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Mobile follower robot as an assistive device for home oxygen therapy – evaluation of tether control algorithms

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Abstract

Home Oxygen Therapy (H.O.T.) is a medical treatment for severe lung diseases in which the patients are supplied concentrated oxygen. This paper investigates the use of a follower robot as a support device for H.O.T. patients, consisting of a two-wheeled differential drive robot connected to the user by tether. Two different control algorithms were studied using dynamic simulation and motion capture experiments with healthy subjects. In further experiments with H.O.T. patients, including a questionnaire survey, it was confirmed that *Follow the Leader* control was capable of following the user's trajectory more accurately than *Pseudo-Joystick* control, and that overall H.O.T. patients showed a preference for *Follow the Leader* control.

Keywords: Home oxygen therapy; Leader following; Mobile robot; Tether

Background

Chronic Obstructive Pulmonary Disease (COPD) is a common respiratory condition where airflow through the lungs is restricted, often involving permanent lung damage, with patients experiencing coughing, wheezing, and shortness of breath. COPD is an umbrella term, including emphysema and chronic bronchitis, and is usually caused by tobacco smoking (though it can also be caused by exposure to other airborne irritants or pollutants). The World Health Organization reports that COPD is responsible for over 3 million deaths each year, making it the fourth most common cause of death globally [1]. The effect on quality of life can be significant: those with severe shortness of breath may be unable to move around without aid, they may be unable to participate in physical activities, and they may suffer from anxiety and depression as a result [2,3].

The administration of concentrated oxygen for extended periods (over 15 hours per day) can benefit patients with COPD: Home Oxygen Therapy (H.O.T.) aims to further improve the patients' freedom and quality of life by allowing treatment outside of hospital, and previous research has shown a positive correlation between average daily distance walked and health related quality of life [4]. There are currently around 150 000 people using H.O.T. in Japan, and this number is expected to increase as Japan's population ages in future. Oxygen is delivered through a mask worn on the face or nose, through a cannula, from a supply which usually consists of either a canister of pressurized oxygen or a liquid oxygen tank. This equipment typically weighs around 4 kg, and when the user leaves the house they can use a small handcart to transport it. Despite the benefits of H.O.T., it still imposes considerable restrictions on the users' movement and quality of life, since they must expend valuable effort to carry or pull the H.O.T. equipment.

We believe that a follower robot can improve the quality of life of H.O.T. patients by carrying the H.O.T. equipment, thus reducing their physical burden and increasing their freedom of movement. The requirements for such a system are as follows:

- Capable of carrying the H.O.T. equipment (oxygen tank or concentrator)

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- Capable of following the patient's movement in daily life
- Simple to use
- Low weight and compact size
- Low cost

Since H.O.T. requires the use of a cannula to supply oxygen, the system is inherently tethered and this represents a good opportunity to use a tethered robot follower. Tethers — flexible cord-like members with tensile strength but low (or zero) compressive strength — have been widely used in robotics as they are robust and low-cost; they provide a means of mechanical support and leader tracking between vehicles; and they can also facilitate power sharing and communication [5].

Tethered control methods have been developed previously which allow a mobile robot to follow a leader, using a winch to measure the length and orientation of a tether connected between the leader and the follower robot [6]. Although follower robots have proven successful using the previously developed control methods in person following experiments, they have not been tested with H.O.T. patients. Testing with patients is crucial to evaluate the suitability of a robot and control system, as their needs may differ significantly from healthy users, and a number of user factors may affect suitability, including gait, walking speed, reaction to obstacles and the user's perceived effort while operating a robot.

In this paper we discuss the performance of a low-cost tethered follower robot designed to support H.O.T. patients in their daily lives, evaluating two different control algorithms:

- We describe the two leader following control algorithms and evaluate them using computer simulation and motion capture hardware experiments in a controlled environment. We assess the suitability of each algorithm for use in an assistive follower robot.
- We present the results of experiments conducted with H.O.T. patients, including a questionnaire to assess the needs of the users and evaluate the robot's performance.

Methods

For a simple, low-cost, reliable mobile platform which is capable of following a leader we have proposed using a two-wheeled differentially steered robot [7]. Two control algorithms for such a robot are described below.

Pseudo-Joystick control

The simplest control method for a follower robot comprises using the tether length and direction as steering input commands: *Pseudo-Joystick control* (see Figure 1a). Using coordinates relative to the robot's reference frame, and given the measured tether length l_m, the desired tether length l_d and the measured tether angle θ, we can use the following control laws for the robot translational velocity V_r, angular velocity Ω_r and target direction ϕ:

$$V_r = -K_p(l_m - l_d) \tag{1}$$

$$\Omega_r = -\frac{2V_r}{b}\sin\phi \tag{2}$$

$$\phi = \theta \tag{3}$$

Where K_p is a proportional velocity gain, and b is the axle track. Since the target angle is set equal to the tether angle in Equation (3), the robot will always try to move in the current direction of the tether. The desired angular velocities for the left and right wheels (ω_L, ω_R) are found using the non-holonomic kinematic equation (4):

$$\boldsymbol{V} = \boldsymbol{A}^{-1}\boldsymbol{q} \quad where: \tag{4}$$

$$\boldsymbol{V} = \begin{bmatrix}\omega_L & \omega_R\end{bmatrix}^T \tag{5}$$

$$\boldsymbol{A} = \begin{bmatrix} r/2 & r/2 \\ -r/b & r/b \end{bmatrix} \tag{6}$$

$$\boldsymbol{q} = \begin{bmatrix}V_r & \Omega_r\end{bmatrix}^T \tag{7}$$

In Equation (6), matrix A transforms the wheel angular velocities to body velocities, where r is the wheel radius.

Follow-the-leader control with constant distance

Leader tracking

If the robot can determine its own posture relative to an inertial reference frame $\Sigma_g X_g Y_g$, more sophisticated tracking of the leader position can be achieved by recording the position of the tether tip over time (see Figure 1b). We define the trajectory of the tether tip as $\boldsymbol{T}(s_t)$ and the trajectory of the follower robot as $\boldsymbol{P}(s_r)$, where s_t and s_r represent the distance travelled along each respective trajectory. We can calculate the target angle using the following steps:

Step 1: Estimate the follower robot posture by dead reckoning.

i) Estimate the translational and angular velocity at time t:

$$\boldsymbol{q} = \boldsymbol{A}\boldsymbol{V} \tag{8}$$

ii) Calculate Γ, the orientation of the follower in inertial reference frame $\Sigma_g X_g Y_g$:

$$\Gamma(t + \Delta t) = \Gamma(t) + \Omega_r(t)\Delta t \tag{9}$$

iii) Calculate the distance travelled by the tether tip Δs_r:

$$\Delta s_r = V_r \Delta t \tag{10}$$

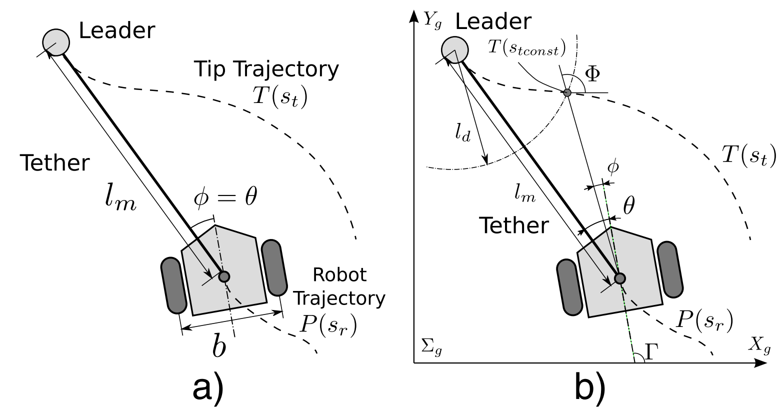

Figure 1 Two-wheeled robot models. (a) Pseudo-Joystick control; **(b)** Follow the Leader with Constant Distance control.

iv) Update the position of the follower $\boldsymbol{P}(s_r + \Delta s_r)$:

$$\boldsymbol{P}(s_r + \Delta s_r) = \boldsymbol{P}(s_r) + \boldsymbol{E}^{k\Theta} \begin{bmatrix} \Delta s_r \\ 0 \end{bmatrix} \quad (11)$$

where :

$$\Theta = \Gamma + \theta \quad (12)$$

$$\boldsymbol{E}^{k\Theta} = \begin{bmatrix} \cos\Theta & -\sin\Theta \\ \sin\Theta & \cos\Theta \end{bmatrix} \quad (13)$$

Θ is the tether angle in the inertial reference frame $\Sigma_g X_g Y_g$.

Step 2: Compute the position of the tether tip $\boldsymbol{T}(s_t + \Delta s_t)$.

$$\boldsymbol{T}(s_t + \Delta s_t) = \boldsymbol{P}(s_r + \Delta s_r) + \boldsymbol{E}^{k\Theta} \begin{bmatrix} l_m \\ 0 \end{bmatrix} \quad (14)$$

Step 3: Calculate the distance travelled by the tether tip.

$$\Delta s_t = \|\boldsymbol{T}(s_t + \Delta s_t) - \boldsymbol{T}(s_t)\| \quad (15)$$

Constant distance control

At this point, the leader trajectory is known, so it is possible to select some forward point on this trajectory and command the robot to steer towards it. However, while the robot should accurately converge on the leader trajectory, there is another important consideration for this application. H.O.T. uses a cannula of limited length between the oxygen supply on the robot and the user, so to avoid stressing this cannula it is necessary to keep the distance between the robot and the user constant (or close to constant).

Step 4: Determine the target angle ϕ.

We find a point on the leader trajectory a fixed distance of l_d from the leader (Figure 1b), $\boldsymbol{T}(s_t const)$, and calculate the angle from the robot to this point:

$$\phi = \arctan\left(\frac{\boldsymbol{T}(s_t const)_y - \boldsymbol{P}(s_r)_y}{\boldsymbol{T}(s_t const)_x - \boldsymbol{P}(s_r)_x}\right) - \Gamma \quad (16)$$

We can then modify the control equations (1, 2) so that the magnitude of the robot's velocity is decreased proportional to the target angle ϕ, introducing control gains K_a and K_b:

$$V_r = -K_p(l_m - l_d)(1 - K_a\|\phi\|) \quad (17)$$

$$\Omega_r = -K_b\phi \quad (18)$$

V_r and Ω_r can then be transformed into desired wheel velocities (ω_L, ω_R) using the inverse matrix $\boldsymbol{A}^{-1}$ (6). In this paper, we refer to this second algorithm as *Follow the Leader Control* for simplicity.

Dynamic simulation

Simulation environment

To investigate the performance of the follower robot, we developed a dynamic simulation with the open source *V-REP* software package, using the *Bullet* physics engine. V-REP was selected because it allows different experimental conditions to be modelled in a relatively short time, and it has been widely used for a range of robotics application [8]. For this research, we modelled a two-wheeled, differentially steered follower robot (similar to Figure 1) with a frictionless caster at the front and at the rear. The leader was modelled as dummy point moving along a predetermined path at a fixed speed of 0.5 m/s. A model tether connected the robot to the leader, and a sensor provided length, l_m, and angle, θ, data to be used in the control algorithm.

In order to characterize and compare the two control methods detailed in the previous section, both Pseudo Joystick and Follow the Leader algorithms were implemented in the V-REP simulation. The robot was first set to use Pseudo Joystick control to follow the dummy leader as it moved along the pre-set path, and the resulting trajectories were plotted. The simulation was then repeated using Follow the Leader control with the same leader path.

Simulation results

From the leader and robot trajectories in Figure 2a, we can see that the robot using Pseudo-Joystick control exhibits basic following behaviour. As expected, the robot's trajectory is close to the leader's, but deviation occurs when the leader path turns with a tight radius. We see that the robot tends to 'cut corners': when the leader turns and moves to the right, the robot will immediately begin steering towards the right and therefore will miss part of the leader trajectory (but still always following the general trajectory). This suggests that Pseudo-Joystick may be unsuitable in environments where the user needs to make many tight-radius turns, or if there are many obstacles to walk around.

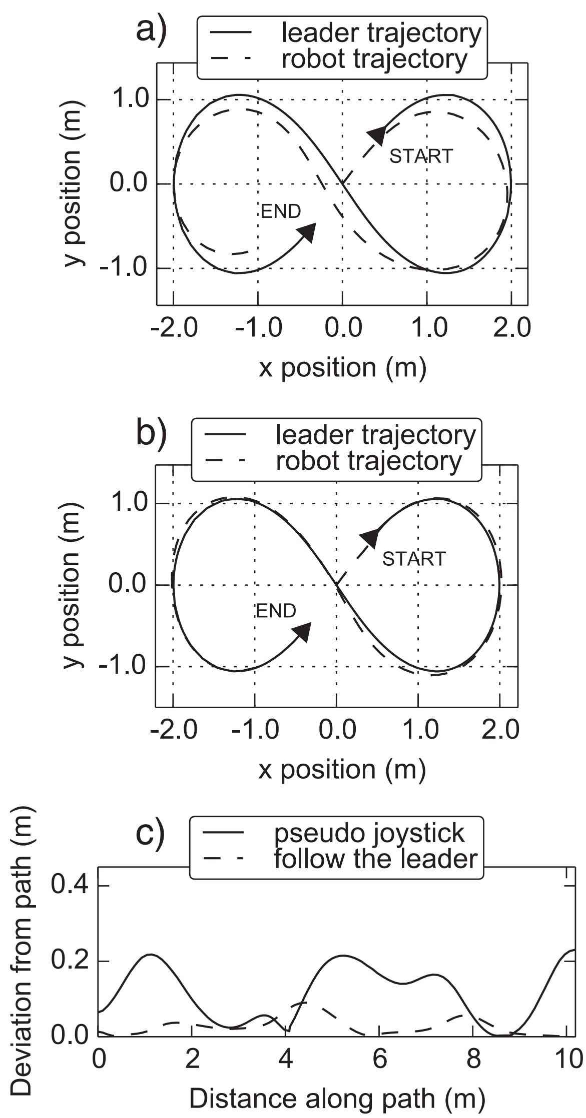

Figure 2 Simulation results. Robot and leader trajectory for **(a)** Pseudo-Joystick control and **(b)** Follow the Leader control. **(c)** compares the normal path deviation for both control algorithms.

When using Follow the Leader control, the robot's trajectory follows the leader trajectory much more closely (Figure 2b), though we still see some small deviation from the leader path when the robot moves around curves. It is possible to reduce this deviation by increasing the gain K_b, however this can decrease stability and lead to dangerous over-rotation (risking damage to the oxygen cannula). To quantitatively compare follower performance, we have used *normal path deviation* as a metric: we divide the leader trajectory into small segments, and calculate the normal distance to the robot trajectory for each segment. Figure 2c compares the two algorithms using this metric, and clearly shows that Pseudo Joystick exhibits greater deviation from the leader path.

Experiments in controlled environment

Following the simulation, we conducted experiments to validate the follower performance in a hardware prototype.

Follower robot

The follower robot we have developed consists of a tether interface, a chassis to store the H.O.T. equipment, and four wheels in a rhomboid configuration (see Figure 3). Two large active drive wheels mounted on the left and right provide good traction and simple controllability, while smaller casters mounted on the front and rear provide stability. Each drive wheel is powered by a 20 W in-wheel motor and reduction gear, giving a high reduction ratio to overcome obstacles, while maintaining a low-profile to maximize the available luggage capacity. The robot can securely carry a 2.5 kg oxygen tank and a 12 V 3200 mAh battery to provide power. The chassis includes an inclined parallel bogie linkage, making it capable of traversing vertical steps of 80 mm (the typical height of a street kerb in Japan). A summary of the robot's specification is given

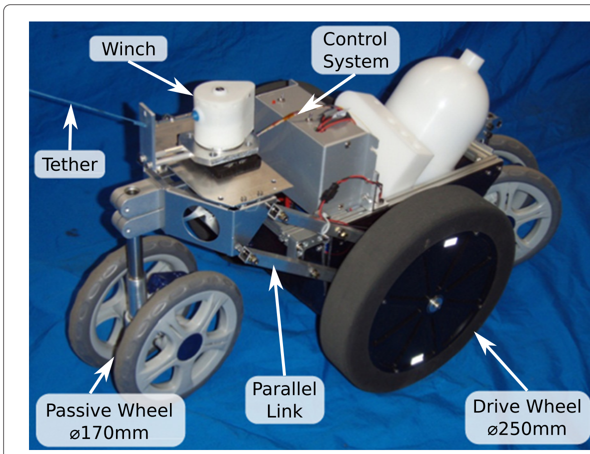

Figure 3 Follow robot showing major components.

in Table 1. The tether tip can be held by the patient or attached to a waist belt, while the tether base is attached to a compact, lightweight winch reel. The winch reel includes a flat spiral spring to keep the tether under tension, rotary potentiometers to measure the tether length and angle and bearings to allow free rotation about the yaw axis.

Method

To evaluate the robot's performance in a controlled environment, we conducted an experiment where the robot followed a healthy human leader around a series of simple obstacles. Three obstacles were placed in a straight line at 1.5 m intervals, and the user was instructed to walk from one end to the other and back while weaving in-and-out of the obstacles (a total distance walked of around 10 to 12 m). The robot was positioned 0.5 m behind the user, and the tether was attached to a belt on the user's waist. Prior to each experiment, the robot was set to use either Pseudo Joystick or Follow the Leader control, and the experiment was then repeated using the second control method. Five different subjects participated in using the robot for these tests. Tracking and recording was achieved using a *MotionAnalysis* motion capture system, which used 10 digital cameras to measure the position of reflective markers with an accuracy of ±1 mm (sampling rate: 200 Hz). Markers were placed at various points on the user and the robot, especially measuring the position of the user's waist and the robot's center. Calibration, data collection and post-processing was performed using *Cortex* analysis software. Figure 4 shows the experimental setup and the resulting motion capture model.

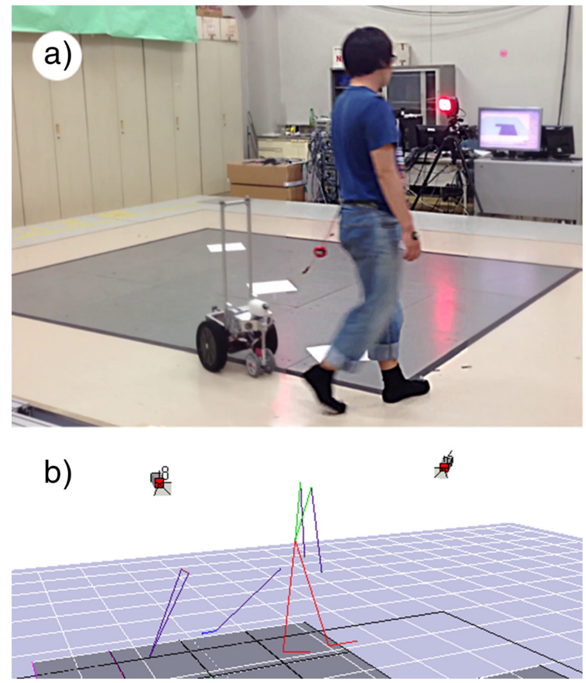

Figure 4 Motion capture experiment. (a) motion capture room; **(b)** the user and robot models constructed from motion capture data using *Cortex* software.

Results

Figure 5 shows the results from one of the subjects, and the results for all test subjects are summarized in Table 2. As before, the robot follows the leader's path more closely with Follow the Leader (Figure 5b) than with Pseudo Joystick control (Figure 5a) in most cases. Though Pseudo Joystick follows the general trajectory, Figure 5a shows it had significantly greater deviation from the leader path, and this gave rise to a risk of collision with the obstacles. While Follow the Leader control had low deviation and less risk of collision, there was still some error in its trajectory. This was likely due to slip between the drive wheels and the floor surface having a detrimental impact on the robot's odometry, and the possible offset between the actual measured tether tip and the tracked marker on the subject's waist.

Table 1 Follower robot specification

Dimensions L × W × H	670 × 330 × 350	mm
Mass	7.5	kg
Max. Velocity	1.0	m/s
Max. Step Height	90	mm
Operating Time	180	min
Payload	2.5	kg

Experiments involving H.O.T. patients

After confirming that the robot could perform adequately in a controlled environment, further experiments were carried out with H.O.T. patients to assess the robot's suitability as an assistive device for Home Oxygen Therapy. We conducted a simple follower experiment (similar to the motion capture experiment described above), and used a questionnaire to gather patient feedback about the robot's performance.

Method

We conducted our evaluation in January 2013 at a *Meeting for the Pulmonary Rehabilitation Studies* in Nagano, where 14 people volunteered to take part in a practical robot experiment and a questionnaire survey. We obtained informed consent from all the participants before starting the experiments, and no form of compensation was given. This evaluation with H.O.T. patients was approved by the ethical review board for epidemiological study in the Tokyo Institute of Technology (approval No. 2012014).

At first, the purpose of the research was explained to all participants, including a description of the robot and how to operate it. For each volunteer, the robot tether

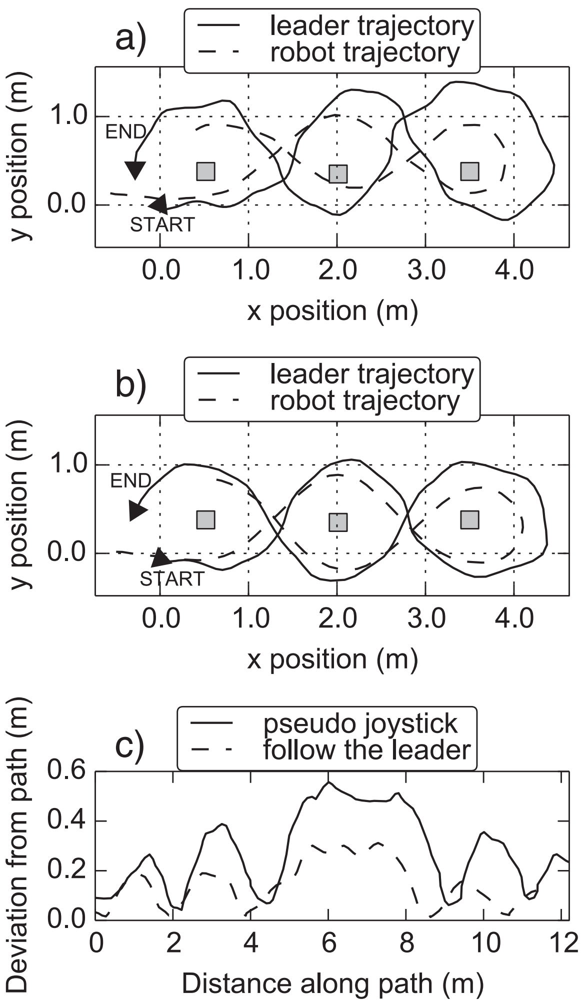

Figure 5 Motion capture experiment results. Robot and leader trajectory for **(a)** Pseudo-Joystick control and **(b)** Follow the Leader control. **(c)** compares the normal path deviation for both control algorithms.

was attached to a waist belt, and the robot was randomly assigned to use either control 'method A' (Pseudo Joystick control) or 'method B' (Follow the Leader control). As in the previous experiment, the user was asked to walk in and out of cones placed at 1.5 m intervals, while the robot followed them (a total distance walked of around 16 to 18 m). The subjects were instructed that, when using Pseudo-Joystick control they should occasionally look back to check the robot's position; these additional instructions were necessary since early tests had shown that without glancing back it was almost impossible to avoid obstacles. A researcher walked closely behind the patient to provide assistance in case of any unexpected problems, and medical staff were present to supervise (Figure 6 shows patients operating the robot). After completing the walking activity with both control methods, each patient was asked to answer a short questionnaire. If a patient felt unable to answer all of the questions for any reason, they were able to skip questions (always under medical supervision).

Position tracking from video data

Due to the limited space available in the testing area, and the risk of burdening patients by attaching sensors, it was not possible to use motion capture or other sensing equipment to record the position of the user and the robot in real-time. For this reason, the experiments were recorded with a video camera, and this video data was later analysed to determine the trajectory data. The video was analysed, frame by frame, to record the position of the user's feet when they struck the floor. This position was then compared to a known map of the experiment floor to measure the position, and the positions of the left and right feet were averaged to approximate the user's center of gravity (motion capture experiments have confirmed that this gives a reasonable approximation of the user's center of gravity). A similar procedure was used for the robot's wheels. Though coarse, this procedure allowed rough trajectory tracking without overly burdening patients; we estimate the accuracy to be around ± 40 mm. The trajectory data of five subjects, selected at random, is presented in this paper.

Table 2 Follower performance in motion capture experiment

	Normal deviation from leader path (m)			
	Pseudo-Joystick		*Follow the leader*	
	Mean	**Std. deviation**	**Mean**	**Std. deviation**
Subject 1	0.167	0.095	0.153	0.085
Subject 2	0.154	0.073	0.168	0.065
Subject 3	0.243	0.135	0.094	0.059
Subject 4	0.267	0.150	0.134	0.095
Subject 5	0.226	0.130	0.143	0.109
Average	0.211	0.117	0.138	0.083

Figure 6 Experiment with H.O.T. patients. Patients operated the robot while walking around cones. *(Photographs used with subjects' permission).*

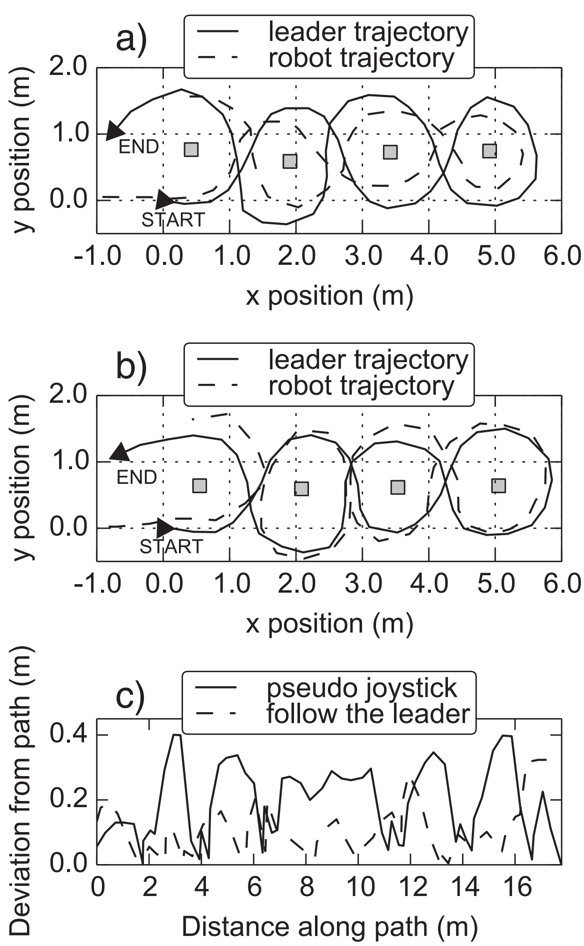

Figure 7 Results of experiment with H.O.T. patients. Robot and leader trajectory for **(a)** Pseudo-Joystick control and **(b)** Follow the Leader control. **(c)** compares the normal path deviation for both control algorithms.

Results and discussion

Follower trajectory

Figure 7 shows that the robot was able to follow the patient successfully around the cones using both control methods, and that as expected, Pseudo Joystick control (Figure 7a) shows slightly greater deviation than Follow the Leader control (Figure 7b). The results for the five subjects analysed are summarized in Table 3. It is likely that odometry errors caused by wheel-slip contributed to the deviation when using Follow the Leader control. Since both control methods have been shown to give reasonable following performance in the cones task, it is next necessary to examine the questionnaire responses to determine the patients' evaluation and preferences.

Questionnaire survey

The questionnaire was completed by 14 volunteers after operating the robot; there were 12 men and 2 women, with an average age of 71.6 years. In addition to asking about the patient's basic information, lifestyle, and use of H.O.T., the questionnaire also asked questions about the control of the robot, as presented in Figure 8.

The responses to Question 1, 'How easy was it to walk around the cones without colliding with them?' established a baseline for the effectiveness of the robot in this task (Figure 8). Most of the patients responded 'Easy' or 'Very Easy', with only one responding 'Difficult'. This is important as the cones walking task is an approximation of some of the daily activities that real H.O.T. users undertake, such as walking to the shops while avoiding other people, and any assistive device should be able to complete this activity without causing difficulty.

Question 2, 'Which control method was better: A (Pseudo Joystick) or B (Follow the Leader)?', gives a qualitative comparison of the control methods (Figure 8). The results are mixed but show a slight preference for Follow the Leader (8 positive responses) over Pseudo Joystick (4 positive responses). The preference for Follow

Table 3 Follower performance in experiment with H.O.T. patients

	Normal deviation from leader path (m)			
	Pseudo-Joystick		*Follow the leader*	
	Mean	**Std. deviation**	**Mean**	**Std. deviation**
Subject 1	0.153	0.110	0.194	0.145
Subject 2	0.204	0.131	0.119	0.095
Subject 3	0.178	0.110	0.155	0.087
Subject 4	0.179	0.116	0.102	0.078
Subject 5	0.171	0.133	0.127	0.089
Average	0.177	0.120	0.139	0.099

the Leader may be due to the relative comfort: there is no need to glance backwards at the robot when using it. The fact that other users preferred Pseudo-Joystick control may be explained by the better responsiveness: with Pseudo-Joystick control, the robot will respond almost immediately to a steering input, while Follow the Leader inherently involves a delayed steering response since it records the history of the leader's position. Thus some users will find Pseudo-Joystick more intuitive in this sense. In addition to evaluating the technical efficacy of control methods it is essential to also consider the users' preferences; and the fact that different users prefer different control methods may suggest that user-switchable control could improve the robot's usability.

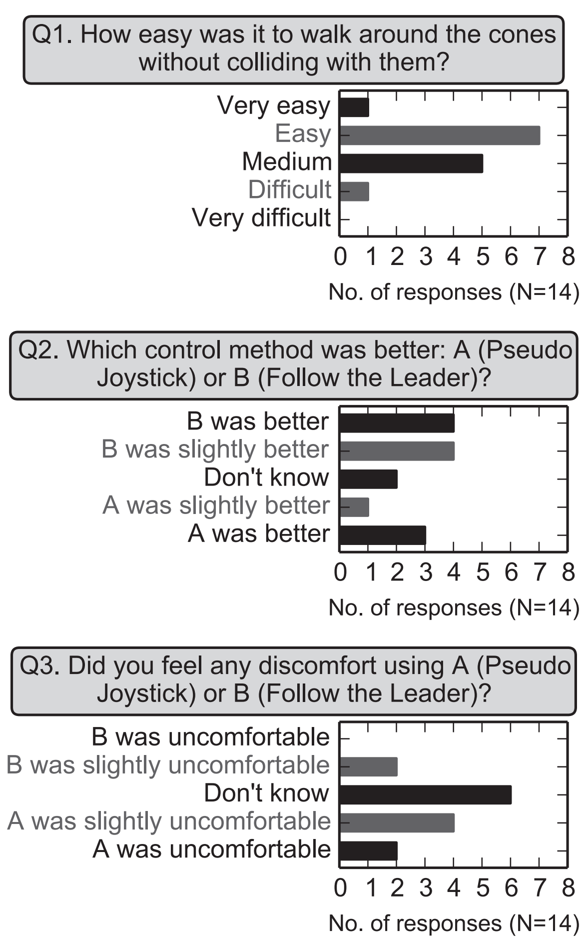

Figure 8 Questionnaire survey results.

Question 3, 'Did you feel any discomfort using A (Pseudo Joystick) or B (Follow the Leader)?', was asked to identify further usability problems (Figure 8). Among the responses there was a clear trend that Pseudo Joystick was more uncomfortable to use (6 'uncomfortable' responses) than Follow the Leader (2 'uncomfortable' responses). Pseudo-Joystick may be more awkward to use since it requires the user to occasionally glance backwards, and while this is an easy task for a young, healthy user, it is important to note that it places relatively more physical strain on an elderly person (particularly a person using H.O.T.). These results guide further design revisions as avoiding discomfort is of paramount importance in this application: as the goal is to increase the users' freedom and well-being, the assistive robot must avoid causing any unnecessary distress which could have a negative effect on breathing and overall health. The responses collected so far indicate that Follow the Leader is likely to be a safer choice for H.O.T. users.

Conclusion

This paper investigated the use of a leader following robot as an assistive device for Home Oxygen Therapy patients. We examined and compared two different control algorithms for the robot using dynamic simulation, motion capture experiments in a controlled environment and most importantly experiments involving H.O.T. patients. From the practical experiments we showed that the Follow the Leader algorithm was capable of following the user more accurately than Pseudo-Joystick, but both algorithms gave reasonable following performance in the walking-around-cones task. The questionnaire survey of H.O.T. users identified that overall they found Follow the Leader to be better and found Pseudo-Joystick control to be more uncomfortable. Pseudo-Joystick control is likely to be more intuitive to some users because of its immediate response to user commands, but the need to look back and check the robot's position can introduce some discomfort. In addition to the data and analysis presented in the paper, it is important to highlight the active role of H.O.T. users during experiments. It is essential to involve such stakeholders early in the design process, and the members of *Meeting for the Pulmonary Rehabilitation Studies in Hokushin* were enthusiastic about helping in the development of assistive robotics, providing the researchers with invaluable feedback and encouragement.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
GE lead and directed the research, proposed the concept, designed the experiments and submitted the proposal for ethical review. BA performed the motion capture experiments, drafted the manuscript and analyzed experimental data. YI conducted the experiment with H.O.T. patients and implemented the algorithms in the robot. EFF developed the follower algorithms and contributed to the design of the experiment with H.O.T. patients. MI and MO arranged the experiment with H.O.T. patients. TT provided a medical review of the experiment. All authors read and approved the final manuscript.

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