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Enhancing Patient Motivation through Intelligibility in Cardiac Tele-rehabilitation

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Physical exercise training and medication compliance are primary components of cardiac rehabilitation. When rehabilitating independently at home, patients often fail to comply with their prescribed medication and find it challenging to interpret exercise targets or be aware of the expected efforts. Our work aims to assist cardiac patients in understanding their condition better, promoting medication adherence and motivating them to achieve their exercise targets in a tele-rehabilitation setting. We introduce a patient-centric intelligible visualization approach to present prescribed medication and exercise targets to patients. We assessed efficacy of intelligible visualizations on patients' comprehension in two lab studies. We evaluated the impact on patient motivation and health outcomes in field studies. Patients were able to adhere to medication prescriptions, manage their physical exercises, monitor their progress and gained better self-awareness on how they achieved their rehabilitation targets. Patients confirmed that the intelligible visualizations motivated them to achieve their targets better. We observed an improvement in overall physical activity levels and health outcomes of patients.

RESEARCH HIGHLIGHTS

- Presents challenges currently faced in cardiac tele-rehabilitation.
- Demonstrates how intelligibility was applied to two core aspects of cardiac rehabilitation- promoting medication adherence and physical exercise training.
- Lab., field and clinical studies to demonstrate efficacy of intelligible visualization, impact on patient motivation and resultant health outcomes.
- Reflection on how similar HCI approaches could be leveraged for technology-supported management of critical health conditions such as cardiac diseases.

Keywords: mhealth; patient centered computing; self-management; patient motivation; secondary prevention; tele-rehabilitation; intelligibility; self-awareness

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1. INTRODUCTION

Cardiac rehabilitation programs have proven to be effective to minimize recurrence and risk of disease, leading to reductions in risk of premature deaths (by about 40%) and cost savings (Rauch et al., 2016). There are several studies that test the effectiveness and applicability of home-based rehabilitation (tele-rehabilitation) approaches for various medical applications as summarized by Mampuya (2012). Medication adherence and physical activity form core components of cardiac tele-rehabilitation. Conventional physical activity training programs in hospitals or specialized rehabilitation centers involve supervised exercise sessions that are guided and monitored by physiotherapists (Mampuya, 2012). Continuing with exercising independently at home is crucial in order to avoid relapses and is often difficult for patients. In tele-rehabilitation, remote monitoring of medication adherence and physical activity to evaluate progress towards rehabilitation targets is challenging as it relies on the willingness and motivation of patients (Frederix et al., 2013; Hansen et al., 2010). We target patients suffering from Coronary Artery Disease (CAD) who have to continue their rehabilitation in the absence of supervision. For these patients, the challenge starts with interpreting their overall rehabilitation targets. This could include understanding the influence and importance of certain medications, identifying the types of physical activities they should do, and tracking their progress over time. For rehabilitation exercises, targets are more complex to determine than for general fitness exercises: patients are expected to exercise at a specific level of intensity and at appropriate heart rate zones for a predetermined duration. Therefore, it is important to make physical exercise prescriptions simple and understandable for patients, and to ensure easy self-monitoring of progress. Besides, it is also important that the process is not cumbersome and helps in enhancing motivation of patients.

In our work, we applied principles of *intelligibility* to support patient self-awareness, comprehension and in enhancing motivation. The prevalent method to communicate physical exercise tasks and medication prescriptions is by medical professionals orally communicating it to the patient or writing these on a prescription paper during a consultation. Lack of a clear and standardized way to describe and structure this information makes it difficult for patients to interpret their targets correctly and hinders communication between medical staff and patients. Given the complexity of this domain and the importance of a correct approach for our target group, we involve different expertize domains (cardiologists, physiotherapists and computer scientists) to guide the research, design and development work presented in this paper. Additionally, we draw upon other systems in literature that focus on comprehensive approaches to rehabilitation and integration of persuasive design principles (Sankaran et al., 2016; Tavella et al., 2015). Specifically, we apply the persuasive design principles for cardiac tele-rehabilitation as delineated by Sankaran et al. (2016).

In this paper, we focus on optimizing the representation of medication prescription and physical activity training for patients, as they are two key components in cardiac rehabilitation. We describe how we integrated aspects of intelligibility, alongside persuasive principles, to make patients more self-aware of their targets and progress. We present the insights gathered from various lab. and field studies to validate the efficacy of these aspects. In initial lab. studies, we evaluated how the intelligible visualizations supported patients in becoming more self-aware in comprehending their rehabilitation targets. We further assessed the impact on enhancing patients' motivation to achieve their goals in 4-week field studies using HeartHab, a prototype mobile application. Finally, we evaluated the impact of their self-awareness and motivation in increasing physical activity levels, promoting medication adherence and health outcomes in an 8-week clinical study. Based on these outcomes, we can ascertain that using persuasive design and intelligible visualizations to make patients more self-aware can contribute in motivating them to achieve their rehabilitation targets. Additionally, we observe that the nudges triggered via the HeartHab application increases overall physical activities performed by patients and promotes better medication adherence, thereby creating a positive health behavior.

2. INTELLIGIBILITY IN THE CONTEXT OF CARDIAC REHABILITATION

It is often difficult for users to understand how many intelligent interactive systems work, especially context-aware and recommender systems. It feels like a 'black-box' where users do not understand *'why'* or *'how'* they receive certain information from a system. This reduces trust and credibility in intelligent interactive systems (Johnson and Johnson, 1993). Bellotti and Edwards (2001) argue that in the absence of the ability of a system to make meaningful inferences about human context, a set of design principles is required. These principles enable human beings to reason for themselves about the nature of their systems and environments. It also empowers them to decide how best to proceed. To this end, they suggest the design principles of intelligibility. An intelligible system allows users to understand the system and even learn about the inner working of the system. It has been shown that intelligible systems are easier to use and are more trusted by their users (Dourish, 1997; Lim and Dey, 2013). Furthermore, the comprehension and trust thus gained, gives users the confidence to take necessary action (Konstan and Riedl, 2012).

Traditionally, intelligibility has been a means to inform users better in context-aware systems. Context-aware systems are intrinsically complex as the system behavior observed by their users is typically a reaction to internal and external contextual parameters (such as environment, location or user proficiency levels). Therefore, the system behavior of context-aware systems is not always transparent to the user. Applying principles of intelligibility contributes to making systems more transparent. Similar problems can also arise in systems that present patients with information, prescriptions and recommendations pertaining to their health condition based on personalized, context-specific as well as generic variables. Therefore, it also becomes important to unravel the 'black-box' to inform patients better on what is being presented or prescribed in the system and also facilitate better comprehension. In our work, we use intelligibility to improve patient's autonomy and self-awareness of their condition. Applying intelligibility acts as a means to persuade them to better adherence and better target achievement. To do this, we draw upon some basic design principles and human-salient features to support intelligibility as defined by (Bellotti and Edwards, 2001):

(i) **Inform users** of current contextual capabilities and understandings.
(ii) Provide feedback, including
  - *Feedforward*: What will happen if I do this?
  - *In process feedback*: What is happening currently?
  - *Confirmation*: What have I performed?
(iii) **Enforce identity** and action disclosure.
(iv) **Provide control** to the user over system and other user actions.

The *enforce identity and action disclosure* principle is achieved in our context of cardiac rehabilitation since a medical team was involved in providing information and personalizing prescriptions and targets. All patients were informed and were aware of this, thus adding to the credibility and trust in the system.

3. MAKING MEDICATION PRESCRIPTIONS INTELLIGIBLE

Noncompliance to medication prescriptions has been a ubiquitous problem in healthcare. Promoting medication adherence has been a key focus in many eHealth applications and certainly forms an important aspect in cardiac rehabilitation as well (Haynes et al., 2002; Mampuya, 2012). Although clinicians assume and expect a strict compliance to medication prescriptions, it is not uncommon and even likely for patients to forget to follow these prescriptions over longer periods of time. Multiple studies have investigated various reasons for noncompliance to medication in cardiac rehabilitation (Ferdinand et al., 2017; Gandapur et al., 2016). Some of the main reasons include (a) forgetfulness, (b) lack of a proper routine and (c) side effects and *perceived* side effects of medication.

Most approaches in literature try to solve this problem by sending reminders (mostly in terms of SMSs). While such approaches can support repetition, they do not necessarily yield habit formation or behavior change in the long term. In HCI research, Kaptein and Van Halteren (2013) developed an adaptive persuasive messaging system in order to support habit formation by means of sending adaptive reminders via email. In their approach, they created specific persuasion profile groups of users and altered the reminders for each group. While the application of persuasive principles reveals promising insights, for our target population of cardiac patient, it is not feasible to create groups of patients given the variability in cardiac risk profiles. Stawarz et al. (2015) propose yet another approach by using contextual cues to send reminders and thereby gradually support habit formation.

In our work, we apply principles of intelligibility to make patients more self-aware of the reasons why they need to take certain medication, thereby enabling them to reflect on the importance of compliance.

We first present patients with an overview of medication to be taken in a day (Fig. 1a). Each quadrant in the overview represents different moments of the day (morning, noon, evening and night) showing a quick view of the number of medicines to be taken at each moment. The current moment is highlighted in blue. There is also a bar below that is dynamically updated to show the current compliance percentage. This corresponds to the *'provide feedback'* principle of intelligibility. Upon selecting a quadrant, patients are navigated to the prescription which lists the medicines to be taken at that moment (Fig. 1b). The medication prescription of each patient is entered by the caregivers using a caregiver dashboard application. Further, patients can expand each medication to get detailed information on the different moments they have to take the medication, a description about the medicine to help them understand why they need to take the medication and the possible side effects the medication could have (Fig. 1c). These descriptions relate to the '*inform user*' principle. Once the medication is taken, the patients can mark it by selecting the medication. The medication icon and check then turn green and the compliance bar is updated, thereby providing both *'in process feedback'* and *'confirmation'*. Additionally, patients also get a pop-up notification with an audio alert when it is time for them to take the medication (Fig. 1d).

While we applied intelligibility and the persuasive principles for the front-end visualization, we also adopted a method similar to the adaptive messaging approach of Kaptein and Van Halteren (2013), to adapt reminders in the back end. Figure 2 shows a flowchart depicting the process of adapting medication reminders to promote better adherence.

4. INTELLIGIBILITY IN EXERCISE PRESCRIPTION

It is essential for patients to understand and grasp relevant information from the exercise prescription. We target cardiac patients, who are mostly 50 years or older and may have a fear of exercising (kinesiophobia). Moreover, a majority of them are unaccustomed to unsupervised exercise training due to prolonged sedentary lifestyle and lack of proper guidance

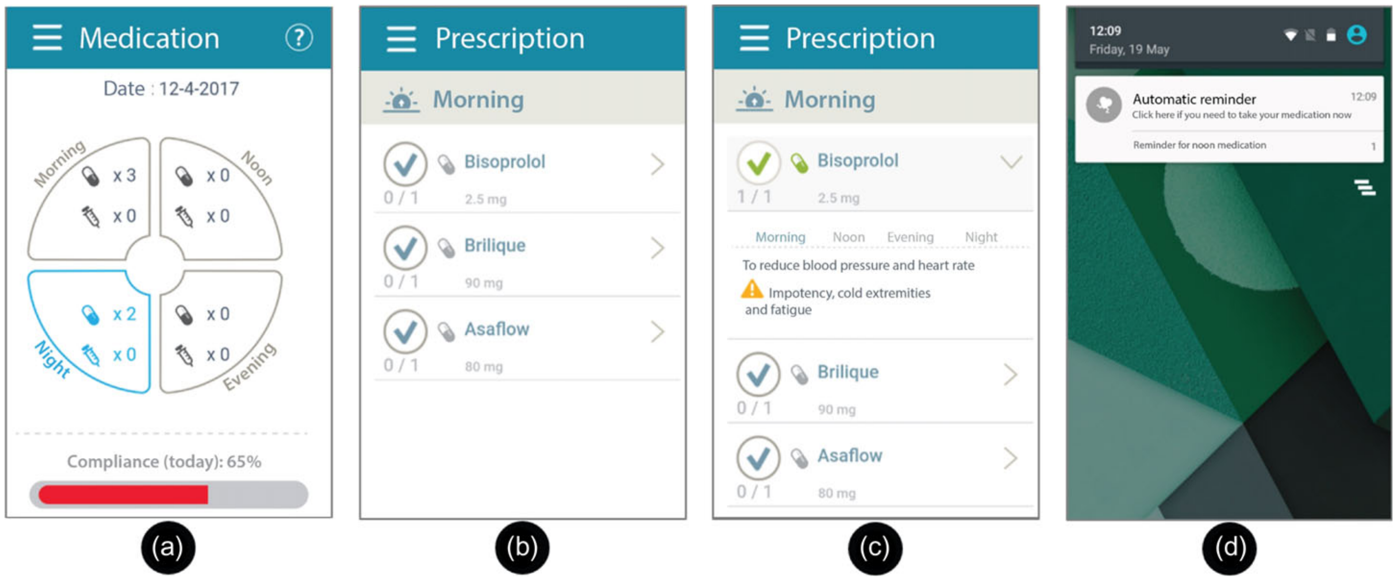

FIGURE 1. Screenshots of intelligible medication prescription showing—(a) overview of prescription representation and compliance bar, (b) details of medicines to be taken at a certain moment upon selecting a quadrant from the overview, (c) details of a specific medication including its side effects upon selecting the medication and (d) automated medication reminders triggered periodically.

after their hospital-based rehabilitation. Therefore, it is critical that their interpretation of the prescription and progress is precise. Supporting personalization of prescriptions and designing comprehensible information representation on a mobile device is essential for this target group of patients. O'Kane and Mentis (2012) emphasize on the important difference between information needs of clinicians and patients, where patients need an interpretation of what it means for their lives. We accomplish this using intelligibility. Through appropriate usage of this design principle, we can make patients more self-aware of their condition and progress, which can in turn persuade them to achieve and even surpass their rehabilitation targets.

We contribute to increasing patients' self-awareness on their progress by focusing on the following aspects of intelligibility:

(i) Visualizations that support correct interpretation and understanding of how progress is tracked.
(ii) Feedback on and prediction of progress.
(iii) Personalized visualizations based on patient profile.

4.1. Correct Interpretation and Understanding

Visualizing all components of an exercise prescription in a simple non-overwhelming manner for patients is not trivial. The user interface should make patients aware of what activities contribute to their rehabilitation targets, and how much they contribute in different settings (e.g. longer exercise sessions or increasing the intensity or frequency of exercise training). This implies that the interface visualization needs to train the patient to make reasonable estimates of their efforts and progress. We worked together with patients, cardiologists, and physiotherapists to iteratively design and improve our visualizations. When dealing with visual representation for a target group consisting of patients, it is essential to focus on information visualization rather than scientific visualization such as complex graphs or medical charts (Faisal et al., 2013). For example, in this study, we use an animated character running towards the target to visualize the progress patients make as shown in Fig. 3. This makes the idea behind the progress bar more perceptible than using just bar charts or graphs as is the case in most applications available for monitoring physical activity (Walters et al., 2010). To enable patients to make sense of personal health information, it is necessary to exploit the patient's perceptions to present targets and prescriptions (Lim et al., 2016).

Figure 3 shows a representation of the prescription in the mobile application interface. An exercise prescription for rehabilitation describes the type, intensity, frequency and duration of exercises. For example, the patient would be advised to indulge in moderately intense physical activities up to 5 days a week for 40–60 min per exercise session. To simplify it for patients, we combined these parameters into a unified metric, the Metabolic Equivalent of Tasks (METs represented as kilocalories) using guidelines of ACSM (American College of Sports Medicine) for exercise prescription and testing as detailed in subsequent sections (Swain, 2014). This metric is proven to be precise and suited for measuring physical exercise volume (Jetté et al., 1990). In our work, we express this metric as a target score for patients. Given that intensity, frequency and duration are represented as range (e.g. moderate–

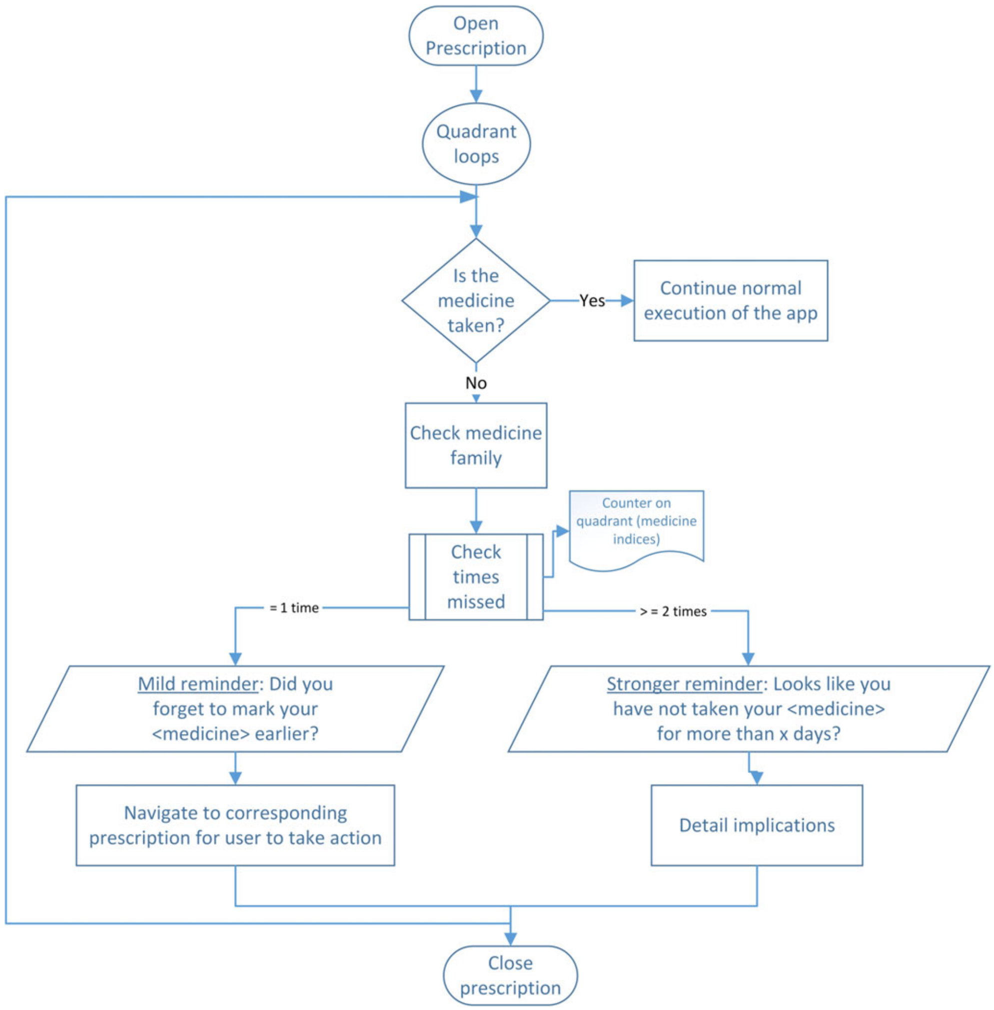

FIGURE 2. Flowchart representing the process of adapting medication reminders to promote better medication adherence.

high intensity for 40–60 min per session); the final targets are also presented to patients as a range (minimal and maximal targets). Patients are free to choose the type of physical activity they wish to do from an extensive list of activities, conforming to the *'provide control'* principle. This list is curated by medical experts, and contains activities that contribute to achieving their rehabilitation targets. Two flags are used to visualize the minimal and maximal target values.

The finish flag (maximal target) subtly nudges the patient to aim for the maximal achievement and not stop exercising after reaching the minimal target. This is validated by field tests presented in later sections. Frequency and duration of physical activities are visualized numerically. Apart from these elements, the number of exercise sessions completed by the patients and the ones yet to be done can also be easily consulted in the visualization of session progress and the completed frequency. Patients also get motivating textual feedback above the session progress visualization such as 'keep going' or 'good progress'. Despite the apparent simplicity of the prescription display, the two flags provide a better insight in the rehabilitation progress. Our representation is different from the goal setting and visualization in most fitness and physical activity applications (Stawarz et al., 2015): using a target range instead of a singular goal allows patients to self-manage their target achievement, instead of feeling pressurized to achieve one single goal. The results of our field studies confirm that some patients strived to reach the maximal target or go beyond it, while other patients stopped after reaching their minimal target.

4.2. Progress feedback and prediction

Quantifying exercise effort/capacity based on activities performed is challenging as it can largely vary between individuals. Methods used to collect this data can either be objective measurements obtained from monitoring devices (such as pedometers, accelerometers, metabolic carts, etc.) or subjective

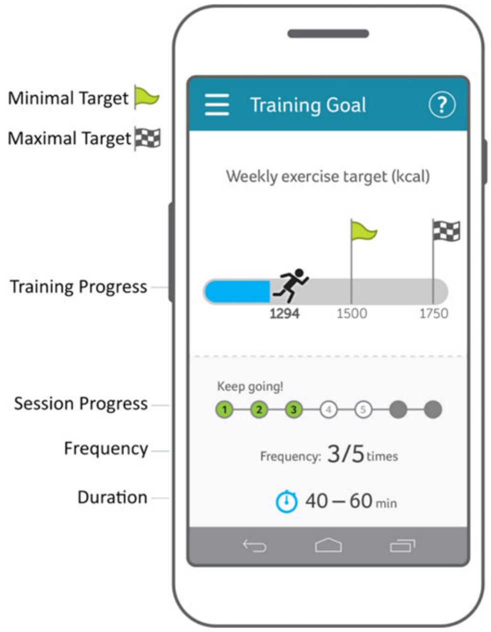

FIGURE 3. Intelligible visualization of exercise training prescription parameters, goals and progress.

FIGURE 4. Visualization of exercise progress prediction upon selecting a future session.

values that are self-reported by the user (such as diaries, questionnaires, surveys, etc.). We collected self-reported activity logs on the app and data using IPAQ (International Physical Activity Questionnaire) (Kurtze et al., 2008). We obtained objective measurements on exercise capacity using ergo-spirometry.

A vast literature survey of 293 articles on self-reported against measured values revealed the need for valid, accurate, and reliable measures of physical activity (Prince et al., 2008). A known major shortcoming of subjective approaches is their heavy reliance on an individual's recollection of events and knowledge of what is the definition of exercise training/physical activity. Therefore, depending on the context, such approaches may be prone to under- or over-reporting of physical activity volume/intensity (Celis-Morales et al., 2012). On the other hand, there is also evidence suggesting barriers of engaging with objective measurements such as activity monitors (e.g. discomfort, hardware issues or drop in usage over time) (Harrison et al., 2015). Therefore, it is essential to find a balance between both means of measurements and identify an approach that can work in both contexts.

We use a dynamic mapping that, based on the patient profile, calculates personalized METs scores achieved per exercise. The METs target evolves when the patient's exercise capacity improves. Studies suggest that no single technique can be used to gather exercise capacity and energy expenditure information and it is recommended to use multiple complementary methods (Altini et al., 2013; Schutz et al., 2001). This is critical in evaluating current and changing physical activity levels, physical activity interventions, and the relationships between physical activity and rehabilitation outcomes.

Feedback on progress gently nudges them to increase their efforts when appropriate, catering to the *'in process feedback'* principle. An important feature here is that patients can consult their future training efforts in advance: their predicted progress is shown when tapping on a 'yet-to-be-completed' exercise session (Fig. 4). Drawing upon the *'feedforward'* principle, when users tap on a future session number, the predicted progress is visualized as an overlay on top of the existing progress. The cumulative effort of the completed exercise sessions is used to compute the predicted progress, as we currently do not ask patients to plan a specific exercise type. Since the prediction is essentially an estimate based on the previous effort and not a precise value, the prediction visualization is shown as a bar that fades out towards the end. The extent of fade out gradient is based on the number of exercise sessions completed. For example, if the patients have done only one session out of 5, the extent of fade out is greater since the subsequent activities they will be performing can have a large variation in energy expenditure. Our system uses the completed exercise sessions to calculate the current exercise capacity of the patient.

4.3. Dynamic personalized visualizations

The visualizations are generated dynamically based on the personalized targets computed for every individual patient. The targets and parameters are configurable by physiotherapists through a remote dashboard application that integrates the validated EXPERT tool (Hansen et al., 2017). Patients are informed about the involvement of physiotherapists for their goal setting and with respect to progress monitoring. The position of the flags, the values and the session progress visualizations are adapted accordingly. In addition, if patients' targets are modified during the course of rehabilitation based on their progress, the visualizations are updated accordingly. This ensures that the visualization presents the most recent state of the rehabilitation process, based on the physiotherapists' input as well as the progress they make during the rehabilitation program. Unlike fixed goals or user-defined goals in other fitness and behavior change apps (Stawarz et al., 2015), this method of gradually increasing targets based on the evolution of patients' condition over time helps in sustaining motivation and gradually nudging them to achieve their targets. This approach motivates patients that are unwilling to make a greater behavior change by giving them achievable minimal targets to trigger them to be more physically active and sustain their motivation. Patients being aware of the involvement of physiotherapists in the process of tailoring targets further adds to the trust and credibility of the approach, thereby ascertaining the intelligibility principle of *'enforce identity and action disclosure'*.

5. TAILORING EXERCISE TARGETS AND MONITORING PROGRESS

For the overall rehabilitation program to be successful, it is essential that patients have the ability and willingness to accommodate these prescribed exercise regimes in their everyday lives (Gjoreski et al., 2013). This implies that they need to feel motivated, in control and are accorded a sufficient degree of freedom in choosing what physical activities to perform, when and at what intensity. Campbell et al. (2001) reported that such exercise regimes can appear counterproductive to patients because of perceived ineffectiveness or discomfort they may experience. Patients often struggle to understand the progress they make through their rehabilitation program, because of a lack of feedback on their progress. A rehabilitation program, if done right and in absence of unexpected health incidents, gradually improves a patients' exercise capacity and overall health condition. Yet, observing improvements in their condition over time is difficult for patients (Harrison et al., 2015)—especially when the goal setting is not adapted according to these improvements. We break down the overall goal into weekly targets (micro goals), as this is a custom practice by physiotherapists in conventional hospital-based rehabilitation. These weekly targets are gradually adapted based on patients' progress over time and allow patients to see their overall progress. In this section, we describe in detail the process adapted by physiotherapists to tailor exercise prescriptions and monitor progress of the patients. The physiotherapists do this using a remote caregiver dashboard interface that dynamically communicates with the patients' mobile application.

5.1. Tailoring exercise targets

The key underlying principle behind calculating the tailored micro goals for patients is the 'Frequency, Intensity, Time and Type' (FITT) principle (Thompson, 2013). In our approach, the process of prescribing exercise training is divided into three steps:

Step 1: Assess the current health and fitness condition of patients. To get this information, an ergo-spirometry test (a monitored biking effort in a clinical setting) is done at the hospital. This non-invasive and objective method can generate an accurate assessment of cardiopulmonary functions and metabolism of an individual. The result of this test helps us establish preliminary estimates of maximal thresholds of exercise capacity for every patient.
Step 2: Determine individual risk factors and exercise capacity. Based on the threshold values obtained in the previous step, a physiotherapist determines the individual risk factors and the exercise capacity of every patient.
Step 3: Formulate the exercise training prescription. Based on the determined exercise capacity, the physiotherapist establishes the frequency, intensity and time of training using the EXPERT tool (Hansen et al., 2017). This tool enables the physiotherapists to further tailor the FITT-based prescription as per individual patient pathologies and risk factors. Using the mobile application, patients are free to choose the type of activity they wish to perform and that fit the prescribed intensity levels. An activity-specific MET value that corresponds to the prescribed exercise intensity is used together with activity duration and patient parameters to compute the targets represented by the flags (Vanhees et al., 2012). These computed targets are configured individually for every patient in the application.

5.2. Monitoring progress

The individually prescribed targets, presented as weekly training scores, essentially refer to workloads determined by the amount of energy expenditure that needs to be achieved in a week. Our approach to determine the progress is divided into four key steps:

Step 1: Identify METs based on activity performed. We do this using the filtered METs table (Table 1) derived from the Compendium of Physical Activities (Ainsworth et al., 1993).
Step 2: Factor for an individual's body mass and resting metabolism (also known as 'idle burn', the amount of energy expended when a person is sedentary or at rest). We use Equation 1 to calculate energy expenditure (in kcal per minute) derived from the widely used American College of Sports Medicine's guidelines for exercise testing and prescription (Swain, 2014).

TABLE 1. Selected list of activities and corresponding MET values of each activity.

Activities	METs	Activities	METs
Bicycling	8	Jogging	7
Dancing Duo	4.5	Badminton	4.5
Dancing Individual	8.5	Basket	6
Modern	4.8	Bowling	5
Walking Animals	5	Football	9
Mowing lawn	4.5	Handball	8
Caring animals	6	Horeseback Riding	4
Golf	4.5	Fighting sports	10
Tennis Double	6	Skating	7
Single	8	Table tennis	4
Water aerobics	4	Volleyball	4
Water jogging	8	Hiking	6
Rowing	7	Using stairs	8
Circuit training	8	Swimming Fast	10
Splitting logs	6	Swimming Slow	7
Weight bearing	6	Planting	4.5
Pushup/sit-ups	8	Playing musical instruments	4
Skiing	7	Farming	4.5
Fishing	5	Truck driving	6.5
Hunting	5	Walking 4.5/km/u	4
Clearing/spading land	5	Walking 5 km/u	4.5
Multiple household task	5	Gardening	5
Splitting logs	6		

Step 3: The energy expenditure is converted into gross and net expenditure by multiplying the duration and frequency of selected activities (Equation (2)).

Step 4: As a final step, the net energy expenditure that is acquired from different activities is cumulated to arrive at the total expenditure (Equation (2)). This total energy expenditure is expressed as a single score to quantify the progress made by the patient.

$$(\text{METs} \times 3.5 \times \text{body mass in kg})/200 = \text{Energy Expenditure in kcal} \times \text{min}^{-1} \quad (1)$$

where $3.5\,\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ is the standard factor for resting energy expenditure. (1)

$$\text{Total EE} = \sum_{\text{no.ofactivities}=1}^{n} \upsilon(\text{Gross EE}_{\text{activity}})$$
$$\text{Gross EE}_{\text{activity}} = \tau\left[\frac{\text{METs} \times 3.5 \times \text{bodymass}}{200}\right] \quad (2)$$

where τ is the duration of an activity in min; υ is the frequency of each activity in times; EE is the energy expenditure in kcal/min.; 3.5 is resting oxygen consumption = 1 kcal/kg·h; body mass is in kg

The total energy expenditure score that results from Step 4 is used in the progress visualization in both the caregivers' dashboard interface and the patients' application interface. Presenting the score as a number (in kcals) in the user interface ensures that users also get to see fine-grained feedback on their progress. A caloric representation enables patients to not just relate their goals to physical activity but also to diet instructions they receive during rehabilitation. It also helps them to gain insight on the contribution of specific activities (including their intensity and duration) toward their goals. Furthermore, since the target scores shown underneath the two flags can also change over time, users are also informed about the evolution of their exercise capacity, i.e. a better exercise capacity implies a higher maximal target. The caregivers or therapists can follow up the progress of a patient remotely using the remote caregiver dashboard interface, shown in Fig. 5. They can further check individual activities performed by the patient by clicking on each week's progress in comparison to what was recommended. All these elements facilitate physiotherapists to more precisely tailor targets and adapt them better based on individual patients' exercise patterns.

6. EVALUATING INTELLIGIBILITY

To gain insights on patients' understanding of rehabilitation progress, the impact of their understanding and self-

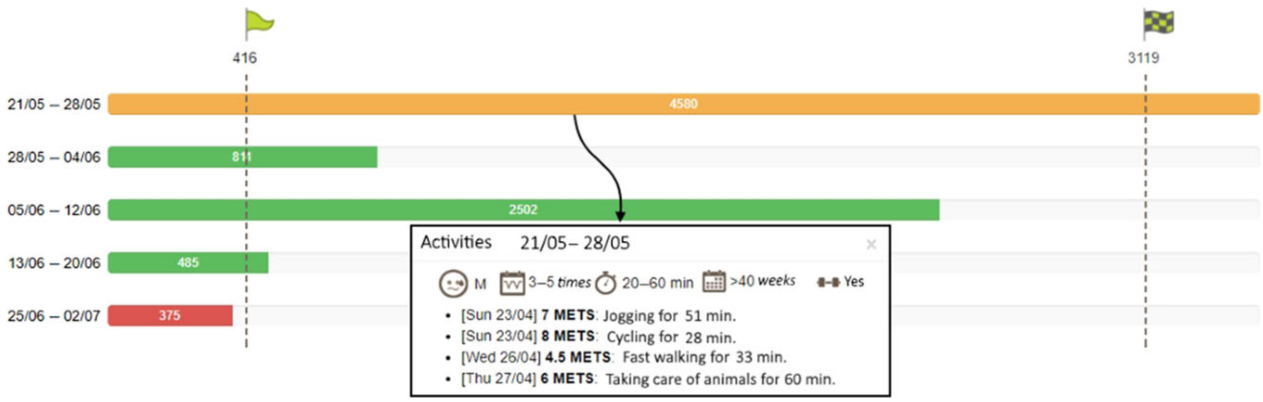

FIGURE 5. Screenshot of the caregiver's dashboard interface showing the weekly progress of a patient with respect to prescribed targets.

awareness in enhancing motivation, its influence on their activity levels and medication compliance, we conducted various lab., field and clinical studies (presented in Table 2). The key patient demographics of participants in the different studies is presented in Table 3. Two ethical committees (one of the hospital and one of the university) approved these studies. Patients signed an informed consent during start-up and could quit the study at any stage. All patient data procured, used and analyzed during the various studies were handled anonymously and confidentially. All data were stored at a dedicated encrypted server at our research department and only the primary investigators had access to this data.

6.1. Lab. studies

6.1.1. Process

These studies were scenario-driven with an aim to (a) gather immediate insights regarding patients' understanding on how they perceive intelligible visualizations in different task scenarios, and (b) observe their subsequent interpretations and understanding as the scenarios evolved. Gaining detailed knowledge on their understanding of different scenarios would have been difficult in the field. Participants were presented with realistic scenarios based on situations they may encounter during their rehabilitation process. For the study with the medication module, the scenarios included tasks on interpreting various elements of their medication prescription, logging medication intake across different moments of the day and observing the influence it had on their overall compliance percentage. For the study on the exercise module, tasks included interpreting exercise training parameters, logging activities on the app with different frequencies, duration and intensity levels, and investigating a future situation using progress prediction based on performed activities. Participants were encouraged to think aloud while performing different tasks. A camera was positioned to record their interaction with the application while recording the audio and video. As the participant went through the tasks, the observer took notes. Each test session was concluded by a semi-structured interview to gain insights into their overall understanding, usefulness and perception of the intelligible visualization.

6.1.2. Findings

In the medication study, participants were asked to rate the usefulness, understandability, ease of use and attractiveness on a 5-point Likert scale (from strongly disagree to strongly agree). These criteria for rating were created based on the key investigation areas of the study. Five out of six participants were positive and found the intelligible visualizations attractive, understandable and easy to use (Fig. 6). There was only one participant that was negative but this participant reasoned that he/she was not comfortable with using smart phones in general and prefers the conventional approach of managing medication with a physical pill box.

In the exercise study, since there were multiple components in a single visualization, participants were asked to give a score on 10 for each of these aspects—their interpretation of the represented parameters, perceived usefulness and the presentation of the prescription. Presentation of parameters and usefulness of these visualizations received an average score of 7 and the interpretation of prescription got an average score of 8 (Fig. 7).

While for some participants everything was clear right away, others acknowledged that they struggled to interpret the difference between two flags (minimal and maximal target) in the beginning but it got clearer as they progressed through different scenarios. Participants were able to interpret the impact on progress of variations in activities, duration and intensities.

> *'Yes, this way you have an overview. This way you see that you have to be active. You see that you need to have a good workout. Otherwise you would always write it down (referring to different prescription elements) which will give you a lesser overview with respect to your goals.' [PLE2]*

These findings imply that our intelligible visualizations can facilitate in increasing self-awareness of patients and

TABLE 2. Overview of setup, evaluations and data collected during different studies.

Lab. studies		Field studies		Clinical study
Medication	Exercise training	Medication	Exercise training	Both medication and exercise training
6 CAD patients (PLM1-PLM6)	8 CAD patients (PLE1-PLE8)	7 CAD patients (PFM1- PFM7)	5 CAD patients (PFE1-PFE5)	32 CAD patients (PC1-PC32)
Undergoing rehabilitation at the hospital + independently rehabilitating at home		Undergoing rehabilitation at the hospital + independently rehabilitating at home		Finished rehabilitation at the hospital + independently rehabilitating at home
Study duration: ~1 hour Evaluated aspects: – Understandability of visualizations – Usefulness in tele-rehabilitation – Presentation of targets		Study duration: 4 weeks Evaluated aspects: – Understandability of visualizations – Usefulness in tele-rehabilitation – Presentation of targets – Impact on motivation		Study duration: 8–10 weeks Evaluated aspects: – Impact of various elements on motivation – Change in physical activity levels and medication compliance – Other health outcomes
Data collection: – Startup: Elicitation questionnaire – During study: Task scenarios – End: Semi-structured interview		Data collection: – Startup: Elicitation questionnaire – During study: Usage and activity logs, diary – End: Semi-structured interview		Data collection: – Startup: Elicitation questionnaire, IPAQ, physiological parameters – During study: Usage and activity logs; followed up via caregiver dashboard application – End: Semi-structured interview, IPAQ, physiological measurements

TABLE 3. Consolidated demographics of patient participants in the different studies.

	Lab. studies		Field studies		Clinical study
Demographics	Medication	Exercise training	Medication	Exercise training	Both medication and exercise training
Number (N)	6	8	7	5	32
Age	59.1 ± 6.4	62.3 ± 6.8	66.6 ± 5.9	63.9 ± 5.3	60.9 ± 8.2
Gender	5M 1F	7M 1F	7M 0F	5M 0F	27M 5F

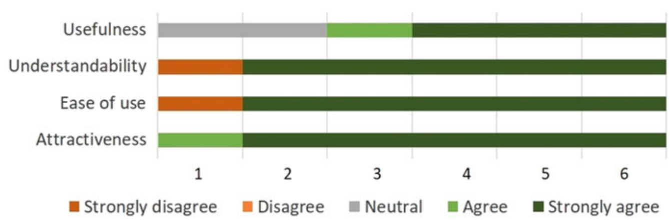

FIGURE 6. Outcomes of the lab. study on usefulness, understandability, ease of use and attractiveness of the intelligible medication prescription.

correspond to the *'inform user'* principle. Participants also found it useful to track their progress and adherence in this manner.

6.2. Field studies

After we iterated on the feedback collected from the lab. studies, we conducted two field tests to assess how patients' perception of their condition evolved, and to evaluate the efficacy of the intelligible visualizations on increasing self-awareness and sustaining motivation over a longer period. In the field tests, alongside the medication and exercise training modules, participants used different modules of the mobile application corresponding to other rehabilitation components such as risk factor management. In addition to evaluating patients' motivation over the span of 4 weeks when interacting with these visualizations, this allowed us to evaluate whether our intelligible visualization also functions in a broader self-management application context with a more holistic rehabilitation approach.

6.2.1. *Process*

In both field studies, participants used the mobile application to record activities performed at the rehabilitation center, activities performed independently at home, their medication intake, and other physiological parameters such as weight and blood pressure (if they had the appropriate measuring devices). Participants also received a paper-based diary to

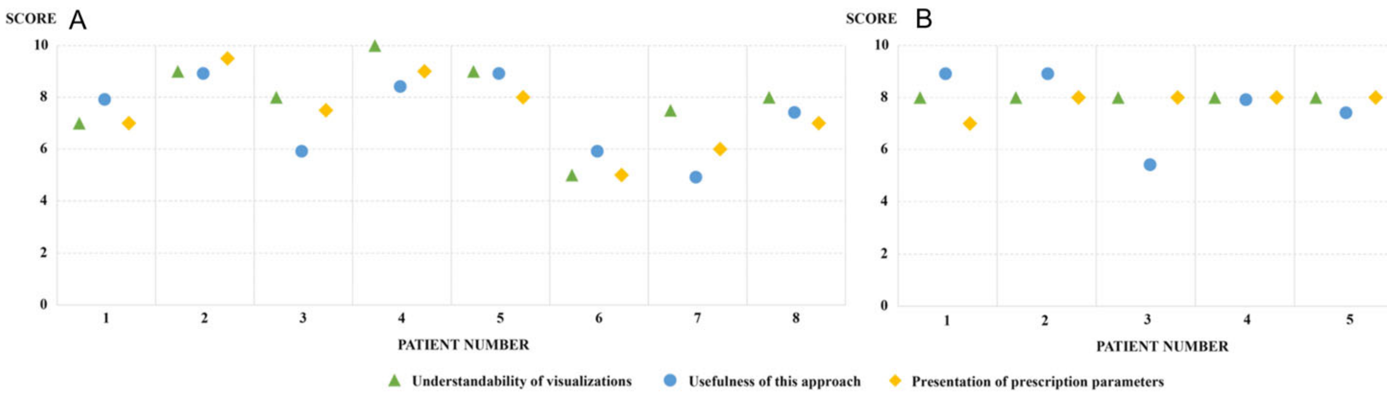

FIGURE 7. Results from initial (a) lab. and (b) field studies on understandability, perceived usefulness and presentation of exercise prescription.

record their feedback each week using a 5-point Likert scale (from strongly disagree to strongly agree). For the medication study, they had to log the influence of the compliance bar on their adherence each week. For the exercise study, the participants rated the visualizations on two criteria: (1) to verify how viewing progress with respect to the goal motivated them to exercise more and (2) checking if the estimated prediction was helpful to assess whether their efforts were sufficient to reach their goals. Similar to the lab studies, the assessment criteria were created based on the main objective of the field studies. At the end of the study duration, they were invited for a semi-structured interview to gather insights on the influence of using this application on motivation, their overall understanding of their targets and progress, the usefulness of using such visualizations, and other general perceptions about the application.

6.2.2. Findings

In both studies for exercise and medication, the results in terms of understandability, usefulness and overall perception were comparable to the earlier lab. studies on assessing intelligibility. In the medication study, four out of six participants found the intelligible prescription quite useful. However, they remarked that it did not necessarily influence adherence since they were already compliant. This was reflective of the selected group of participants. In the pre-study questionnaire, six out of seven participants mentioned that they never forget their medication and were fully compliant. All eight participants mentioned using the conventional pill box and were comfortable using that approach. Nonetheless, all of them agreed that it was reassuring to see the intelligible visualizations and found them useful. This ascertained the *'confirmation'* principle. In the paper-based diary, four participants either 'agreed' or 'strongly agreed' (across all four weeks of the study) that seeing their adherence on the compliance bar was useful. Two participants were 'neutral' and one participant 'disagreed' stating that the bar had no influence on his adherence. Participants were also positive about other intelligible aspects of the medication prescription that increased their self-awareness confirming the *'inform users'* principle.

> *'Knowing the side effects was really useful. It helped me link it to my health issues'. [PFM3]*

> *'.it (the visualization in general) was very easy to understand. This (pointing to medication descriptions in the screen) gave me more info about what I'm taking which is very useful.' [PFM7]*

In the exercise study, the average score for usefulness and presentation of prescription parameters increased from 7 to 8, suggesting that participants find it useful after having used it in a real-life context (Fig. 7). In terms of motivation, all participants perceived this approach of viewing their weekly targets, and the progress they make against it, as motivating. All participants found the visualization of a man running towards the goal as motivating and felt the 'nudge' to keep progressing towards the flags (target). At least three participants also said that the session progress visualization and the textual feedback additionally contributed to their motivation as they felt a sense of achievement each time they completed a session. These correlate to the *'in process feedback'* principle. We also probed participants if the application triggered them to do more activities than their usual routine, to gain an initial understanding on how it might facilitate habit formation or long term behavior change. Two participants increased their activities to try to achieve their goal.

> *'I saw that I did not make much progress even after completing all my 5 sessions (his target frequency). So I tried to do more to get as close to the flag as possible'. [PFE3]*

One participant forgot to record his feedback using the paper-based diary. All other participants either 'agreed' or 'strongly agreed' (across all 4 weeks of the study) that viewing their progress motivated them to exercise more and the prediction (reflective of the *'feedforward'* principle) was helpful to estimate if their efforts were sufficient. These findings reaffirm the efficacy of our intelligible visualization on promoting self-awareness in patients, thereby, persuading them in achieving rehabilitation targets.

6.3. Clinical evaluation

Integrated in an overall clinical evaluation of the mobile application, we assessed patients' physical activity levels and medication adherence along with overall medical improvements. In this paper, we focus on reporting on aspects related to our medication and physical activity representations, such as physical activity levels, patients' motivation to achieve activity targets and influence of intelligible visualizations on promoting better medication adherence.

In this way, we further ascertain the positive outcomes of the lab. studies on intelligibility and the field studies on the impact on motivation in the clinical evaluation. Of the 32 participants that were recruited, four participants had to quit the study after developing another health problem, three others did not use the app and one participants did not use the 'physical activity' module of the app. Therefore, the results presented are of the remaining 24 participants who used the app including its exercise target module and completed the study.

6.3.1. Process

This clinical study was conducted as a crossover randomized control trial where all participants were randomized into two groups on a 1:1 ratio. The total study was for a period of 4 months with a crossover point at 2 months (± two weeks). Participants randomized into group 1 used the app for the first 2 months and then received usual care for the subsequent two months. Participants in group 2 received usual care first and used the app in the second phase. In this manner, each participant used the app for a period of 8–10 weeks (Fig. 8) and we were able to compare the progress and experience of all patients when using the app or in its absence. For the participants in group 1, we also gathered insights if the behavior fostered by the app in the first phase was carried over to the second phase even in the absence of an active intervention using the app.

We measured participants' physiological measurements such as weight and blood pressure at start-up. We collected baseline data on medication adherence and their current approach to managing medications using a pre-test questionnaire. Their exercise capacity (VO2max) was measured using a standardized ergo-spirometry test. We also collected information on their physical activity behavior over the week before start-up using the International Physical Activity Questionnaire (IPAQ). We collected usage and activity logs via the app. At the end of the first 4 weeks, we sent them an online intermediate questionnaire to assess the influence of intelligible features on their motivation to achieve their goals. We followed up on these questions at the end of the study in individual semi-structured interviews with each participant. The responses of the interviews were translated, transcribed and analyzed using a computer assisted qualitative data analysis software (NVIVO) (Richards, 1999; Welsh, 2002).

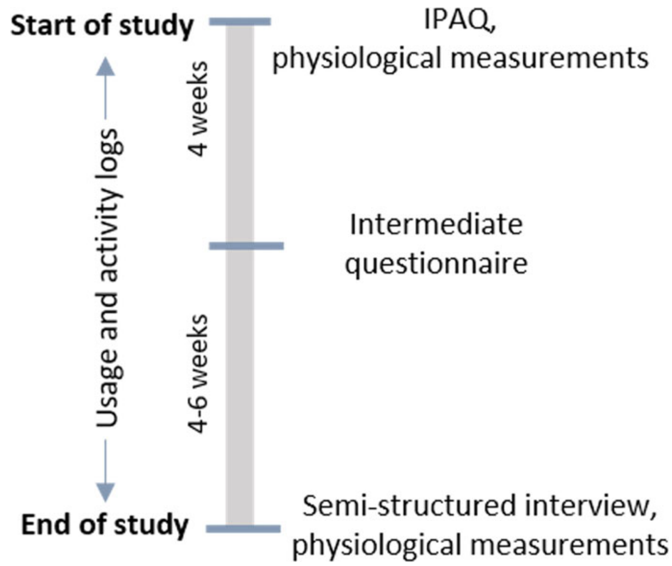

FIGURE 8. Timeline of the clinical study (during app usage phase) to evaluate the impact on medication adherence, physical activity levels and health outcomes.

6.3.2. Findings

With respect to the intelligible medication prescription, we received mixed responses on how it supported in better medication adherence. Similar to what was observed in the lab. and field studies, only 25% of participants mentioned that they forget to take their medications occasionally. 83% of participants used a standard pillbox to manage their medication and were comfortable with their approach. Yet, we received some positive feedback when asked about the impact of intelligible visualizations in supporting them to be more medically compliant (Fig. 9).

Participants found the reminders helpful even though they were already quite compliant and some others also felt that it helped them spread the medication better throughout the day.

> *'The progress bar made me remember if I forgot to take a certain medication- 'Oh! I only still have 66%'. I was adherent already; but reminders helped to not miss a single time.' [P11.7]*

> *'It motivated me more, because it pushed and nudged me at the right moment to take my medication.' [P11.20]*

One participant also explicitly remarked that he found the descriptions and side effects very useful.

> *'It was very good to know. I had some cold shivers at moments but I did not log it in my symptoms because I learnt that it is a side effect of Bisoprolol (a medication that the patient was prescribed)' [P11.24]*

On the other hand as previously observed, patients that already followed a certain system and were compliant did not find the reminders useful. They agreed that it was useful to have an overview as visualized in the app but the reminders or the compliance bar were not specifically helpful for them.

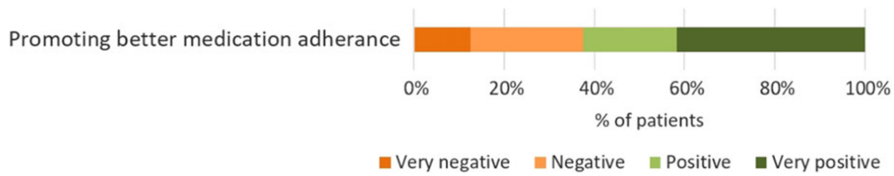

FIGURE 9. Outcome of sentiment analysis using NVIVO on patient perceptions of the impact of intelligible medication prescription on promoting better medication adherence.

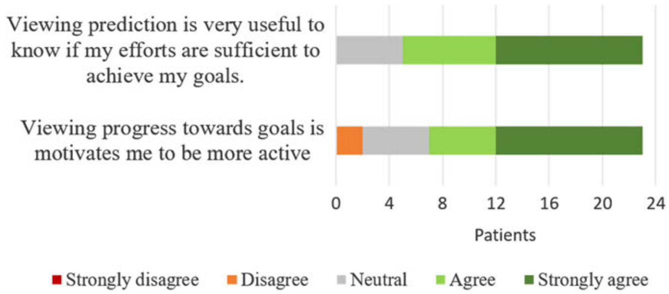

FIGURE 10. Outcomes from intermediate questionnaire at the end of 4 weeks of usage of the application (one participant forgot to fill the questionnaire; hence his data is missing).

> *'It is already a habit… no extra motivation by (sic.) the compliance bar. But yes, it helped to spread it [referring to medication intake] across the day. Before, I took it all during dinner to avoid forgetting.' [P11.26]*

Therefore, for the medication module, the principles of *'inform users'*, *'in process feedback'* and *'confirmation'* seemed to be the most applicable aspects of intelligibility.

For the exercise training module, understandability and the influence of progress and prediction in motivating patients to achieve their goals, the results were similar to the results of the field study (Fig. 10). All participants were positive about the influence of various app elements (visualization of goals, their progress and prediction) on their motivation to achieve prescribed goals (Fig. 11).

> *'I really liked the fact that I could explore the effect of different activities on the goals! So I chose my activity sometimes based on the effect it would have on my progress towards the goals'. [PC10]*

The participants who reported that there was no extra motivation through using the app, attributed this to the fact that they already led an active lifestyle and only used the app to merely log their daily activities and not strive to increase their effort. These participants acknowledged that it was reassuring to see their goals and progress and they feel more confident in logging it in the application since they know their therapists are following them up.

> *'.liked the motivational messages the app would give after entering a new activity. 'keep going', 'doing well'. I was already active, so did not do more. But was nice to see progress'. [PC12]*

Therefore, for the exercise training module, all the principles of intelligibility (listed in Section 2) seemed relevant and applicable.

We translated the data collected during start-up from the IPAQ questionnaire into METs scores based on IPAQ's scoring protocol (IPAQ, 2005). We compared these to the mean METs score achieved by patients during the study. For 52% of patients, there was an increase in mean METs as compared to baseline values. For the remaining patients, the baseline could not be considered owing to over-reporting or incomplete data. With respect to achieving the targets visualized in the app, 44% of the patients were mostly within the target range (between the minimal and maximal prescribed targets) and 52% of patients mostly exceeded the maximal target. Only 4% of patients on average fell short of achieving the minimal target.

In terms of health outcomes, we observed a minor increase in average VO2max (1.4%) indicating increase in average exercise capacity of patients. We also observed an average reduction in weight (0.6%) and blood pressure (0.2% in systolic and 2.3% in diastolic blood pressure) indicating the positive influence of increased physical activity levels on other physiological parameters. Overall, we could see positive trends in target achievement rates and impact on other health outcomes.

7. DISCUSSION

7.1. Reflection on outcomes

In both the field and clinical tests, patients who were already leading an active lifestyle, met their physical activity targets or were medically compliant, mentioned that they did not really change their habits and continued as they do in their daily lives. The app or the intelligible visualizations did not persuade them to increase their physical activity levels further. However, even these patients found that the intelligible visualizations were reassuring. For example, being able to see their activities contribute towards prescribed rehabilitation goals and seeing the medication compliance bar in the manner presented reassured them and gave them the confidence to sustain their current behavior. This is also essential from a tele-rehabilitation perspective since studies report a decrease in progress of patients during tele-rehabilitation owing to lack of interest in the system and gradual decline in motivation over time (Savage et al., 2011).

As with most persuasion approaches, there is a great dependence on an individual's willingness and attitude to

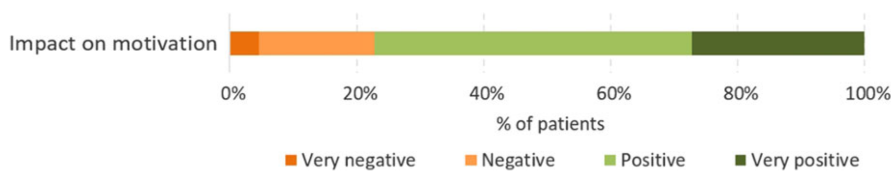

FIGURE 11. Outcome of sentiment analysis using NVIVO on patient perceptions of the impact of intelligible exercise prescription on increasing physical activity levels and target achievement.

change behavior. We could also observe that in our studies where some patients were not willing to change behavior even though they were fully aware of their health consequences. In that perspective, being remotely monitored by therapists 'compelled' a few patients to perform some activities just to be able to log it in the app.

> *'I did not pay much attention to it (referring to the part of being monitored), but I knew it was checked. So I took some effort to follow (referring to prescriptions) more strictly'. [PC13]*

Therefore, it could be postulated that patients who seek constant reassurance or are incapable of complying with prescriptions in unsupervised settings might benefit the most from this type of intervention.

We gathered that the majority of the patients either achieved their weekly targets or exceeded the maximal target. All patients were also fully compliant to their medication and did not forget their medication intake at any point of time during the field and clinical studies. This certainly suggests a positive influence of the intelligible prescriptions on their overall rehabilitation process.

We also observed that some patients were not interested in active sports but instead chose to perform other activities such as dancing to achieve their goals. Therefore, giving users the option to choose various activities (as long as they meet the intensity and duration constraints of the prescription) that can contribute to their targets also proved to facilitate in motivating them to reach their goals. For example, PC10 remarked:

> *'I don't like to sport and the app does not motivate me to do more sports. But I do move more in general because I want fill it in, and I am more consciously reflecting that I am moving. For instance, I would walk to the supermarket or ride my bicycle (instead of the car).Watching the man run to the flag (referring to the progress visualization) is super fun!'*

Two patients were not comfortable with using technology in general and had no experience in using a smartphone. They remarked that while it was interesting to see their progress and log their activities, they would not continue using it over a long term since they find it quite challenging to cope and work with modern technology, which is often a common issue in our target population of patients. However, we can overcome this problem by automating most tasks, requiring minimal user input from patients.

In terms of health outcomes, there was a promising indication that it may be possible to achieve a gradual improvement in overall health. However, a longer study with a larger group of participants is required to ascertain that claim which is beyond the scope of our study. These insights establish that applying intelligibility alongside persuasive design can help in increasing patient self-awareness, enhancing and sustaining motivation and achieving rehabilitation targets; thereby, reducing dropout rates in tele-rehabilitation programs.

7.2. Applicability of intelligibility in mHealth

In HCI research, intelligibility has been applied mostly in context-aware or recommender systems and only limited in other areas. However, representing human and social aspects of context can be challenging (Bellotti and Edwards, 2001). We reason that there are human aspects of context that cannot be sensed or even inferred by technological means. Specifically, given the variability in patient conditions, capabilities, risk factors and motivations, it is difficult to design systems for chronic health conditions such as cardiac disease, to act on behalf of humans (i.e. such systems cannot replace clinicians and caregivers). Rather, we chose to turn to our patients in an efficient and unobtrusive fashion. Therefore, by applying principles of intelligibility, we can enable patients to reflect on their own interpretations or misinterpretations, and have an impact on both rational and emotional drivers of their behavior.

Furthermore, it is important to make patients better aware of their own progress, goals and conditions. To this end, it is critical to go beyond data collection and translate it into motivational feedback to support users in attaining their individual health goals (Katz et al., 2016). Studies are now laying increasing importance on trying to not erode the self-determination of users since people have diverse priorities in life such as family, career, or lifestyle that sometimes take precedence over what clinicians might consider 'ideal' disease management. Rogers and Marsden (2013) suggested that HCI research should move away from third person thinking and instead embrace the design of flexible tools for self-empowerment and re-appropriation. They argue that such promotion of user autonomy becomes important when algorithms and fully autonomous systems have the potential to dispense medication, treatment plans and offer advice based on standards and not necessarily desired by the user. As described in this paper, we give patients flexibility and control over how they choose to reach their goals and manage their compliance. Furthermore, by supporting better comprehension of their condition, progress or compliance, we aim to increase their self-awareness without impacting their self-determination.

8. CONCLUSION

We presented how principles of intelligibility were applied to visualize medication prescription, physical activity targets and progress in remote cardiac rehabilitation. Intelligible visualizations ensured that users understand and trust the user interface, and become more aware of their own performance. We described how principles of intelligibility could be interpreted in the context of cardiac rehabilitation to increase self-awareness of patients. We achieved this by providing: (1) correct interpretation and understanding, (2) progress feedback and prediction and (3) dynamic patient-centric visualizations. Intelligible visualizations support patients to have a correct perception and understanding of their prescriptions as assessed in our lab. studies. It also enables patients to learn to make good estimates of their rehabilitation progress in different scenarios. Being more self-aware of their progress and condition facilitates in reassuring patients and keeping them motivated to achieve their rehabilitation targets as evaluated in our field studies. Finally, increasing self-awareness using intelligible visualizations helps in increasing overall health outcomes as indicated by the clinical evaluation.

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