Designing a Personal Decision Support System for Congestive Heart Failure Management

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ABSTRACT
In this paper, we describe the design of the HeartMan Decision Support System (DSS). The DSS is aimed at helping patients suffering from congestive heart failure to better manage their disease. The support includes regular measurements of patients' physical and psychological state using a wristband and mobile device, and providing advice about physical exercise, nutrition, medication therapy, and environment management. In the paper, an overall architecture of the DSS is presented, followed by a more detailed description of the module for physical exercise management.

Categories and Subject Descriptors
H.4.2 [Types of Systems]: Decision support.
J.3 [Life and Medical Sciences]: Medical information systems.

General Terms
Algorithms, Management, Measurement, Design, Human Factors

Keywords
Decision Support System, Personal Health System, Congestive Heart Failure, Physical Exercise, Decision Models

1. INTRODUCTION
Congestive heart failure (CHF) occurs when the heart is unable to pump sufficiently to maintain blood flow to meet the body's needs [1]. Symptoms include shortness of breath, excessive tiredness, and leg swelling. CHF is a common, chronic, costly, and potentially fatal condition [2]. In 2015 it affected about 40 million people globally. In developed countries, around 2% of adults have heart failure, increasing to 6–10% in age over 65.

HeartMan (http://heartman-project.eu/) is a research project funded by the European Union's Horizon 2020 research and innovation programme. The project aims to develop a personal health system to help CHF patients manage their disease. CHF patients have to take various medications, monitor their weight, exercise appropriately, watch what they eat and drink, and make other changes to their lifestyle. The HeartMan system will provide accurate advice on disease management adapted to each patient in a friendly and supportive fashion.

In this paper, we present the design of the HeartMan Decision Support System (DSS), which was finalised in June 2017 [3]. In section 2, we describe the overall functionality and architecture of the system, and define the roles of its modules that address (1) physiological measurements, (2) physical exercise, (3) nutrition, (4) medication, (5) environment management, and (6) management of calendars and plans. In section 3, we focus on the physical exercise module and present its most important components for (1) patients' physical capacity assessment, (2) weekly exercise planning, and (3) daily exercise management.

2. DESIGN OF THE HEARTMAN DSS
The HeartMan DSS aims at providing medical advice to CHF patients using predictive models, clinical care guidelines and expert knowledge. The purpose of a typical DSS is to passively present information to decision makers so that they can make maximally informed decisions. This DSS, however, is intended for patients who have limited medical knowledge and are consequently expected to follow guidelines with little discretion. Because of that, the DSS actively provides advice to patients, although it does offer choice where appropriate. In this way, it belongs to the category of cooperative DSS [4].

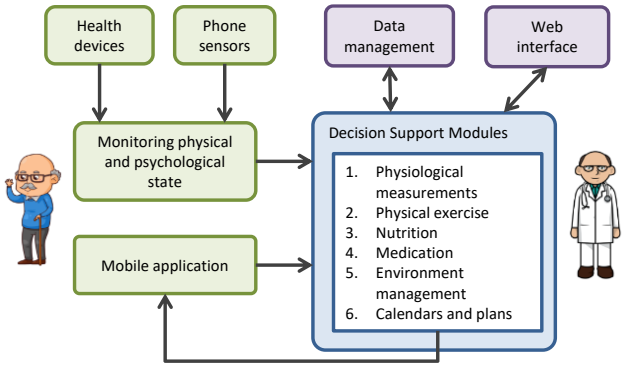

Figure 1: Overall architecture of the HeartMan DSS.

The overall architecture of the HeartMan DSS is shown in Figure 1. The system will use wrist-band sensors to monitor patient's physical activity, heart rate and some other physiological signs. In

addition, it will receive data from additional devices, such as scales, smartphone and from the patient via the user interface of the mobile application. This will allow the system to identify the patient's current physical and psychological characteristics. This data will be combined with patient's health data to help them decide on disease control measures. This will serve providing the advice tailored to the patient's medical condition. The advice will be adapted to the patient's psychological profile (such as normal, poorly motivated, depressed, and anxious) and current health state. The advice will be shown at the mobile app. A web-based interface will be provided to the physician, too, who will be able to monitor the patient's health state and progress, and define or approve parameters that affect the advice given to the patient.

The core of the HeartMan DSS are modules that interpret patient's data and make recommendations. There are six main modules, which address the following aspects of health management:

1. *Physiological measurements*: CHF patients should perform various physiological measurements on a regular basis, such as measuring their weight, blood pressure, heart rate, etc. This raises the patients' awareness of their health, provides valuable information to their physicians, and provides inputs to the DSS. For this purpose, the DSS reminds the patient to regularly perform these measurements, provides the functionality to carry out them, and manage the collected data.
2. *Exercise*: Physical conditioning by exercise training reduces mortality and hospitalization, and improves exercise tolerance and health-related quality of life. For this purpose, the DSS provides a comprehensive exercise programme, which is detailed later in section 3.
3. *Nutrition*: CHF patients should maintain their body weight and take care of their diet, for instance, not eating too much salt or drinking too much fluid. The DSS assesses the patients' nutrition behavior, educates them through a quiz and provides advice towards a healthy diet.
4. *Medication*: Good adherence to medication therapy decreases mortality and morbidity, and improves well-being of CHF patients. For this purpose, the DSS reminds the patient to take medications and assesses the patient's adherence to the medication scheme. For each medication, the patient may obtain an explanation why the adherence is important.
5. *Environment management*: Environmental conditions, such as temperature and humidity, may affect the patient's feeling of health. Combining both, the patient's and environmental conditions, the DSS advises the patient how to change the environment to improve their health feeling.
6. *Calendars and plans*: Given all the DSS aspects (measurement, exercise, nutrition, medication and environment management) and many interactions between them, it is important to sensibly arrange all the activities and notifications, for instance not sending nutrition advice during exercise or suggesting physical exercise after taking diuretics. This DSS module thus coordinates the activities and arranges all the plans into one single calendar.

To date, all these modules have been designed in terms of their functionality, requirements, input data, processing, outputs, and distribution between the client (patient's mobile app) and the server (the DSS in "the cloud") [3].

3. PHYSICAL EXERCISE MODULE

The HeartMan DSS administers a comprehensive exercise programme. At the beginning, the DSS collects medical information and assesses patient's physical capacity in order to plan the difficulty level of the exercises. Then, the DSS provides a weekly set of endurance and resistance exercises, which increase in difficulty as the patient becomes fitter. The DSS also guides the patient during each exercise session: it checks whether the patient is ready to start, then provides instructions, and finally asks the patient to evaluate the exercise. The exercise module follows the guidelines provided in [5] with minor modifications to fit in a mobile application.

3.1 Physical Capacity Assessment

Prior to starting using the HeartMan DSS, the patients should perform a cardiopulmonary exercise (cycloergometry) test to assess their physical capacity. Alternatively, when using the system in a supervised, standardized setting, patients can perform a 6-minute walking test. On this basis, the *physical capacity* of each patient is assessed as "low" (less than 1 W/kg measured by cycloergometry or less than 300 m walked in 6 minutes) or "normal" (otherwise).

3.2 Weekly Exercise Planning

The DSS system provides the patient with a combined *endurance* and *resistance* exercise programme. Both types follow the same principle described with four parameters: *frequency* (times per week), *intensity*, *duration* and *type*. These parameters are combined with the physical capacity to make a *weekly exercise* plan for each patient. For instance, low-capacity patients start with very light 10-15-minute endurance exercises twice per week.

According to the patient's progress, these parameters may change with time. In the HeartMan DSS, the progress is prescribed by two models:

- *EnduranceFrequency*: a model for suggesting weekly frequency of endurance exercises;
- *EnduranceTime*: a model for suggesting weekly time boundaries of endurance exercises.

Both models are formulated using a qualitative multi-criteria decision analysis method DEX [6]. Here, we illustrate the approach describing the *EnduranceFrequency* model, whose structure is shown in Figure 2.

Attribute	Scale
EnduranceFrequency	2x; 3x; 4x; 5x
├**Normative**	2x; 3x; 4x; 5x
│ ├Category	low; ***normal***
│ └Week	1; 2; 3; 4; 5; 6; 7; 8; 9; 10; 11; 12; 13; 14; 15; 16; 17; 18; 19; 20; 21; 22; 23; 24; ***more***
├Current	2x; 3x; 4x; 5x
└**Transition**	decrease; stay; increase; automatic
├MedicalAssessment	decrease; stay; increase; automatic
└PatientsAssessment	decrease; stay; increase; automatic

Figure 2: Structure of the *EnduranceFrequency* model.

The *EnduranceFrequency* model is aimed at suggesting the *frequency of exercises* for the next week, based on the patient's physical capacity, week in the programme, current frequency, and the possible physician's and patient's suggestions for the change. In other words, the model takes into account both the normative (as proposed by a general programme) and actual (as practiced by the patient) frequency, leveraging the patient's and physician's opinion about the suggestion for the subsequent week.

The overall recommendation, which is 2, 3, 4, or 5 times per week, is represented by the root attribute *EnduranceFrequency* (Figure 2). The recommendation depends on three sub-criteria:

1. *Normative*: Frequency as suggested according to the default programme. It depends on the patient's physical capacity ("low" or "normal" *Category*) and the current *Week*. The progression is defined by rules presented in Table 1.
2. *Current*: The frequency of exercises currently carried out by the patient; it can run ahead or behind the *Normative* plan. In order to make only small and gradual changes to the frequency, *Current* is compared to *Normative* and only a one-step change is suggested in each week.

***Transition* is an attribute that captures the patient's wish and the physician's opinion about changing the frequency. The possible values are "decrease", "same", "increase" or "automatic"; the latter is meant to suggest the frequency according to the normal plan, for instance, when neither the patient or physician have given any suggestion. The patient's and physician's suggestions are combined according to decision rules shown in**

3. Table 2. The first two rules say that whenever the patient or the physician suggest to decrease the frequency, it should indeed be decreased (the symbol '*' represents any possible value). Rules 3 and 4 suggest to keep the current frequency whenever one of the participants suggests so, unless the other participant suggests "decrease" Rules 5 and 6 define a similar reasoning for "increase". If both participants have no particular suggestions, the "automatic" transition according to the normal plan takes place.

Table 1: Decision table defining the *Normative* frequency.

	Category	Week	Normative
1	low	<=4	2x
2	low	5–12	3x
3	normal	<=6	3x
4	low	13–18	4x
5	normal	7–12	4x
6	low	>=19	5x
7	normal	>=13	5x

Table 2: Decision rules for *Transition*.

	MedicalAssessment	PatientsAssessment	Transition
1	decrease	*	decrease
2	*	decrease	decrease
3	stay	not decrease	stay
4	not decrease	stay	stay
5	increase	increase or automatic	increase
6	increase or automatic	increase	increase
7	automatic	automatic	automatic

3.3 Daily Exercise Management

Once a weekly plan has been established, the HeartMan DSS assists the patient in carrying out their daily exercises. This consists of four activities: (1) reminding the patient, (2) pre-exercise checking, (3) exercise monitoring, and (4) post-exercise assessment.

3.3.1 Reminding the patient

Patients can choose the days when they want to exercise (e.g., every Tuesday, Thursday and Sunday). On these particular days, the patients are in the morning reminded about the daily exercise. Another reminder is issued if the exercise has not been completed before the given afternoon time.

3.3.2 Before the exercise

Before the start of each exercise session, the HeartMan DSS checks if all prior-exercise requirements are met, and advises the patients about safety. Figure 3 shows the decision model.

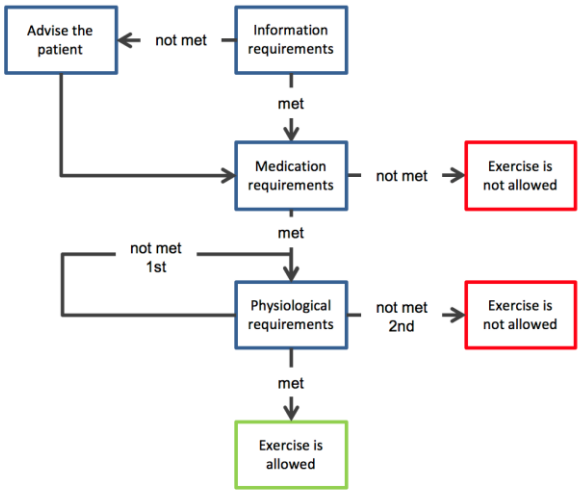

Figure 3: Pre-exercise assessment.

1. *Information requirements:* The blood pressure should have been measured during the day. If not, the patients are instructed to measure it. The pre-exercise heart rate is measured automatically by the wristband; the system makes sure that it is actually worn.
2. *Medication requirements*: Patients are asked to fill a check-list of frequently seen side effects based on their medication schemes and symptoms (e.g., dizziness and chest pain). On this basis the DSS checks for any possible restrictions due to medications or symptoms and suggests rescheduling the session if necessary. The physician or nurse are contacted if severe side effects are present. In the case of dizziness or chest pain, patients are instructed to rest until the symptoms are no longer present.
3. *Physiological requirements*: If all the requirements are met, patients can start with the exercise, otherwise they are instructed to repeat the measurements after five minutes of rest. If after re-checking the measurements are still not within safe limits, exercise is not allowed and patients are advised to contact their physician or heart failure nurse.

Again, a DEX [3, 6] model is employed for assembling and checking the medical conditions, which include medical intake, comorbidities and current physical condition of the patient. The structure and scales of the *PreExerciseRequirements* model are shown in Figure 4. All attributes are binary ("yes"/"no" or "not_met"/"met"). The values of the input attributes are determined from patient data whenever the pre-exercise requirements are checked (normally once per day before making

exercises). The subtrees of the model comprise four main groups of possible reasons against participating in the exercises:

- *Blood coagulation*: Whenever the patient takes anticoagulants and there are symptoms indicating a possible bleeding: rash, hemorrhages, or neurological symptoms.
- *Medication intake*: Whenever one of the following medications has been taken 2 hours or less before the exercise: beta blockers, ACE inhibitors, ARBs, diuretics, or loop diuretics.
- *Heart rate*: Whenever the patient takes Digitalis and his/her HR is less than 45 bpm.
- *Blood pressure*: Whenever there are risks of hypertension (taking ACE inhibitors or ARBs, and the patient has persistent low blood pressure or persistent cough) or problems regarding the systolic blood pressure (when the patient's systolic blood pressure is less than 105 and he/she recently took loop diuretics).

Attribute	Scale
PreExerciseRequirements	not_met; *met*
├**BloodCoagulationReasons**	yes; *no*
│ ├TakesAnticoagulats	yes; *no*
│ └**PossibleBleeding**	yes; *no*
│ ├Rash	yes; *no*
│ ├Hemorrhages	yes; *no*
│ └NeurologicalSymptoms	yes; *no*
├**MedicationIntakeReasons**	yes; *no*
│ ├Intake<2hours	yes; *no*
│ └**ExercisePreventionMedications**	yes; *no*
│ ├TakesBetaBlockers	yes; *no*
│ ├TakesACEInhibitors	yes; *no*
│ ├TakesARBs	yes; *no*
│ ├TakesDiuretics	yes; *no*
│ └TakesLoopDiuretics	yes; *no*
├**HeartRateReasons**	yes; *no*
│ ├TakesDigitalis	yes; *no*
│ └HR<45	yes; *no*
└**BloodPressureReasons**	yes; *no*
├**HypertensionReasons**	yes; *no*
│ ├***TakesACEInhibitors***	yes; *no*
│ ├***TakesARBs***	yes; *no*
│ ├PersistentLowBloodPressure	yes; *no*
│ └PersistentCough	yes; *no*
└**SystolicPressureReasons**	yes; *no*
├***TakesLoopDiuretics***	yes; *no*
├TookLoopDiuretics	yes; *no*
└SYS<105	yes; *no*

Figure 4: Structure of the *PreExerciseRequirements* model.

3.3.3 During the exercise

If the exercise is allowed, a list of exercises is shown to the patient, who can then select the preferred exercise. After selecting the exercise, a detailed description (text or graphical) regarding the exercise is provided.

During the exercise, the heart rate and systolic blood pressure are continuously measured by the wristband. The patients are advised to stop the exercise in case of symptoms or measurements lying outside of prescribed safety margins. If the heart rate is within the safety limits, but too low or too high, the patent is advised to increase or decrease the intensity, respectively. The system also advises the patients about the exercise duration and is capable of recognizing a premature ending.

3.3.4 After the exercise

After completing the exercise, the patients can rate their feeling of intensity (very light, light, moderate, intense, very intense). Then the system assesses the exercise based on measurements recorded during the exercise. It checks if the exercise was prematurely finished and if the intensity was on average in the prescribed limits. The system takes into account this information when assessing the adherence to the exercise plan and the patient's improvement. Independent of this, the exercise is shown as completed and the weekly plan is updated.

4. CONCLUSION

This paper described the design of the HeartMan DSS that is concerned with "medical" interventions (i.e., interventions that try to improve the patients' physical condition as opposed to psychological). The DSS is based on clinical guidelines for the self-management of CHF, additional medical literature and expert knowledge from the project consortium. The DSS is designed in terms of process models (the order of actions and questions) and decision models (how to make some complex decisions – branching in the process models) for five main topics of CHF management: physiological measurements, exercise, nutrition, medication, and environment management.

The DSS is currently being integrated in the overall HeartMan platform. A comprehensive validation involving 120 HF patients (of whom 40 are controls without this system) is planned for 2018.

5. ACKNOWLEDGMENTS

The HeartMan project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 689660. Project partners are Jožef Stefan Institute, Sapienza University, Ghent University, National Research Council, ATOS Spain SA, SenLab, KU Leuven, MEGA Electronics Ltd and European Heart Network.

6. REFERENCES

[1] Heart failure. *Health Information*. Mayo Clinic. 23 December 2009. DS00061. http://www.mayoclinic.org/diseases-conditions/heart-failure/basics/definition/con-20029801.

[2] McMurray, J.J., Pfeffer. M.A. 2005. Heart failure. *Lancet* 365 (9474): 1877–89. DOI= https://doi.org/10.1016%2FS0140-6736%2805%2966621-4.

[3] Bohanec, M., Vodopija, A., Dovgan, W., Maslov, P., Luštrek, M., Puddu, P.E., Clays, E., Pardaens, S., Baert, A. (2017). *Medical DSS for CHF*. HeartMan Deliverable D4.1.

[4] Turban, E., Sharda, R., Delen, D., King, D. (2010). *Business Intelligence*. 2nd Edition, Prentice Hall.

[5] Piepoli, M.F., Conraads, V., Corrà, U., et al. (2011): Exercise training in heart failure: from theory to practice. A consensus document of the Heart Failure Association and the European Association for Cardiovascular Prevention and Rehabilitation. *European Journal of Heart Failure* 13, 347–357.

[6] Bohanec, M., Rajkovič, V., Bratko, I., Zupan, B., Žnidaršič, M. (2013): DEX methodology: Three decades of qualitative multi-attribute modelling. *Informatica* 37, 49–54.