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Mobile Robot Companion for Walking Training of Stroke Patients in Clinical Post-stroke Rehabilitation*

Horst-Michael Gross[1], Sibylle Meyer[2], Andrea Scheidig[1], Markus Eisenbach[1], Steffen Mueller[1]
Thanh Quang Trinh[1], Tim Wengefeld[1], Andreas Bley[3], Christian Martin[3], Christa Fricke[2]

***Abstract*— This paper introduces a novel robot-based approach to the stroke rehabilitation scenario, in which a mobile robot companion accompanies stroke patients during their walking self-training. This assistance enables them to move freely in the clinic practicing both their mobility and spatial orientation skills. Based on a set of questions for systematic evaluating the autonomy and practicability of assistive robots and a three-stage approach in conducting function and user tests in the clinical setting, we present the results of user trials performed with N=30 stroke patients in a stroke rehabilitation center between 4/2015 and 3/2016. This allowed us to make an honest inventory of the strengths and weaknesses of the developed robot companion and its already achieved practicability for clinical use. The results of the user studies show that patients and fellow patients were very open-minded and accepted the robotic coach. The robot motivated them for independent training and leaving their room, despite severe consequences of stroke (lower limbs paralysis, speech/language problems, loss of orientation, depression), provided a very self-determined training regime, and encouraged them to expand the radius of their training in the clinic.**

I. ROREAS Project in a Nutshell

It is well known that patients recovering from a stroke must play an active role in the rehabilitation process if improvement is to occur [1]. This finding was the motivation for the research project ROREAS* running from mid 2013 till March 2016, which aimed at developing a robotic rehabilitation assistant for walking self-training of stroke patients in the clinical post-stroke rehabilitation [2] [3]. Compared to other known approaches in stroke rehabilitation, the goal of ROREAS was to develop a robotic assistance for stroke patients, which does not require treadmills or special areas (gait labs, walking courses) reserved for gait training. Instead, the patients should be enabled to move freely in the clinic practicing both their mobility and spatial orientation skills. The autonomy of the robot companion should allow the patients to use the robot for themselves alone, to decide which training route they choose and how long they want to walk, and to do self-training in the evening and at the weekend not dependent on the supervision by qualified therapists. The target group of ROREAS were stroke patients in late stages of the clinical post-stroke rehabilitation with (i) impaired walking ability (suffering from lower limbs paralysis up to mild or moderate hemiparesis), (ii) cognitive impairments (limitations in orientation or difficulties in speaking and finding words), and (iii) mental impairments (depressions and anxiety to leave the room alone). Based on the autonomy of the robot, ROREAS should motivate the patients to train more and over longer distances and reduce their anxiety to leave their rooms and move around in the clinic without assistance of therapists or family members. So, the robot-assisted training should bridge the gap between training with human therapists and independent, unaccompanied exercising. In this way, not only the training of the lower extremities and the corresponding brain areas and the orientation ability can be supported, but also the patients' independence and autonomy, self-efficacy, and empowerment. The essential precondition to involve selected, voluntary patients in this study was, however, the medical consent to walk on their own in the clinic without professional assistance. In the following, the phases of a typical robot-assisted walking training session are outlined from the robot's point of view (see [3] for a detailed description), which have been tested in a series of user trials under clinical conditions (see Sec. VI, Table IV):

Fig. 1. Robotic training companion "ROREAS" following a stroke patient during his walking training in our test site, the "m&i Fachklinik" rehabilitation center in Bad Liebenstein (Germany).

1) *Autonomous drive to the patient room:* Robot drives to a waiting position near the door of the patient room.
2) *Sitting-down detection for initial contacting:* Contacting is triggered by the patient by taking a seat at the starting point (a chair in front of the patient room).
3) *Approaching the patient:* Robot approaches the patient for initiating multi-modal interaction (GUI, speech).
4) *Tour selection and learning the user model:* After the patient has logged in and selected the training tour on the screen, a clothing-based user model is learned for

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[1]H.-M. Gross, A. Scheidig, M. Eisenbach, St. Mueller, T.Q. Trinh, and T. Wengefeld are with the Cognitive Robotics Lab, TU Ilmenau, 98684 Ilmenau (Germany); [2]S. Meyer and Ch. Fricke are with the SIBIS Institute for Social Research, 10585 Berlin (Germany); [3]A. Bley, Ch. Martin are with the MetraLabs GmbH, 98693 Ilmenau (Germany)
Horst-Michael.Gross@tu-ilmenau.de

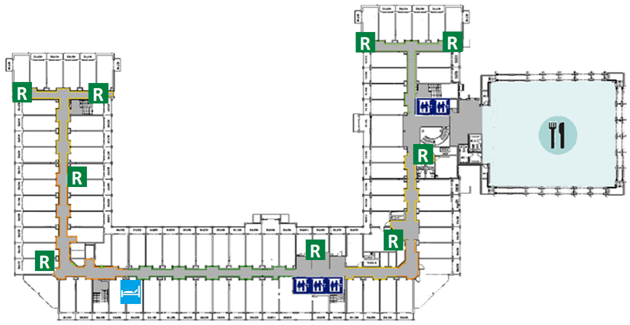

Fig. 2. Plan of one floor of the eight-storey rehabilitation center (m&i Fachklinik) in Bad Liebenstein (Germany) used as test site in the ROREAS project. The length of each corridor is about 170 meters. R marks resting points for the patients during their walking training along the corridor.

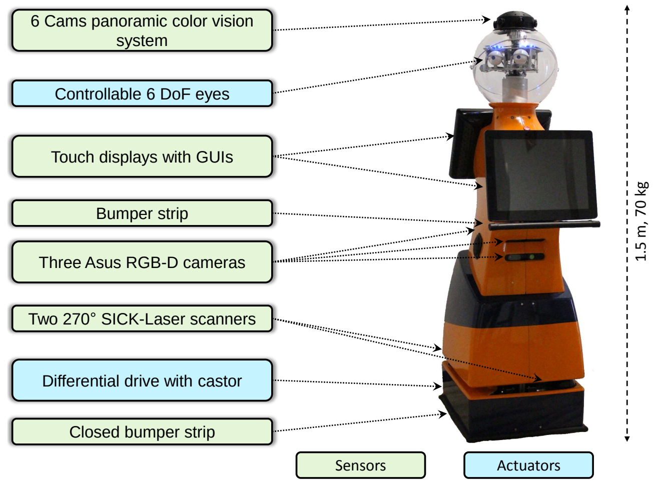

Fig. 3. Robot companion ROREAS developed together with project partner MetraLabs Robotics Ilmenau with its main equipment for environment perception, navigation, and HRI.

visual user re-identification along the walking tour.

5) *Following the patient:* Robot follows the patient to resting points ('R' in Fig. 2) or the destination point.
6) *Sitting-down detection at resting points:* The patient takes a seat as trigger for resting or intended interaction with the robot (e.g. for terminating or proceeding the training) via GUI-dialog
7) *Farewell dialog:* The robot presents the training results (length of the walking tour, duration of training, average walking speed) in front of the patient room.

During the training, the robot follows the patient in the "Follow mode" at a comfortable and safe distance (2-3 meters), while navigating along the corridors autonomously. It indicates resting places (Fig. 2) and waits with the patient while s/he rests. When the patient decides to proceed, the robot follows. If the robot detects, that the patient has sat down too often, signalizing that s/he is tired or overstrained, the robot suggests to finish the training and offers going back to the patient room or calling for the nurse. If the patient takes the wrong way during a tour to a destination, the robot detects this as well, points the patient on this issue, and waits for the patient to go the right way. If the patient gets any physical or mental problems, for instance cannot go further of looses his pace, the training session is canceled and the nursing staff gets informed by means of a text message. If the patient has lost orientation and wants to return to his room, the robot guides the patient back to the starting point. The training is always terminated at the patient room.

Challenges of the clinical setting: Our test site for developing and testing the robot-based walking training is a complex U-shaped environment (Fig. 2) which accommodates more than 400 patients. The building has eight storeys, the length of each corridor is 170 meters. This environment is highly dynamic and often very crowded. Staff members and patients are moving in the corridors and in the public areas, many of them using walking aids (e.g. wheeled walkers or crutches) which makes person detection and re-identification very challenging. Often beds, supply and cleaning carts, or wheelchairs are occupying the hallways, resulting in very restricted space conditions at some times (Fig. 1). Further challenges of the clinical setting are described in [3].

II. Related Work

So far, a common approach in the field of rehabilitation robotics is the application of intelligent orthoses – robotic solutions that physically interact with persons suffering from motor disorders [1], [4]. This includes for example lower extremity devices such as the LOKOMAT [5], ALEX (Active Leg EXoskeleton) [6], or the novel mobile robotic gait rehabilitation system MOPASS [7] that measure and apply forces and torques to the patient's legs to assess or encourage specific motor task practice. Intelligent walkers, so-called smart walkers or iWalkers [8], equipped with navigation and guiding capabilities also have some bearing to ROREAS, as they try to assist disabled people in walking alone using the active physical motion support of the walker. These works are, however, less relevant for our approach, as ROREAS belongs to the field of *Socially Assistive Robotics* (SAR), which is defined as "*provision of assistance through social (not physical) interactions with robots. ... A SAR system uses noncontact feedback, coaching, and encouragement to guide a user during the performance of a task*" [4]. Although SAR has shown promise in a number of domains, including skill training, daily life assistance, and physical therapy [9], there is no SAR project known that aims in the same direction as ROREAS - a mobile robotic training companion which can accompany patients fully autonomously during their walking training within a clinical setting.

Therefore, the so called *tour guide robots* are at least of a certain relevance for ROREAS (see [10] for an overview of the early works). Usually, all these robots guide people to a set of exhibits and, thus, show some functional similarity to the walking training function in ROREAS. The same also applies to the still relatively small group of robotic shopping assistants which guide customers in supermarkets or other stores on the shortest possible route to the goods shelves with the wanted products [11], [12]. Of similar relevance are the *Zuse-Guide* project [13], where a robot-based mobile visitor information system guides visitors to labs and offices in a

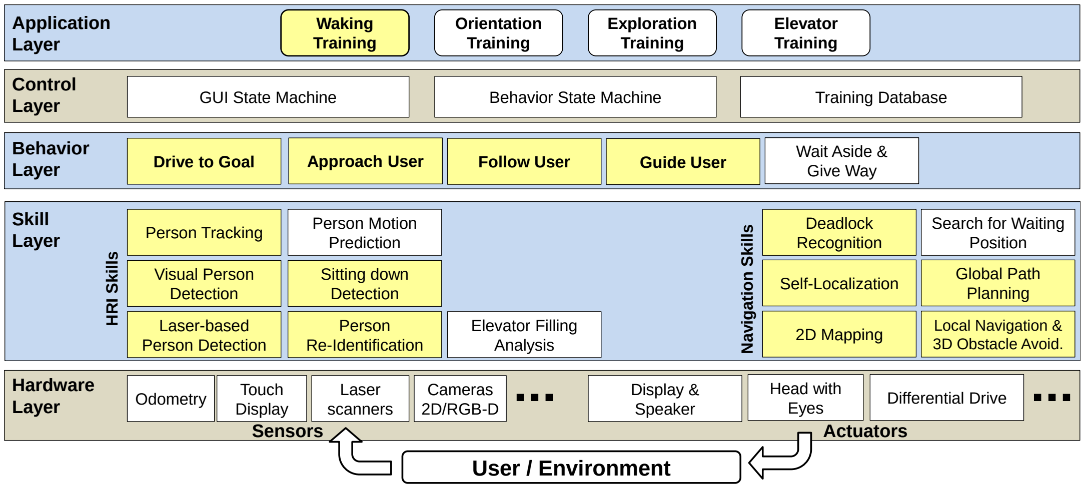

Fig. 4. System architecture of the ROREAS training assistant consisting of *Hardware Layer*, *Skill Layer* with navigation and HRI-specific skills, *Behavior Layer*, *Control Layer* orchestrating the behaviors, and *Application Layer* implementing the specified applications for post-stroke self-training. Only the skills and behaviors highlighted in yellow (see Table I for a brief description) are of relevance for this paper, as they are the essential components of the "Walking Training" application, whose practicability is evaluated in this paper. The "Walking Training" is implemented by the State Machines of the *Control Layer* activating the different phases of a walking training session (see Sec. I). The other envisaged training applications are also of relevance for the post-stroke self-training, but could not be implemented yet for various reasons (liability issues, warranty regulations concerning the elevator hardware).

crowded multi-storey university building, or the *SPENCER*-project [14], where a mobile robot guided passengers in large airports to the gates. The CoBot project [15] dealing with mobile robots capable of performing pick up and delivery tasks of objects or people in a multi-storey office building, or the robotic walking group assistant of the STRANDS project [16], that accompanied walking groups of elderly with advanced dementia at a care site to support their physical therapy, also belong to this group of research works.

In contrast to the ROREAS-project, however, all these robot guides only have an instrumental function – namely guiding interested users on a pre-defined tour or on the shortest possible route to a target position. The robot guide typically takes the initiative, and the user has to follow the robot more or less strictly. In ROREAS, however, the patient takes the initiative and decides how and how long the walking training has to proceed, whereas the robot has not to guide but to follow and actively observe the patient to assist in appropriate manner if necessary. For such a robotic assistant that is supposed to train with the same patient again and again for a few weeks, besides the pure instrumental training function a patient-robot relationship needs to be established. In this relationship such social-emotional factors, like co-experience, the feeling of safety when interacting with the robot, motivation and empowerment, as well as joy of use [17] will play an important role for the acceptance and success of a robot-assisted training.

III. Mobile Walking Companion ROREAS

According to the specific requirements for an autonomous robotic training companion, an appropriate training platform has been developed within the ROREAS-project (Fig. 3). This platform is explicitly tailored to the user group of stroke patients with a focus on easy usability while standing or sitting, joy of use, and positive user experience, but also on later production and operational costs (see [3] for a detailed description). The functional system architecture of the robot is a continued development of our shopping guide robots' architecture [12]. In comparison with this, however, the ROREAS architecture includes more human- and situation-aware navigation and interaction skills and behaviors (Fig. 4), and allows more flexibility in implementing specific training applications. Since a complete description of all behaviors and skills of the training assistant required for the different training applications would go beyond the scope of this paper, in Table I only a tabular overview of those skills and behaviors is given that are of direct relevance for a human- and situation-aware *Walking Training*. A more detailed description of these requirements, the developed system architecture, and the implemented skills and behaviors is also given in [3]. In continuation of this publication, the paper presented here is more focussing on the question how the developed robotic training companion, its implemented services, and the underlying basic functionalities for HRI and navigation can be evaluated systematically to assess its final practicability and acceptability for the clinical use from both technical and social sciences point of view.

IV. Evaluating the Robotic Training Companion

In the assistive robotics community, more and more researchers are already aware of the challenges involved in studying autonomous, interactive systems "in the wild" and follow best practices in evaluating these robots in natural interaction settings, as suggested by [18] and [19]. However, often the setup and the actual implementation of the tests are still not described in a sufficient level of detail, leaving room for speculations, particularly with respect to the achieved autonomy, the range of implemented services, and the

TABLE I

OVERVIEW OF THE BEHAVIORS AND SKILLS REQUIRED FOR THE WALKING TRAINING APPLICATION SHOWN IN FIG. 4.

HRI Skills	**Brief description**	**Ref.**
Visual and Laser-based Person Detection	Set of asynchronously working detection modules (2D laser-based leg detector, Part-HoG based upper-body shape detector, motion detector) for people standing, sitting or walking around	[3] [20] [21]
Person Tracking	Multi-hypotheses person tracker for filtering asynchronous, multi-modal detections using 7D-Kalman filters (6D-positions & velocities of the head, upper body orientation) for each person tracked	[22]
Person Re-Identification	Appearance-based approach using a user-specific multi-feature template (HSV-Histograms, maximum stable color regions) learned after logging-in at the beginning of the training	[23]
Sitting down Detection	Rule-based decision based on a threshold referred to the user's head height determined at the starting point	–
Navig. Skills	**Brief description**	**Ref.**
2D Mapping	Hybrid, hierarchical approach combining a topological graph for modeling floors and elevators between the floors with metric 2D occupancy maps of the aisles of each floor	[3]
Self-localization	Usage of AMCL ROS with 2D occupancy grid maps and 2D laser scans	–
Local Navigation & 3D Obstacle Avoidance	Usage of NDT maps for 3D modeling of the robot's local surroundings in combination with a DWA and tailored DWA-objectives for human-aware navigation as local planner	[24] [25] [26]
Gobal Path Planning	Hierarchical approach combining topological path planning (Dijkstra) between the floors with metric path planning (E*) on each floor	[27] [2]
Deadlock Recognition	Approach describing narrow passages in conjunction with predicted space conflicts with moving persons	[28]
Behaviors	**Brief description**	**Ref.**
Drive to Goal	Hierarchical approach combining the "Global Path Planning" and the "Local Navigation" skills	–
Approach User	Multi-criteria search using PSO for a robot pose where the patient can comfortably operate the GUI	–
Follow User	Dynamic re-planning (E*) to follow a moving hypothesis provided by the person tracker	[2]
Guide User	Similar to the "Drive To Goal" behavior but additionally keeping a constant distance (1-3 m) to the user following the robot	–
Wait Aside & Give Way	Multi-criteria search for a temporary waiting position by using a PSO approach (not used in the user trials)	[28]

practicability of the developed solution from technical point of view. In the scope of our previous projects, the *ShopBot* TOOMAS [12], the companion robot in CompanionAble [29], and the health assistant in SERROGA [30], we gained wide experience in making assistive robotics suitable for real-world applications. Based on this expertise, in [31] we have introduced the following set of questions to better specify the autonomy and practicability of a developed robotic solution:

Spectrum of available services and skills:

S1: What *services* for the users are already available (autonomous on the robot / require external sensors / require remote control by an operator)?

S2: What *skills* for navigation and HRI are available for the robot at which level of autonomy?

S3: What kind of IT-infrastructure is required on-site?

Maturity level:

M1: What is the *maturity level* of the robot system to be tested (demonstrator, lab prototype, product)?

M2: Have there already been *function tests* outside the lab in the field (when, where, how often, how long, what conditions)?

M3: Have there already been *user trials* with end users in the final environment (when, where, methods)?

M4: Was *accompanying personnel* present during the user tests, and where was the staff during the tests?

M5: How long was the robot available for the user, how was the usage rate?

Function tests of basic functionalities (skills/behaviors):

F1: What *navigation functionalities* have been tested under what conditions?

F2: Are there *navigation problems* encountered during the tests, and how were they quantified (e.g. number of collisions, deadlocks, localization failures, etc.)?

F3: What *HRI functionalities* have been tested under what conditions?

F4: Have there been *HRI-malfunctions* (e.g. in person detection/tracking, user re-identification, etc.)?

F5: What *success rates* of basic functionalities have been determined (e.g. in user search, etc.)?

F6: Were *manual interventions* necessary before and during the tests (e.g. labeling no-go areas, etc.)?

F7: Was the *complexity* of the test environment quantitatively evaluated (e.g. by navigable area, clearance, mean passage width, etc.) (see [30])?

User tests at technical level and encountered failures:

U1: *Uncritical failures*: can be handled by the application itself (e.g. driving to the next meeting point)

U2: *Critical failures*: can only be resolved by remote intervention through an operator (e.g. correction of a wrong person re-identification hypothesis)

U3: *Very critical failures*: cannot be resolved by remote intervention through an operator without interrupting the test (e.g. due to sensor failures).

In the following sections, when describing our tests and user trials and the achieved results and observed problems, we make use of links to these questions, e.g. (F3).

For correction of lacking or wrong decisions of selected skills (e.g. person re-identification [23]) and, with that, for the sake of an interruption-free testing process, we developed a tablet-computer based correction interface connected with the robot by WiFi (Fig. 5), which allows an external test observer to manually correct these decisions from a non-

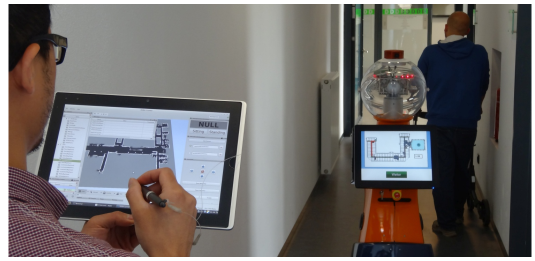

Fig. 5. Tablet-computer based correction interface for correcting lacking or wrong decisions allowing for an interruption-free testing process.

distracting distance ($> 5m$) (M4). By this option for *remote intervention*, the user trials in the clinic could be started much earlier, than this would have been possible from the readiness level of the respective skills. Moreover, the developers got an objective and situation-specific feedback, in which situation the basic skills and behaviors were still facing problems. Furthermore, this way a direct measure of quality for the autonomous operation of the robot was available, as the number of necessary interventions could be counted (F5, F6). This option for remote intervention must not be confused with a robot remote control, which is often used for user studies, as our robot was operating autonomously most of the time. The tablet only allowed the distant observer to add lacking decisions (e.g. from sitting-down detection), to correct erroneous decisions (e.g. from person re-identification), or to modify the training process in order to keep the training application flowing.

V. Three-stage Approach for the User Tests

Before it was possible to evaluate the robotic training companion together with stroke patients in user trials, it had to be assured that all required skills and behaviors (see Fig. 4) did work as expected in the clinical setting. Therefore, we applied a *three-stage approach* in conducting function tests and user trials with the developed prototype (M1) in the clinic under everyday conditions [31].

Stage 1: Functional on-site tests with staff members: To ensure, that all skills and behaviors (see Fig. 4) required by the robot companion do work accurately and securely, in 2/2015 we performed functional on-site field tests with staff members of our lab (4 days, driven distance of 15,000 meters at several floors of the clinic at different times) (M2). For quantitative assessment of the skills and behaviors, diverse measures (e.g. number of person mismatches, needed travel time) were determined. A detailed quantitative analysis of the tested skills (F1, F3) and the determined success rates (F5) has already been presented in [3].

Stage 2: User tests with "patient doubles": After successfully completing these functional tests, in 4/2015 and before each user trial we evaluated the robot companion again – but this time with the help of persons of the same age group who had no understanding of therapeutical of technological implications and imitated the walking behavior of stroke patients (M2, M3). In these tests, among the stability of the required HRI- and navigation skills (F1, F3) the actual training application, the comprehensibility of the training procedure, and the necessity of manual remote interventions by the observer (F6) were tested. The purpose of these tests with patient doubles was more a benchmark, if it is reasonable to include real stroke patients in the trials from technological, medical, and ethical point of view. In our opinion, tests with patient doubles are a crucial precondition to confront vulnerable users with autonomous robots.

Stage 3: Field trials with stroke patients: Based on the emulated user tests with staff members and patient doubles, from 4/2015 till 3/2016 six campaigns of user tests with N=30 stroke patients (Table II) were conducted (M3). In all campaigns, only volunteers from the group of stroke patients who already got the permission for doing self-training were involved. While in the first user trials till 9/2015 only one predefined short training route was available (Table III), in the following trials from 11/2015 till 3/2016 the patients could freely select from three training routes of different length. Depending on the patients' state of health, in this way sessions with a duration of up to one hour were made possible (M5). The patients' interactions with the robot were documented through video recordings from far distance whose results were processed for improving the training application and for analysing the social and therapeutical outcomes of robot-based training. The continuous involvement of users significantly contributed to the ongoing development and optimization of the technical implementation.

TABLE II

Participants of the user studies in stage 3 by age and sex.

Age	Female	Male	Total
$<$ 60 years	4	7	11
60-74 years	6	5	11
$>$ 74 years	5	3	8
Total	15	15	30

VI. Results of Trials with Patients in Stage 3

A. *Results from Technical Point of View*

An overview of the conditions of all conducted field tests with patients and their results is given in Table III (M3, M5) distinguishing between *predefined training* and *free choice training*. Beginning with a pre-test in 4/2015 and followed by field trials in 6/2015 and 9/2015, all seven training phases of a typical walking training session (see Sec. I) were conducted and documented from technical and social-scientific point of view, however, still along a predefined training route. The autonomy already achieved in the different phases of the training session is described in Table IV (S1, F6). For example, in the first user trial the test observer still had to react by remote intervention 19 times (3.1 times in 10 minutes on average) (F6) to confirm uncertain or to correct wrong hypotheses of the re-identification module (U2). Only two of these cases were false decisions, the others were too uncertain and only required confirmation. It became apparent that the clothing-based re-identification of patients [23] has a higher degree of difficulty compared to the test with staff members and patient doubles in stages 1 and 2. The cause study for the observed failures showed that the vertical field of view of the panoramic head camera still used in this early test was too limited, and the approaching to sitting patients was still sub-optimal, as the distances for a comfortable handling of the touch screen were too large. Moreover, further remote intervention options for the control of the training process had to be added to better correct occurring failures immediately to keep the training flowing.

Following this test strategy, between 11/2015 and 3/2016, three more field trials with volunteer patients were conducted (see Table III), but this time with free choice from three training routes of different length to assess the improvement

TABLE III

OVERVIEW OF THE USER TESTS CONDUCTED AT THE TEST SITE "M&I FACHKLINIK BAD LIEBENSTEIN" (GERMANY) IN 2015 AND 2016.

Criteria	Pre-test	1st user trial	2nd user trial	3rd user trial	4th user trial	5th user trial
Period / Duration	4/2015, 2 d	6/2015, 2 days	9/2015, 2 days	11/2015, 2 days	1/2016, 2 days	3/2016, 2 days
# of patients (N)	**4**	**5**	**7**	**4**	**3**	**7**
Walking aids used	3 x walker 1 x crutch	5 x walker	3 x walker 3 x crutch, 1x w/o	4 x walker	3 x crutch	5 x crutch 2 x walker
Training type **# of training sessions**	Predefined 11	Predefined 11	Predefined 14	Free choice 15	Free choice 6	Free choice 14
Driven distance (tot.) **Average per session**	660 m **60 m**	873 m **80 m**	2109 m **150 m**	2714 m **181 m**	1966 **327 m**	6650 m **475 m**
Walking distance min. **max.**	40 m 80 m	40 m 100 m	100 m 160 m	170 m 630 m	100 m 500 m	120 m 1240 m
Training time (total) **Average per patient**	51 min **12.7 min**	56 min **11.2 min**	108 min **15.4 min**	190 min **47.5 min**	88 min **29.3 min**	330 min **47.2 min**
# of passers-by	not logged	78 8.9 per 100 m	353 16,7 per 100 m	311 11,4 per 100 m	235 11.9 per 100 m	679 10.2 per 100 m
# Remote interventions # when restrained use	not logged -	19 (3.1 in 10 min.) -	56 (3.9 in 10 min.) -	not logged -	27 (4.9 in 10 min.) 9 (1.6 in 10 min.)	43 (2.5 in 10 min.) 19 (1.2 in 10 min.)

of the navigation and HRI functionalities. In the *fifth and last user trial in 3/2016*, the following issues were in the focus of the practicability investigation: quality of the user sitting down detection and the clothing-based person re-identification using a new high resolution panoramic color camera with larger vertical field of view (see Fig. 3), and robustness of the "Approach User" behavior. Of special significance was the question, how the overall behavior of the robot companion and its practicability will be changed, when the remote interventions by the test observer will be restricted to really critical exceptional cases only (referred to as "restrained use") (F6). Essential aspects of this user test are also characterized in Table III (M3, M5), while the achieved autonomy is described in Table IV (S1, F6).

In the case of an offensive use of interventions (on the first day of the trials) in 43 situations (2.5 per 10 minutes) remote interventions were carried out (U2) for user re-identification. Reasons for that were missing person detections, temporary occlusions of the patients after turning round the corner, or non-detections after taking a seat. By comparison, when a restrained use of the interventions was applied (on the second day), only in 19 situations interventions were necessary (U2), that is 1.2 per 10 minutes. In 16 cases, the patients could not be re-identified due to missing detections of the person detector or temporary occlusions by other persons or obstacles, and in 3 cases there were mismatches with passers-by. A robust sitting down detection is required for the start of the training and for unplanned breaks during the training. From the 14 initial situations (7 per day), 12 were detected autonomously (85%), 2 were not detected due to missing person detections and had to be triggered by remote intervention (U2). The sitting-down detection during the breaks at resting points was necessary in 97 cases, 75 cases were detected autonomously (77%), 22 (23%) still had to be triggered by remote intervention. Reasons for that were temporarily absent person detections because of very atypical views

TABLE IV

ACHIEVED AUTONOMY IN ALL PHASES OF A TRAINING SESSION

Training phases	1st user test	5th user test
1. Drive to patient room	100% autonomous	100% autonomous
2. Sitting-down detection for initial contacting	100% by remote intervent.	85% autonomous 15% by remote interventions
3. Approaching the patient	100% auton., 30% successful	100% auton., 47% successful
4. Tour selection & Learning user model	Predefined short route 100% autonomous	Free choice from 3 long routes 100% autonomous
5. Following the patient # corrections of wrong ReIDs	largely autonomous → 3.1 in 10 minutes	largely autonomous → 1.2 in 10 minutes
6. Sitting-down detection at resting points	100% by remote intervent.	77% autonomous 23% by remote interventions
7. Farewell dialog	100% autonomous	100% autonomous

during sitting-down. 111 times the robot had to approach the users while they were sitting. Only in 52 of the final approach positions (47%), the patients could conveniently operate the touch-display. In 59 cases (53%) the approaching had to be terminated by the robot, because the used walking aids or other dynamical obstacles blocked the way to the patient (see Fig. 6), or the robot had problems to robustly detect and track some of the sitting patients. In all sessions of this last test, during the training the average distance between the robot and the patient was 1.4 m for the two slowly walking patients and 2.5 m for the five faster walking patients (F5).

These results demonstrate that most skills and behaviors (see Fig. 4) do function autonomously without necessary corrections by remote interventions. Nevertheless, there are three important issues, that need to be further improved to allow for an autonomous walking training without external interventions: (i) visual person re-identification, (ii) sitting-down detection, and (iii) approach a sitting user behavior. So, at the end of the project we have to conclude that the robotic training companion has *not yet reached a maturity level which would allow autonomous operation with patients in the clinical setting* (M1).

Despite these difficulties and deficits, we could provide a full-value robotic training assistant for the sociological studies that were running in parallel in stage 3 with the

Fig. 6. Critical situations preventing successful approaching: (left) laundry trolley and own walker prevent approaching, (right) dynamic obstacles block optimal interaction position in front of the patient.

stroke patients. This was enabled due to the option of doing remote interventions in case of lacking or wrong decisions (see Fig. 5). Thus, without functional constraints we could evaluate the acceptability, friendly usage, training effects, and benefits for motivating patients to train self-reliantly.

B. Findings from Social Sciences Point of View

The examination of the acceptability of robotic walking training included the same patients (see Table II). Different methods for evaluation were combined: ethnological and structured observations, and in-depth interviews before and after the training sessions. To proof these subjective experiences, video documenting files recorded during the training sessions were analysed to show how the patients interacted with the robot and how successful the robot therapy worked. Almost 60% of patients who had trained with the robot, and interestingly 75% of the eldest group ($>$ 75 years), stated that robot-escorted walking training is preferable over walking without this service. And almost two thirds of users actually feel a greater motivation to train with the robot than without. This increased motivation induced by the robot is explained by the interviewees with a series of arguments. Essential arguments include *"One can entirely concentrate on oneself", "One is not distracted by a human companion", "It's fun when such a metal comrade rolls behind you!"* or *"The robot is always patient - and never in a bad mood."*

The observation of the robot users indicates that the patients, who practiced with the robotic assistant, covered greater distances during their training (see Table III, Walking distance min./max.) than before (Quote: *"I have never walked this far"*). This not only shows an increased motivation, but also that the project's therapeutic goal (expanding independent training and intensification of the training sessions) is fulfilled, or at least supported by the use of the robot companion. Furthermore, patients are increasingly confident to explore previously unknown areas of the clinic. Again, this is an indication for the motivational character of the robotic training. Accompanied by the robot, patients ventured out to explore remote hospital corridors outside the established routes to the dining room or the elevator. This in turn leads to an increased self-confidence, increasing the patient's area of exercise. Certainly, an additional motivational factor is the feeling of being "something special", when the patient is followed by a robot. Fellow patients who observed and encountered robot users in the corridors showed interest and asked the users about their experience.

The user evaluation showed another interesting aspect of user acceptance: the patients did not have any fear of the robot companion. This low expression of fear towards robots in stroke therapy is astonishing. The tested robot 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, the patients exposed themselves to their fellow patients and the clinic staff, which would expectedly rather promote than dismantle reservation and anxieties. None of the robot users rejected the robotic companion after having personally experienced the robot. This was true even for some of the initially sceptical users. When asked for further factors that could increase the motivation to exercise, non-medical factors came into play. Most notable here is the element of variety and diversification of training methods which comes with the accompanied walking training. Almost 90% of users indicated that this aspect has led them to engage with the robot-assisted training: variety compared to monotonous training alone as well as variety compared to the traditional training with a physiotherapist. Similarly, patients felt that training with the robot is a fun and pleasurable experience. Almost 70% of the users confirmed this pleasure after having experienced the robot assisted training.

VII. Conclusions and Outlook

The main achievement of this project is a novel robot-based approach to the stroke rehabilitation scenario, in which a robotic coach accompanies stroke patients during their self-training and motivates them through a specially developed human-robot interaction[1]. Even in the currently realized, still restricted version, the robot provides various training regimes and promotes the motivation for self-training as well as broadening the radius of training and challenging the patients despite orientational difficulties. This, in turn, not only shows evidence of patients' motivation, but also proves that the therapeutic goals of the project (to intensify self-training without a therapist, strengthen the patients' training motivation, and increase their empowerment and autonomy) are supported by using a mobile robot companion. The project has demonstrated the feasibility of walking self-training with a robotic accompaniment.

In a follow-up project, instead of only focusing on improving the correctness of all skills and behaviors, we follow a more promising strategy to better handle missing or wrong detections, unexpected situations, or still latent shortcomings in the training procedure. So, we plan to implement a recovery strategy for the most critical case of contact loss to the patient as a result of a failed re-identification. In such a situation, the patient is asked to wait at the next resting point along his tour to give the robot the chance to search for its user in this area or on the way to this goal. Another objective will be to further integrate the aspect of orientation training into the walking training and to integrate

[1] See https://www.youtube.com/watch?v=5r11ZKCYMHQ (in German)

the robot into therapy software of the clinic, so that the robot-assisted self-training and the conventional training assisted by a physiotherapist can be better interlinked. Furthermore, an extension of the training over several floors is planned, which could not be realized yet due to warranty regulations of the elevator producer and liability issues.

The question, how such a robotic trainer may be integrated in the clinical practice in the future is still an open issue, that depends on numerous factors. Most important are the therapeutic benefit of a robot-assisted self-training, the everyday and long-term suitability of the robot coach, its costs for acquisition and operation, new opportunities for the clearing of the training with health or pension insurance funds, safety regulations, and of course the usability and acceptance of the robot coach by patients and clinic staff. Regarding the therapeutic benefit, we are aware, that any claims of benefits of robot-assisted self-training can only be assessed in a clinical field trial with a comparative study, directly comparing robot-based training to relevant conventional approaches. This will be placed on our agenda as soon as the robot can act as a really autonomous training assistant in the "wild" setting of a clinic.

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