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Development of a Practical Robotic Follower to Support Home Oxygen Therapy Patients
- Empirical Evaluation in Public Space -

Gen Endo[1] Ben Allan[1] Masatsugu Iribe[2] and Toshio Takubo[3]

***Abstract*— Home Oxygen Therapy is a medical treatment for patients suffering from severe lung diseases. High purity oxygen is usually supplied to the nose via cannula (air tube), and it can give patients a high quality of life outside of hospital. However, whenever patients go out they must carry portable oxygen equipment which typically weighs about 4kg. In order to support H.O.T. patients, we have proposed a mobile following robot to carry the heavy oxygen equipment, consisting of two active differential drive wheels and two passive wheels connected by two parallel linkage mechanisms so as to form a rocker-bogie mechanism to negotiate a step or bump sideways. A tether interface is introduced to achieve robust measurement of the relative position of the user with respect to the robot. In this paper, we evaluate the size of the robot taken on public transportation. Moreover, an initial evaluation of the robot by Home Oxygen Therapy patient on a public road is reported, suggesting effectiveness in reducing the physical burden of the patient.**

I. INTRODUCTION

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].

Home Oxygen Therapy (H.O.T.) is a form of Non-Invasive Ventilation[4] which involves the administration of concentrated oxygen for extended periods (usually over 15 hours per day). Home Oxygen Therapy can benefit patients with COPD[5] as it aims to further improve the patients' freedom and quality of life by allowing treatment outside of hospital[6], and previous research has shown a positive correlation between average daily distance walked and health related quality of life[7].

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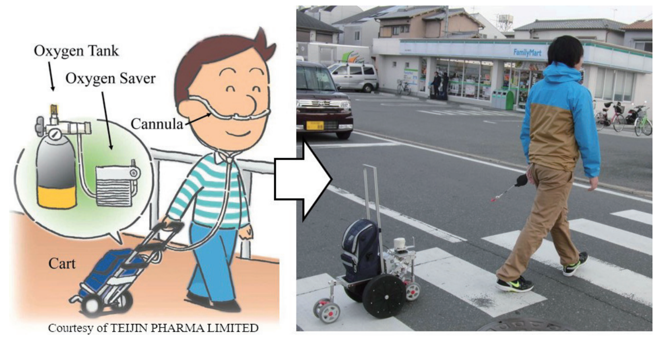

Fig. 1. Conventional portable oxygen supplier (left) and proposed following robot (right)

There are currently around 160,000 people using H.O.T. in Japan, and this number is expected to increase as Japan's population ages in the future. Oxygen is delivered through a mask worn on the face or nose, through a cannula, from a supply which may consist of either a canister of pressurized oxygen, a liquid oxygen tank, or a small oxygen concentrator device. This equipment typically weighs around 4 kg, and when the user leaves the house they can use a small handcart to transport it. An example of typical cart and device used for H.O.T. is shown in Fig. 1 (left). 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.

In order to support H.O.T. patients, a mobile following robot carrying their H.O.T. equipment might be effective to reduce their physical burden. Many researchers and robotics venture companies have made various attempts to develop following robots to carry heavy object instead of humans. For instance, the products [8][9] are for logistics use, and the references [10][11] are for shopping support. However, most of the previous products are planned to be used on flat smooth ground, and utilize multiple expensive wireless sensors such as LiDAR, beacons and cameras, which usually require high computational cost for robust measurement in an outdoor environment.

Therefore, we have proposed a mobile following robot with a special suspension mechanism based on the rocker-bogie mechanism in order to increase rough terrain adaptability. We also proposed to use a tether interface to detect the patient's relative position by measuring the length and direction of the tether, with a slight tension applied (less than 1.5 N) regardless of the length. The tether length and direction are measured by rotary potentiometers which are extremely cost effective compared to measuring the force applied by the user. An image of the actual use case is shown in Fig. 1. This mechanical configuration reduces the production cost and achieves robust measurement. Moreover, the tether interface is very intuitive and easy to use for elderly people.

In our previous work, we developed a prototype model and its following control algorithm[12][13]. The prototype was evaluated by H.O.T. patients in an indoor controlled environment. However, with the aim of supporting H.O.T. users in their daily life, it is vitally important to test the robot in conditions which closely approximate daily activities. The activity and mobility of H.O.T users varies for each individual, but in general they wish to enjoy the freedom to visit local shops, the park, the train station and other amenities, as well as exercising outside. It is often medically beneficial to perform some limited physical exercise, and a patient's doctor might recommend some daily/weekly exercise targets.

In this paper, our goal is to empirically evaluate our prototype robot in a public space assuming realistic situations. After describing our prototype models in Section II, the robot size is evaluated to determine whether it is suitable for use on public transportation and in an individually owned compact car in Section III. Next we report initial results that the proposed robot actually decreases the physical burden of a H.O.T user walking on a public road in Section IV. We conclude this paper with a discussion of future work in Section V.

II. PROTOTYPE MODELS

In this paper, we use two prototype models shown in Fig. 2. These two models essentially have the same structure: a four-wheeled rhomboid configuration where the front and rear wheels are passive casters, and the middle right-and-left wheels are active wheels. The front passive caster is connected by the two inclined parallel linkages to the middle wheels in order to appropriately adjust the distribution of the ground vertical reaction forces on each wheels when the robot negotiates a step. This mechanism can also minimize the required maximum driving torque to negotiate a step. In order to maximize the luggage space of the robot, we designed a special low-profile in-wheel motor with a large diameter (for more details see [12]). The tether mechanism consists of a reel mechanism and a rotational joint around the vertical axis, installed on the base structure. The length of the tether is measured by the rotational angle of the reel, and the direction of the tether is measured by the angle of the rotational joint. These angular measurements are achieved simply by potentiometers. We implemented two following algorithms, pseudo-joystick steering control and modified follow-the-leader control [12], and the user can select the desired control mode. Pseudo-joystick steering control directly utilizes tether length and direction information as a target velocity vector to drive the two wheels, while modified follow-the-leader control records and tracks the trajectory of the leader in an absolute coordinate system, minimizing the relative distance between the leader and the robot. For more mathematical formula and their evaluation, see reference [12].

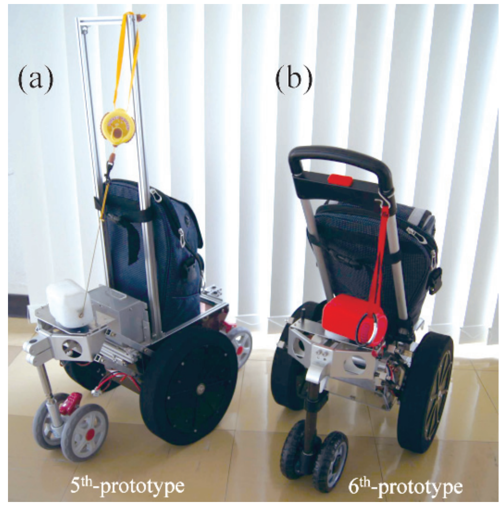

Fig. 2. Prototype models: (a) 5th prototype, (b) 6th Prototype

Dimension [W x H x D]	325 x 710-1000 x 535 [mm]
Weight	5.4 [kg] with Battery
Wheel Diameter	120 [mm], 250 [mm]
Battery	LiFePO4 : 13.2V-5Ah x 1 (4S-2P 66Wh, Cosmo Energy)
Actuator	20 [W] x 2: Maxon RE25
Reduction Ratio	86.4
Direction Angle Sensor	Potentiometer
Tether Length Sensor	Potentiometer
CPU	SH7047F CLK/44.2MHz (TITech SH2 Tiny, Hibot)
Motor Driver	1 Axis DC Power Module (Hibot)
Payload	2.5 [kg]
Maximum Velocity	1.0 [m/s]
Operational Time	3.2 [hours]

Fig. 3. Overview and specification of 6th prototype

We confirmed that the 5th prototype, carrying the equivalent payload of the oxygen equipment, could negotiate a step of 96mm, which is almost 2 times higher than that of the chassis mechanism of a normal differential driving mobile robot with two drive wheels such as [14]. We also verified that the 5th prototype could follow a narrow winding trajectory by using modified follow-the-leader control.

The 6th prototype (Fig.2(b)) is an improved version of the 5th prototype based on users' feedback. The most commonly requested improvements for the 5th prototype model were the following:

- Lighter in weight
- Smaller in size
- Quieter in operation
- Variable handle height and angle
- Easy to hold handle

Regarding weight reduction which was most demanded, we changed the type of battery from lead-acid to lithium polymer ferrite, and the main structural materials from aluminium alloy to CFRP. These replacements saved 1.6kg in weight,

Fig. 4. Empirical size evaluation in various transport vehicles

which is 23% of the total weight of the robot. As for the size of the robot, any reduction in the size of the robot represents a trade-off with the maximum step climbing capability. We tested the maximum step climbing height by reducing the total length of the robot, adjusting the rear wheel position. Consequently, it was found that an 80mm length reduction decreases the maximum step climbing height from 96mm to 72mm. Since the height of the step separating sidewalks and roadways is commonly 50mm in Japan, we consider a step climbing ability of 72mm to be sufficient to operate on sidewalks. The specification of the 6th prototype is shown in Fig. 3.

III. SIZE EVALUATION IN PUBLIC SPACE

Our ultimate goal is to develop a practical mobile following robot which can truly help H.O.T. users in their daily activities. Thus we believe that we should evaluate our mobile robot in public space, assuming plausible usage situations. Actually in several user feedback meetings, H.O.T. users, especially those living in the Tokyo area, frequently asked us if this robot can fit on public transportation. In this evaluation with the 6th prototype model, we turned all electric power off and removed the battery inside the robot because our primary concern was to evaluate the size of the robot.

Firstly, we brought the robot on a bus, using the entrance located in the middle of the bus. The robot could be put between a seat and a partition as shown in Fig. 4(a). The left wheel fits under the seat, but if the wheel diameter were larger than this model it would be difficult to fit in this place. When we got off the bus, we had to go though the front entrance, which was narrower than the middle entrance due to the payment equipment located next to the driver. Even in this case, we could successfully pass through the front entrance without problems.

Secondly, we brought the robot on a train, using an escalator to access the train platform. In Japan, there is a custom to keep the right (or in some cases the left) half of the escalator steps clear to make way for passengers who are walking. Fig. 4(b) shows that the robot is sufficiently short to keep half of the step clear. Many walking passengers walked through the clear half of the escalator without paying special attention, suggesting the robot length is sufficiently small. Furthermore, the robot width (325mm) also fit within the width of the step (400mm). The robot was very stable on the escalator because the middle tire, made of foam sponge, has sufficient width of 50mm. Fig. 4(c) shows that the robot could fit in the area close to a door. In this case, the robot did not become an obstacle for other passengers. However, we found that the robot was sometimes moved by the train vibration due to a low gear ratio driving wheel design. We think the low gear ratio design is very important for safety reasons because it allows the robot to be manually pulled if the battery runs out. Electrical braking (by short circuiting the actuator power line) provides the robot with sufficient braking force without consuming electric energy. We also brought the robot on a bullet train as shown in Fig. 4(d). It was possible to store the robot in the space under the table by changing the handle angle and length. Although this position is a bit cramped, the robot could fit in space for a single seat. If we separate the bag for oxygen equipment, the robot could be stored in the overhead shelf (Fig. 4(e)).

Thirdly, we evaluate the robot size by putting it in a compact car (Nissan MICRA) because moving by car is essential for H.O.T. users living in suburbs or rural areas. Fig. 4(f) shows the robot stored in the luggage space of a compact car, where it fit without changing the handle position. Fig. 4(g) shows the robot stored in the front passenger seat. Although it was necessary for the seat to be moved backwards, there was sufficient space to carry the robot. Although many H.O.T. users want the robot to automatically get into the car, it is a really difficult task. Thus, putting the robot in the car requires lifting the robot up, and since the total weight of the robot is more than 7kg including battery and oxygen equipment it is very difficult for H.O.T. users. Hence an easily detachable bag is one promising solution to reduce the weight needed to be lifted at once.

In summary, we conclude that 6th prototype is sufficiently small to fit public on transportation as well as in a compact car.

IV. EVALUATION BY H.O.T. USER ON PUBLIC ROADS

This section describes an experiment to investigate the performance of the robot in a realistic outdoor situation: supporting the user on short trips around a local park. When evaluating service and support robots it can be very difficult to get a quantitative measure of their usability or effectiveness. In this respect, H.O.T. provides a very fortunate research opportunity since we can measure the user's heart rate and oxygen saturation as a quantitative estimate of a device's effectiveness. These values are affected by the user's physical exertion, and they in turn affect the user's health and safety (particularly oxygen saturation). Sensors were used to record the condition of a volunteer patient as they undertook some walking courses while the robot carried the oxygen tank. The performance of the robot would be compared to a manual oxygen tank cart (typically used by H.O.T. patients currently), and also to a commercial shopping cart with powered wheels.

To make statistically significant conclusions about the effectiveness of the robot, it is clear that we need to conduct experiments with a large number of participants (eight participants is a reasonable minimum for this kind of research; more is better). However, recruiting Home Oxygen Therapy patients is difficult, with many having restrictions on their physical activity as advised by their doctors, and setting up experiments requires considerable time and funding. The final goal of this research is to reach the most vulnerable users, testing the robot a with a wide and representative range of participants, but before this can be achieved it is necessary to demonstrate that the robot can perform safely. As such, this section describes a preliminary experiment in which the robot was tested with one H.O.T. user. We cannot make statistically robust conclusions about the robot's performance from these experiments, but any implied trends or relationships are still useful in justifying and preparing for further research.

This experiment was approved by the ethical review board of the Institute of Biomaterial and Bioengineering at Tokyo Medical and Dental University (approval number: 2014-02). Prior to the experiment, permission to use public roads was obtained from regional police (Suita Police, Osaka), and permission to use a municipal park was obtained from Suita City Office, Osaka. The experiment and participants were covered by suitable accident and liability insurance. This experiment was financially supported by the Association for Technical Aids (ATA).

Fig. 5. Conventional cart (left) and power assisted shopping cart (right)

A. Assistive Devices Tested

Three different devices were tested: a conventional oxygen tank cart, a commercial shopping cart with powered wheels, and the proposed robot.

The conventional oxygen tank cart, shown in Fig. 5(left), is a widely available design often used by Home Oxygen Therapy Patients. The oxygen tank is stored in a purpose-built bag and secured to the tank's aluminium frame with velcro straps. The cart has two passive wheels and is steered manually by the user pulling the handle. Naturally, since the cart is unpowered, the user must support the weight of the cart and oxygen tank.

The commercially available power assisted cart shown in Fig. 5 includes electric motors to power the wheels (Sueet, Fuji Micro co., ltd., [15]). The handle includes a spring sensor: when the user grasps the handle more firmly, the cart velocity is increased. A sensor detects when the cart is tilted forward greater than 15 deg, and turns on the drive motor. If the cart topples over or is dropped, the cart should turn off automatically. The intended effect is for the motor to assist the user and therefore reduce the effort required to pull the cart. However, the user must still support the vertical component of the load (which increases as the cart is inclined more). It is not designed for medical use, rather the intended application is assisting elderly people when carrying shopping or other heavy loads. During the experiment the oxygen tank was placed at the bottom of the large bag.

The robot was described in Section II. In this experiment, we used the 5th prototype due to the high reliability of the system. For these experiments, the oxygen tank (inside its purpose-built bag) was placed inside the intended compartment and secured to the frame with velcro. The user held the end of the tether in their preferred hand, and the robot followed using the Pseudo Joystick algorithm [12]. For safety, a researcher walked closely behind the robot at all times during the experiment, holding a cut-off switch which could quickly disable the robot in case of a problem.

B. Participant

The participant in these experiments was a 70-year-old male volunteer; a regular Home Oxygen Therapy user. The location of the experiment was the local area around the participant's home, so he was familiar with the park area and the routes were similar to those he walks regularly. He was very keen to participate actively and contribute to the research. Among Home Oxygen Therapy users, there is a wide variation in the severity of condition, physical fitness, quality of life and other factors. It is important to note that this participant was particularly healthy for a H.O.T. patient. He regularly exercised: he walked several kilometers each day, he cycled, and he visited the gym frequently. His relatively good health condition made him an ideal candidate for these outdoor experiments, as the risk to his health was limited (compared to more severe COPD patients).

C. Measurements

Heart rate was measured using a wrist-mounted heart rate monitor, such as those typically used by athletes for sport training. Naturally, when the user exerts themselves physically, their heart rate will increase, and this allows us to consider heart rate as a proxy measurement of the physical effort spent on a task.

Peripheral capillary oxygen saturation, or SpO2, is a measure of the oxygen saturation in the blood, estimated from measurements taken at an extremity (e.g. a finger). Oxygen saturation is an important measurement in patients with COPD [16], and SpO2 can be monitored as a measure of the patient's condition during exercise. SpO2 is stated as a percentage, and typically values below 90% are undesirable for healthy people. During the experiment, SpO2 was recorded using a pulse oximeter attached to the user's finger. Additionally, a glove was worn over the user's hand to prevent cold weather affecting the measurement.

D. Experiment Location

The location used for this experiment was Esaka Koen, a park in Suita City, Osaka, Japan. This area was chosen partly because it was close to the participant's residence, and because it gave a good representation of the daily trips H.O.T. users are likely to undertake (e.g. to local amenities such as the library). Fig. 6(top) shows an aerial view of the park and the nearby amenities. Within the park, two specific courses were identified for analysis.

- Course A: Long, straight section along the north edge of the park. Very flat. 200 m long. Expected to be relatively easy to walk on. See Fig. 6(bottom left).
- Course B: Short, uphill section near the library in the center of the park. 47 m long. Moderately steep. Expected to be require slight effort to walk up. See Fig. 6(bottom right).

The slope of the uphill course was measured at eight points along the length, with the average slope found to be 8.0 deg (approximately 14% grade).

E. Experiments and Results

Prior to the experiment, the researchers met with the participant to clearly explain the task to him, and the participant was able to test using the devices so he was familiar with their operation. The measurement instruments (pulse oximeter, heart rate meter, GPS) were attached to the participant. The two courses, A (flat) and B (uphill) were then traversed at a natural pace with the conventional oxygen cart. Following completion of the courses, the experiment was repeated with the commercial powered cart, and again with the robot follower. The participant then repeated all of the above experiments in a second trial (carried out the following day). During the experiment, the condition of the participant was monitored and several researchers were on hand to give assistance if required. In the case of the robot follower, one researcher also walked closely behind the robot holding an emergency stop switch in case of any safety problems. The participant was also instructed to monitor their SpO2 level and adjust their activity level to try to keep it above 90%. After the experiment was completed, the data was downloaded from the measurement instruments for analysis. Fig. 7 shows an overview of the experiment. The participant breathed oxygen supplied from an oxygen tank on the robot.

(a) Course A: flat ground, 200 m long (b) Course B: uphill slope (14% grade) 47 m long

Fig. 6. Map of the outdoor experiment location, Esaka Koen (adoped from Google Map)

Fig. 7. The participant walking on a public road with the robot

Figures 8 and 9 present the heart rate and SpO2 profiles measured for the participant. With the H.O.T. user, the robot appears to perform better than the conventional cart on the uphill course, and similarly on the flat course. The user's heart rate was lower when operating the robot on the uphill course, implying less physical exertion, while the SpO2 levels were the same or higher. Heart rate and SpO2 results on the flat course varied somewhat, but overall the robot's performance was similar to the conventional cart. Crucially, in all the trials the oxygen saturation level when using the robot was similar to the conventional cart, sometimes higher. This implies that the robot can provide a level of user safety which is, at minimum, no worse than the current solution (the conventional cart). The recorded results show a noticeable amount of fluctuation and some variation between measurements. This was likely due to insufficiently strict experimental controls: the temperature, weather, and even the user's fatigue levels varied during the recordings.

It is also important to consider the feelings and opinions of the users, and for this reason the participant was interviewed after the experiments. Considering the conventional cart, the participant felt that it was tiring as they always had to support the cart as they pulled it. When evaluating the commercial powered cart, they found it unattractive due to the need to constantly control the cart and pull it with one hand.

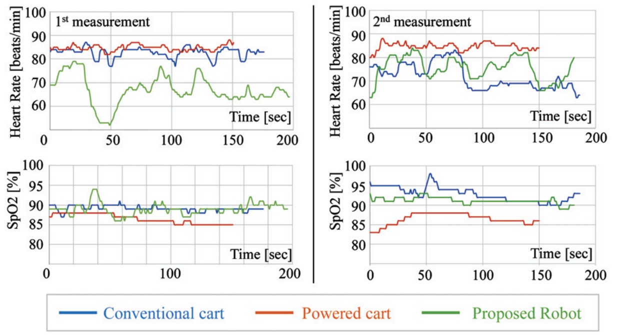

Fig. 8. Variation of heart rate and oxygen saturation (SpO2) during walking experiment on flat ground (Course A)

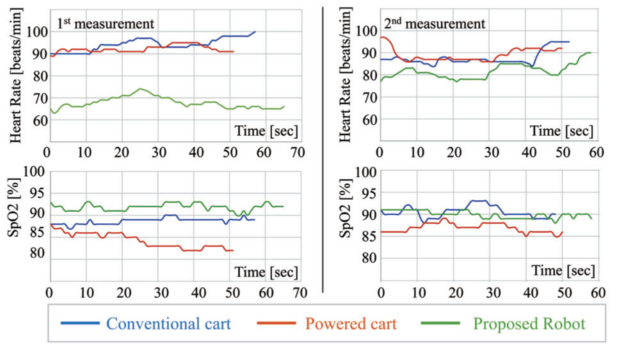

Fig. 9. Variation of heart rate and oxygen saturation (SpO2) during walking experiment on slope (Course B)

Regarding the robot, they felt the following performance was better than they expected, and that walking with free hands is beneficial. However the noise of the robot was a problem: too loud for use in daily life. Lastly, they remarked that it would be better if the robot could move in front of them, where they could easily see its position. Although there was no critical trouble (such as the robot falling over), the low tether tension did not give little feeling of presence of the robot, which might cause anxiety for the user. Positioning the robot in the user's view or active force feedback using tether tension to communicate with the user seems to be important to increase the usability of the robot.

These results are encouraging and show that more experiments should be conducted in future to further confirm the effectiveness of the robot.

V. CONCLUSIONS

In this paper, we empirically evaluated our prototype robot in public spaces assuming realistic situations. The size of the robot was evaluated to determine if it is suitable for use on public transportation and in an individually owned compact car. We also reported initial results that the proposed robot actually decreases the physical burden of a H.O.T user walking on a public road. Three different devices were compared: a conventional oxygen cart (unpowered); a commercially available cart with powered wheels; and a robot follower. The user's heart rate and oxygen saturation (SpO2) were measured, and these values were then used to compare the effect of each device on the user. While the single participant in this experiment was too few to draw statistically robust conclusions about the robot's performance, the results of the experiment implied that the robot performed comparably to the conventional cart, and sometimes better. This represents an interesting preliminary result which can be used to justify further experiments with a larger number of Home Oxygen Therapy patients in future.

Any future trials should involve a larger number of participants (ideally, more than eight) to measure the significance more robustly. Additionally, future experiments should seek to improve the controls of the experiment. Factors such as temperature, weather, walking speed and fatigue may affect the data and should be controlled wherever possible. However, conducting such experiments outdoors in a real environment in a safe manner is difficult to arrange, and the user's comfort, consent and safety should always be considered before any experimental controls.

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