Sensors and Instrumentation for Unobtrusive Sleep Quality Assessment in Autistic Children

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***Abstract*—Little is understood about the sleep quality of children with autism and other developmental disabilities. Conventional sensors and instrumentation for objective sleep quality assessment, such as those used in polysomnography, are highly obtrusive and not well-suited to this patient population. This paper presents a set of sensors and instrumentation for unobtrusive measurement of physiological and behavioral parameters indicative of sleep quality. Specifically, load cells, an electromechanical film, and thermocouples are used to measure respiratory rate, pulse rate, and physical activity of a subject lying on a bed. The sensor suite is being developed to monitor sleep quality of children at Heartspring, a residential and educational facility in Wichita, KS that serves children with severe developmental disabilities. These technologies have the potential to provide objective sleep quality assessment for children in their home environment.**

***Keywords*—autism, ballistocardiogram, instrumentation, sleep quality assessment, unobtrusive sensors**

I. Introduction

Sleep disorders in children with an autism spectrum disorder (ASD) are more prevalent (50-80%) than in age-matched neurotypical children (9-50%) [1, 2]. Poor sleep quality in autistic children correlates with aggressive behavior, anxiety, and developmental regression. Nocturnal polysomnography is the gold standard to diagnose sleep disorders and assess the impact of interventions. This technique tracks multiple neurophysiological and cardiorespiratory signals and parameters, including electroencephalograms (EEGs), electrooculograms (EOGs), electromyograms (EMGs) of the chin and lower-limbs, electrocardiograms (ECGs), oronasal airflow, and arterial oxygen saturation [3]. A polysomnograph (PSG) is clinically used to diagnose sleep disorders like narcolepsy, periodic limb movement disorder, hypersomnia, and sleep apnea.

While a PSG provides valuable data to characterize sleep quality, the signal-acquisition technologies are obtrusive and not easily tolerated by children. The cost of the procedure and the necessary travel to a sleep laboratory also make it impractical for long-term sleep monitoring. For instance, biopotential measurements require wired electrodes in constant contact with the skin. Oxygen saturation is typically measured with a bulky finger-clip sensor, although reflectance-mode sensors are becoming available.

Actigraphy has emerged as a clinically validated indirect measurement of sleep quality [4, 5]. The technique employs accelerometers worn on the wrist or ankle, and it helps to distinguish between sleep and wake periods based on movement detection [6]. Activity monitoring via video recording of sleeping subjects has recently been proposed as a technique for characterizing movement and activity of children with attention deficit hyperactive disorder [7]. Wireless monitoring devices are also under development to acquire physiological parameters during sleep in a home setting. While less invasive than PSGs, these technologies require sensors to be attached to the subject (e.g., via headbands or wristbands) and are thus not well-suited for use with children with disabilities. Some technologies developed for unobtrusive measurement of nocturnal pulse and respiratory rates of elderly subjects may be suitable for use with children [8]. An unmet need remains for the development of integrated, low-cost, unobtrusive technologies to quantitatively characterize nocturnal sleeping patterns of severely disabled children in their homes.

This paper reports on work in-progress towards the development of an unobtrusive suite of sensors to monitor sleep quality of children with ASD and other developmental disabilities. Sensors and accompanying instrumentation are proposed to assess sleep quality in children at Hearstpring, a residential and educational facility in Wichita, KS that works with severely disabled children.

II. Background

A. Heartspring, Wichita, KS

Heartspring is a not-for-profit residential facility and day school serving children (ages 5—21) with ASD and other developmental disabilities. The current Heartpsring enrollment is 52 students who sleep on the residential campus in Wichita, KS. Most of these children have significant, multiple disabilities, meaning concomitant

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impairments (e.g., mental retardation-blindness, mental retardation-orthopedic impairment), the combination of which causes such severe educational needs that the student cannot be accommodated in special education programs solely for one of the impairments.

B. *Sleep quality parameters*

Multiple physical and physiological parameters are indicative of sleep quality. Some of these parameters are incorporated within polysomnographs, actigraphs, and other clinically established sleep assessment tests. The parameters identified for this work include

- heart rate,
- respiratory rate,
- activity/movement,
- bed wetting incidents, and
- ambient sound and lighting.

This paper focuses on the unobtrusive measurement of heart and respiratory rates, activity, and bed-wetting incidents.

III. Methods

A. *Approach*

The team has identified sensors that can be unobtrusively embedded in a typical Heartspring bed frame to monitor the physiological and physical status of a disabled child, supplemented with devices that can measure environmental conditions within their bedroom. Fig. 1 depicts these sensors laid out on a typical Heartspring bed frame/mattress. The bed frame depicted in Fig. 1 is a heavy, enclosed wooden structure. Sensors will be embedded in/under the mattress and bed frame, and accompanying electronics will be stored in the empty space beneath the bed. An electromechanical film placed on the mattress will be used to measure a child's ballistocardiogram (BCG), which includes data related to cardiac and respiratory cycles. Load cells placed underneath the bed frame will provide an alternative means to collect a BCG as well as a method to track subject activity. A grid of thermocouples distributed on the mattress surface will provide body surface temperature and potentially offer a thermal method to detect bed-wetting incidents. Sensor data will be streamed to a central acquisition station, where these data will be assembled, stored, and analyzed to provide caregivers with just-in-time child status updates.

B. *Ballistrocardiograms (BCGs)*

A BCG is a measure of the ballistic forces produced by the heart during the cardiac cycle. This sensing mechanism provides a means to measure heart rate without requiring electrodes to be physically attached to the patient. Several types of sensors have been proposed to acquire BCGs, including load cells, pneumatic sensors, and electro-mechanical films; these are reviewed in [9]. Since these sensors measure forces exerted during the cardiac cycle, they also pick up the forces exerted by the diaphragm and other muscles during the respiratory cycle.

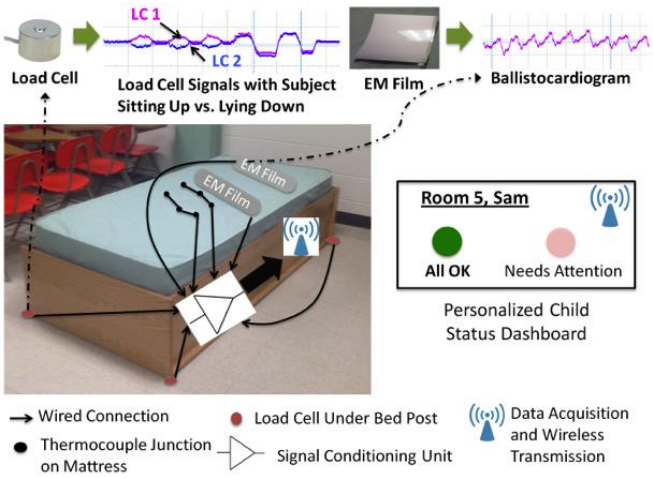

Fig. 1. Depiction of the bed sensor suite and the residential dashboard interface indicating the current status of the child on the bed. Also shown are sample movement and BCG data.

C. *BCG Measurement with Electromechanical Film*

Two mechanisms are explored here to acquire BCGs from a child lying on a typical Heartspring bed. The first technique employs a pair of electromechanical force films (EMFit L-series electromechanical films, each 300 mm × 580 mm) placed on top of the mattress. A half-inch-thick memory foam is placed on top of these films to improve comfort and ensure that the child cannot perceive the films. Forces exerted on this type of film change the thickness of the film, yielding a charge on the interfacing electrodes, which are coupled to a voltage amplifier. While a single film is sufficient to measure a BCG with this approach, two films improve the likelihood of a successful measurement given that a child will move around on the bed. Fig. 2 illustrates the signal conditioning circuitry employed tp amplify the BCG signal sensed by each EMFit film. An active highpass filter (corner frequency = 0.07 Hz) is employed to eliminate the DC baseline but retain the low-frequency respiratory rate information. The highpass filter is followed by an amplification stage (gain = 47 V/V) to boost the signal amplitude prior to digitization.

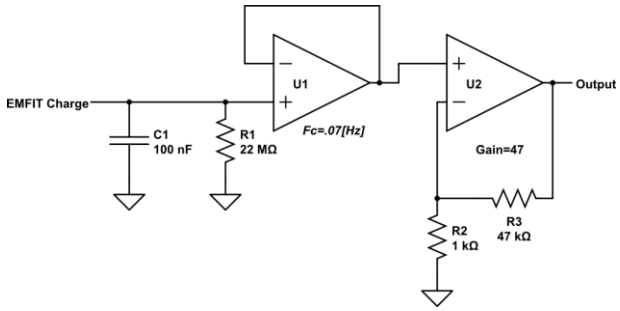

Fig. 2. Signal conditioning circuit for interfacing the electromechanical film to the data acquisition unit. This simple circuit consists of an active highpass filter (corner frequency = 0.07 Hz) followed by an amplification stage with gain = 47 V/V.

D. *BCG and Activity Measurement with Load Cells*

As an alternative method to acquire a subject's BCG, six

load cells (LCM 302-200N, OMEGA Engineering, Stamford, CT) are positioned underneath the bed frame – one under each corner and two under the midpoints of the sidewalls. An LCM 302-200N load cell contains a high-quality strain gauge enclosed in a 19 mm stainless steel housing. The signals from these load cells offer the potential to (1) identify whether or not a child is lying on the bed, (2) characterize the level of activity/movement of the child lying on the bed, and (3) measure the child's BCG. Fig. 3 depicts the signal conditioning circuit through which the load-cell signals are passed prior to digitization. The first gain stage is implemented with an AD 620 instrumentation amplifier, followed by a set of highpass and lowpass filters to limit the spectral content of the signal to the 0.07–70 Hz range. A final adjustable gain stage helps to ensure uniformity amongst the signals obtained from all six load cells.

The load cells also provide data reflecting subject physical activity/movement on the bed. After the initial amplification stage, these load cell data are passed through a lowpass filter (corner frequency = 50 Hz) prior to digitization. These data will be used to track subject movement during sleep, similar to an actigraphy procedure that employs a wrist or ankle bracelet sensor. Activity data derived from the six load cells also offer researchers the potential to discriminate between activity types and subject position on the bed.

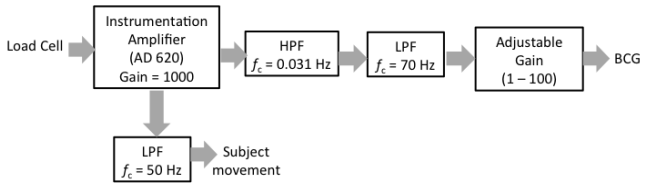

Fig. 3. Conditioning circuit for load cell signals.

E. Bed Surface Temperature Measurement

Some children at Heartspring do not have complete bladder control and may have frequent bed-wetting incidents. Automatic detection of these incidents would alert caregivers of their occurrence, save time normally expended on manual bed-wetting checks, and provide a method to accurately track the frequency of bed-wetting incidents in response to different therapies. While several technologies employing moisture sensors do exist, these sensors are typically embedded within a diaper and are disposable. Preliminary tests indicated that moisture sensors embedded within the mattress would not suffice, as students with a history of bed-wetting typically wear diapers. We hypothesize that a bed-wetting incident, where urine from the bladder (equilibrated to core temperature, ~37 °C) is released on to the bed surface, could be detected with temperature sensors. A grid of thermocouple sensors (J-type; TC direct 201-144) is therefore placed on the mattress.

F. System Integration

A National Instruments data acquisition (DAQ) module (NI 9205-32, 32 channels, 16 bits, 250 kS/s) collates data from all sensors and uploads them through a wired or wireless link to a central LabVIEW virtual instrument (VI). The central station presents the measured data in summary form on a 'dashboard' that can take various forms: a display as indicated in Fig. 1 that simply indicates whether all is well versus a complicated display that depicts signals/data, sleep-quality metrics, and trends.

IV. Results

A. Electromechanical Film Measurements

The electromechanical (EM) film and the load cells yield BCG signals that contain information about cardiac and respiratory cycles. The signal from the electromechanical film, which is positioned directly under the subject's torso, is dominated by lower-frequency content corresponding to their respiratory cycle (Fig. 4). Cardiac cycle information is readily observable from this signal, and may be extracted with digital filtering techniques as described in [10]

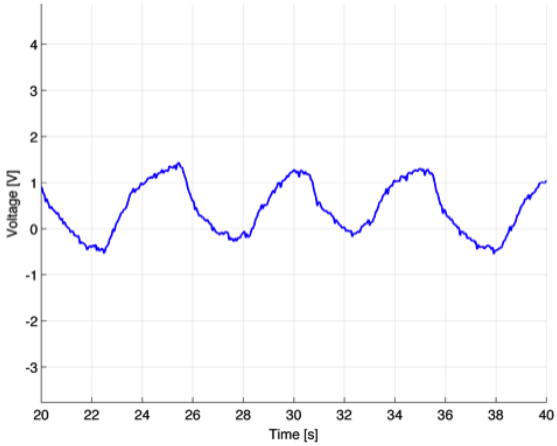

Fig. 4. Sample ballistocardiogram acquired from the EM film with the subject lying prone on the mattress. Respiratory activity is readily identified from this trace.

B. Load Cell Measurements

Fig. 5 depicts cardiac cycle information measured with one of the load cells positioned under the corner of the head of the bed. Preliminary tests indicate that reliable BCG data with clearly distinguishable cardiac and respiratory cycle are obtained when the patient lies prone, supine, or on their left/right side.

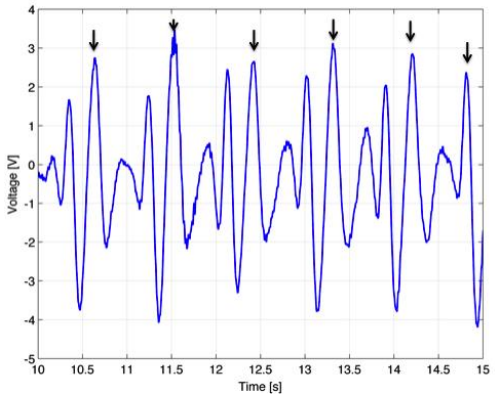

Fig. 5. Load cell ballistocardiogram exhibiting cardiac cycle activity. Arrows indicate successive cardiac cycles.

C. Temperature Measurements

Fig. 6 depicts the results of a preliminary experiment designed to assess the feasibility of detecting bed-wetting incidents with thermocouples positioned on the mattress. A quick rise in temperature was observed after the subject entered the bed. Once the thermocouple temperatures reached equilibrium, 50 mL of warm water (T = 37 °C) was injected onto a diaper resting on the bed sheet. This resulted in a short, rapid rise in temperature followed by a slower decline in temperature. This simple experiment illustrates the potential to detect the onset of bed-wetting incident via thermocouples positioned on the mattress surface.

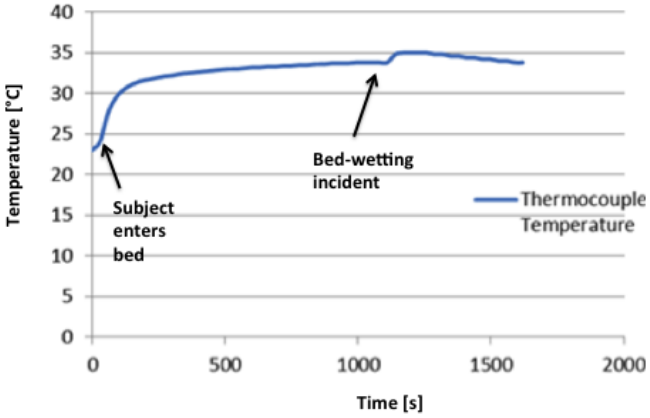

Fig. 6. Measured temperature prior to and immediately following a simulated bed-wetting incident, illustrating the feasibility of detecting bed-wetting with thermocouples on the mattress surface.

V. Conclusion and Future Work

This paper presented a bed-based sensor suite for unobtrusively measuring physiological and physical parameters of severely disabled children during the night. BCGs measured with electromechanical film sensors and load cells provide cardiac and respiratory cycle information as well as movement/activity data. The feasibility of detecting bed-wetting incidents via thermocouples positioned on the mattress surface is also illustrated.

Efforts are underway to translate this sensor suite to the Heartspring environment for pilot studies to measure physiological parameters from subjects during sleep. Initial studies will assess the system's ability to measure reliable physiological and physical parameters. Ongoing work includes the development of algorithms to automatically extract heart and respiratory rate information from measured signals. Future efforts will be directed towards correlating measured physiological and physical parameters against objective sleep quality measurements as indicated by polysomnography. The accuracy of pulse- and respiratory-rates as measured by load-cells and electromechanical film will be evaluated. Ultimately, this research may provide technologies suitable for assessing sleep quality in children with ASD and other developmental disabilities.

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