECTION AND HRI

For this study and training concept, a new robotic platform was developed. This requires the robot to: a) navigate the clinic autonomously [14], b) recognize and follow its patient [15], c) be operated in a seated (walking stick users) or standing position (walking frame users) [19] and present information and dialogs simultaneously via screen and voice synthesis.

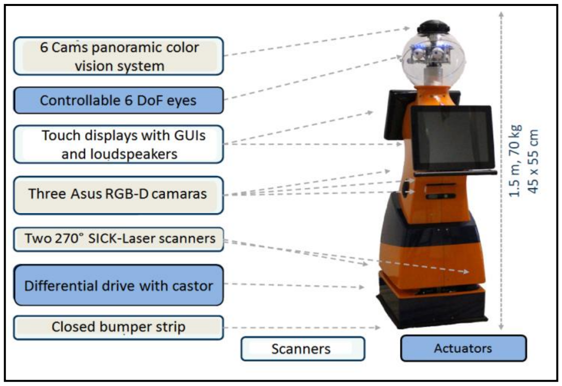

Figure 5. ROREAS demonstrator consisting of the SCITOS platform (MetraLabs, Ilmenau) with its main equipment for environmental perception; navigation and human recognition (Technical University Ilmenau).

While the new robot platform was designed by the Technical University of Ilmenau and MetraLabs Ilmenau, Germany, the HRI was conceptualized by SIBIS Institute and the project's medical partners directly in the clinical environment.

Since the platform was not yet available in the project's earliest phases, we used our own qualitative design methods and tools. Our focus was to integrate patients into experimentations within their environment as soon as possible; the stroke clinic. For this, the role "robot-imitator" was developed: a clinic employee simulated the movements which the robot would later perform and carried a tablet in front of their chest which displayed the information and programmed dialogs. Initially, the robot imitator also simulated the speech synthesis, later this was carried out via tablet.

Aims of these tests:

- Intuitive movements: The robot's navigation system was designed to adjust to patients' intuitive movements. During the development, the imitator's movements were adapted to the patient's intuitive movements until the simulated navigation became patient-friendly and predictable.

Figure 6. The patient and robot-imitator are working together to conceive a navigation system that can adapt to the patient's intuitive movements. A third person is observing and documenting the process via video

- HRI: the robot should communicate verbally and simultaneously display this information as text on the screen. The patient should enter their feedback and give commands by pressing buttons on the robot's touch screen. Operation of the robot must be possible from both a standing position (for walking frame users) as well as a seated one (for walking stick users). The robot must therefore carry two screens at different heights (see Figure 2).
- Guideline for Speech Synthesis:
  Simple language
  Sufficient volume (audible even from the corridor)
  Intelligible modulation
  Slow tempo
  Repetitions when necessary
- Texts: The information on the screen must be intelligible despite many patients' cognitive limitations. SIBIS Institute has developed an intelligible screen layout which was derived from existing usability-design-concepts. (see Figure 7)

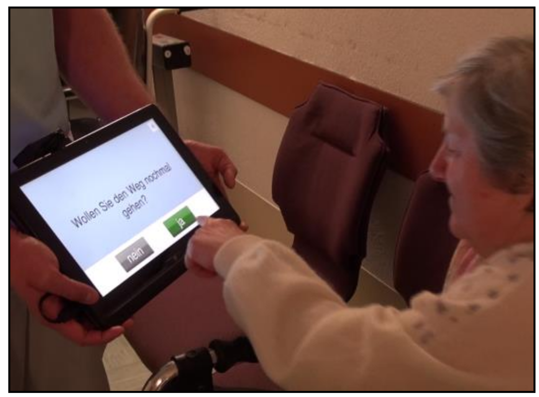

Figure 7. Intelligible screen layout: "Would you like to repeat the training?" – "no" / "yes"

The user trials took place in 2014/2015 in five runs during which the HRI and Graphical User Interface (GUI) were further refined.

TABLE I. 5 USER TRIALS CONDUCTED TO DEVELOP HUMAN-ROBOT INTERACTION (HRI) AND GRAPHICAL USER INTERFACE

Evaluation	GUI	Speech output	Robot	Patients
I	Version 0.1	speech by imitator	robot imitator	N=6
II	Version 0.2	speech by imitator	robot imitator	N=3
III	Version 0.3	synthesised voice	robot imitator	N=3
IV	Version 0.4	synthesised voice	robot	patient imitator
V	Version 1.0	synthesised voice	robot	patient imitator

This elaborate procedure has paid off. By the end of the development process, the GUI became clear and intelligible, the colours were easily recognizable and font sizes and button fields were sufficiently allocated. The developed HRI concept could successfully be implemented in the user evaluation (see section IV) and needed little improvement.

Figure 8. The robot-imitator simulates the HRI with a patient

IV. CONCEPT OF FINAL USER EVALUATION

After the integration of the navigation, person recognition and HRI, the assessment of the robot in the clinical environment and evaluation of the training concept could begin. Following the project's approach, these tests were conceptualized as user studies in the normal clinical surrounding. User studies were conducted in six runs from April 2015 – March 2016 (see Table II and III).

A. Methodological approach of user studies

N= 30 patients were included in the evaluation of the robotic training. User trials were carried out in six runs, between April 2015 and March 2016. The robot's performance (increased autonomy of navigation and person recognition) progressively improved from one run to the next.

The authors applied a specific methodological approach to this proceeding [20, 21] and compared these strategies with those of comparable studies [22]. Crucial to this approach are the following three steps [15]:

Step 1: Before each user trial, the robot's functions were tested in the clinic corridors. To ensure that all skills and behaviours required for the next run were accurate and secure, tests were undertaken with staff members of the Technical University. For the quantitative assessment, diverse measures were determined (results can be found here [24]).
Benchmark: All required navigation abilities for the next user run must fulfil benchmark criteria.

Step 2: User trials with "patient-imitators". After the successful execution of functional tests and before user trials with actual stroke patients, the robotic companion was evaluated using "patient-imitators". Patient-imitators are persons of the same age as the prospective target group, who have been trained to imitate the walking behaviour of stroke patients. The purpose of these tests was to establish a benchmark from which to decide whether it is socially, technologically, medically, and ethically viable to include actual stroke patients in these trials. Tests with patient-imitators became a crucial precondition to confronting vulnerable users with the autonomous robot.
Benchmark: Navigation and HRI abilities as well as ethical standards must fulfil the benchmark criteria, preparing the robot for the trial with actual stroke patients.

Step 3: Steps 1 and 2 must be successfully completed in every trial run before Stage 3 can be carried out. From 4/2015 to 3/2016, six trial runs with N=30 stroke patients (Table I and II) were conducted. This means that Stage 1 and Stage 2 had to be completed six times, after each trial run, in order for the final stage, Stage 3, to be carried out.

B. User studies concept and evaluation data

During the first set of user trials, a predefined, short training route was necessary (4/2015 - 9/2015) as the robot's navigation skills were not autonomous enough to realize a training course adapted to the individual user. In these three early trial runs, N =16 were included (see Table I). In the next three trial runs (11/2015 - 3/2016), patients were able to freely select their training routes and could train for as long as they wished for (N=14 included; see Table II). In this second set of trial runs, patients were able to train up to one hour per session, in accordance with their state of health.

Each patient trained on two days. Consequently, the patient's learning progress, the variation of length and duration of the training, as well as the change in motivation and acceptance, could be measured.

TABLE II. FIRST SET OF USER TRIALS: PREDEFINED ROUTES

Predefined training route*	Number of patients	Average duration of training/ per patient
April 2015	N=4	12.52 min
June 2015	N=5	11:12 min
Sept. 2015	N=7	15:32 min
Total	N=16	13:30 min

* Predefined training routes: Moving from patient's room to a set destination and back again; shorter and longer distances offered

TABLE III. SECOND SET OF USER TRIALS: INDEPENDENT TRAINING

Independent training**	Number of patients	Average duration of training/ per patient
November 2015	N=4	47:40 min
January 2016	N=3	37:07 min
March 2016	N=7	51:13 min
Total	N=14	47:26 min

** Independent training: The user can decide independently where to go and how long to train

The evaluation of the user trials is based on an extended video recording analysis. In total, 14.5 hours of video material was analysed. Additionally, extended interviews were conducted with all patients. The interview results were compared to the video data.

C. *Sample stratification:*

Inclusion criteria for test users:

- patients' clinical diagnoses (assessed by medical partners)
- patients have only recently recovered their ability to stand or walk alone without assistance of therapist (assessed by physical therapists),
- cognitive limitations and weak orientation skills (assessed by medical partners)
- require walking aids
- male : female = 50% : 50%

TABLE IV. SAMPLE STRATIFICATION: AGE AND WALKING AIDS

	Patients			
Walking aid	**Total**	**≤60 years**	**61 - 74 years**	**> 75 years**
Walking frame	17	4	7	6
Crutches	11	7	2	2
Tetrapod stick	2	0	2	0
Total	30	11	11	8

Table IV shows the sample included in the trials. Patients have been separated by age and their walking aids.

V. RESULTS FROM USER STUDIES TO ASSESS THE ROBOTIC GAIT TRAINING

A. *User friendliness*

The analysis of the human-robot interaction is based on in-depth video analyses of the start and final phases of the training. The evaluation was carried out by two researchers independently of each other through the means of previously defined benchmarks. The results show that 25 out of 30 patients had no difficulties interacting with the robot.

Subsequently, these video-based results were compared to patients' subjective appraisals which were obtained from extended interviews. These results show that 26 of the 30 consulted patients perceive the touch input and the specifically developed GUI as easily operable. This does not vary between the different age groups and almost no differences can be noted between the different patients' clinical diagnoses. Patients' subjective usability appraisal confirm the results of video analysis (see Table V).

TABLE V. RESULTS OF USABILITY ASSESSMENT BASED ON VIDEO ANALYSIS AND PATIENT INTERVIEWS

	Usability feedback	**≤ 60 years**	**61-75 years**	**> 75 years**
Video-analysis	no difficulties	11	10	4
	difficulties	0	1	4
Patient's subjective assessment	no difficulties	9	10	7
	difficulties	2	1	1

The usability results paint an exceptionally positive picture. The continuous involvement and integration of users has enabled the realisation of a human-robot interaction which allows cognitively impaired patients to deal with the robot in a largely autonomous way. The development of a human-computer interaction, which allows all patients to operate the robot intuitively, has been successful. This should be understood as one of the project's most important achievements. The robot is accessible to, and operable by, patients with strongly impaired motor functions, visually impaired patients, patients suffering from aphasia as well as by cognitively impaired patients. These findings will be pursued in subsequent projects.

B. *Patient's acceptance of a robotic assistant*

To raise patients' acceptance of the robot, an ethical and social guideline was established in the starting phase of the project. This was then later implemented in the development of the robot's navigation skills and the HRI. The main objective of this guideline is to strengthen the patient's autonomy, to motivate the patient to walk for longer distances and to feel a sense of success. The initial hypothesis was that if the patient feels empowered and in control over the robot, this will strengthen the motivation to practice and increase the acceptance of the robotic training.

The ethical guideline includes the following factors:

- The robot should follow behind the patient to avoid obstructing the patient's view and disturbing their orientation. The patient should be able to look ahead without any diversion and specify the direction of the training independently, while the robot follows.
- The patient should always retain complete command over the robot; the patient's freedom should not be restricted. The robot must be able to adapt to the patient's desires, for example when they wish to take a break, talk to another patient or end the training.
- The robot should build trust. Anxious patients especially will be more motivated to an independent gait training if they can rely on the robotic assistance. This means that the robot must be able to establish its location at all times in order to lead the patient safely back to their room. This can only be guaranteed if the robot's person-recognition and navigation abilities are robust and comprehensible, and even more so, predictable to the patient.
- Human-robot interaction should be "face-to-face", never from behind the patient. Furthermore, communication in the corridor could endanger patients with limited walking ability and lack of balance. Therefore, communication should take place primarily at two distinct locations: in front of the patient's room and at the designated resting points on the floor, never on the corridor. This is to ensure an easy comprehension of both verbal communication and information depicted on the screen.
- Polite navigation and interaction. When the patient wishes to take a break on one of the provided chairs, ROREAS should move to an appropriate position and wait patiently next to the patient (the robot should not wait in front of the patient). This is to relieve the patient

and give them the freedom to decide when to continue with the training. The robot should be situated close to the wall so that it will not pose an obstacle to other patients or hospital staff when it is in this resting position.

- Respect of privacy. The gait therapy takes place on the hospital corridors, and so, in the public areas of the clinic. These public areas do not only place strains on the robot's person recognition system and navigation [17, 18], but also on the patient's privacy and personal rights. This means that performance feedback at the end of the training course will be communicated to the patient exclusively by text and not by speech. This will ensure that neither fellow patients nor nursing staff can "listen in".
- The training with the robot acts as a transition between training with a therapist and independent walking. Therefore, the robot should appear less 'human' than 'technical'. Nonetheless, the robot features a head and eyes to motivate the patient. The robot's eyes should always point in the direction of the patient; the robot should "look at the patient".

Patients' acceptance of a robotic companion following these principals is remarkable.

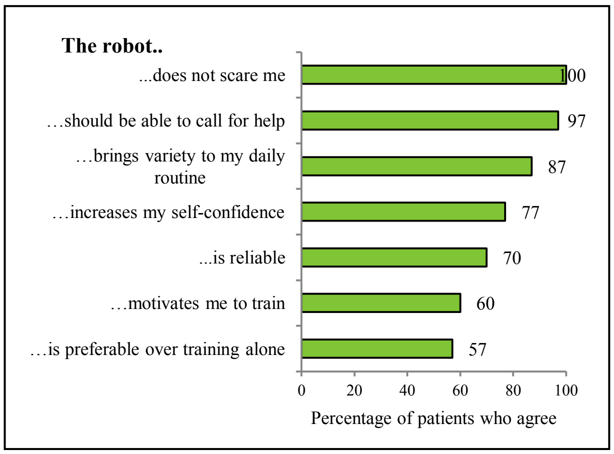

Figure 9. Acceptance meassured by seven questions

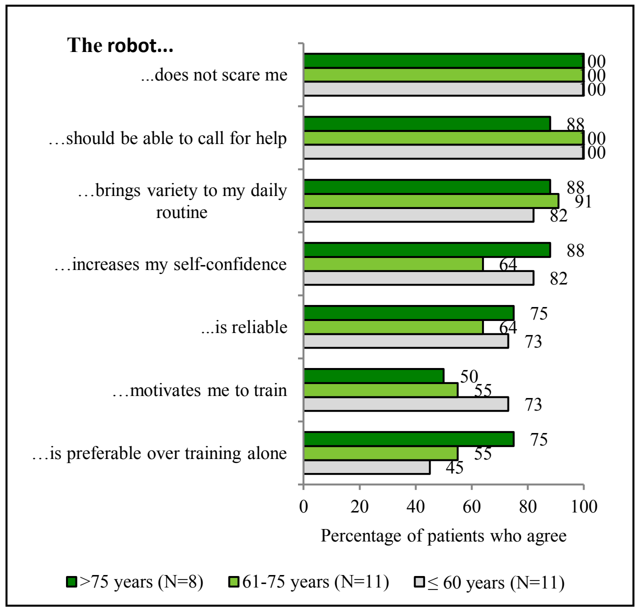

Figure 10. Acceptance by age groups

No fear of the robot: Interviews conducted with patients show that not a single patient was afraid of the robot or the robot-assisted training. This low expression of fear towards robots in stroke therapy is remarkable. ROREAS is not an automated version of the traditional fitness equipment which patients are familiar with from the gym. Rather, it is an autonomously acting robot companion. Accompanied by the robot, patients expose themselves to their fellow patients and hospital staff, which would expectedly rather promote reservation and anxieties than dismantle them. None of the robot users however rejected the robotic companion after having personally experienced it. This is true even for some of the initially sceptical users.

Reliability: 70% of patients remark that they trust the robot. They believe that this autonomous companion will always retain its orientation and is able to guide them safely back to their room. Hardly any differences can be noted between the different age groups (Figure 11); 75% of older patients and 73% of younger patients indicate that they trust the robot.

Patients who train with the robot become increasingly confident to explore previously unknown areas of the clinic. Again, this indicates the motivational character of the robotic training. Accompanied by the robot, patients venture out to explore remote hospital corridors outside the established routes. This in turn leads to increased self-confidence, subsequently increasing the patient's area of exercise.

Observations indicate that patients who practice with the robotic assistant cover greater distances than before. ("I have never walked this far!"). This not only shows an increased motivation, but also that the project's therapeutic goal (intensification of independent training and increased intensity of training) is fulfilled, or at least supported, by the use of the robotic companion in stroke rehabilitation. The latter aspect however should be systematically investigated further.

Call for help: To reduce anxiety and develop further confidence in the robot, an emergency call would be helpful. This function would reassure patients in case of problems regarding their own health or the robot's technical capabilities. An emergency button would also encourage patients to train during evenings, when corridors are less busy, or to explore areas of the clinic which are vacant outside of therapy times.

Training preferred with robot: Almost 60% of patients who have trained with the robot state that a robot-assisted gait training is preferable over training without accompaniment (see Figure 10). Interestingly, 75% of the eldest group (over 75 years) preferred the robot-assisted training (Figure 11). This result is especially noteworthy as it contradicts current empirical studies of elderly persons' acceptance of new technology which state that they are critical to innovative technologies even if they seem to be useful and fit into their everyday lives. [24, 25, 26]

Motivation to train: Almost two thirds of users – regardless of their age – feel more motivated to train with the robot than alone. Here the reaction of the younger patients is much more positive than those of the older patients (73% of younger patients, 50% of older patients; Figure 11). The increased motivation induced by the robot is explained by the interviewees through a range of arguments. Common arguments include “one can entirely concentrate on oneself", "one is not distracted by a human companion", "it's fun when a metal companion rolls behind you!" or "the robot is always patient and never in a bad mood."

Variety of daily routine: When asked for further factors that could increase the acceptance of the robot, non-medical factors come into play. Most notable here is the element of variety and diversification of training methods, and hence to the patient’s daily routine. Almost 90% of users indicate that this aspect has led them to engage with the robot-assisted training; variety as opposed to both monotonous training alone and traditional training with a physiotherapist. Similarly, patients feel that training with the robot is fun and a pleasurable experience. Almost 70% of users confirm this positive experience after having experienced the robot-assisted training.

Increased self-confidence: On average, 77% of users state that being able to command a robot increases their self-confidence and even over 80% of the oldest and youngest age groups confirm this feeling. Observations show that patients react with joy and excitement when the robot follows their commands. They are proud when their fellow patients acknowledge “their” robot and some even give it an amiable nickname. .

C. Impact of Robot-Assisted Gait Training

The success of the developed training is ultimately dependent on its therapeutic efficacy, for which psychological factors are critical to the increase of training motivation, the increase of self-confidence and the support of patient autonomy. The interviews conducted after the tests show how impressed patients were with their own training performance. They were surprised by how they had never walked so far and by how they were able to explore previously unknown areas of the clinic. Typical quotes include: "I have never walked so far before"; "by the first day I had already walked further than ever before, by the second day, I had managed even a little further – I set my mind to it" and "of course the robot has motivated me to go further than before. It makes you want to prove it to yourself”.

The motivation to train independently further increases when patients can move freely and training routes are no longer prescribed. The resulting autonomy asks patients to challenge themselves and to practice more than would be possible on shorter and predetermined routes.

The robotic training increases the motivation to train independently, promises diversity of the training regime, challenges patients to leave their room despite difficulties with orientation and increases the patient’s radius of training in the clinic.

TABLE VI. LENGTH OF ROUTE ACCORDING TO TYPE OF ASSISTANCE AND TYPE OF TRAINING

	Walking frame	**Crutches**	**Tetrapod stick**
Predefined training route	81m (N=11)	85m (N=4)	106m (N=1)
Independent training	422m (N=6)	300m (N=7)	105m (N=1)

The analysis of the video data confirms patients’ subjective assessments: 9 of the 14 patients who tested the robot-assisted training moved along the entire clinic floor and some covered even further distances. Most patients had never trained on the entire clinic floor before.

VI. DISCUSSION AND FURTHER STEPS

The results of this project show a successful social and technical approach to the therapeutic scenario of “free gait training on hospital floors”, in which a robotic companion navigates the hospital corridors predominantly autonomously, accompanying patients during their training and motivating them through a specially developed human-robot interaction.

Crucial for the project’s approach was to integrate users from the beginning. N=12 patients were integrated in the development of HRI and N=30 stroke patients in the evaluation of the robotic companion. The entire project was carried out in the users’ actual environments; the corridors of a rehabilitation clinic. The robotic platform and HRI were developed specifically for the medical, social and ethical requirements of a robotic assisted gait training and bridge the gap between human assisted gait training and independent training.

Empirical results show that the majority of robot users accept the companion. Despite severely impaired mobility and/or cognitive handicaps, patients could handle the robot without difficulties. The robotic gait training motivated patients to leave their room despite difficulties in spatial orientation. They were able to expand the radius of their independent gait training and the length of their training units.

The robot motivates patients to train independently, broadens the radius of training and challenges patients to train despite difficulties with orientation. This in turn not only shows evidence of patients’ motivation, but also proves that the therapeutic goals of the project (intensification of independent training and enhancement of training intensity) can be addressed through the use of the robotic companion.

The approach seems so promising to us that a continuation of the concept "independent training with a robotic companion" is planned. In the future, focus will be placed on further investigating the therapeutic effect of this concept. The evidence obtained so far must ultimately be confirmed by systematic clinical evaluation studies and complemented by cost-benefit-analyses to assess whether the additional costs resulting from the implementation of robotic companions are medically and therapeutically justifiable.

Ultimately, the question arises whether, in the future, robot companions can succeed in bridging the gap between therapist-led gait training, autonomous independent training in the clinic and further training at home.

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