Pervasive Body Sensor Network:
An Approach to Monitoring the Post-operative Surgical Patient

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Abstract

Patients recovering from abdominal surgery are at risk of complications due to reduced mobility as a result of post-operative pain. The ability to pervasively monitor the recovery of this group of patients and identify those at risk of developing complications is therefore clinically desirable, which may result in an early intervention to prevent adverse outcomes. This paper describes the development and evaluation of a pervasive network of body sensors developed for monitoring the recovery of post-operative patients both in the hospital and homecare settings.

1. Introduction

Abdominal surgery is commonly performed for a range of conditions such as colon cancer (requiring bowel resection), gallstones (requiring cholecystectomy or removal of the gallbladder), or hernias (requiring repair of a defect in the abdominal wall). Although the indication for abdominal surgery may vary, one thing that these patients all have in common is their abdominal wound. In open surgery, this wound is continuous and may be as long as the abdomen itself (for example 30cm), whereas in laparoscopic (keyhole) surgery a patient may have four or five wounds, each of 2cm in length. All patients with abdominal wounds experience some post-operative pain despite efforts to control this with analgesic medication, and this pain impairs chest expansion, the ability to cough, and postoperative mobilization. Inadequate chest expansion and a reluctance to cough can have a dramatic effect on patient recovery because they result in a failure to adequately oxygenate venous blood and clear respiratory secretions. This in turn results in shortness of breath as well as a susceptibility to developing post-operative chest infections. Mobilization in the postoperative period in terms of standing, walking, and performing daily activities is important not only because this prevents venous stasis in the legs thereby reducing the risk of deep venous thrombosis (DVT), but also because it helps the patient return to a normal pattern of life.

In an attempt to reduce these wound-related complications, two strategies have been used. The first is to reduce the size of the wound using laparoscopic techniques, which as mentioned earlier results in multiple small incisions. Laparoscopic surgery does significantly reduce the length of hospital stay and increase post-operative mobilization as compared to open surgery [1], but it can itself result in impaired post-operative lung expansion for a different reason. Laparoscopy requires the insufflation of carbon dioxide into the abdominal cavity to allow visualization of the organs during surgery. This can cause splinting of the diaphragm and basal atelectasis (collapse of the lung bases) which impairs respiration and predisposes to chest infection [2]. The second strategy that has been used is the development of initiatives such as “ambulatory” [3] and “fast-track” [4] surgery. Both involve carefully selecting patients who can be mobilized quickly following their operation, and actively encouraging them to do so with focused physiotherapy. Such initiatives have been welcomed by many patients with some evidence suggesting that when given the choice, most patients prefer to recover at home as compared to being in hospitals [5].

The rate-limiting factor in safely discharging patients from hospital following abdominal surgery has been the need to closely monitor them until they have shown adequate signs of recovery, both in terms of mobility (the ability to mobilize independently) and adequate respiratory function. In addition, “at risk” patients are often visited at home following discharge by a district nurse to monitor their progress. It is however often difficult to quantify both the recovery they are making, and whether their vital signs show a trend towards the development of a respiratory complication during such a visit which is essentially a “snapshot” in their recovery time.

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In an attempt to quantify post-operative convalescence, pedometer systems [6] and ankle-worn accelerometers have been used [7], but the bulkiness of these devices combined with an absence of wireless capabilities has made data collection in a pervasive and continuous manner difficult. Ubiquitous wireless monitoring systems offer the ability to continuously monitor a patient as they move freely around their home or hospital environment. The use of Body Sensor Network (BSN) [8] allows multiple sensors to be connected to a single network and detect changes in patient wellbeing as they recover from their operation, with on-body processing and wirelessly transmission of data to a desired destination where their progress can be monitored. The wireless nature of this approach removes the need for the patient to be attached to bulky equipment which in turn impairs their mobility

This study intends to evaluate the suitability of a pervasive wireless body sensor network of vital signs and motion sensors for measuring the heart rate, oxygen saturation, and motion patterns in post-operative surgical patients. It presents the preliminary data from this system, which was tested in a group of normal volunteers as they underwent a range of activities similar to those of post-operative patients during the recovery period.

2. Methods

A wireless ear-mounted device containing a pulse oximeter (MCC ChipOX®) clipped to the subject's earlobe, two dual axis accelerometers (Analog devices: ADXL102JE), a BSN node [8], and a CR2 camera battery, was worn by our subjects. The entire wireless apparatus was worn on the right ear, with the BSN node receiving data from the sensors, and wirelessly transmitting the information to a laptop via a secure low-power wireless link. Data was then stored onto the laptop where results could be accessed and analyzed. The pulse oximeter allowed the measurement of heart rate and oxygen saturation, whilst the output from the two accelerometers were used to determine the motion pattern in X, Y, and Z planes as the subjects performed different activities.

In order to simulate the range of activities that a surgical patient may undertake during their recovery period, a test circuit was set up and each subject asked to perform the following activities in the order stated: sitting down and standing up (five times), lying down on a mattress and standing up again (five times), eating a banana, drinking a cup of water, walking on a treadmill for three minutes (at a speed of 5 km/h), running on a treadmill for three minutes (at a speed of 8 km/h), walking on a treadmill again for three minutes (at a speed of 5 km/h), and finally sitting down and recovering from the exercise. The total circuit time lasted approximately 25 minutes.

The main outcomes of interest in this study were: 1) the ability to differentiate the activities that the subjects were performing on the circuit using the ear-worn accelerometers; 2) the ability of the an ear-worn pulse oximeter to monitor the heart rate and oxygen saturation over a range of activities; 3) the ability of the sensor to pick up physiological recovery from increases in heart rate such as that following treadmill exercise.

3. Results

Twenty normal subjects volunteered to take part in this study, all of whom were fit and well at the time. The mean age of the group was 29.7 (+/-4.71) years, and a male: female ratio of 17:3. The perceived level of fitness of the varied greatly between subjects, with the duration of weekly exercise ranging from 0 to 240 hours.

Motion pattern data from the two accelerometers showed that for the activities of sitting, standing, lying down, walking, and running, very distinguishable motion patterns were noted. Figure 1 shows the pattern generated when subjects were asked to lie down on a mattress, with Figure 2 showing the change in pattern from walking to running, and back to walking again.

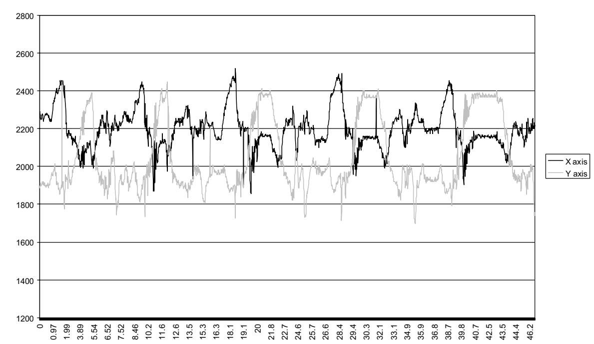

Figure 1. The accelerometer patterns generated when subjects were asked to lie down on a mattress and stand up five times.

These patterns were found reproducible for each subject and whilst some differences in these patterns were noted for different subjects, they were notable as obvious periods of activity. In addition to this the accelerometer data was able to provide us with context information when interpreting the heart rate and pulse oximeter results.

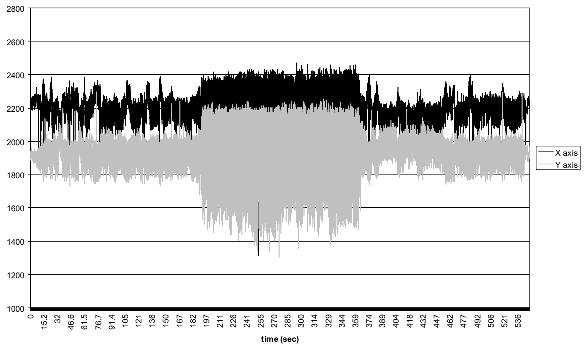

Figure 2. The change in accelerometer patterns when the subjects went from walking to running, and back to walking again.

In all the twenty subjects studied, the heart rate rose when they performed an activity such as lying down and standing up five times, as well as walking and running. Whilst viewing these in isolation would not allow us to understand why this was happening, the simultaneous accelerometer context data showing a dramatic increase in subject mobilisation made interpretation possible.

Following a three minute running period, the ear pulse oximeter was able to detect and clearly show the recovery time to a heart rate of less than 100 beats per minute in all but one subject. In this subject, the sensor did not transmit the data on heart rate accurately to the laptop. Figure 3 below shows the heart rate pattern of a subject as they start running, run for three minutes, and stop running.

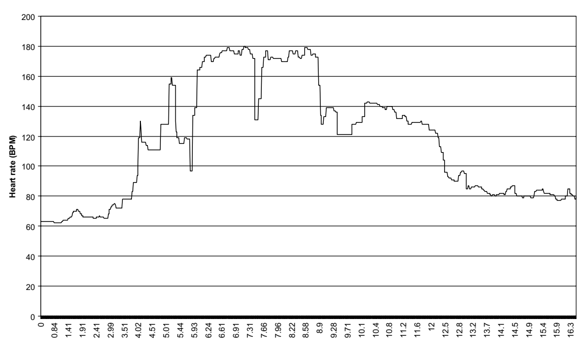

Figure 3. Heart rate data from the time subjects start running to the time they recover after stopping, this pattern was seen and captured in 19 subjects

Table 1 shows the recovery times of the 19 subjects in home heart rate recovery measurements were possible, ranging from 1.76 to 6.87 minutes. The subjects were also asked now many hours a week they exercised, and although our results suggest that those subjects who claimed to exercise more per week had quicker recovery (The two subjects at the top both exercised regularly for more than three hours a week, and the last four undertook no active exercise), the actual fitness of the volunteers was not objectively measured in this study.

Table 1. Recovery times and weekly exercise patterns of the 19 subjects included in the study. Resting and maximum heart rates (HR) achieved during the circuit are also given.

Subject	No. of min exercise per week	Recovery time to 100 bpm	HR Rest (bpm)	HR Max (bpm)
1	150	1.76	61	162
2	240	1.84	77	142
3	30	2.48	71	188
4	60	2.81	65	150
5	160	3.07	68	162
6	240	3.31	52	173
7	100	3.38	81	160
8	165	3.41	68	131
9	100	3.46	80	147
10	60	3.65	80	161
11	180	3.74	66	155
12	30	3.86	57	180
13	90	3.87	64	159
14	60	3.93	79	162
15	0	4.46	72	157
16	0	4.82	74	160
17	0	5.99	70	172
18	0	6.82	82	166
19	0	6.87	89	146

Oxygen saturation could be detected throughout the study, but was least accurate during the running exercise, when data from the sensor was either not sent, or shown as being erroneously low. This suggests that the movement produced by running was significant enough to affect the pulse oximeter readings from the ear lobe. During the remainder of the circuit including walking, the oxygen saturation remained above 95% for all our subjects, which is as expected in this healthy population group. Validity of the physiology data from the ear sensor was tested by simultaneously measuring these parameters using electrocardiogram (EKG) and finger probe oxygen saturation sensors, showing excellent correlation.

4. Discussion

This study has demonstrated the potential suitability of an ear-worn sensor for the post-operative monitoring of patients both in terms of their respiratory function (oxygen saturation and heart rate), as well as their mobility (accelerometer data). The wearable nature of this ear-mounted sensor means that patients are likely to be able to perform their daily activities without being hindered, but also that they may not notice the device at this location as much as if it was placed on their trunk or limbs. The finding that the device was able to pick up distinctive movement patterns in a reproducible way, and allowed pairing of this information to heart rate and oxygen saturation data, is likely to be an important determinant of its success in a surgical patient group for two reasons. Firstly, such an ear-worn device may be able to quantify the mobility of a recovering patient, thereby determining their rate of recovery over a period of time following surgery. This has clinical importance because if a patient is not recovering adequately following surgery, they can be selected to receive a more tailored intervention such as chest and mobilization physiotherapy. Secondly, knowing the context in which physiological changes are occurring is a vital part of any pervasive monitoring system, and simple accelerometer data that shows that the patient is actively moving at the time of an increase in heart rate, makes interpretation of this information as "normal" or "abnormal" more accurate.

The finding that motion artifacts during running affected the pulse oximetry results is an important and well-known limitation of this method of oxygen saturation assessment [9]. Whilst it may be relevant for a more active group, patients who have had recent abdominal surgery are unlikely to undertake this level of exercise in the immediate post-operative period. Indeed, once patients recover and start to actively exercise by running, the need for pervasive monitoring has passed. Motion artifact should not therefore play a significant part in these patients.

It has been shown that pre-operative assessment of cardiovascular and respiratory status prior to surgery, allows a better appreciation not only of a patient's response to surgery and the physical strain this imposes, but also of their likely recovery [10]. The use of a pervasive monitoring system such as the ear-mounted device mentioned in this study may therefore be extended to the pre-operative period as well as the post-operative one. The former might be able to identify those at risk of developing a complication such as DVT or chest infection due to reduced mobility. It will also allow for the determination of the person's "baseline" activity prior to surgery, meaning that recovery towards their normal baseline could be more accurately tracked. The benefit of a system that identifies those at risk and intervenes to prevent complications is that it can potentially reduce the cost of their care reducing the need for further hospital admission. Limitations of this study include the fact that this sytem was tested on volunteers and not patients, and that other motion detection systems such as kinematic data were not used to compare data obtained from the accelerometers. Further evaluation and clinical testing in post-operative patients is now required to assess if this system is able to accurately evaluate recovery following abdominal surgery in both the hospital and home settings.

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