A Hybrid Robotic and Mobile System to Promote Deep Breathing Exercise Adherence

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Abstract

Patients recovering from heart surgery often experience pulmonary complications that can be alleviated through deep breathing exercises (DBE), yet adherence to these exercises remains low. This study presents a novel system designed to increase adherence to DBE by combining a physical humanoid robot (NAO) with a mobile application featuring a virtual robot avatar. The system is grounded in the Transtheoretical Model (TTM) of behavior change, enabling personalized engagement strategies based on an individual's readiness to adopt new health behaviors. A short-term simplified preliminary trial with 15 healthy participants evaluated the feasibility and user reception of the system. Participants interacted with the NAO robot in an initial session, followed by daily use of the mobile app for one week. Results indicated full adherence of the 15 participants to the daily DBE regimen with an average app daily usage time between 6 and 12 minutes, as well as significant reductions in perceived stress scores from an average of 21.7 to an average of 11.5 on the scale of perceived stress, and high user satisfaction across multiple usability metrics. These findings suggest that this approach is promising in supporting the maintenance of health-promoting behaviors. Future work will involve long-term clinical trials integrating the full TTM-based personalization and comparing the effects of physical versus virtual robotic agents.

Keywords

Human-Robot Interaction, Socially Assistive Robotics, Health-Behavior Change, Virtual Robot Avatar, Trantheoretical Model

1. Introduction

Patients undergoing heart surgery may experience a number of consequences, such as restrictive pulmonary impairment and early postoperative gas exchange issues. Programs for cardiac rehabilitation (CR) are frequently utilized to mitigate or prevent these effects. A range of deep breathing exercises (DBE) are advised, particularly for patients who breathe on their own, to lessen atelectasis and enhance lung function in the initial postoperative period [1].

While CR programs have been shown to be effective, it is well-documented that patient adherence to these programs is poor [2, 3]. Some studies even reported adherence to be lower than 50% [4, 5, 6]. Low levels of social and practical support in addition to a lack of motivation have been linked to non-adherence to CR [7]. Effective medication adherence tactics, such as boosting patient self-efficacy, treatment belief, and social support, are likely to be closely mirrored in successful CR adherence strategies [8]. DBE would probably benefit from additional medication adherence techniques as well, such as routines and cues like hourly smartwatch or phone notifications that serve as reminders [9]. Smartphone applications, which typically include extra elements to boost engagement (e.g., tracking, leaderboards, customization, education), have been demonstrated to promote adherence to lifestyle interventions [10].

Additionally, there is evidence that the presence of an embodied agent can boost adherence and make people more obedient [11]. Socially supportive robots have been demonstrated in multiple rehabilitation studies to increase user motivation and engagement [12, 13, 14]. Furthermore, to improve motivation and task performance during repetitive exercise in healthcare programs, supportive feedback and

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ongoing monitoring are crucial [12, 15]. Several studies used social assistive robots to interact with patients in CR programs and monitor their activity [16, 17, 18]. All these studies reported higher patient adherence and motivation compared to a non-robot control group. Only one study used social robots for DBE: CLARA, a physical therapy assistant, was developed with the intention of assisting patients with arduous and repetitive spirometry exercises [12]. However, this study only examined the short-term advantages (one session) in healthy participants and no clinical trials were carried out.

An additional and often overlooked aspect in improving adherence is through grounding the system with an appropriate behavioral theory. By looking at DBE as a routine behavior that must be reinforced, we can draw from the theories of behavior change to support our design. Behavior change is regarded as an internal process. In other words, a target behavior can not be forced on an individual, resulting in limited adherence, but they must “want” to change their behavior. Studies have shown that interventions are more effective when they are grounded in an appropriate theoretical model for behavior change [19]. These models would help clarify why a person engages in a certain behavior and how we can influence said behaviors. Some widely used behavioral theories include the Health Belief Model [20], the Theory of Reasoned Action [21], the Social Cognitive Theory [22], the Theory of Planned Behavior [23], and the Transtheoretical Stage-of-Change Model [24].

In this preliminary work, we focused on developing a system for increasing adherence to DBE that is grounded in the Transtheoretical model (TTM) of Behavior change. The system would make use of a physical robot and a virtual avatar on a mobile app that could serve extra elements to boost engagement. The aim of this work is to increase adherence to DBE by using a hybrid robot-mobile system grounded in behavior theory.

2. Method

2.1. Behavioral Model

Even though the aim of this work is to enhance adherence to DBE, we wanted to design the framework to be applicable to multiple pathologies. We thus chose to use the TTM as it is the most flexible and can be applied in a multitude of scenarios. It is much less rigid compared to the other models, in that it can provide a template to create a behavior change system for any health-related behavior (in theory). It is flexible enough that other behavioral theories can even be derived from it.

The TTM identifies five separate stages that a person goes through in order to change a certain behavior as outlined by Prochaska and DiClemente [24]. Separate processes and strategies will be more effective depending on where the person is along these five stages. The stages are as follows:

1. Precontemplation: The state in which an individual may not even be thinking about adopting the recommended protective behavior, let alone plan to do so.
2. Contemplation: The state in which a person plans to adopt a behavior but has not yet done so.
3. Preparation: The state in which the person consciously decides to change their behavior in the near future and starts making an effort to do so.
4. Action: The state in which the intended behavior is being consistently carried out but has not been sustained for more than six months.
5. Maintenance: The state in which the behavior has been consistently carried out for longer than six months.

Stage assessment can simply be done by asking the user to rate how ready they feel to adopt the new behavior. This can be very useful in the beginning, but is better improved by tracking the user’s progress through monitoring their adherence over time. Our framework for DBE based on the TTM is shown in Figure 1.

As this work is aimed to be used with patients who are assigned DBE by a physician, we will always place patients in the first stage of the TTM. The reason for this is that patients might have felt an obligation to perform the exercises, in a hospital setting for example, even if they did not want to. In

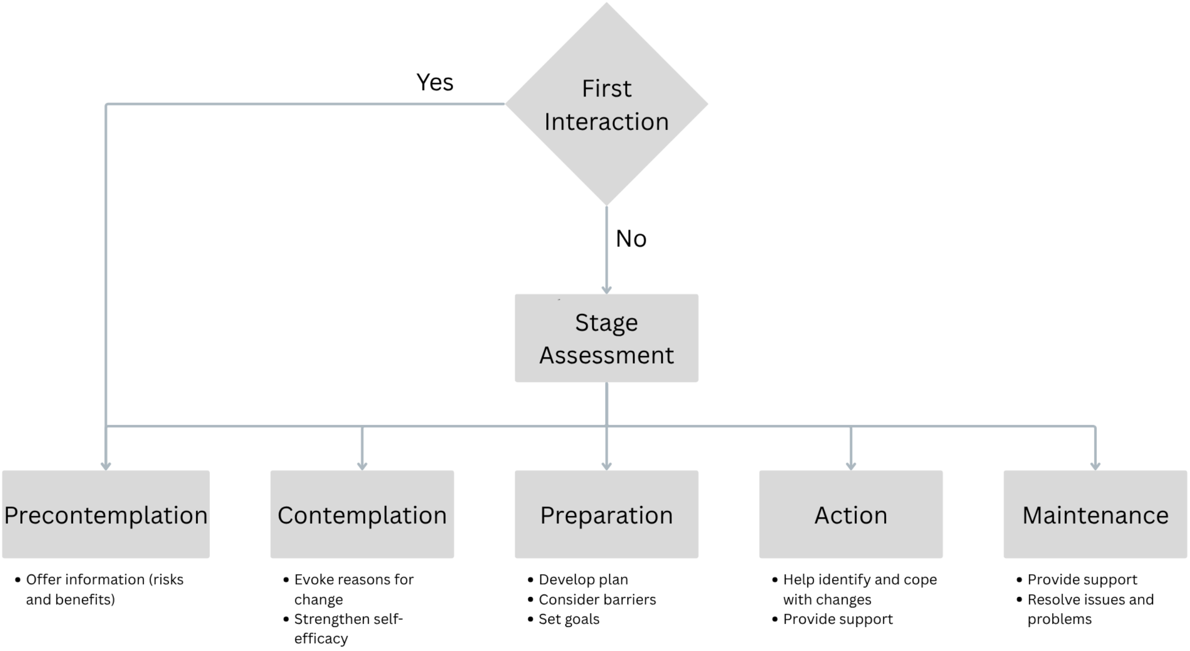

Figure 1: Flowchart of the behavior change framework for DBE.

this case, even though they might have been doing exercises for a few days, this does not reflect their true readiness to engage in such a behavior.

Based on their assigned stage, different strategies and methods will be used to influence their behavior and to successfully move them to a successive stage.

2.2. Preliminary Test

The overall described system would make use of a NAO robot for physical interactions with the patient in a clinical setting. The robot would speak to the patients (based on the precontemplation stage of the TTM) and would guide their exercise performance. When the patient is discharged from the hospital, they would use a mobile phone app, that would allow the patient to progress through the TTM stages while having daily conversations with a NAO robot avatar. The app would also provide daily reminders to perform the exercises, and provide incentives through the tracking of exercise completions.

For a short-term preliminary test, we developed an Android app with a NAO avatar. The avatar has an interactive conversation with the user upon opening the app daily. The avatar would answer any questions relating to DBE that the user might have. Then the app would show a short video giving instructions on how to properly perform the exercise. The avatar would appear under the video to give motivational messages to the user as shown in Figure 2. Upon completion of the exercise, the user is taken to an activity that shows their achievements, including how many exercises they have finished so far, how many consecutive days they have performed exercises, and how many total days. The user can press a button at any time to have a conversation with the avatar. The app will also send an alarm to remind the user to perform the exercises three times per day. The user can snooze the alarm for up to one hour. The user can also adjust the three alarm times in the settings of the app.

A NAO robot was used for the first interaction with the participants. The participants had an interactive conversation with the robot and watched a video to instruct them on how to do the exercises. They were then asked to install the Android app and to perform the exercises daily for seven days. The interactive conversation with the robot and the app was created using a mixture of rule-based responses and an LLM (Llama-3.2-3B-Instruct model).

Fifteen participants in total were recruited and fully completed the trial. The participants had an average age of 24 with a standard deviation of 2. As this was a short-term trial with healthy individuals,

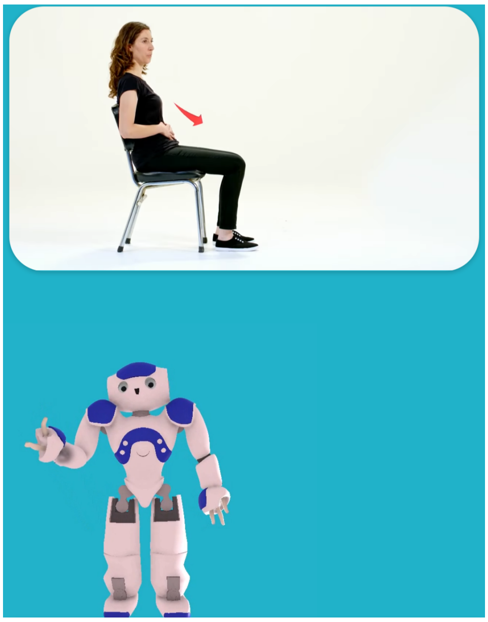

Figure 2: The exercise guidance video with the avatar giving motivational messages.

personalization using the TTM was not adopted and the effect of DBE on their stress was measured using an Italian translation of the scale of perceived stress [25]. Finally, the participants' impressions of the conversation system were measured using the chatbot usability scale [26].

Before the start of the experiment, each participant filled out an initial questionnaire for obtaining demographic information, and the perceived stress scale. In the first phase, carried out in the laboratory, participants interacted with the NAO robot, which guided them in an initial approach to deep breathing exercises. After a short presentation, the robot explained how the interaction worked, providing instructions on how and when to answer its questions and asking for the participant's name to make the experience more engaging and immersive. Subsequently, the robot explained the importance and benefits of deep breathing and guided each participant through a simple practical exercise that lasts 2 minutes, giving precise instructions and motivational support to the participant. At the end of the session, NAO expressed appreciation for the commitment shown and reiterated the importance of continuing training in the following seven days via the Android application. In the second phase, participants continued the experiment from home, using the application daily to perform DBE. Thanks to the virtual avatar of the NAO robot, the app maintained a motivational approach similar to the one tested in the laboratory, ensuring continuity and constant support. During the week of use, data were collected on the frequency of access, time of use, and completion of training sessions, allowing the level of involvement of the participants to be monitored. At the end of the experimental period, each participant completed the perceived stress scale to measure any differences and the chatbot usability scale.

3. Results

The usage data from the application showed that the participants all adhered to the daily exercise regimen, with an average daily usage time between 6 and 12 minutes. The initial results show that the stress score of the participants was significantly reduced from an average of 21.7 and a standard deviation of 5.1 before the experiment to an average of 11.5 and a standard deviation of 5.4 after the seven days of the experiment.

The analysis of the responses provided by the participants in the questionnaire regarding the system impressions highlights a high level of satisfaction with the conversational aspect of the system. The participants had the opportunity to express their opinion through a Likert scale from 1 to 5, where

1 indicates “strongly disagree” and 5 indicates “strongly agree”. The clarity of communication was particularly appreciated, with a mean of 4.87 and a standard deviation of 0.35, demonstrating that the instructions provided, both by the robot and the avatar, were perceived as understandable and effective. The ability to maintain a coherent interaction with respect to the context also received a very positive evaluation with a mean of 4.53 and a standard deviation of 0.64, while the ease of understanding the answers and their accuracy reached a mean score of 4.73 and a standard deviation of 0.46. Furthermore, the waiting time for the answers was considered short and adequate, with an average score of 4.733 (with standard deviation = 0.594). Finally, the perception of how much the robot and the avatar actually helped the participants achieve their goals was high with an average of 4.600 and a standard deviation of 0.632.

The results obtained demonstrate a positive impact on the psychophysical balance of the participants thanks to the interaction with the NAO robot and the use of the Android application. The reduction of stress in managing daily life highlights how technological support can facilitate the maintenance of healthy habits even in the context of a stressful life. The overall experience of the participants, highlighted by the satisfaction expressed during the initial testing phase, suggests that the interaction with the robot and the use of the application not only had immediate positive effects but also promoted confidence in managing daily difficulties and one’s emotions. The clear and motivating communication of both the avatar and the robot, combined with the ease of use of the application, improved participation in the suggested training sessions, demonstrating the importance of a user-friendly and engaging approach. The positive feedback from participants, both for the quality of the interaction with NAO and for the experience of using the mobile application is confirmed by the average scores, collected from the final questionnaire, and by the average time of use of the application. This indicates that the robot and the application were not only perceived as useful but were easily integrated into the daily routine of the participants. This result is particularly significant for the rehabilitation sector, where continuity and motivation are essential elements for the success of treatments.

Therefore, testing has shown that the NAO robot and the mobile application have not only favored an improvement in the psychophysical well-being of the participants but can also represent a valid support in therapeutic paths. The results obtained indicate that these technologies can promote stress management, increase adherence, and support the maintenance of healthy behaviors.

4. Conclusion

This short-term preliminary trial was successful in showing the promise of using a physical robot and a virtual avatar in a mobile application in order to promote adherence to DBE. The participants received the trial positively and adhered strictly to the regimen resulting in a decrease in their perceived stress levels. This simplified trial did not include the use of the TTM, which can only be implemented in a long-term study, in addition to implementing the system with patients who would greatly benefit from DBE but might be more reluctant to adhere to it due to physical discomforts. In our future work, we will conduct long-term studies making use of the personalization of the intervention using the TTM as described in the method section, in addition to comparing the effectiveness of this system with a system that only utilizes a robot or only a mobile avatar.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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