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Autonomous Exercise Rehabilitation for Heart Failure Patients based on Six-Minute Walk Test through Internet-of-Thing Devices

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Abstract— **Heart failure (HF) is one of the most common causes of hospitalization for people over 65 years old, and over half of patients who diagnosed with severe HF conditions at first time cannot survive over 5 years. It is also noticed that rehospitalization rate of heart failure patients may increase to 50% in three months and the mortality rate from 33% to 50% within five years if HF patients are not treated with proper medication and physical therapies. Here we provide a classification system and an early warning mechanism for detecting HF disease based on integrating 6-minute walking test (6MWT), Internet of medical thing devices, and cloud computing technologies. This study performed 6MWTs for 50 HF patients accompanied by medical staffs for recording walkway distance, walking heart rate, and resting heart rate. All retrieved features and classified functional levels of heart organ of HF patients are trained as a target referencing dataset. According to the selected features and trained results, the clustered information representing various heart conditions is applied for detecting potential HF patients at earlier stages. In addition, the newly obtained self-exercise rehabilitation records from HF patients in a real-time manner will be compared to her/his previous 6MWT patterns. The compared differences are considered as important information for doctors to arrange medical treatment and adjusted physical therapy during the next follow-up visit in hospital.**

Keywords: 6-minute walk test, heart failure (HF), early warning mechanism, self-exercise rehabilitation

I. INTRODUCTION

Heart failure(HF), also known as congestive heart failure (CHF), occurs due to her/his heart organ cannot supply blood sufficiently when a person is at rest or during exercises. HF may lead to dyspnea, wheezing, poor exercise tolerance, fatigue, and cardiac hypertrophy [1]. Although the improved medicine and advanced vascular interventional surgery techniques have successfully extended the lives for HF patients, incidence and prevalence of HF disease keep increasing worldwide. One of the obvious features of HF patients is the decreased conditions of cardiovascular endurance and exercise tolerance. Compared to healthy people, only fifty to seventy percent of endurance functionalities are remained, and as a result of HF patients always feel tired and difficult to perform daily activities. However, a lot of HF patients intentionally neglect the importance of exercise rehabilitation and lead to a vicious cycle of heart organ deterioration. Previous studies showed that appropriate and suitable increment of physical activities may provide effective results of reducing the risk of cardiovascular related diseases [2]. Under clinical trials, it was observed that cardiovascular related patients with proper exercise training possess better cardiac functions than those patients who did not regularly perform exercise rehabilitation [3]. It is important to persuade HF patients that exercise rehabilitation plays an important strategy to regain heart functions of HF patients. To validate the heart conditions of HF patients, a six-minute walk test (6MWT) is frequently applied for diagnosed HF patients. The test can simply verify the cardiac function level of HF patients according to measured walking distances. Obviously, in addition to different stages of HF patients, walking step sizes, height, weight, gender, and age may subjectively influence the measured walking distances. Therefore, the 6MWT should be performed, measured, and analyzed for each HF patient individually. In this study, we have constructed a classification mechanism for evaluating the different stages of HF patients, and an early warming mechanism based on 6MWT was also developed. Utilizing Internet-of-Medical-Thing(IoMT) devices and connected them to a cloud computing mechanism was constructed, and the results were discussed in this study. All users' physiological data from accompanied 6MWT were individually analyzed and recorded for future monitoring applications. Since chronic diseases require follow-up visit appointments to meet doctors after one or a few months, self-homecare becomes an important activity and an effective way to maintain patients on a certain healthy level. The developed system would provide a real-time function of receiving self-exercise training data, and the data will be compared to the previously registered accompanied 6MWT data. Especially, the Hospital cloud server could also receive the physiological data from registered patients and the compared results would be provided to associated doctors for follow-up diagnosis and treatment. The proposed mechanism reduces the probability of risky incidents or avoids seriously deteriorated conditions for HF patients. Regarding general users, the proposed system could retrieve and compare the 6MWT data with previously clustered HF groups, and it might be helpful to identify whether the users are potential HF patients or to diagnose the heart function levels of users.

A. Heart Failure

Heart Failure (HF), also called congestive heart failure (CHG), is commonly caused by coronary artery disease, hypertension, atrial fibrillation, valvular heart disease, and cardiomyopathy. These diseases might change heart tissue structure or function and lead to heart failure. Due to irreversible myocardial damage and necrosis, HF patients cannot be completely cured but slowing down the progression of the disease could be achieved. There are improved medical treatments and advanced interventional surgery techniques for HF patients. However, taking heart failure medicine is only to relieve the symptoms, to delay the deteriorated condition, and to reduce the risk of death. Alternatively, exercise rehabilitation is a non-drug therapy which can effectively improve the aerobic fitness and enhance the whole body health of the patients. Unfortunately, due to insufficient strength and lack of endurance symptoms of heart failure disease in common, exercise rehabilitation is often evaded by HF patients. This phenomenon may lead to a bad circulation problem. According to previous statistical reports, heart failure is one of the most common causes of hospitalization and re-hospitalization for people over 65 years old [4] and over half of patients who diagnosed with severe HF condition at first time cannot survive over 5 years. Without appropriate treatment, HF patients even with mild conditions may become very serious in a short period of time. Therefore, an early detection technique for normal people or a monitor mechanism for diagnosed HF patients has become an important issue and is urgently required.

B. 6-Minute walk test

The 6-minute walk test (6MWT) is a simple, non-invasive, and convenient test that reflects cardiovascular endurance condition of HF patients immediately [5], and it provides the basis and references for clinical diagnosis and treatment. It mainly measures the walking distance that a subject is able to traverse back and forth on an indoor flat walkway for a duration of 6 minutes. The subject is allowed to take a rest or adjust walking speed as needed during the test. After finishing 6MWT, accompanied medical staffs record the walkway distance and a simple assessment of cardiac endurance could be adjusted according to the distance. The walkway distance of 6MWT is divided into 4 different levels: Level 1, patients with a 6MWT distance over 450 meters; Level 2, patients within a walking range from 375 to 449.5 meters; Level 3, patients within a walking range from 300 to 374.9 meters; Level 4, less than 300 meters. Higher levels reflect more serious cardiac functions of the subject. So far, 6MWT has been widely performed for evaluating a variety of diseases such as chronic obstructive pulmonary disease(COPD), Alzheimer, down syndrome(DS), and heart failure diseases [6-9].

II. SYSTEM CONSTRCTION ARCHITECTURE AND DATA ANALYSIS

HF patients frequently feel tired and/or suffer cardiac asthma when doing exercises or even at rest. Therefore, most of HF patients often neglect or intentionally evade doing physical treatment. In such a vicious cycle, it would accelerate the destruction of heart function and lead to a high rehospitalization rate of HF patients. Clinical data shows that performing proper exercises does not deteriorate the remodeling processes of heart tissues, and even suppressing abnormal tissue remodeling. Based on the existing healthcare programs executed in current hospitals, we construct an intelligent system connecting IoMT devices, cloud servers, and big data analytical modules to facilitate HF patients, doctors, and caregivers. When an HF patient possesses 6MWT records in the health information system and wears the registered IoMT bracelet, the developed system keeps comparing patient's cardiac function with previous records in a real-time manner. The compared results will be recorded and responded to his/her doctors to indicate current status of cardiac function and differences with previous conditions. For healthy people, the designed system could help to classify the user's cardiac functional levels according to the collected and defined distributions of verified 6MWT groups. It provides a simple and easy way to monitor the effects of exercise rehabilitation for HF patients at home, and it could also facilitate novel discovery of potential HF patients at an earlier and initial stage.

A. System mechanism

The designed system is divided into three main modules. The first module includes the medical health information database and the cloud server. The initial medical raw data of HF patients was obtained by performing 6MWT for each HF patient accompanied by medical staffs. In this study, we have collected 6MWT data records of different levels of HF patients from Chang Gung Memorial Hospital (Keelung Division, Taiwan) as raw database (IRB number: 201601400B0). Training data include 6MWT walkway distances, walking heart rate variances, and resting heart rate variances. The second module is designed for HF patients' self-exercising and tracking function. After downloading the APP module, users are required to enter their personal information including gender, age, height, and weight. Through automatic and regular notifications from the system, users should find a flat ground to perform 6MWT activities. The IoMT bracelet worn on a patient's wrist will collect all physiological data and send the data to the APP through Bluetooth modules. The third module is the cloud server for collecting and analyzing personal digital data. After the APP verifying personal information and receiving 6MWT records, the system will send them to the cloud server for following analytical procedures. The system configuration is shown in Figure 1. If a user was diagnosed as an HF patient by doctors, the cloud server will collect user's 6MWT records obtained by accompanied medical staffs, and the newly collected data by user herself/himself at home will be compared to the previously measured records. The compared results will be applied to determine whether the heart rate status of patients is improved. This information will be provided to his/her doctors for follow-up outpatient treatment. In other words, doctors are able to determine whether the training intensity for a specific patient is enough, and the self-exercise rehabilitation program can be adjusted before the next appointment. For all new users jointing the program, the system will initially compare her/his 6MWT pattern with clustered medical database to classify the new user's cardiac condition.

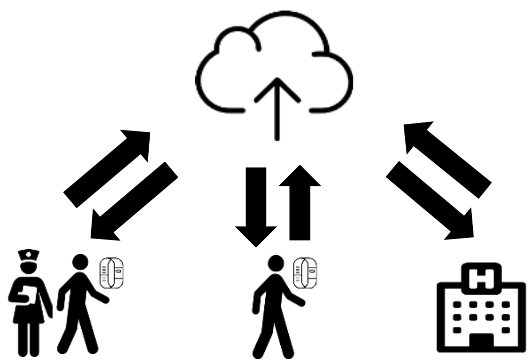

Figure 1. The proposed system configuration for monitoring self-exercise rehabilitation.

B. Training dataset description

The training dataset is consist of seven physical data features retrieved from CGMH HF patients, including age, gender, height, weight, heart rate, HF group, and the 6MWT distance. We classified HF patients into three groups according to corresponding cardiac conditions. The three major groups are related to the New York Heart association classification of heart failure (NYHA) [10]. Group 1 represents NYHA-1 and NYHA-2; Group 2 for NYHA-3; Group 3 for NYHA-4. Four attributes were applied in this study including distance (maximum walking distance), heart rate variance of 6MWT, heart rate variance at resting time, and cluster information of HF patients. A total of 50 subjects diagnosed with HF disease were collected in this study, of which 40 males and 10 females. Due to unbalanced data collection regarding the gender feature, we only trained data from males as our pilot study. After data re-validation, only 34 male patients were applied in this study. The age is distributed from 31 to 89 years old, and the accompanied distances of 6WMT are obtained within a range from 120 to 505 meters.

C. Raw data analysis

The proposed analytical system requires four attributes described in the previous section. To exploit the collected time series data, we construct heart rate sequences for each 6WMT. In addition, we constructed a status transition series based on different transition conditions for each 5-second interval. We define that a continuous decline or rise of 5-second interval is considered as identical status without any status transition. In other words, if the increasing or decreasing trends were changed at a certain 5-second interval, then the time point is defined as a status transition. Therefore, any 6WMT could be transferred into a profile of status transitions. If the changing frequency of the status transition series is high, the corresponding heart rate variance parameter is also high. To demonstrate and visualize the features in three-dimension space, here we select the 6WMT distance as the x-axis, walking heart rate variance score as the y-axis, and resting heart rate variance score as the z-axis. The proposed feature space can be easily constructed by 3D scattering plots. An example is shown in Figure 2. Here we applied multidimensional curve fitting to find an obviously trend to cluster three different levels of HF patients. The blue cluster represents the Group 1 with mild HF conditions, the green cluster stands for the Group 2 with medium level of HF conditions, and the orange cluster depicts the Group 3 for severe HF conditions. We found that features of gender, height, weight, and age parameters were highly correlated with 6MWT. For example, if the patient A in Figure 2 is classified only according to 6WMT distance feature, the patent might be classified as a mild heart failure patient. However, if we combined with the other two proposed features, after performing clustering analysis, the patient A should be clustered into the Group 3. In other words, the A subject should be classified as a severe heart failure patient.

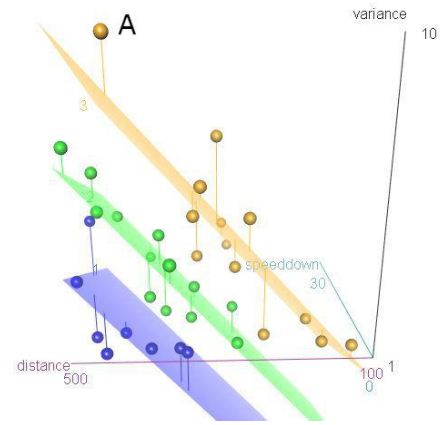

Figure 2. Blue dots represent the Group 1 for patients with mild HF conditions; Green dots stand for the Group 2 for patients with mild-to-severe HF conditions; Yellow dots depict the Group 3 for patients with serious HF conditions.

D. User data calibration

As soon as a user registers and applies the APP software on smartphone, the software will remind the user to wear a specific bundled IoMT bracelet device and find a flat ground to perform 6MWT program. The bundled bracelet device could detect required physical data and transmit to the APP immediately. After 6-minute walking and 2-minute resting schedule, the APP transmits all associated data to the cloud server system. Based on photoplethysmography technology, the bundled bracelet device is able to detect cardiac pulse. However, it should be noticed that different brands of IoMT devices may provide different timing interval during a testing program. Hence, the system will transfer testing records into a continuous sequence by linear interpolation. The heart rate value is represented as X_t and the time sequence is noted as Y_t. The designed system may use formula (1) to fill up missing values of X_m. After transferring processes, the system applied following measured distances and heart rates to compare with previously recorded raw medical data.

$$X_m = X_{m-1} + \frac{X_{m+1}-X_{m-1}}{Y_{m+1}-Y_{m-1}}(Y_m - Y_{m-1}) \qquad (1)$$

When a user wearing a bracelet IoMT device and performing 6WMT, the proposed system will automatically connect the user, the cloud server, and hospital information system immediately. As soon as the assigned hospital information system receiving patient's new 6WMT records, her/his doctor may monitor whether self-exercise rehabilitation program is regularly executed by the patient. In addition, the analyzed data could facilitate doctors to provide a proper follow-up medicine treatment or adjusted strength of physical training program during patient's next visit. Heart failure is a result of many different diseases, if we could invite more users to join this project, we would collect more valuable data records under various conditions and enhance the performance of the proposed system. It could successfully enhance the 6WMT program for different types of chronic diseases.

E. *Warning mechanism*

Heart failure is a state in which cardiac output cannot supply to meet the need of the body when resting or exercising. The symptoms of HF include shortness of breath, chronic coughing, wheezing, edema, fatigue, lightheaded feeling, nausea, lack of appetite, confusion, and high heart rate. However, any single sign or symptom might not be cautious for potential HF patients at the beginning stage. Thus, this designed system would provide two kinds of warning mechanism for HF patients and general users simultaneously. For HF patients, the exercise program provides the most important self-exercise rehabilitation for patients, which is often evaded or neglect by HF patients. After patients finishing 6MWT through bracelet devices, the system may compare collected data with previous testing results to inform patients whether their exercise intensity is satisfied. From Equation (2), an HF patient needs to reach the assigned target heart rate X_t to achieve the effectiveness of exercise rehabilitation. The system retrieves resting heart rate as X_{rest} from 2-minute resting schedule after 6MWT and the maximum walking heart rate during tests. Doctors can easily update the limits of the exercise program according to the analytical results provided by the system, and it is noted as Y_{lim}.

$$X_t = X_{rest} + [(X_{max} - X_{rest}) * Y_{lim}] \qquad (2)$$

Due to multiple possible causes of HF, the symptoms and signs of HF are relatively complicated compared to other diseases, especially for patients at early stages. However, the developed system provides a chance to solve the detection problem for general users, it could perform classification and prediction after a user taking 6MWT evaluation. The cloud server retrieves user's 6WMT physiological data and compares with the raw medical dataset of HF patients to evaluate user's heart function levels, and testing results suggest the user whether he/she is required to make further detail examinations in hospital. Here, we tested on 5 healthy subjects. The ages are from 22 to 31 years old, and the measured walking distances are distributed ranging from 450 to 600 meters. The testing records are shown in Figure 3. Pink dots represent the recruiting healthy and young users. Their 6WMT features are all located beneath the HF patients with mild conditions.

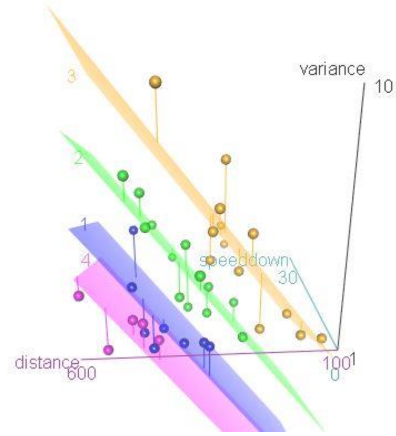

Figure 3. The pink dots represent 6WMT features collected from 5 healthy and young testing subjects.

III. RESULT AND CONCLUSION

In this study, a 6MWT system was successfully constructed for HF patients and general users. We have collected ground-truth physical data from 50 HF patients with different function levels of heart organ from Chang Gung Memorial Hospital (CGMH, Keelung Division, Taiwan). All HF patients volunteered for participating this pilot study and took 6MWT evaluation for the personal monitoring program and these physical data were applied as a training dataset. Although 6MWT is an easy test, non-invasive, and widely applied on several kinds of diseases, patients with different step size, hight, and weight also significantly influence the measured distances that they can afford. Hence, the proposed system utilized more conditions to distinguish the levels of heart failure. The age intervals of the collected dataset are between 31 to 89 years old, and the measured walking distances range from 120 to 505 meters. The proposed system is constructed by integrating IoMT devices, big data analysis, and cloud server computing techniques. By adopting the CGMH medical dataset, we could classify different functional levels of HF patients by featuring 4 different parameters only including 6MWT distance, walking heart rate variance, resting heart rate variance, and diagnosed HF groups as our classification bases. Based on the trend analysis and multidimensional curve fitting, we can divide the training datasets into three different levels of HF patients. It should be noticed, different brands of bracelet devices may provide different recording time, and it should to be calibrated in advance. We have tried to validate our designed system and invited 5 young and healthy testing subjects. The results show that all healthy young people possessing features clearly located beneath the HF patients classified with mild conditions. Depending on the results, the proposed system could send a notification message to encourage and remind HF patients to keep self-exercising to stay healthly. To general users, once the 6MWT results are classified as HF patient groups, the system would send an early warning message to notice him/her to take further examinations. This proposed system provides an integrated mechanism to monitor self-exercise rehabilitation of HF patients, and these tracking functions could facilitate doctors more evidences to diagnose HF patient's recovered conditions. It would be helpful for medical treatment of the follow-up visit in hospital. Utilizing the features of resting heart rate, walking max heart rate, and limitation heart rate, the system could help doctors or rehabilitation trainers to set or adjust a proper target for HF patients. These customized standards are expected to be reached when patients perform self-exercise. Again, among many factors that might lead to heart failure, to invite more volunteers and increase more medical data would enhance the clustering and prediction accuracy of the system. Finally, the successful application of 6MWT for HF patients, the designed system may further be extended to distinct chronic diseases under different patient group training, clustering, and prediction.

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