Ambulatory monitor derived clinical measures for continuous assessment of cardiac rehabilitation patients in a community care model

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***Abstract*— Ambulatory monitoring tools provide a means for continuous assessment of patients compared to hospital based tools. Continuous physiological information such as ECG, heart rate, activity profile and energy expenditure can be derived from a single waist mounted activity monitor. This information when translated into clinically relevant measures, not only reflects patients condition in a similar way as convention tools but also shows the continuous status of functional capacity. In this paper, various such clinically relevant measures which can be derived from acceleration and ECG signals are described.**

I. Introduction

Health care systems worldwide are facing an increasing challenge to monitor and timely intervene in preventing functional loss of the ageing population with chronic diseases. Cardiovascular disease is the leading chronic disease among the ageing population that burdens the global health and economy [1]. Cardiac rehabilitation programmes at hospitals incorporating patient education, exercise training and lifestyle modification have been proved to be effective in improving the functional status or health-related quality of life conditions of chronic obstructive pulmonary disease (COPD) patients [2]. Patient's functional status is determined by measuring the ability to carry out activities of daily living (ADL) independently. Various tools such as 6-minute walk test, sit to stand test, time to up and go test, etc. provide a quantitative measurement of functional status. However, with the increasing aging population and limited hospital resources, it is not sustainable to provide such programs in hospitals anymore. In short, rehabilitation programs have to be shifted from hospital centric mode to community centric mode, i.e., monitoring, interventions and assessment of the patients from their own homes.

Telemonitoring technologies have been proposed as a viable solution to reduce hospital overloads [3]. Using such technologies, relevant data can be accessed remotely by health care professionals through the internet and mobile devices (illustrated in Figure 1). This information which is derived from patients living environment provides more continuous information than the existing hospital based measures. The existing measures to assess functional ability are standard tests carried out at various stages of the rehabilitation. Whereas the ambulatory derived clinical measures from a free living environment are continuous and more physiologically representative information than the constrained hospital environment for health care professionals. Through these measures the health care professionals can monitor the progress of the patients condition remotely and intervene as required.

Over the recent years, ambulatory monitoring of patients using either accelerometers or heart rate monitors have been widely studied telemonitoring technologies due to their low cost and less obtrusive nature. Accelerations of body segments can be measured by attaching accelerometers on one or more body segments (e.g., trunk, thigh, and shank). The body postures (i.e., standing, sitting, lying, etc) can be recognized by analyzing these acceleration signals [4][5]. Similarly, ambulatory heart rate monitors/ECG recorders worn on the chest either through a strap or ECG leads have been useful to obtain continuous cardiac functionality.

Nonetheless, the information recorded from either of these ambulatory technologies needs to be translated into clinically relevant information, i.e., measures which can show the patients condition continuously. For example, total energy expenditure per day can be used as an indicator to assess how the patients activity level varies over a period. Such clinically relevant ambulatory measures to quantify functional performance can be derived from both the accelerometer inferred activities and the ECG derived features such as heart rate variability, RR interval, etc. In this paper, we list some of the measures derived from both accelerometer and ECG signals which can be used for assessing cardiac rehabilitation patients remotely.

The rest of the paper is organized as follows. In next section, we describe the cardiac rehabilitation program along with the existing tools to assess patients functional performance. The clinically relevant ambulatory measures that indicate functional performance are presented in Section III. The results and discussions are provided in sections IV and V, respectively.

II. Cardiac Rehabilitation program

In the rehabilitation program at North Lakes (QLD, Australia), patients attend exercise sessions twice a week at the hospital gym for a duration of six weeks. In every session, patients perform six different exercises for a total duration of one hour. Typical exercises are: biking, rowing, walking on stairs, arms exercise, walking on treadmill, and working with exercise ball. The patient's condition and progress is also

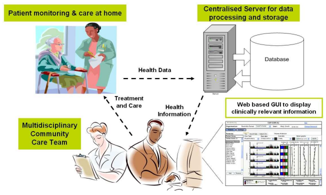

Fig. 1. Community centric care model envisioned through telemonitoring technologies.

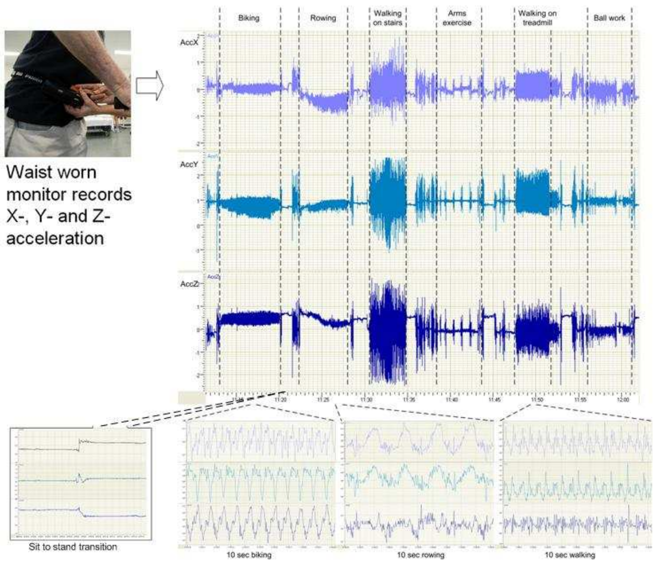

Fig. 2. Acceleration signals during cardiac rehabilitation program for an arbitrarily chosen patient.

monitored during every exercise session by a physiotherapist. Each exercise activity lasts from 3 to 7 minutes and the physiotherapist can vary the load setting and duration of the exercise to achieve optimum performance level for the patient. At the end of each exercise patients record their pulse rate, $SP0_2$ (pulse oximetry), and the Borg scale (difficulty). They wear an accelerometer device for the entire period of rehabilitation. Due to the obtrusive nature of ECG leads patients wear them mainly during the rehabilitation session. The order and timing of the different activities during the session are manually recorded by the patient to enable identification of the activities from the raw signal. Figure 2 illustrates the three axis acceleration signals of a patient during a complete exercise session of cardiac rehabilitation. The characteristics of different activities are apparent in the collected raw signal. Ten second sections of raw signals during high intensity and periodic activities: biking, rowing and walking along with a sit to stand transition are shown in details below the main graph. The activity signals show different patterns during each activity.

Currently, there are various tools used in rehabilitation to assess the progress of patients. In the rehabilitation program mentioned above the patient's condition of functional capacity is assessed at the beginning and end of the program by using a six minute walk test (6MWT), where the patient walks for six minutes and the traveled distance is measured along with their weight. A vast majority of the hospital based rehabilitation tools usually quantify the progress using the information collected before and after rehabilitation. They fail to take into account the role of intermediate information which represents the patients activity style in between the sessions at their home. A more realistic information on patient's condition can be obtained if the measures used to assess rehabilitation progress are derived using continuous information. In the next section, we discuss some of these continuous measures.

III. Ambulatory Rehabilitation progress measures

As discussed earlier, changes in the functional capacity of a cardiac patient undergoing rehabilitation is widely assessed using both quantitative functional tools such as 6MWT, time to up and go test, etc, or objective tests such as self reported questionnaires, etc. Studies have shown that the patients rate themselves on a higher functional level in the self-reported questionnaires than is observed objectively in the performance-based tests, thus underlining the importance of the questionnaires as a tool in assessing progress [6]. The quantitative functional tools are consistent and thus, overcome the inherent drawback of self reporting questionnaires. Nonetheless, we can obtain continuous status of functional capacity by deriving functional tools from ambulatory accelerometer and ECG signals. Each of these ambulatory tools ultimately provide an estimation of the functional capacity which correlates with the variation in the pattern and intensities of daily living activities such as walking, sleeping, posture transitions, exercise intensities, etc.

Hence, we have identified following measures derived from ambulatory accelerometer and ECG signals which can act as continuous cardiac and stroke rehabilitation progress indicators.

A. *Metabolic expenditure*

One of the main objective of cardiac rehabilitation programs is to increase levels of physical activity of patients. An usually accepted recommended level of physical activities to prevent adverse events among the patients is a minimum of 30 to 60 minutes of moderate activity three to four times per week supplemented by an increase in daily lifestyle activity [7]. Studies have shown that increase in metabolic expenditure during rehab session alone may not be sufficient to satisfy these recommendations. In [8] it was shown that the amount of physical activity was generally adequate on the days of rehab, but failed to reach target levels on non-rehab days. Other similar studies encourage patients to incorporate life style physical activity and additional exercises during non rehab days. We have derived metabolic expenditure from the accelerometer data which showed correlation greater than 0.88 with energy expenditure observed with simultaneous VO2 testing. Ambulatory monitoring of metabolic expenditure which can be derived from accelerometer signals can provide a means to assist in achieving this goal.

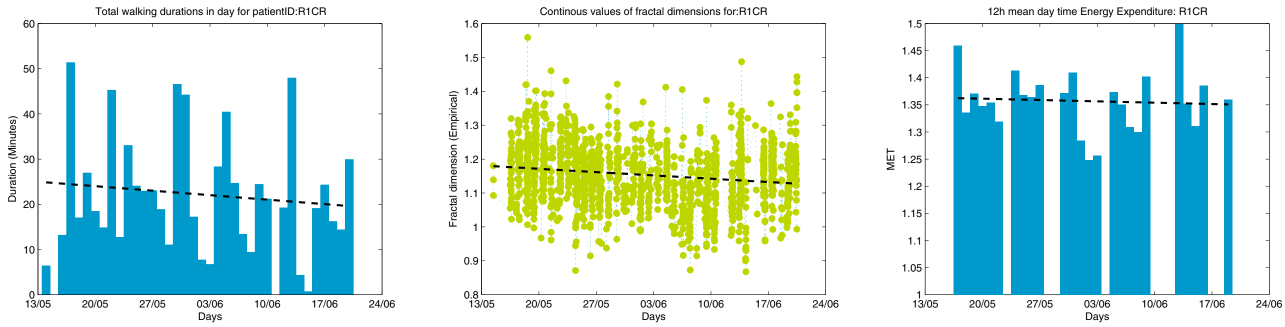

Fig. 3. Rehabilitation progress for a patient as indicated by walking durations (left), fractal dimensions (centre) and energy expenditure (right) for the entire period. Lower values of fractal dimensions indicates improved gait characteristics.

B. Mobility

It is vital to have a good level of mobility to achieve independent living. Changes in mobility of a patient as seen through various mobility tests such as 6MWT, 12 MWT, etc have been shown to correlate with changes in patients functional capacity [9]. Mobility can be quantified by measuring a) total daily walking duration, b) walking speed and c) frequency of daily walking and d) walking control through gait characteristics. Each of these measures can be derived continually by analyzing acceleration signals. For each walk activity detected we can calculate fractal dimensions which demonstrate a measure of gait control [10], thus providing continuous mobility control measures. We have developed techniques to discriminate walking from other high intensity activities in accelerometer data using wavelet decomposition. We further calculate fractal dimensions for every walking activity to using wavelet approach and use it as gait characteristic measure. Rehabilitation interventions that can be designed using these measures are beneficial in helping to improve gait and functional independence among older persons [11].

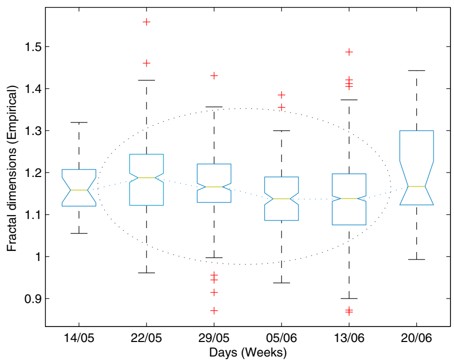

Fig. 4. Box plot of fractal dimensions for weeks 1-6 of the rehab.

C. Postural transitions and balance

The ability to rise from a chair (sit-to-stand transfer task) is considered as one of the most demanding functional tasks, an important indicator of daily-life functional independence for elderly people and as a risk factor for falls. For example, the rate of rise in force (dF/dT) was significantly lower in stroke fallers than in stroke non-fallers and healthy subjects [12] Deterioration in balance function clearly starts at relatively young ages and further accelerates from at about 60 years and upwards [13]. Various measures which can represent the trends in postural transitions and balance can be derived from accelerometer signals. We proposed techniques to detect transitions automatically from accelerometer signal vector magnitude and calculate their durations. A statistically significant difference was found in sit-to-stand transition durations in elderly patients compared to healthy subjects (significance of a one-tailed t-test was P=0.002) [14]. Thus it is possible to assess the functional ability by continuously keeping track of transition durations and intervene based on the trends.

D. Adverse events

Cardiac patients have increased fear of falling due to diminished functional capacity. The ability of accelerometers to discriminate falls from ADL's makes it suitable to detect falls occurring in elderly patients [15]. Detecting adverse events is vital to be able to attend to the patients in a timely fashion.

E. ECG derived measures

Some of the clinically relevant measures which we can derive from ambulatory ECG or heart rate are a) heart rate variability, root mean square difference of successive RR intervals (RMSSD), respiratory rate, low and high frequency powers, etc. These measures are useful in assessing the patient's cardiac functionality. Ambulatory ECG derived measures when obtained along with activity information provides many useful features. For example, reduced heart rate variability is associated with an increased risk factor for future cardiac events [16][17]. The combination of ECG derived measures and activity information provides complementary information to follow up patients condition in a clinically significant way. For example, we can look at the trends in RMSSD during high intensity activities to follow up the patient's autonomic nervous system's parasympathetic performance or respiratory rate during and after high intensity activities to follow up the stamina recovery rate. We can

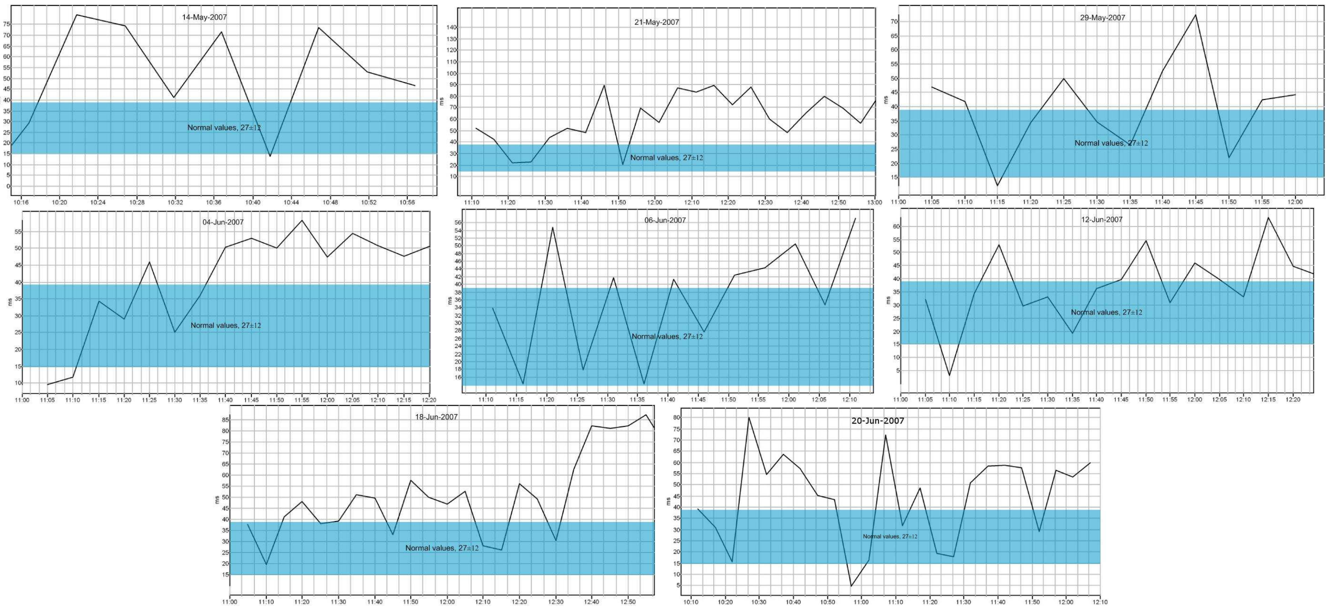

Fig. 5. RMSSD values during rehab sessions for a patient. Each figure represents one session. There were total 8 sessions for this patient.

assess the cardiac risk by tracking these heart rate derived measures coupled with activity information either continuously or intermittently, through ambulatory ECG recordings.

All these ambulatory measures provide clinically relevant information just like the standard measures used in hospital. Besides that they are collected remotely and not restricted to hospital based test administration. Since these measures are obtained continously, it is possible to initiate timely interventions that aim to prevent loss of functional abilities and to improve the quality of life of older people. Interventions based on these measures are expected to reduce the patients partial or total dependence for support in carrying out their activities of daily life (ADL). In the next section, we illustrate some of these measures obtained from an arbitrarily chosen patient.

IV. Methods

As part of a larger study we are currently collecting activity/ECG data from patients undergoing cardiac rehabilitation. We analyze the acceleration signals recorded with a three axis accelerometer, which is mounted on the waist, close to the center of the mass of a person. The acceleration signals provide information on physical activities of the person. The accelerometer used here is part of a personal monitoring device: *Alive Heart Monitor*, marketed by *Alive* Technologies, Australia. It provides data for every spatial axis with sampling frequency of 75 Hz and a range of -2.7 to $2.7\ g$. We down sample the acceleration signals to 25Hz which is more than sufficient enough to contain all the frequencies for human activities. It also records ECG signals sampled at 300Hz through a single lead.

We have derived activity information and the various significant measures described in Section III using acceleration data for the whole 6 weeks to look at trends. Figure 3 shows total daily time spent in walking, gait characteristics of walking and energy expenditure over a period of 6 weeks for an arbitrarily chosen patient (ID:R1CR) undergoing rehabilitation. These plots show an overall improvement in the patient's performance. Box plot for the weekly variations of fractal dimensions which indicate gait characteristics are shown in Figure 4. There is a statistically significant change in means of fractal dimensions between week 2-3 and week 4-5, indicating an improvement in gait performance during this period (based on Analysis of Variance (ANOVA)). However, the fractal dimension mean for week 1 and week 6 are not different statistically. If we use the conventional approach and assess the patients rehab progress by looking at measures only at beginning and end of rehab, we might come to the conclusion that there is no progress and might miss the progress seen in between the rehab.

We also calculate heart rate variability, RMSSD, respiratory rate, etc using the ECG signals obtained during rehab session. The analysis is done using FirstBeat Pro software (Finland). The RMSSD during the exercise sessions for the same patient are shown in Figure 4. RMSSD is a measure of parasympathetic response whose optimal values for a healthy individual are in the range of 27 ± 12 (shaded region in Figures). From Figure 4, we can see that the RMSSD curve during the early stages of rehab is further away from shaded region compared to the later stages. Besides showing the overall trends in RMSSD performance, this information can assist rehabilitation team to provide improved rehabilitation by looking at intermittent variations in the RMSSD values.

Collective information provided by all these measures better reflect patients overall functional capacity than by individual measure. These tools will provide care providers complementary information to improve the care process.

V. Discussion

In this paper, we have described some of the useful measures that can be derived from accelerometer and ECG data which are useful in assessing the progress of rehabilitation. These measures can be used in both free living and hospital based environment. Thus would enable assessments of functional capacity that is required in the ongoing care for chronic disease patients. In addition, we can obtain continuous status of functional capacity using these measures thus overcoming the drawback of conventional measures. Currently, we are evaluating and refining these measures to suit cardiac rehabilitation.

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