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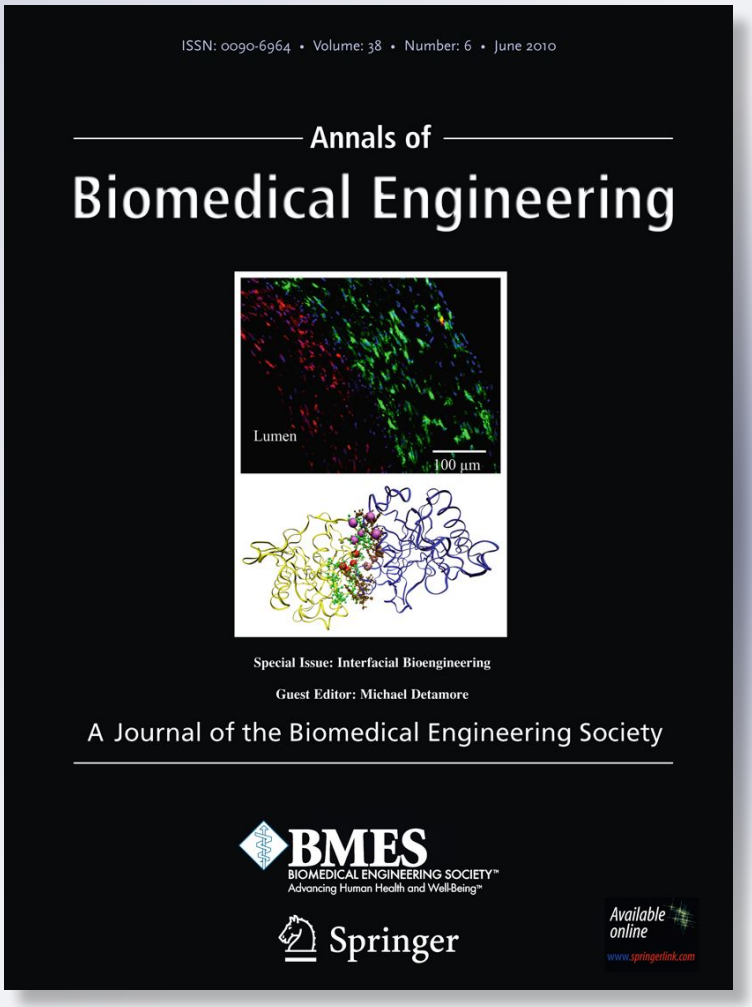

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Integrated Home Monitoring and Compliance Optimization for Patients with Mechanical Circulatory Support Devices

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Abstract—This article presents an integrated, automatic home-monitoring, and assist system for patients suffering from end-stage heart failure, particularly patients with implanted mechanical circulatory support devices, such as ventricular assist devices and total artificial hearts. The system incorporates various biosensors to monitor the vital parameters of the patient unobtrusively in the home environment. Recorded data can be accessed online and in real time by a supervising physician, and these data serve as a means for immediate diagnosis of emergency events. The retrieved information can also be continuously analyzed to generate suggestions for medication, nutrition, and exercise for the patient to optimize their rehabilitation and overall health. An experimental environment (the Future Care Lab) was set up at RWTH Aachen University to serve as a testing environment for the development and evaluation of this novel integrated system. The Future Care Lab was not only used as a platform for technically testing the monitoring system, but also more concretely demonstrating to users the integration of these new medical technologies in a home. Thus, the Future Care Lab provides a unique environment for an interdisciplinary research approach consisting of iterative cycles of system development and evaluation of user acceptance.

Keywords—MCSD, Heart failure, Aftercare, Biosensors.

INTRODUCTION

With the shortage of suitable donor hearts, the implantation of mechanical circulatory support devices (MCSDs) has become a viable and life-saving option for patients with end-stage heart failure. These devices have improved both the survival rate and quality of life both when implanted as a temporary measure (bridge to transplant) as well as when for long-term support (destination therapy).[13] They also serve as a bridge to recovery.

However, the extensive aftercare required in post-surgical patients gives rise to several challenges. Long-term inpatient care and intensive home aftercare requiring professional personnel are very expensive and will continuously deteriorate in the next few years with the aging population.[16] The increasing life expectancy and thus the greater prevalence of chronic diseases generate a considerable demand on nursing personnel beyond the available number of caregivers.[5,6] Advances in healthcare technology for elderly patients with cardiac problems remain a definite need, especially for patients with MCSDs, because of post-surgical complications. This thereby provides the motivation for a new monitoring system which can provide individualized (according to user profiles), adaptive (according to the course of disease), and sensitive (according to situation types and living conditions) support in future home environments.

State of the Art

We investigated the special requirements in post-operative care for cardiac implant patients in collaboration with other heart centers in Belgium (UZ Leuven) and Germany (HDZ Bad Oeynhausen). State-of-the-art aftercare comprises daily monitoring of a variety of parameters. Based on the combination of those values, the attending physician can optimize the treatment mainly by adjusting medication and blood pump parameters. The parameters that have to be monitored differ depending on the type of MCSD. In general, the parameters can be divided into pump-related parameters and vital parameters. The large variety of MCSDs, for example, total artificial

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hearts (TAHs) or left-/right-/bi-ventricular assist devices (VADs), leads to a high complexity of pump-related parameters (e.g., pump flow, speed, power consumption, pulse index, and rotor speed). Typically these parameters are automatically recorded by specific devices and are thus relatively easy to process, and manipulate. The vital parameters, on the other hand, have to be measured separately on a daily basis with external medical devices. Prototype tele-monitoring systems covering at least some of the relevant parameters for MCSD patients are currently under clinical evaluation in the USA and Germany. "Wanda B" is a system monitoring weight, activity, and blood pressure, developed at the University of California Los Angeles (UCLA), which incorporates an alert system and SMS notification.[17] The "Partnership for the Heart" study at the Charité Hospital in Berlin contains a tele-medicine system monitoring electrocardiogram, blood pressure, body weight and self-assessment, using Bluetooth devices to send vital data automatically to a telemedical center.[22] Both systems are functional, working systems, but neither focuses on seamless device integration or usability evaluation.

The Fraunhofer-inHaus-Zentrum (Duisburg, Germany) and the Philips HomeLab (Eindhoven, Netherlands) are prominent examples of living lab settings that follow an approach similar to ours, of implementing intelligent devices in homelike environments. These labs, however, focus on broader medical applications than the ones presented in this article. The Fraunhofer-inHaus-Zentrum, for example, provides various ambient-assisted living technologies for the elderly. This includes not only blood pressure and weight monitoring but also room temperature and lighting control, emergency and fall detection systems, and intelligent furniture like sensor beds which can monitor pulse and activity in the night.

While there are various other initiatives, none of them covers the complete range of vital parameters to be monitored for MCSD patients (blood pressure, heart rate, coagulation, weight, temperature etc.). Thus current practice in aftercare requires the patient to take their vitals with commercially available medical devices individual to each parameter, write down the values each day on paper, and mail or fax it to the physician once a month or more often in case of frequent irregularities.[1] This procedure causes considerable inconvenience for many patients and is prone to error and inappropriate in acute emergency events.

Another major drawback is the inefficiency of the communication modalities between physician/caregiver and patient. On average, patients have direct contact with their cardiologist or specialized nurse only once a month. More frequent contact is only realized by telephone consultation instead of face-to-face communication. Eye contact is important for effective communication, especially between clinicians and patients.[18] A considerable number of complications in patients with implanted MCSDs could be diagnosed much earlier if face-to-face communication between the physician and the patients were more frequent. This includes cases such as infections at the percutaneous driveline exit site in patients implanted with left ventricular assist devices (LVADs).[8,15]

Aims of the Research Approach

Compliance Optimization

The Future Care Lab addresses the above problems. It is intended to monitor vital parameters required for patients with current MCSDs, including blood pressure, coagulation (INR), heart rate, body temperature, and body weight. The major benefit of this system is that the monitored data are automatically processed, analyzed, and distributed to the physician and/or the patient. The provided information is intended to optimize the patients' compliance and the overall treatment success.

Optimization of MCSD Settings

The daily monitoring of vital parameters facilitates, furthermore, the optimization of the MCSD settings (e.g., pump flow, pump speed, pulse index, and rotor speed), which have direct influence on the patient's physical condition. Optimal adjustments require testing the vital parameter response (blood pressure, heart rate, coagulation, temperature, and weight) in many different settings. Our experience at the heart centers in Leuven and Bad Oeynhausen shows that the quality of life of heart failure patients can be significantly improved by continuously optimizing pump parameters. Patients state that they have more energy for their daily activities and an overall improved condition. However, to date, there has been no quantitative study on the effect of parameter optimization.

Physician/Patient Communication

The proposed system also presents a new means of communication between physicians and patients. It provides not only continuous real-time data channels for vital data transmission but also video data channels for visualized diagnostic consultation. The system enables the supervising physician to analyze the patient's vital data immediately when abnormalities occur and to confirm the diagnosis based on personal consultation with the patient at any time.

User Evaluation

The Future Care Lab was designed based on the findings from user tests and acceptance evaluations concerning medical technology in home environments.[1,2,25] In particular, the establishment of new forms of tele-medical consultations and interface modalities, as well as the constant access to personal vital data bring up usability, acceptance, privacy, and intimacy issues which were addressed in a user study on the developed system.

MATERIALS AND METHODS

The Future Care Lab

The construction of the Future Care Lab, started in 2009, focused on the development of a tele-monitoring system for MCSD patients. According to the specifications mentioned above, the Future Care Lab needs to be a medical and a living environment at the same time. For example, the room should provide the necessary medical equipment and assistance features without compromising the comfort and intimacy of a living room. The main design of the Future Care Lab was developed in close cooperation with the heart centers: HDZ Bad Oeynhausen, and UZ Leuven. We consulted the care coordinators of the MCSD stations and supervising physicians over the design of the control interface, parameter representation, device integration, and preferred communication modalities.

The main advantage of the living lab approach, as opposed to testing in normal lab settings or installations in people's private homes, is the balance of being able to efficiently conduct user tests while offering realistic conditions. A variety of potential users can be invited to test the functionality and usability of the installed devices in a realistic home environment. At the same time, new technological developments can be implemented at any time. In this way, iterative cycles of user testing and system development can be performed very effectively.

Communication Interface

The first aspect addressed in the conceptualization of the room was the communication interface between patient and physician as well as the system. As visual communication is the key requirement for remote diagnostics, the room is equipped with high-definition cameras and a wall-sized interactive display (Fig. 1). The multi-touch sensitive display wall serves as a screen and an input device for various applications ranging from medication, nutrition, and exercise management to daily multimedia entertainment (games and movies) or even virtual meetings with physicians or family and friends. This feature allows the patient to access their vital data and medication histories without using different devices during a video consultation with the physician.

FIGURE 1. Interior of the Future Care Lab. The interactive wall display, which serves as the communication and diagnostic interface, is shown on the left side.

The prototype display wall installed in the Future Care Lab consists of six projectors and a special acrylic projection surface. Infrared LEDs and sensors recognize finger movements and touch contact on the projection surface. A more compact apparatus may be possible when using organic light emitting diode (OLED) technology. Surface optimization is beyond the scope of this article.

To use a complete wall as an interface for visual communication is rather unusual, and therefore demands thorough user acceptance and usability evaluation.[3] In particular, electronically mediated patient–doctor communication requires a careful balance of visual, verbal, paraverbal, as well as non-verbal factors and thus relies on a sophisticated communication etiquette between patients and physicians who are aware of intimacy issues.[12]

As mentioned, completely new scenarios of social interaction for cardiac patients derive from this form of telecommunication. Studies show that psychological issues and depression are major challenges in successful rehabilitation.[14,19,20] Especially for patients with implanted MCSDs and limited mobility, live visual access to their social networks is essential for psychological satisfaction. Therefore, the interactive display wall can be both metaphorically and functionally a window through which the patient can interact with the outside world.[9]

Vital Data Monitoring

The vital data monitoring system functions as an assistance and therapy optimization system for both

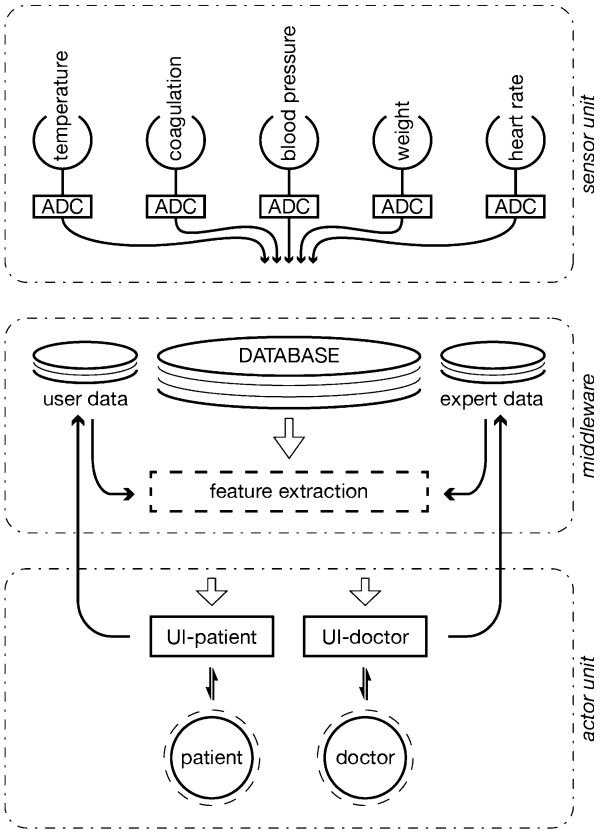

FIGURE 2. Visualization of the system architecture.

the patient and supervising physician (Fig. 2). It consists of three main components: the sensor, the middleware, and the actor unit. In order to increase system reliability, the concept requires the integration of commercially available sensor components and medical devices.

Sensor Unit

The sensor unit consists of four medical sensor devices, which enable daily data acquisition of patients' blood pressure, coagulation, temperature, weight, and heart rate. The acquisition of other heart-related parameters, such as ECG or O_2 saturation, is not required on a daily basis for most MCSD patients and was thus not integrated in the Future Care Lab setup.

The seamless integration of the sensor system is an important factor for user acceptance. Initial user studies indicate that patients, as well as healthy people, prefer not having visible medical instruments in their living environment while having the full functionality and optimized ergonomics of devices.[21] In order to further explore this theory, we integrated the sensor devices in the furniture and room components (Fig. 3) so that the medical equipment is almost invisible to an unacquainted person but still easily accessible for the patient.

Coagulation Sensor

Among the vital parameters mentioned above, monitoring of coagulation is the most difficult to obtain in a home environment because blood samples are required to carry out the measurement. In order to minimize the patient's discomfort, we chose the portable CoaguChek® device (Roche Diagnostics, Mannheim, Germany) which offers compactness, mobility, and direct data access. This device was integrated in a small custom-made table allowing the complete measurement of coagulation within a couple of seconds (Fig. 4).

Blood Pressure and Heart Rate Sensor

To measure heart rate and blood pressure, we chose a standard sphygmomanometer, comprising an inflatable cuff to restrict blood flow and a manometer to measure the pressure (Boso, Jungingen, Germany). The device can directly process digital data and was integrated into the same table (Fig. 4).

Temperature Sensor

Automatic temperature measurement is integrated into the Future Care Lab via a high-precision infrared camera (Flir Systems, Frankfurt, Germany) on the left side of the display wall. When the patient's face is recognized in the camera's field of view, the body core temperature is obtained at "hot spots" between the patient's eyes. The precision of this technique is comparable to conventional techniques such as tympanic measurement. In a study based on a sample of 170 measurements (healthy males and females, aged 24–28 years) carried out simultaneously with a ThermoScan IRT 4020® tympanic thermometer (Braun, Kronberg, Germany) in the ear and the infrared camera at a two-foot distance from the face, the measurements of the infrared camera were 0.34 ± 0.72°F less than the more conventional tympanic temperature.

Weight Sensor

Two sensor systems for weight monitoring are integrated in the floor of the lab. In the first system, a digital scale (Kern, Balingen, Germany) was implemented under one floor tile in front of the display wall. This allows the patient's weight to be measured while he interacts with the display wall (Fig. 3). A pre-set threshold of 44 lbs weight on the tile triggers the measurement. The measurement is considered valid when the value does not fluctuate more than 0.44 lbs for 3 s. The scale is wired to the system's middleware unit where the weight data are stored and further processed.

The second system uses a custom-made network of piezoelectric sensors, which was installed under all the floor tiles. At each of the four corners of each tile, a piezoelectric sensor records pressure signals, which are

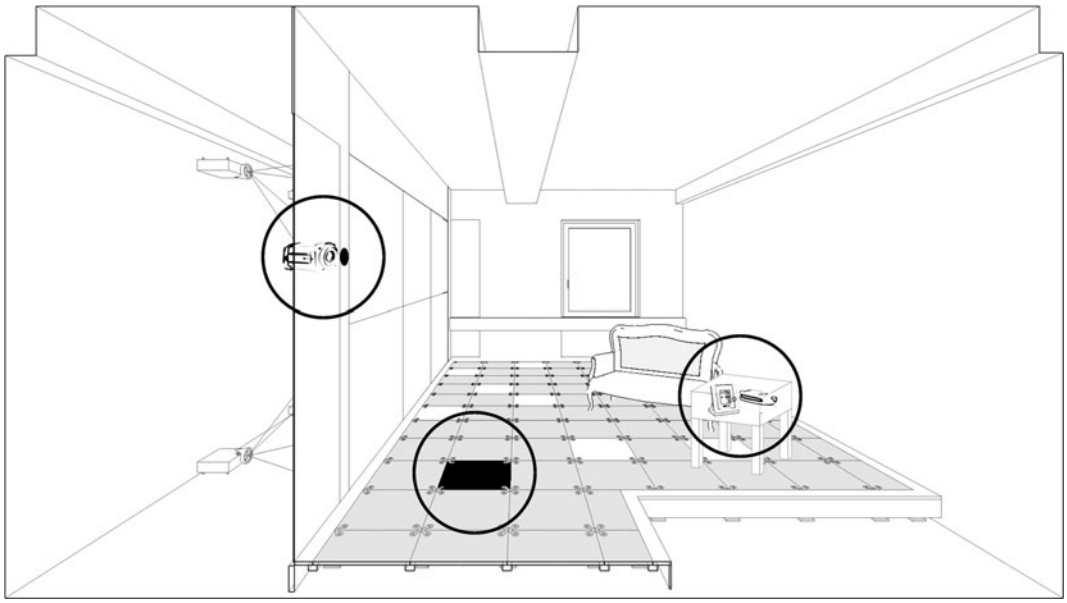

FIGURE 3. Visualization of the monitoring system in the Future Care Lab. From left to right: an infrared camera is integrated in the wall next to the display, weight sensors are installed under the entire floor (additionally a scale is installed under one floor tile in front of the display wall), and blood pressure and coagulation monitoring devices are implemented in a table.

FIGURE 4. Device integration: blood pressure and coagulation monitoring device implemented in a table.

subsequently transformed into weight information. This system was originally intended for position recognition and movement analysis, but our experiments show promising results for weight measurements as well.[10]

Autonomous monitoring and measurement of weight and temperature not only provide convenience for the user but also raise privacy and intimacy issues. Preliminary acceptance studies concerning medical technology in private homes have shown that the protection of private data is especially important for patients.[21] In order to address this privacy issue, we developed an alternative measurement mode in which the users can specify in the software application specially developed for the wall-sized display, how their vital data are being recorded, thus giving them some control over data privacy.

Middleware Unit

All the acquired analog signals are converted to a digital data stream by Analog/Digital Converters (ADC) and transferred to the middleware unit. The software architecture of the middleware is based on the Open Services Gateway initiative framework (OSGi) which facilitates interoperability of various input devices. The system is easily expandable and upgradeable, allowing for the use of additional sensors beyond the current scope of the project to be integrated in the future.[23]

The acquired vital data are stored and accessed from an online database. A feature-extraction software structures the data and extracts relevant information individualized for the specific patient. The software provides information about thresholds under which vital signs are considered physiological as well as all possible combinations of parameters defining critical profiles. The system would, for example, be able to determine that an elevated INR level in combination with normal temperature gives reason to change the nutrition plan, while an elevated INR level combined with an elevated temperature may be caused by cerebral bleeding and requires immediate contact with the supervising physician. The feature-extraction software is adaptive, which means that it can at all times be updated with current user or expert data. User data are especially important for the decision process of the

software. If, for example, the system knows that the patient had eaten fatty foods or had consumed alcohol, the acquired vital data of that day are interpreted differently. We are currently investigating the possibility of synchronizing the patient's personal calendar with the system. In the same way, the physician can also update the feature-extraction software with new information, which may, for example, adapt the thresholds for certain vital signs.

Actor Unit

Software applications at the patient's home as well as in the supervising heart center provide the user interface for both patient and physician. The pre-analyzed vital parameter graphs can be accessed and interpreted by the specialist, as well as by the patient at any time. The user interface mainly presents the data in an intuitive way, customized to the needs of the doctor and the patient. Graphical summaries of the different vital parameters over various time scales, for example, enable the physician to see how elevated vital signs may be interlinked (Fig. 5). The feature-extraction software in the middleware unit also recognizes recurring patterns in the data.

Vital sign values in critical zones can trigger warning messages and establish a direct video connection to the physician. In less urgent cases, the system can offer suggestions for medication, nutrition, or physical training for the patient.

The interface is bidirectional in that the user (patient/physician) can access information and suggestions given by the feature-extraction unit as well as conveniently provide new input (user data, expert data e.g., updated upper and lower limits for the INR value).

Usability Study

In order to get an impression of the system's reliability and functionality in real use as well as an evaluation of its usability we conducted a user study. The study was performed with two user groups: persons with heart disease (e.g., cardiac arrhythmia, tachycardia, coronary heart disease, and myocardial infarction) and persons without a history of heart disease (healthy control group). The study was designed to answer four research questions:

1. How reliable is the vital data acquisition functionality in a real user study?
2. How do users assess the usability and learnability of the proposed system in general?
3. Is there a difference in the assessment of usability and learnability between the two user groups?
4. How is the user's attitude toward privacy, trust, and data security?

It was hypothesized that participants with heart disease (HD) would rate the usability of the system

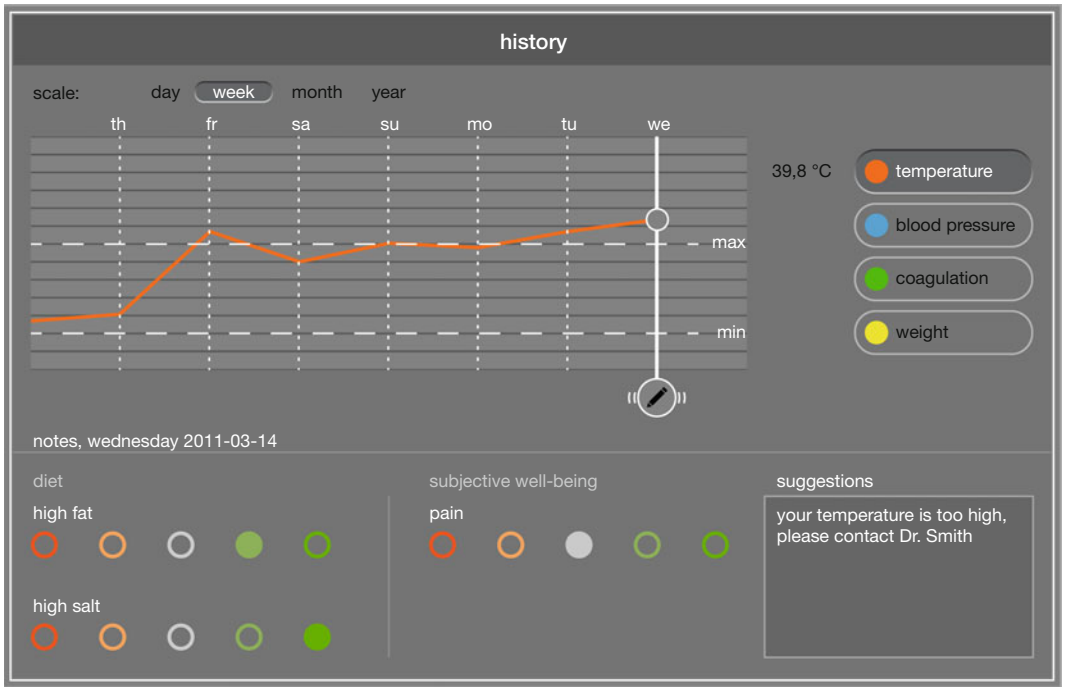

FIGURE 5. Graphical overview of analysis of vital parameters over time (top panel) and interface for user data input (bottom panel).

higher, because of their higher domain knowledge, and their personal involvement and motivation to master the disease. It was furthermore hypothesized that acceptance with respect to personal privacy, perceived trust, and security are not modulated by the health status of users.

System Usability Scale

We examined the usability of the monitoring system with the System Usability Scale (SUS).[4] The SUS is an easy-to-apply ten-item scale, where users are asked to indicate the degree of (dis)agreement to several statements on a 5-point Likert scale from 1 (''strongly disagree'') to 5 (''strongly agree''). The overall scale gives a global view of subjective assessments of usability. In order to avoid any biases, the items are alternated between positive and negative items as follows:

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

The maximum score on the SUS is 100 points. In addition to the calculation of the overall SUS score, two subscores for ''Usability'' (items number 1, 2, 3, 5, 6, 7, 8, and 9) and ''Learnability'' (items number 4, and 10) were also calculated.[11]

Additional Questionnaire Items

In addition to traditional usability patterns as is covered by SUS, factors such as users' attitudes toward privacy, data security, and trust in reliability are important in technology acceptance and for the successful adoption of such modern technologies in the home environment. Users also were asked to rate the following statements: ''I am concerned about the visibility of my health data to third parties'', ''I think that the system is reliable'' and ''I believe that the data security of the system is warranted'' on a 5-point Likert scale. Demographical data and details about the health status and the (daily) usage of medical assistive devices (e.g., blood pressure meter) were collected.

Tasks and Procedure

Participants were first introduced to the concepts of ambient-assisted living and telemedicine, and the possibility of having modern technologies in their homes to monitor vital functions and to improve the efficiency of patient–doctor communication. The experimenter then demonstrated how to interact with the system by weighing himself using the digital scale system under the single tile near the wall display, and taking his own blood pressure. Participants then had to do the same, navigating through the system menu structure to measure their vital signs. After their vital signs were acquired, participants navigated to the graphical measurement overview (Fig. 5) to be able to judge the benefit of the system's functionality. Additional fictitious values for the previous weeks and months were automatically generated based on the values measured during the study. The participants were informed that, in a real-life scenario, the vital data would be stored in an online database. After completing the interaction, participants filled in the usability questionnaire. Participants were also given the opportunity to comment on the general benefits of, perceived barriers of and the willingness to use the technology. All the participants were tested individually, and the duration of the study did not exceed 30 min.

Participants

A total of 28 adults [15 females and 13 males; aged between 24 and 86 years of age, $M = 57.3$ (M = Mean), SD = 16.1 (SD = Standard Deviation)] participated in the study. The proportion of persons who reported having HD was 46% ($n = 13$) and all of them reported use of and reliance on medical assistive devices (e.g., blood pressure meter). In this group, 70% reported to regularly note down the results of vital parameter measurements for consultation with their medical doctor, the majority of which used traditional pen and paper. In the healthy control group (CG), only one person reported using medical devices and visits to the physician for regular checkups.

Participants were recruited through advertisements in a local newspaper as well as through posters in public places. Different professions (including engineers, economists, teachers, business graduates, tailors, and mechanics) and different educational levels were represented in the sample. Participants were not compensated for their participation.

RESULTS

Reliability

All participants successfully completed the task of interacting with the system to measure their weight and blood pressure. In four of the 56 vital parameter measurements, the measurement had to be restarted by the user to achieve a valid result. This results in a high reliability score of 93% for the functionality of the monitoring system.

Usability and Learnability

Overall, judged usability was very high (on average $M = 91$, out of a maximum of 100 points, SD = 12.3), indicating that participants did not experience many difficulties using the system. However, there were significant differences in the perceived usability when comparing healthy persons and those with reported HD ($F_{(1,26)} = 7.7$, $p < 0.05$): persons with HD assessed the usability considerably higher ($M = 96.9/100$, SD = 4.6) than healthy adults in the CG ($M = 85.3/100$, SD = 14.4; Fig. 6).

Users' evaluations of the proposed system's usability were analyzed using bivariate correlation analysis as well as by univariate and multivariate analysis of variance with a level of significance set at 5%. The significance of the omnibus F-tests in the (M)ANOVA was taken from Pillai's trace.

Based on the "Learnability" and "Usability" subscales, results show that persons suffering from HDs reported greater ease in learning the technical system compared to the CG ($M_{HD} = 19.8/20$, SD = 0.7; $M_{CG} = 15.8/20$, SD = 6.7; $F_{(1,26)} = 4.5$, $p < 0.05$) and significantly more usable ($M_{HD} = 77.1/80$, SD = 4.4; $M_{CG} = 69.5$, SD = 10.1; $F_{(1,26)} = 6.3$, $p < 0.05$).

No significant differences in usability were found for different age groups (split by sample median) or gender, suggesting that the positive perception of usability of medical assistive technology under study is comparable in males and females and in users of different ages.

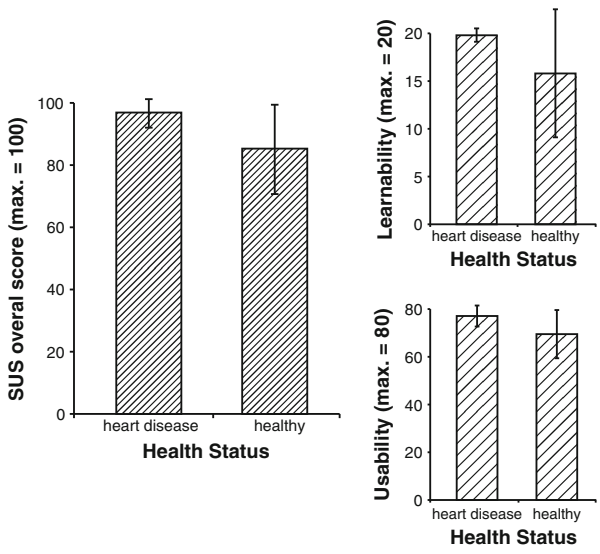

FIGURE 6. Main effect of health status on system usability: SUS overall score analysis on the left side and separate analyses for factors Learnability (right top) and Usability (right bottom).

Privacy, Trust, and Data Security

Independent of personal health, participants reported not to be unduly concerned about the size of the wall-sized display and the increased visibility of their health data during measurement (privacy mean score $M = 1.9/5$, SD = 1). The advantage or disadvantage of the invisibility of the medical devices in a situation where no vital parameter measurement is performed was not evaluated in this study.

Furthermore, participants trusted the data security of the system to a great extent ($M = 4.1/5$, SD = 0.8), and were also quite confident with respect to the system's reliability ($M = 4.3/5$, SD = 0.7). It is remarkable that the perceived reliability (86%) of the system is lower than the reliability that was technically observed (93%).

Associations Between the Research Variables

As shown in Table 1, the two factors of SUS, usability and learnability, are positively linked to each other ($r = 0.51$; $p < 0.05$). In addition, system usability correlates moderately with the trust in system's reliability ($r = 0.39$; $p < 0.05$); that is, the more the users perceived the medical assistive technology as usable the higher their trust in its reliability. Moreover, the more the people were concerned about privacy issues, the less they believed that the system would be able to gather their health data in a reliable way ($r = -0.49$; $p < 0.05$) and the more they questioned its data security ($r = -0.40$; $p < 0.05$). On the other hand, positive opinions about the security of data processing were linked to the perception of the system's reliability ($r = 0.63$; $p < 0.05$).

Separate correlation analyses for persons suffering from HDs and the healthy CG revealed no significant differences. This provides possible support for our hypothesis that acceptance with respect to personal privacy, perceived trust, and security are universal demands for sensitive technology environments, which are valid for *all* potential users, and not modulated by the health status of users.

TABLE 1. Bivariate (Pearson) correlation coefficients between the two dimensions of System Usability Scale, Learnability, and Usability, and acceptance aspects regarding perception of privacy, trust, and security ($N = 28$).

	SUS Usability	SUS Learnability	Privacy	Trust	Security
SUS Usability	1	0.51**	−0.08	0.39*	0.36
SUS Learnability		1	0.20	0.18	0.14
Privacy			1	−0.49**	−0.40*
Trust				1	0.63**
Security					1

*$p < 0.05$; **$p < 0.01$.

DISCUSSION

Facing the growing aging population in many countries of the world, healthcare-related technologies are becoming increasingly important, representing a possible solution to the overstrained healthcare systems and the decreasing number of caregivers. Though the development in medical technology is impressive, practical experience shows that the novelty of technical solutions does not guarantee the successful diffusion of these innovations. So far, research on medical technology has mostly been dominated by technical, medical, and economic disciplines while the usability and the acceptance of these products in target users have not been sufficiently addressed.

In order to reach greater user acceptance, not only is the technical implementation important, but also the usability of these technologies, the way these technologies meet the wants and needs of users, and how they affect their privacy and dignity. Another shortcoming so far is that traditional device development usually seems to assume that users are interacting with a single device in isolation. However, user experience is embedded into a spatial context (e.g., homes), and this spatial and functional context defines the background against which the use of devices has to be investigated. To examine how patients actually communicate and interact and behave in homecare environments, an experimental space that simulates how such technologies would be used in a home, is necessary. We can only understand potential usage barriers and perceived benefits if users can actively interact with the ambient environment and ''feel'' the impact of invisible technology at home.[24] Furthermore, users tend to be oversensitive toward privacy violations if their judgments only rely on the imagined use of the technology (scenario technique, as used in questionnaires).[7,21,25] This caution and reluctance stem from two major sources. One is the novelty of smart home technology and the difficulty for potential users to imagine how medical technology could affect normal living at home. In such cases, the reluctance is not a refusal to use these systems, but more probably a global lack of understanding of how these systems work, fostering an uncertainty of whether these systems bring more negative effects than benefits. The second factor is that people are very cautious whenever technology comes into private spheres that are as intimate and sensitive as body/health, home, and family. It is thus important to note that whenever users have the possibility to experience and feel the technology they have to evaluate, the evaluations are not only more valid but the general attitudes toward electronically supported home technology become much more positive.

The approach adopted here demonstrates that, in general, smart home medical care is indeed promising. The proposed monitoring system addresses the unmet needs in MCSD patient aftercare. An effective environment is the key to optimal therapy and overall success of user-centered system development. The Future Care Lab provides a platform for the future construction and evaluation of a system, which combines performance, data security, and an intuitive interface that minimizes patient concerns about privacy and system usability. The user study overall demonstrated that the learnability, usability, and acceptance of such a system were very high for all users. Interestingly, patients with HDs evaluated the system as more highly usable compared to healthy users, presumably because of their greater domain knowledge and their awareness for the importance of electronic medical care at home in allowing them to maintain their independence.

Future Work

The Future Care Lab is a successful first step in integrated medical home technology development. Our approach and study also raise issues that should be addressed in future research.

Technical Implementation

The elevated floor and backlit multi-touch projector display wall aim to simulate future technology and is optimized for flexibility and extendibility during the ongoing design process. However, existing homes are not easily retrofitted with such a setup. Instead, a more

compact system would be more practically implemented in different home environments. New or future technologies (e.g., OLED displays) will have to be considered in real home environments.

Another major issue is developing business plans to finance these novel technologies as well as service plans. While it could be strictly argued that modern societies will have to finance new solutions (as the number of caregivers will not be sufficient), innovative economic models are still needed for a successful rollout.

We have also mentioned the option of building on the proposed system to offer parameter optimization for MCS devices. Practically, however, sensor-based device control is highly complex, and it is more difficult to guarantee safe operation. Owing to interference, drifting, and other limitations, biosensor measurements can be error-prone and therefore not suitable as the only feedback signal for the automatic closed-loop control of the MCSD. The system has to guarantee safe operation, and ultimately the critical parameters need to be adjusted carefully by the supervising physician.

User Study

One limitation of the user study is the comparably small number of participants. More studies are required to further validate the usability findings and their generalizability. It should also be noted that although the older adults in this sample mostly represent the aging ''baby boomer generation'' which is the main target group of future eHealth technologies, future studies should also integrate even older individuals to provide a more complete picture of potential age-related effects on the usability and acceptance of novel medical home technologies. As the success of such novel approaches also crucially depends on the acceptance and willingness of doctors to share electronic home monitoring systems, physicians also need to be included in further user studies.

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