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Robot Development in Cooperation with Patients: Application of Hyper-Tether to Support Home Oxygen Therapy Patients

Ben Allan, Gen Endo, Yu Iemura, Edwardo F. Fukushima, Masatsugu Iribe, Toshio Takubo, and Mineko Ohira

Abstract— **Hyper-Tether is a highly functional system which uses tethers to connect a wide range of robots, vehicles and humans. Home Oxygen Therapy (H.O.T.) is a medical treatment for severe lung diseases in which the patients are supplied concentrated oxygen through a cannula. The need to carry a portable oxygen supply device limits the quality of life of the patients, and so we have designed a robot follower using Hyper-Tether. The robot, which can carry an oxygen tank and follow behind the patient, was tested by H.O.T. users and evaluated using questionnaires. This paper describes the development and testing of the robot follower, with particular focus on iterative design based on patients' feedback.**

I. INTRODUCTION

To date, tethers have been used in a wide range of robotic and vehicular applications. In the simplest cases, a physical cable may be used to connect a mobile robot to a fixed base station, while in more complex systems a convoy or swarm of robots may cooperate using tethers. Dante II made use of a tether to rappel down the sides of volcanic chasms and reach areas which would be otherwise untraversable [1]. In aerospace, tethers have been proposed to support and control spacecraft [2], while in marine engineering tethered ROVs are commonly used for underwater survey and maintenance tasks. Outside robotics, industrial forestry machines make use of steel ropes to support themselves on steep inclines, off-road driving enthusiasts use winches to pull themselves up slopes, and weather balloons are anchored by tether.

The use of a tether makes it possible to share power, mechanical support and communication between different elements of a system, giving potential improvements in locomotion, energy efficiency and weight. Despite the availability of wireless sensors and communication systems, tethers may offer a robust, low-cost solution to many problems faced in robotics. The concept of Hyper-Tether is to combine the multiple advantages of tethers into a single highly functional system which is flexible enough to be applied to many different vehicles and environments [3].

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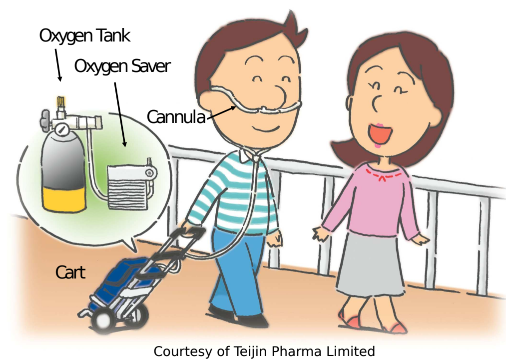


Fig. 1. Portable oxygen supply system.

An application where tethers have great potential is Home Oxygen Therapy (H.O.T.). H.O.T. is a widespread medical treatment where oxygen supply devices are used by sufferers of severe lung conditions such as chronic obstructive pulmonary disease (COPD) or emphysema– conditions which cause shortness of breath and impose considerable restrictions on the patients' quality of life [4]. The patients, typically older adults with limited finanical incomes, often pull these oxygen supply devices on wheeled carts as they go about daily tasks or participate in important rehabilitative exercise (see Fig. 1). Clearly, this is a situation where a follower robot could be of great benefit if it could carry the H.O.T. equipment and follow the patient as he or she performs daily tasks. Since a cannula is used to deliver oxygen, the system is inherently tethered and so we have developed a robot follower using Hyper-Tether to meet the needs of these patients. This paper describes the development and testing of the robot follower, with particular focus on iterative design based on trials with real patients.

II. PREVIOUS WORK ON HYPER-TETHER

The flexibility of the Hyper-Tether system means that past research has included a very wide variety of topics, including leader following [5], tether snagging [6] and far-reach work tools [7]. This section explains the Hyper-Tether concept and summarises selected past research.

A. Hyper-Tether Concept

Fig. 2 shows the three main components that make up the Hyper-Tether system: i) Tip interface; ii) Tether; iii) Base interface. The tip interface provides a connection to the next node in the system, which could be another robot, a vehicle,

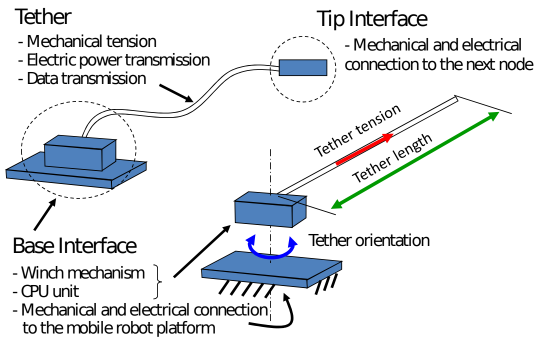


Fig. 2. Hyper-Tether concept.

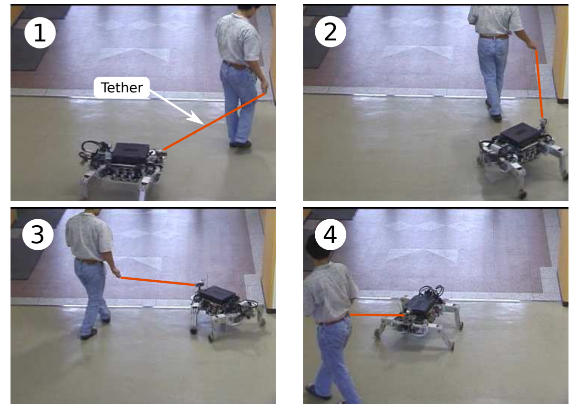


Fig. 3. Leader following with roller-walker.

or a human holding the tether tip. The tether itself allows the transmission of electrical power and communication data, but also facilitates mechanical support between nodes. Finally, the base interface provides a mechanical and electrical connection as well as managing the payout and reeling of the tether. Typically, the base interface would take the form of a winch with additional encoders (or other sensors) to record the angle and length of the tether.

B. Leader Following

Leader following is an important application of Hyper-Tether as it allows coordinated movement between vehicles; an important feature for convoy control and for traversing hazardous terrain such as minefields. The authors previously developed a tethered leader following system and tested it with crawler robots [5]. It was shown that a robot could successfully follow the vehicle in front of it using two different control algorithms: i) following the direction of the tether (termed *Pseudo-joystick* control in [5]); ii) by recording the position of the tether tip and controlling the robot so its trajectory converges on the tip trajectory (*Follow-the-leader* control).

Experiments showed that, as predicted, *Follow-the-leader* followed the tip's trajectory more accurately, while *Pseudo-joystick* would 'cut corners'. Additionally, to demonstrate that the control was not limited to wheeled or crawler vehicles, experiments were carried out using the leg-wheel hybrid robot *Roller-Walker* [8]. Fig. 3 shows Roller-Walker, moving by roller-skating, successfully following a human leader using *Pseudo-joystick* control.

However, while these experiments have shown how a robot can follow a variety of different leaders – human, crawler, roller-skater – they do not show how a follower robot could be operated by real patients.

C. Tether Snagging Behaviour

When using tethered follower robots outside the laboratory, we cannot ignore the problem of *tether snagging*: when an obstacle lies in between the tether tip and follower in such a way that the tether is bent (see Fig. 4. In this situation, position tracking becomes difficult as the computed leader trajectory will deviate from the true trajectory, thus causing the follower to go off-course. Previous investigation has shown that tether snagging is mainly affected by three parameters: i) following distance, ii) vehicle size, and iii) distance to obstacle; and that for some restricted cases the follower can use an algorithm to correct the snagging behaviour [6].

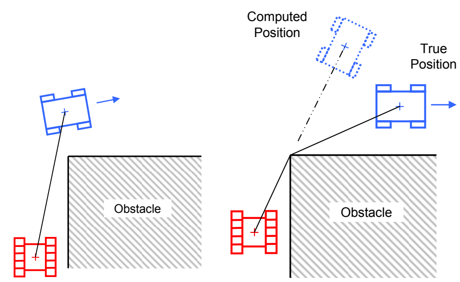


Fig. 4. Tether snagging prevents measurement of the leader position.

D. Far Reach Tethered Working Tool

When multiple vehicles are connected by tethers, it introduces the interesting possibility of suspending a tool from the tether and operating it far from the base vehicles. One application of such tools is using a grass cutter to remove vegetation for humanitarian landmine removal, and there are other potential applications in agriculture or forestry. Since tools suspended from tethers are vulnerable to vibration and stability problems, previous work on hyper tether proposed a grass cutter which utilized the gyro-effect of the cutter disc itself to provide stability [7].

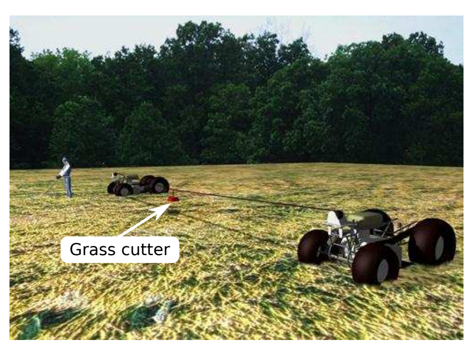


Fig. 5. Far reach work tool cutting vegetation.

III. FIRST PROTOTYPE ROBOT FOLLOWER

This section gives some background information on Home Oxygen Therapy and describes the design of the first prototype follower robot we built.

A. Home Oxygen Therapy

Home oxygen therapy (H.O.T.) is a medical treatment for patients suffering from severe lung diseases such as chronic obstructive pulmonary disease (COPD) or emphysema– conditions which cause shortness of breath and impose considerable restrictions on the patients' quality of life. H.O.T. alleviates symptoms by having the patient breathe concentrated oxygen through a nasal cannula; users of H.O.T. have an increased survival rate but can also have a reduced quality of life. Janssens et al. studied the health-related quality of life (HRQL) and found that H.O.T. users suffered from impaired HRQL and increased rates of anxiety and depressive disorders compared to the general population, with a positive relation between average daily distance walked and HRQL [9]. Tada et al. reported that quality of life in Japanese H.O.T. users was related to their roles and level of activity in the community in addition to their economic status [10]. An estimated 160 000 people receive H.O.T. in Japan [4], and there are many oxygen supply devices available, such as the cart shown in Fig. 1. These devices are designed to increase freedom and may allow the user to take part in rehabilitative exercise (usually walking).

However, such equipment weighs over 4 kg including the cart and therefore places considerable strain on the patient and prevents effective rehabilitation. We aimed to design a mobile robot which could carry the H.O.T. equipment with little or no effort from the patient, while following behind the patient and accompanying them on daily tasks in an outdoor environment. Although a number of follower robots (sometimes called 'robo-porters') have been developed and demonstrated [11], [12], these systems make use of expensive wireless sensors and they operate in indoor environments [13]. Since people who use H.O.T. are often older adults with low incomes, a lower-cost solution is needed; one which can accompany the patients outdoors to enhance their freedom of movement. To allow the patient to travel to their local shops and cross the street, the robot should be capable of overcoming a vertical step of 80 mm or more as this is the height of a typical kerb in Japan.

B. Platform Overview

Since the patients are already tethered to the H.O.T. equipment via a cannula, we use a tether to connect to the robot to the patient and facilitate steering/following. The main components of the first prototype are described below.

1) Chassis Design: The chassis has four wheels in a rhomboid configuration: two large diameter active wheels on the left and right, and two passive casters wheels on the front and rear (the overall shape is similar to the second prototype shown in Fig. 9). An inclined parallel bogie linkage connects the front caster to the main chassis and allows the robot to traverse vertical steps up to 80 mm (the height of a typical street kerb in Japan) with minimal driving torque.

2) Drive System: Each active wheel is powered by a 20 W in-wheel motor with a gearhead and an additional ladder chain and sprocket drive giving a total reduction of 204:1. This gives a low-profile drive mechanism with high torque to overcome steps, while also maximising the available luggage capacity.

3) Tether Mechanism: The tether tip is either held by the patient or connected to a waist belt, while the tether base is attached to a compact, lightweight winch reel. The winch reel can pivot freely around the yaw axis, and a constant force spring keeps the tether under tension, while the tether length and angle are measured by rotary potentiometers.

IV. FIRST EVALUATION BY USERS OF H.O.T.

The mobile platform was tested with patients to evaluate its performance both as a robotic follower and as a support device for H.O.T therapy. Feedback was gathered using a questionnaire focused on the needs of the patients; the results and discussion are presented in this section.

A. Methodology

1) Participants: The participants were Japanese men and women who suffered from COPD and used H.O.T. daily; they are the target users of the platform and so they are best suited to evaluate the design. The experiments were conducted in collaboration with *Meeting for the Pulmonary Rehabilitation Studies in Hokushin* and its adjunct group *Hokushin Flying Disc Club*. The former group, established in 2004, is run by an association of medical stakeholders including doctors, nurses, nutritionists and pharmacists with affiliations to medical institutions in the Hokushin region in northern Nagano, Japan. One of the rehabilitation activities coordinated by *Meeting for the Pulmonary Rehabilitation Studies in Hokushin* is *Hokushin Flying Disc Club*: a group in which patients meet monthly to take part in flying disc games under the supervision of medical support staff.

The first evaluation was conducted with volunteers from a meeting of *Hokushin Flying Disc Club* in September 2012 [14]. 20 patients volunteered to participate in the questionnaire and of these 20, 15 volunteered to participate in a practical robot follower experiment. We obtained informed consent from all the participants before starting the experiments. No form of compensation was given to participants.

2) Experiment Conditions: The purpose of the research and an outline of the robot was explained to all participants, including a description of how to operate the robot. For the follower experiments, each patient who volunteered to operate the robot was asked to hold the tether tip and walk for a 20 m round trip. Throughout the follower experiments, a researcher walked closely behind the patient to provide assistance in case of any unexpected problems. Fig. 6 shows patients taking part in the experiment. After they had taken part in these tasks, the patients completed the questionnaire. In occasional cases where a patient felt unable to complete all of the questionnaire, they skipped some questions (always under medical supervision).

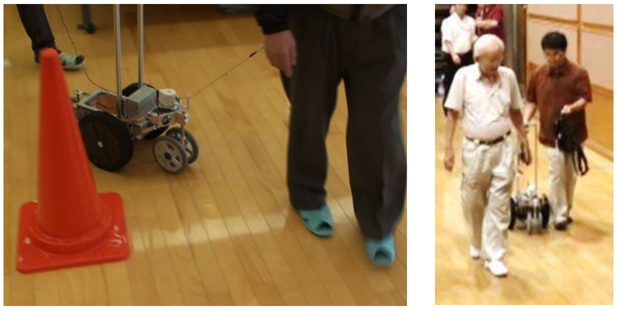


Fig. 6. Following experiments with users of H.O.T.

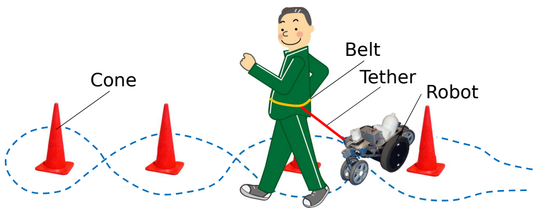


Fig. 7. Patients were asked to walk around several cones.

B. Results

This section presents selected results from the first questionnaire, which was answered after participants had seen and (for some voluinteers) interacted with the follower robot. We received 20 responses in total, and 75 % of those respondents had also operated the robot in the follower experiment earlier in the day. The average age of the participants was 74.4 years old, with 15 men and 5 women. Fig. 8 shows the questionnaire responses.

Questions 1 and 2 investigated the patients' opinions about the oxygen carts they currently use. The responses to Question 1, "What do you think of the weight of the cart you are using?" show that the carts are felt to be heavy by most patients. Question 2 asked the respondents to identify which features of oxygen carts they would like to see improved (with multiple answers allowed). The results show that the top priorities are lower weight and smaller size, followed by increased maneuverability (smaller turning radius and lower pulling force). In addition to the questionnaire feedback, some patients expressed concern that it was difficult to pull the robot when the power was turned off.

V. SECOND PROTOTYPE ROBOT FOLLOWER

Based on feedback we received from patients at the evaluation, we made a number of changes to the design. The second prototype is shown in Fig. 9 and the specification is listed in Table I.

TABLE I

SECOND PROTOTYPE SPECIFICATION

Dimensions L×W×H	670×330×350 mm
Mass	7.5 kg
Max. Velocity	1.0 $\mathrm{m\,s^{-1}}$
Max. Step Height	90 mm
Operating Time	60 min
Payload	2.5 kg

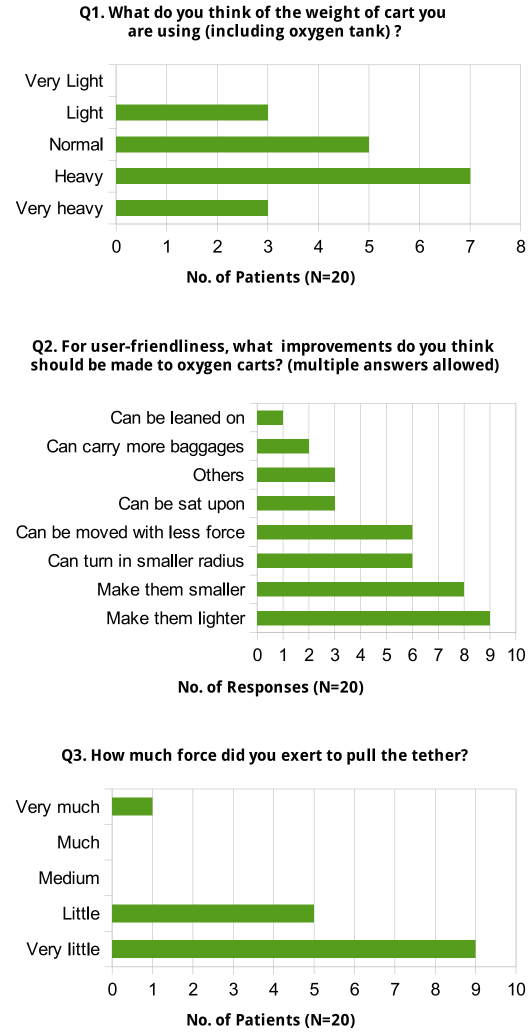


Fig. 8. First questionnaire results.

A. Reduction ratio

The drive reduction ratio has been reduced from 204:1 to 86.4:1. In the previous prototype, a higher ratio was selected to overcome larger obstacles, however testing revealed that there was no 'backdrivability': when the power was turned off, it was impossible to move the robot. This was likely due to the high gear ratio in the drive wheels and low efficiency in the transmission mechanism, making it very difficult to backdrive the wheels. If the robot were to run out of power, e.g. if the batteries were to run flat during a longer outing, this would pose a problem for the users as they might be unable to maneuver the robot. Although the system should be designed with ample power capacity, we cannot ignore the possibility that the user will have to maneuver it without power sometimes, and the design should accommodate that. The new, lower reduction ratio offers less resistance and allows the robot to be pulled more easily.

B. Noise

Earlier prototypes used a ladder chain and sprocket as part of the in-wheel drive. While the ladder chain was effective

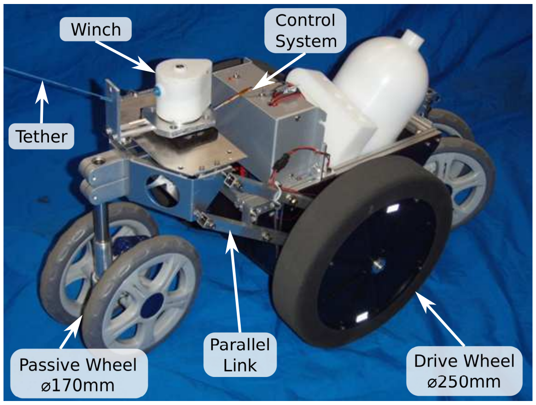
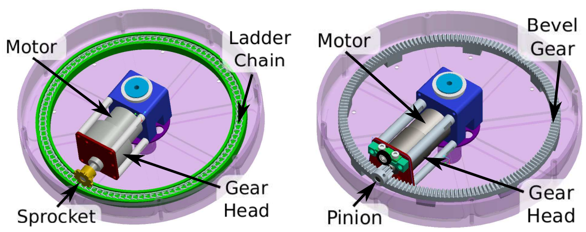


Fig. 9. Second prototype follower.

and economical, it was found to be uncomfortably noisy, and so it was replaced with a custom made bevel gear with a reduction ratio of 16:1. The previous ladder chain drive is shown next to the new bevel gear drive in Fig. 10.



(a) Old ladder chain (b) New bevel gear

Fig. 10. Drive mechanisms.

VI. SECOND EVALUATION BY USERS OF H.O.T.

A. Methodology

To evaluate the revised prototype, we conducted a second experiment and questionnaire in January 2013, also at the *Hokushin Flying Disc Club* in Nagano. The experiment was similar to the first evaluation, except this time each participant was asked to walk around a series of cones placed at 1.5 m intervals with the tether attached to a belt on his or her waist (see Fig. 7).

B. Results

We received 14 responses to the second questionnaire, with an average age of 71.6 years (12 men and 2 women). 100 % of those respondents had also operated the robot in the follower experiment earlier in the day (shown in Fig. 6), and 78.5 % had also attended our first experiment in September 2012. The results are shown in Fig. 11 and Fig. 12.

The responses to Question 4, "What did you think about having the tether attached to your waist?", were divided between good and bad. From previous feedback we had found that many patients wished to have their hands free while walking, so we expected a more positive response. It could be that some patients simply prefer to hold the tether in their hand, or perhaps this particular waist attachment did not suit them.

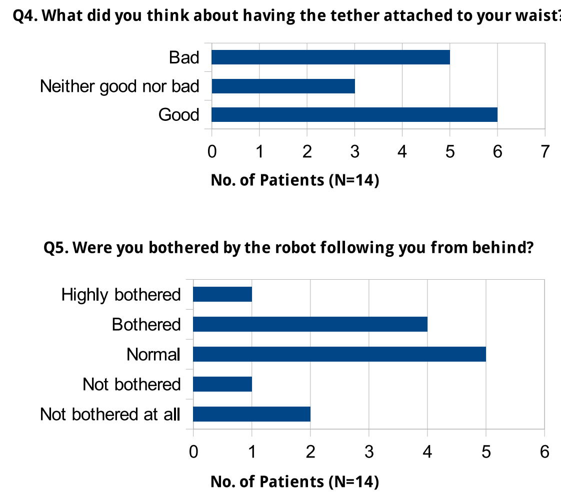


Fig. 11. Second questionnaire results.

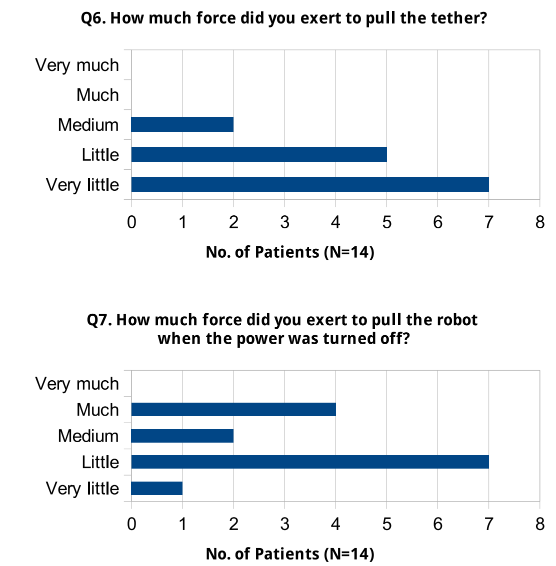


Fig. 12. Second questionnaire results.

Question 5 asked "Were you bothered by the robot following you from behind?", and the responses were very mixed. Many patients were not bothered, however 77 % of the responses were either neutral or negative, suggesting that the most suitable position for the robot may not be behind the patient.

The responses to Question 6 show that it was not difficult to operate the robot in terms of physical pulling force, as most patients (86 %) felt it required little or very little force. Question 7 was designed to address a concern which was raised by patients at previous experiments: that the robot would be difficult to pull if it lost power. The results show that most patients (57 %) were able to pull the robot with little or very little force, while 29 % had more difficulty as they answered "much" force. This confirms an improvement in the drive mechanism as described in the *Reduction ratio* section above.

C. Discussion

This section discusses the findings of the experiments in detail, including the implications for the future direction of the research.

The results raised several issues relevant to the design of a robot to support users of H.O.T. We found that the patients' responses to having the tether attached to their waist was mixed (Fig. 11), despite the feedback from previous experiments indicating that patients would prefer their hands to be free. One advantage of the simple tether design is flexibility: the tether can be attached to the waist or held in the hand to suit the comfort of each particular patient. Future studies will investigate this further.

When we design a follower robot, it is straightforward and relatively easy to position the robot behind the user. The robot can measure the position of the leader in front of it, and then move along the same trajectory. This also has the advantage of presenting a small profile, enabling it to move along crowded streets or through doorways more easily. However the patients did not feel entirely comfortable with the robot moving behind them (Fig. 11), and they indicated that they would prefer the robot to be in their field of vision. This highlights the importance of considering feedback from real users when evaluating a robotic human support system. The technical merits of following from behind are clear from lab experiments [5], but this is not sufficient to know if a system really meets the needs of its target users. Additional "following modes" could be useful, for example one mode where the robot moves alongside the user (where they can see it), and another mode where the robot follows behind (to allow it to enter doorways etc.). The development of such side following modes and the switching between them will be the subject of future research.

Overall the results were positive, as the robot successfully performed its following task and proved the validity of the basic concept of a robotic follower to support users of H.O.T. The response from the patients was also very enthusiastic: they were keen to take part in the experiments and offer insight into their needs. There was a mutual exchange of information and ideas as the researchers received invaluable design feedback, while the patients learned about robots and the potential role they might play in society in future.

VII. CONCLUSIONS

This paper introduced the concept of Hyper-Tether and its application in the field of Home Oxygen Therapy. We described our robot follower and reported the results of experiments and evaluations with users of H.O.T.

We found that the robot was well-received and generally successful as an aid to users of H.O.T., and we obtained invaluable design feedback which will help improve the robot control and mechanical design. When designing such a robot it is important to include users as early in the design process as possible. The members of the *Hokushin Flying Disc Club* provided comments and advice to refine our design and steer future research, but they also provided a clear motivation to develop robots which can help society.

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