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Continuous Remote Vital Sign/Environment Monitoring for Returning Soldier Adjustment Assessment

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Abstract— **A three-stage study to develop and test an unobtrusive room sensor unit and subject data management system to discover correlation between sensor-based time-series measurements of sleep quality and clinical assessments of combat veterans suffering from Post-traumatic Stress Disorder (PTSD) and mild Traumatic Brain Injury (TBI), is described. Experiments and results for testing sensitivity and robustness of the sensor unit and data management protocol are provided. The current sensitivity of remote vital sign monitoring system is below 20% and 10% for respiration and heart rates, respectively.**

I. INTRODUCTION

Traumatic Brain Injury (TBI) and Post-traumatic Stress Disorder (PTSD) are important concerns for soldiers returning from combat. TBI has become the so-called signature wound of soldiers serving overseas in modern combat. These soldiers experience repeated concussive injury to the brain, surviving in greater numbers due to improved protective gear. Repeated explosions may be damaging to soldiers in the long-run even when not in direct conflict with the enemy. As of February 2011, the US Army has experienced over 10,400 casualties wounded in action worldwide [1].

The Returning Soldier Adjustment Assessment (RSAA) research is seeking to discover correlation between sensor-based time-series measurements of sleep quality and clinical assessments of combat veterans suffering from PTSD and mild-TBI. The research program is implemented in three stages over two sites:

1) Unobtrusive room sensor unit (RSU) and Subject Management System (SMS) design and development at the General Electric Global Research (GEGR) in Niskayuna, NY
2) Clinical and sensor data collection in the Warrior Transition Battalion (WTB) barracks at Fort Gordon, Georgia
3) Sleep quality and activity metrics development and statistical analysis at the GEGR

In the first stage, our goal is to develop a sensor unit and data management system to store and process de-identified sensor and clinical data. The Room Sensor Unit consists of a collection of unobtrusive sensors, including a data acquisition device, installed in a small cabinet above the bed. There are two types of sensors in the RSU: 1) A low-energy Doppler radar that estimates heart and breathing rates whenever the subject is in the range and 2) room environment sensors that measure light, sound, room motion, temperature and humidity. In addition to the RSU, each subject will wear an actigraphy wristband that identifies activity intervals including general activity, rest, and sleep. The SMS is a web application residing on the portable study drive(s). The data will be transferred and inserted into the RSAA GEGR database for further processing.

In the second stage, we plan to collect clinical and sensor data at the WTB in accordance with an Independent Review Board (IRB) protocol. The IRB protocol is pending final approval. Volunteers will be enrolled in the study for 3 months. Each subject will be examined by clinicians in behavioral health and traumatic brain injury clinics periodically, pre-and post-deployment. Active research will continue for 1 year. All study data will be coded and de-identified by the Chief of Clinical Research at Fort Gordon, Georgia. In the final stage, we will develop algorithms to provide sleep quality metrics and various intervals of activity based on the data collected from RSU and actigraphy watch, respectively. The sleep quality and actigraphy metrics will be compared and correlated with clinical assessments including the Pittsburgh Sleep Quality Index, the Headache Impact Test, the Post-Traumatic Stress Disorder Military Checklist, and other clinical instruments. Data and information will be shared with the RSAA study partners including Eisenhower's Army Medical Center and the Georgia Health Sciences University (GHSU), formerly known as the Medical College of Georgia.

In this report we describe the first stage of the RSAA research in detail and provide an overall view of the data collection system. This paper is the first in a sequence of papers describing development of an unobtrusive sensor unit for measuring sleep quality. Our goal is to introduce the sensor unit and data collection system and challenges within. The papers following this study after the completion of data collection will describe our results. The paper is organized as follows. In Section II, we summarize findings on sleep quality and PTSD. In Section III, we describe the subject data management system and room sensor unit. In Section IV we

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explain our experiment setup to test the sensitivity the RSU. We conclude with future work.

II. SLEEP QUALITY AND PTSD/MILD-TBI

Sleep is one of the common complaints of those suffering from PTSD [2] and mild-TBI [3]. Two aspects of subjective sleep-related symptoms are included in the American Psychiatric Association's Diagnostic and Statistical Manual of Mental Disorders, fourth edition (DSM-IV), as diagnostic criteria for PTSD: the reexperiencing of the traumatic events in the form of nightmares and difficulties in initiating and maintaining sleep [4].

Although lower sleep quality is a common symptom among PTSD subjects, objective sleep-laboratory investigations are conflicting. For example, according to some studies on sleep efficiency, PTSD subjects have lower sleep efficiency compared to the control group while other studies have not found this trend (see reference therein [5]). Studies on Rapid Eye Movement (REM) sleep variables are also conflicting.

We can summarize the consistent findings correlating sleep variables to PTSD as follows. One consistent REM finding is that PTSD subjects experience an increase in REM density and higher the density more severe the PTSD (for at least combat veterans) [6]. Another finding is that PTSD subjects tend to have more violent sleep behaviors, sleep paralyses, sleep talking, and hypnogogic and hypnopompic hallucinations [7].

An increased rate of gross body movements and periodic leg movements, which are particularly associated with light sleep, is a prevalent finding in patients with PTSD. Patients with war-related PTSD had higher awakening thresholds than normal controls, as determined objectively with the use of acoustic stimulation during both REM and non-REM sleep [8], i.e., it is more difficult to awake PTSD subjects than normal control group subjects.

There may be few reasons why the results are conflicting. According to [4], the coexistence of inhibitory processes resulting in the deepening of sleep and a state of hyperarousal may explain at least some of the episodic sleep disturbances observed in patients with PTSD, as well as the divergence of sleep-laboratory findings. Also, it may be the case that PTSD subjects become so engrossed in dream-like mentation in *delta* sleep that it becomes difficult to wake them [4].

Sleep-wake disturbances (SWD), excessive daytime sleepiness (EDS), fatigue and hypersomnia are common in TBI sufferers in early stages of injury [3]. Some research suggests that decreased levels of hypocretin-1, a wake-promoting neurotransmitter, in Cerebrospinal fluid (CSF) affect sleep quality in TBI subjects. Objective sleep and activity metrics may eventually improve trending and assist clinicians in treating mild-TBI.

III. SYSTEM DESIGN

Reliable and accurate data acquisition is exceedingly important to the success of any research study. Disseminating and sharing information among the study partners is equally imperative. The RSAA data includes both relatively large-sized, novel waveform data (40 samples per second) collected in the subject's room over the course of a few months, as well as more traditional study information such as subject demographics, survey responses and clinical evaluations. Also, subject actigraphy data is periodically collected providing information on general activity patterns. Ensuring a good information flow requires creating several applications and a robust transfer mechanism.

A. Subject and Data Management System

The SMS is a web application residing on the portable study drive(s). Subjects are identified by ID only. The application is password protected. The SMS is used by the CRC to manage subject activity including adding and removing subjects, recording clinical evaluations and self-assessments, sensor assignments, scheduling data collection, and for general reports. The portable SMS database is regularly exported and imported from the portable application to the GEGR RSA database. The SMS database is eventually used by the GEGR Import Application (IA) and other research software systems to link subjects to sensor data and all assessment outcomes. This link is crucial for study analysis.

Room sensor waveform data is recorded on a secure digital (SD) card by the data acquisition box (DAQ) connected to the sensors in the subject's room. Signal samples are recorded at the rate of 40 Hz for Doppler radar, motion, light, sound, temperature and humidity. Sample recordings can grow to four or five hundred megabytes of data per week per subject. The CRC copies the subject waveform data file from the SD card to a portable drive on a weekly basis. A new SD card is placed in the DAQ and the existing card is archived. After all subject data is collected for the week, the portable drive is shipped overnight to GRGR. Several portable drives are cycled back and forth from Fort Gordon to GEGR over time.

Actigraphy data consists of 30-second accelerometer samples and is imported weekly into a proprietary database maintained by the CRC. After importing, estimates of activity intervals including daily rest and sleep are produced by the accompanying software. Subject interval estimates are exported to a comma separated file and the files and database are transferred to GEGR along with the DAQ waveform data as described earlier.

At GEGR the SMS, the waveform and the actigraphy data all come together. The DAQ uses a naming convention that codes every waveform file it creates. The GEGR IA compares each filename to an assigned DAQ table in the SMS and registers the incoming files in the data collection table. A scheduled task eventually processes registered waveform files, performing signal processing, evaluating room environment conditions, and estimating heart and breathing rates. Results are inserted into the Returning Soldier Analysis (RSA) database. Our goal is then to generate sleep quality and activity metrics and perform a statistical correlation analysis for PTSD and mid-TBI as shown in Fig. 1.

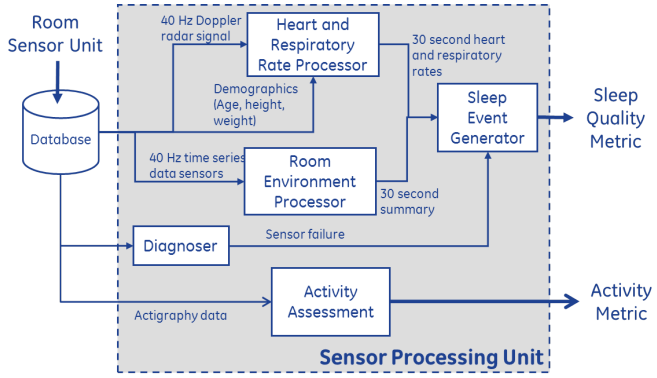

Fig. 1. A block diagram of the room and activity sensor processing from data collection at the barrack to the generation of metrics correlation analysis for PTSD and mild-TBI.

B. Room Sensor Unit

The room sensor unit (RSU) contains two types of sensors: 1) Vital Sign Sensor (VSS) and 2) Room Environment Sensors (RESs). The VSS is a pulse Doppler radar operating at 5.8 GHz with a pulse repetition frequency of 108 kHz. The pulse Doppler radar is used to detect the periodic motion of the chest wall from breathing and heartbeat. The respiratory and heart rate monitoring using microwave doppler radar were first achieved in late 70s. In 80s and 90s, signal processing tools were incorporated into the radar configuration to separate the waveforms for respiratory and heart rates. Recently, ultra-wideband radar has been used to monitor heart and respiratory rate. In [9], authors describe a Fast Fourier Transformation (FFT)-based method to determine the heart and respiratory rates upon detection of a human subject in the radar range using an ultra-wideband radar. A more detailed history of utilizing radar in physiological monitoring can be found in [10].

The Doppler shift due to periodic movement with no net radial velocity can be described as a phase modulation [10]. The transmitted radar signal is

$$T(t) = T_0 \cos(2\pi f_c t + \phi(t)) \quad (1)$$

where f_c is the pulse carrier frequency and $\phi(t)$ is the phase noise of the oscillator. The received signal can be approximated as

$$R(t) \approx R_0 \cos(2\pi f_c - \frac{4\pi d_0}{\lambda} - \frac{4\pi x(t)}{\lambda} + \phi(t - \frac{2d_0}{c}) + \theta_0) \quad (2)$$

where $\lambda = c/f_c$ is the wavelength of the transmitted wave. When $x(t) \ll \lambda$, the mixing of the transmitted and received waves results in the baseband output to have the *same frequency as the periodic motion*, which makes it possible to determine heart or respiratory rates by measuring the frequency of the baseband output signal [1].

In order to determine the heart and respiratory rates, the Doppler radar output signal needs to be decomposed into two signals corresponding to the movements of the chest wall due to heartbeat and respiration. In general, resting heart and respiratory rates have distinct rates. The resting heart rate of an adult is between 50 to 90 beats per minute (bpm) and the resting respiratory rate of an adult is between 9-24 breaths per minute (brpm). We consider three different methods from the literature for separating the heartbeat and respiration signals. The first method, peak-finder, determines the location of the peaks from the time-domain signal. The second method calculates the short-time Fourier transform to determine the frequency component with maximum amplitude (power) over sliding windows [10]. The third method assumes that the heart rate signal is nearly periodic with slight variation and uses maximum likelihood [11].

The RESs consist of light and motion sensors, temperature and humidity probes, and sound meter. The light sensor is optimized to detect wavelengths that are visible to the human eye (380nm to 780nm) [12]. It has a built-in optical filter for spectral response similar to that of the human eye. The motion sensor detects changes in infrared radiation which occur when there is movement by a person (or object) which is different in temperature from the surroundings. Circuitry is contained in a TO5 metal package, providing at least twice the noise withstanding capability as conventional type [13]. The humidity and temperature probe is durable and cost-effective [14], and is suitable for battery powered applications because of its very low current consumption. The relative humidity measurement range is 0-100% RH. The temperature measurement range is -40-60 Celsius degrees with accuracy $\pm$0.6 Celsius degrees. The sound level meter contains a 0.5" electret condensor microphone with measurement bandwidth of 31.5 Hz- 8 kHz.

IV. DESIGN EXPERIMENTS

In this section we describe our experiments to determine the sensitivity of the VSS with respect to respiration and heart rates measured by spirometer and oximeter, respectively. We conducted the experiments on human subjects in accordance with IRB protocol 10036-01. We collected spirometer, oximeter, and RSU data with BIOPAC MP, a computer-based data acquisition system similar to a chart recorder or data viewing device. The BIOPAC MP data acquisition device has a differential amplifier module (DA100) to the MP150 module and a high sensitivity differential pressure transducer (TSD160) with an airflow head (RX137) as spirometer. For oximeter measurements, BIOPAC MP has a pulse oximeter module (OXY100C) with finger clip SpO2 transducer (TSD123A). The pulse oximeter module (POM) provides pulse waveform that can be used to extract heart beats per minute.

We conducted 12 experiments on each subject with varying respiration rate (fast and normal/slow), sleep position (facing left, right, up, or down), and antenna height (low/high). During the experiment, we had the antenna angle setup such that the beam is focused slightly below the pillow on the bed. Each experiments lasted for 2 minutes. Our objective was to tune our system and algorithms to generate heart and respiration rate estimates every three seconds with

[1]Few restrictions apply since the phase shift in Equation 2 may result in null points. Methods to overcome this problem are provided in [10].

a normalized mean square error, difference between the rate obtained by the RCR and the spirometer (or oximeter) normalized by the latter rate, of 10% and 20% for heart and respiration rate, respectively. The heart and respiration rates extracted from one of the subjects is shown in Fig. 2, The RCR rates are shown with blue "o" markers while spirometer and oximeter rates are shown with black dashed lines. We observe that the estimates from RCR are within the sensitivity range for this subject. We plan to collect more data to statistically validate the sensitivity of the system. Currently, we have data collected from 2 male and 1 female human subjects within the age range of 30-55.

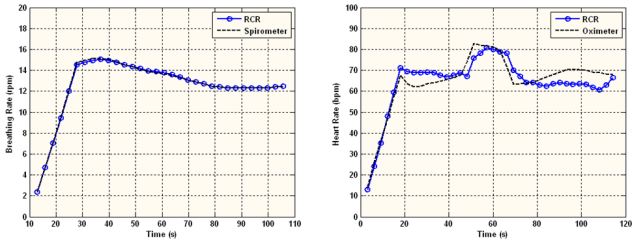

Fig. 2. The respiration rate extracted from RCRH and spirometer signals (left) and the heart rate extracted from RCRH and oximeter signals (right) by applying windowed-DTFT method .

In order to test the RES, we setup a control unit to switch an FM radio, fluorescent light (in addition to fluorescent ceiling lights) and oscillating fan on and off during the day for a fixed period. We placed the FM radio and light near the bed. We put the oscillating fan on the bed to mimic the periodic motion of chest. The temperature changes were captured as part of the daily workplace routine. A 2-day excerpt from the RSU collected in the simulated room environment is shown in Fig. 3. The repeated simulation patterns can easily be identified while we can identify sparse motion events, probably generated by foot-traffic in the laboratory.

V. FUTURE WORK

The initial results obtained from the Doppler radar and the room environment sensors are encouraging, and our data systems were shown to be robust during human subject study tests and in room environment simulations during which lights and sound sources are switched randomly. The GEGR is currently preparing to test the described system with soldiers returning from combat with PTSD and TBI.

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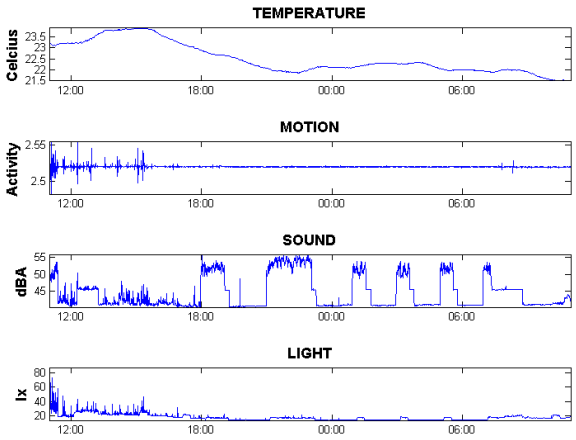

Fig. 3. The RES excerpt from the RSU in the simulated room environment generated by switching an FM radio, fluorescent light and oscillating fan on and off during the day for few days.

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