Characterization and Implications of the Sensors Incorporated into the SenseWear™ Armband for Energy Expenditure and Activity Detection

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Abstract -- The SenseWear Armband is a versatile and reliable wearable body monitor created by BodyMedia, Inc. The device is worn on the upper arm and includes a 2-axis accelerometer, heat flux sensor, galvanic skin response sensor, skin temperature sensor, and a near-body ambient temperature sensor. Each sensor is described and their specifications are delineated. This innovative, multiple sensor array gathers and analyzes physiologic data from the body under all environmental conditions and provides the researcher, clinician and user with accurate and reliable energy expenditure information.

Index Terms-- Body monitoring, sensor array, characterization, energy expenditure, TEE, AEE, REE, accelerometer, heat flux, skin temperature, ambient temperature, galvanic skin response

INTRODUCTION

Poor lifestyle habits are a significant contributor to a number of health problems such as heart disease, diabetes, hypertension and cancer. Lifestyle issues include a lack of exercise, inappropriate eating habits, sleep deprivation, and ineffective stress management. In particular, a lack of physical activity has been linked to a number of adverse health outcomes. Strong epidemiological data exists to support the claim that physical inactivity and an overweight status contribute to increased rate of premature death and chronic illnesses. Conversely, increased physical activity and weight control have been shown to result in a number of health benefits.

The role poor lifestyle plays in the onset of chronic health conditions has made it clear that individuals must take greater responsibility for their own health. Nowhere is this more evident and desirable among clinicians and consumers, than in the area of weight management. Critical to weight loss is managing a balance between energy intake (food) and energy expenditure. Until now, there has not been an accurate and reliable, nor convenient and cost effective way for weight loss researchers, clinicians and consumers to monitor 24-hour energy expenditure; important information essential to weight management.

With the availability of microprocessors, wireless technology, software and the internet, personalized body monitoring is now a possibility. As technology rapidly decreases in size, wearable monitoring devices has become a viable and practical reality. These advances make moving beyond simple motion detection possible and sets the stage for non-invasive and convenient access to physiologic information, recorded directly from the body. BodyMedia has taken advantage of this opportunity by developing the SenseWear Armband, a wireless, wearable body monitor that enables continuous collection of physiologic data any time and anywhere, including body movement, heat flow, galvanic skin response, skin temperature, near body ambient temperature and heart rate. The multiple sensors employed in this device facilitate utilization of a tiered approach to gathering and analyzing physiologic data from the body in order to provide accurate, reliable, energy expenditure information. This paper provides a description and characterization of the individual sensors that are part of the SenseWear Armband's multiple sensor array.

I. THE SENSOR ARRAY

The rationale for multiple sensors

Review of the medical and physiological literature reveals that there are numerous procedures and devices that have been used to assess energy expenditure. Each has its own strengths and weaknesses. The most accurate "gold standard" approaches including doubly labeled water, calorimetry, and oxygen uptake are limited by their cost and inconvenience. As a result they are not applicable to wide scale use by consumers for daily health monitoring in free-living environments. The more convenient and less expensive devices such as pedometers, accelerometers, and heart rate monitors are limited in their accuracy and reliability, particularly in relation to non-ambulatory physical activity (e.g., bike riding) and resting energy expenditure.

In recent years, several attempts have been made to combine sensors in order to achieve greater accuracy. To date, most attempts at combining sensors have relied on motion sensing with the addition of one other type of sensor. One combination using heart rate monitoring in association with motion sensing, e.g., (Rennie, et al 2000: Luke, et all, 1997) demonstrated improved accuracy over either approach used in isolation. Despite this improvement, this combination also had difficulty with accurate detection of non-ambulatory activity. Non-ambulatory physical activity by its very nature is difficult, if not impossible, to detect by motion sensing. The addition of heart rate monitoring increases the ability to track these activities but, by itself, is not sensitive or accurate enough for reliable energy expenditure calculation.

BodyMedia has taken combining sensors to the next level – an array of sensors. The SenseWear Armband not only includes a 2-axis accelerometer for motion detection and an optional heart rate monitor but also includes additional sensors to measure energy expenditure via monitoring heat flow off the body, skin temperature and galvanic skin response. These multiple sensors can sample a number of different physiologic parameters simultaneously over time. The physiologic information gathered by this sensor array along with simple body measurements can be processed using SenseWear's algorithms to provide accurate and reliable estimations of energy expenditure encompassing all types of activity over the course of the entire day.

*Description of the sensors included in the
SenseWearÔArmband*

The SenseWear Armband includes a 2-axis accelerometer, heat flux sensor, galvanic skin response sensor, skin temperature sensor and a near-body ambient temperature sensor. The SenseWear Armband also offers the addition of heart rate detection through the use of a Polar™ chest Strap. The following is a brief description of each sensor and its function in the device.

The SenseWear™ Armband
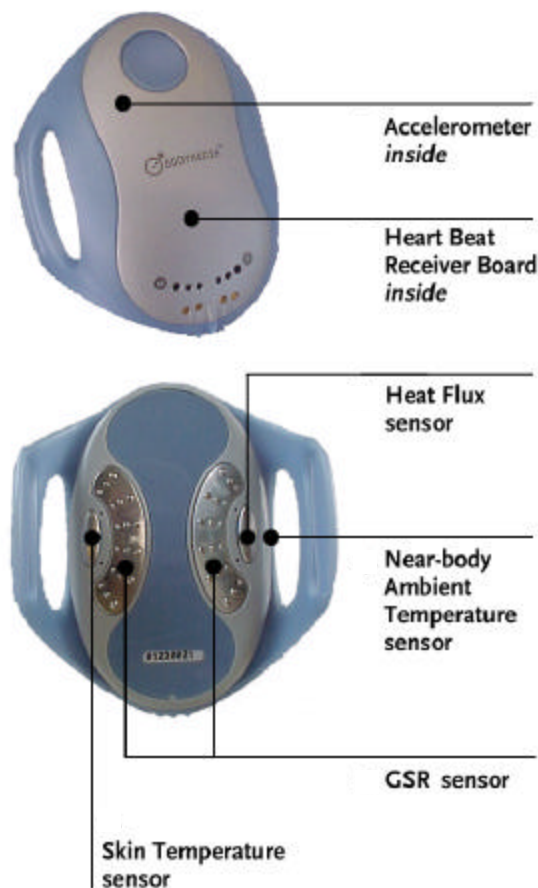
1) The accelerometer in the armband is a 2-axis accelerometer that utilizes a micro-electro-mechanical sensor (MEMS) device that measures motion. A poly-silicon spring supports a small mass that moves when subjected to acceleration that results from muscular activity, gravity and other external forces. These accelerations can be mapped to forces exerted on the body, which can, in turn, be mapped to energy expended by the muscles of the body to generate these forces. SenseWear has companion software that uses this physical energy as part of the calculations to determine energy expenditure. By taking into account the direction of the force of gravity on the sensor (a form of acceleration) the companion software predicts the context in which the armband is operating including typical activities of daily life such as standing, reclining, sitting, walking, running and biking. This contextual knowledge facilitates the automatic journaling of activities and thereby modulates the data captured by the other sensors. As a result the accuracy of the derived energy expenditure algorithms is refined.

2) The heat flux sensor measures the amount of heat being emitted by the body. The body dissipates heat to the surroundings in many forms: heat convection through the skin being in contact with the air, heat conduction through clothing, evaporation of sweat on the skin, evaporation of exhaled moisture and heat radiation. The SenseWear's proprietary heat flux sensor specifically measures representative values of the heat convection part of the total thermal energy dissipated to the surroundings. The heat flux sensor is made with very low thermally resistive materials and includes extremely sensitive thermocouple arrays that are placed in a thermally conductive path between the skin and the outer side of the armband exposed to the environment. A high gain internal amplifier is used to bring the heat flux signal to a level that can be sampled by a microprocessor in the SenseWear Armband.

3) The SenseWear Armband includes two hypoallergenic stainless steel electrodes on the lower portion of the underside of the unit connected to a circuit that functions as the galvanic skin response (GSR) sensor. GSR is a measurement of the skin's conductance between the two electrodes. A low level electric voltage is applied to the skin and the skin's conduction of the current is measured. Skin conductance is considered to be a function of the sweat gland activity and the skin's pore size. Skin conductivity is impacted upon by both the sweat from physical activity and by emotional stimuli such as pain, anger, and surprise. GSR reflects evaporative heat loss and can be an indicator for the onset, peak, and recovery of maximal sweat rates.

We have conducted studies comparing the GSR sensor in the SenseWear Armband to the more traditional fingertip GSR sensor. The results demonstrate that the GSR sensor in the armband provides a linear analogy to digital values for conductance but that it is significantly less sensitive than a GSR placed on the finger or palm.

4) Skin temperature is measured with a thermistor-based sensor located on the backside of the SenseWear Armband near its edges. Thermistors are resistors that change value with temperature. The thermistor forms one-half of a resistor divider that converts the changing electrical resistance into a corresponding voltage. As the skin temperature changes, a change in the electrical resistance of the sensor causes a change in the voltage sampled by the microprocessor. The skin temperature sensor is thermally connected to one of the smaller metal pads on the back of the armband.

5) The near-body ambient temperature sensor is attached to the heat flux sensor and thermally in contact with the side cover of the heat flux assembly. Near-body ambient temperature is defined as the temperature at the outer edge of the heat flow sensor. It is altered by heat coming off the body around the unit and the immediate environmental conditions around the armband. The rate of change in near-body ambient temperature can be used to assess the type of physical activity being engaged in, the presence of sleeves or other thermal barriers, and variations in environmental conditions. The near-body ambient temperature sensor can also be used to verify whether the heat flux sensor is receiving noisy signals.

6) Heartbeat detection is an option available with the SenseWear Armband. Several companies manufacture chest straps for heartbeat detection. These devices transmit a 5kHz burst of electromagnetic

energy that is detected by the armband. The SenseWear Armband houses a custom receiver board to receive the pulses emitted by a heart beat detection chest strap. The SenseWear Armband captures the exact time that each heartbeat is detected. By timing the interval between sequential beats, the instantaneous heart rate can be determined. A high quality data stream that captures every beat can be analyzed to provide beat-to-beat variability. Under controlled laboratory conditions during physical activity, heart rate and energy expenditure are closely related and exhibit a linear relationship particularly between heart rates of 110 to 150 beats per minute (Rowlands et al, 1997). Physical activity patterns can be distinguished as to their frequency, intensity and duration with heart rate monitoring (Freedson, 2000).

II. SENSOR SPECIFICATIONS

The following is a more specific description of the characteristics of the sensors in the production version of the SenseWear™ Armband and their positions in the device. It should be noted that all values presented have been extensively tested. When testing a discrepancy revealed between results of a sensor housed in the SenseWear™ Armband unit and the stated characteristics from the manufacturer, the values reported are those measured by BodyMedia studies done in the context of the SenseWear™ Armband system.

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1) Accelerometer

The characteristics of the accelerometer are:

Zero: Zero offset is set with the sensor level during our calibration procedure, and is typically +/- 1°. This translates to 17 mg.

Scale: +/- 2g (in practice it can sense greater accelerations than rated)
Resolution: Sensor typical sensitivity is 167 mV/g, which translates to 3.66 mg per A/D tick
Noise: +/- 2 ticks typical

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2) Heart Beat Detection

Characteristics of the heart beat detection of the SenseWear™ Armband include a free-running 8kHz timer that counts the time between sequential heartbeats received from the chest strap. This yields 125-microsecond resolution between beats. The timer is derived from the crystal controlled microprocessor clock that is accurate to 50 ppm.

Low Resolution Mode: Each heartbeat is watched over one - minute at 125-microsecond resolution. Average heart rate, beat- to - beat variability, and an approximation of respiration rate are recorded for each minute

High Resolution Mode: The time between every sequential heartbeat is recorded with 10 - millisecond resolution. This yields a 1% error rate at 60 BPM, a 2% error rate at 120 BPM, and a 3% error rate at 180 BPM. With the detailed information of every heartbeat, more precise variability calculations and algorithms are possible offline. This mode consumes much more memory than the low-resolution mode.

3) Heat flux

The heat flux sensor is specified to be +/- 15% in un-calibrated scale.

Zero: Zero offset is set with the sensor under zero heat flow during our calibration

Low Gain:
Scale: +/- 500 W/m^2
Resolution: 244 mW/m^2 per A/D tick
Noise: +/- 1 tick typical

High Gain:
Scale: +/- 90 W/m^2 (high gain)
Resolution: 44 mW/m^2 per A/D tick
Noise: +/- 5 ticks

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4) Near-Body Ambient Temperature

The near-body ambient temperature sensor is rated for 3% accuracy, which translates approximately to +/- 1° C of un-calibrated accuracy. A calibration of the sensor occurs at room temperature (23-25° C) and is stored for offset correction.

Scale: 0-50 °C
Resolution:0.018 °C per A/D tick
Noise: +/- 0.5 ticks typical

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5) Galvanic Skin Response Sensor

The characteristics of the galvanic skin response sensor include:

Zero: Zero offset is set with the sensor under zero conductivity during our calibration

Low Gain
Scale: 0-17 uSiemens, 56 K? -20 M?
Resolution: 8.3 nSiemens per A/D tick
Noise: +/- 0.5 ticks typical

High Gain:
Scale: 0-1.7 uSiemens, 600 K? -20 M?
Resolution: 830 pSiemens
Noise: +/- 2 ticks typical

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6) Skin Temperature

The skin temperature sensor is rated at +/- 0.1° C from 0-70° C. It is connected through a 1% resistor for bias. A calibration of the sensor occurs at room temperature (23-25° C) and is stored for offset correction.

Scale: 0-50 °C
Resolution: 0.018 °C per A/D tick
Noise: +/- 0.5 ticks typical

Channels vs. Raw Data

It is important to understand that the SenseWear Armband collects six different streams of continuous raw physiological data. However, the armband is actually storing approximately 30 channels of data. All but one (i.e., event button) of these channels contain data that is

derived from the raw data streams themselves. For example, it is possible to capture directional information, total motion information, and motion frequency characteristics all from the same 2-axis accelerometer (1 sensor, 6 channels). Similarly, the first derivative of GSR is potentially more meaningful than the moving average of GSR values over the same interval (1 sensor, 2 channels). For heat flux, it is possible to obtain the moving average, as well as the variation in heat flux over the same time period (1 sensor, 2 channels). The accuracy of data in the channels is obviously impacted upon by the limitations of the sensors, however, the channels themselves do not introduce any new errors or noise except with regard to computational choices done for efficiency sake (e.g., rounding error).

Intra-Person Repeatability

BodyMedia has utilized multiple opportunities to characterize the intra-person variability with respect to the sensors and their companion algorithms. For example, during an initial energy expenditure study the relationship of accelerometer and heat flux data collected by the SenseWear Armband to kilocalories burned as measured by VO2 metabolic analysis: Implications for algorithm development that we conducted, each participant wore a SenseWear Armband on each arm. The supposition being that the sensors could be viewed as highly repeatable if, all other conditions being equal the units on different arms collected very similar information. For the accelerometer, the correlation coefficient between the right and left arms across 80 trials in this study was 0.89, making that measure highly repeatable across a range of activities and individuals. As a partial explanation for the remaining difference between the values collected by the two units, at least some of the lack of correlation can be ascribed to the fact that most individuals have a dominate hand and move their limbs differently as a result. This was born out by the fact that the correlation coefficient is closer to 1.0 during periods of rhythmic upper arm exercise (e.g., walking or jogging) where the arm-swing tends to cancel out the effect just cited. Alternatively, the correlation is somewhat lower during low activity periods such as sitting.

For the GSR sensor, the correlation coefficient between the right and left arms across these 80 trials was 0.80 making measurements from that sensor somewhat less repeatable than those from the accelerometer but still very repeatable across a range of activities and people. The same "handedness" issue described above appeared to apply to the GSR, but to a much smaller extent. Also worthy of note is the fact that the absolute values of GSR that were used to calculate correlation values may not be as precise an indicator as other GSR channels pulled from the same data stream (e.g., variance from the mean over each minute). Anecdotal information suggests that some of these other values may correlate even better than absolute magnitude values.

Due to the fact that the SenseWear Armband is not perfectly symmetrical (i.e., only one edge has a "vent" for heat flux sensor) utilizing the two armbands on one-person strategy is not appropriate for testing the repeatability of the temperature sensitive sensors. This is because the "vent" on the left arm is anterior and vents faster than on the right arm where it is posterior, tucked closer to the armpit, resulting in slower venting. As a result, this strategy for testing repeatability was not used for the heat flux, skin temperature, or near-body ambient temperature sensors.

To further define repeatability, data gathered by the same armband on the same person participating in the same activity protocol on different days was compared. Clearly, this approach did not provide perfectly controlled conditions because there were important factors that could not be accounted for (e.g., variations in food intake on the two different days). This evaluation was conducted by giving to ANOVA, a statistical method for finding statistically significant differences between data sets, pairs of data sets (each data set had 150 value sets, one for each minute of the trials, with a range of different raw values for each minute) such that for each data set pair, both data sets were drawn from a test with the same person. The results showed that in 92% of the set pairs, no statistically significant variation was found between the sets. This provided another strong indication that the SenseWear Armband has reliable, repeatable performance characteristics.

II. DESIGN AND PLACEMENT OF THE SENSEWEAR

Placement on the upper arm

The SenseWear Armband was designed for upper arm placement. This placement was selected based on a number of factors including dynamic wearability guidelines (Gemperle et al) and the requirements of the various sensors housed in the device. Due to the presence of heat flux, GSR, and skin temperature sensors in the SenseWear Armband, it became necessary for the device to be in constant contact with the skin and placed in a position free of potential interference from clothing and accessories.

An important consideration in the design and development of the SenseWear Armband has been whether the upper arm is a satisfactory location for the heat flux sensor. The forehead might be considered to be a more optimal site for a variety of reasons. First, the forehead is known to be the "radiator of the body" with the highest heat transfer rates to the surroundings compared to other areas of the body. In our preliminary studies, the heat flow off the forehead was four to eight times greater then that of the upper arm. While the forehead is almost always exposed to airflow, there is also significant noise in heat flux readings taken from the forehead. This noise is substantially greater than the noise experienced in gathering heat flux measurements from the upper arm. Much of the heat flow off the forehead is accomplished through sweating which interferes with the stability of the attachment of the sensor. Furthermore, the heat flux sensor in the current SenseWear Armband does not capture heat transfer resulting from evaporation loss such as sweating. Finally, though the forehead provides good information about heat flow, it is not a convenient or socially acceptable position for a device designed for continuous monitoring of free-living physical activity and energy expenditure. By contrast, the upper arm was seen as providing a stable base for a sensor which is not affected by most typical physical movements. It could also inconspicuously support the device.

Another body area we considered for the measurement of heat flux was the torso or trunk, due to the fact that, like the forehead, it is a site of considerable heat loss. However, problems were seen with utilizing the torso as a site for heat flux sensors. These included a variety of common movements which might interfere with the need for constant contact, layers of clothing which might compromise the

accuracy of measurements, and the unpleasant effect of applying a constricting fastening device to the chest wall. Interestingly, some investigators have considered the upper arm to be part of the torso for heat sensing purposes.

More peripheral sites such as the wrists, hands, fingers and feet which could be seen as appropriate for heat sensing purposes, are subject to excessive movements and frequent peripheral vascular changes that vary according to changes in body temperature. These peripheral sites are also used for jewelry and other accessories, thereby, making them less available for a body-monitoring device.

The presence of an accelerometer in the sensor array necessitated a body placement where motion could be accurately sensed. Motion sensing requires a placement that is not subject to the kind of extraneous motion which can lead to overestimation of physical activity such as commonly occurs with devices worn on the wrist. Furthermore, placement on the wrist often limits the sensing of motion of the upper body leading to underestimation of physical activity.

From this evaluation, the upper arm emerged as the ideal candidate. It provides a convenient, unobtrusive, and stable platform on which to position the SenseWear Armband. Though there is inter-individual variability in the size and shape of the upper arm, this variability is not as extensive as that of other potential body parts (e.g., the upper thigh, the torso, the wrist, etc.). In the end a number of design and sensor requirements identified the upper arm as an appropriate placement for the device.

Design

The design of the device itself is also based on dynamic wearability guidelines and the requirements of the sensors. Placement on the body necessitated that the shape and size of the SenseWear Armband be unobtrusive and comfortable. Design also considered both physical and perceptual size. That is, a device placed on the forehead or around the neck would be perceived as more intrusive or bigger than the same sized device placed on the back of the upper arm. Furthermore, as noted above, the size and shape of the device needed to provide a skin contact area to support the heat flux, skin, ambient temperature, and GSR sensors and an interior room large enough to house the microprocessor, sensors and electronics.

Durability

The design of the device also needed to be sturdy enough to withstand normal daily use under extremely diverse conditions. To that end, a series of environmental and lab tests were conducted:

High impact (infrequent free fall shock): Testing that ensures that the device and all its subcomponents can survive relatively infrequent but "high shocks" on its most vulnerable surfaces. These studies demonstrated that the device could sustain a controlled drop 26 times from a height of 6' on to a cement surface. Two orientations: (1) bottom bumper striking perpendicular to cement surface (2) monitor "face" striking parallel to cement surface. MIL-STD 516.4 Low impact (frequent low impact shock): Testing that ensures the monitor can survive bumps and unexpected "knocks" unique to

wearable devices. In our testing, the monitor experiences 365 impacts, each impact, 10 pounds of force against its face on a cement surface.

Abrasion resistance: Painted surfaces are subjected to repeated abrasion. Two tests: (1) 100 abrasions (medium coarse) across the monitor's face (2) 500 abrasions monitor-into-cradle (the act of initiating recharge). The monitor and cradle use the same finishes and achieve the same durability as leading cell phone products.

Humidity and Thermal Operation 0 (performed at Western Pennsylvania Hospital independent lab):

Equipment:

Econolab Model 7201 Environmental Chamber with temperature and humidity control. Temperature range -40° C --- 200° C

1 PC with support software to monitor the Firefly during testing.

1 Portable RH and Temperature Meter to verify ambient and test environments.

1 Firefly Beta version firmware.

1 Recharging Cradle.

Test Summary:

The test chamber was set for a ramp cycle starting at 48° C 90% humidity. After 1.5 hours, the chamber began a cooling cycle to bring the temperature down to -20° C and then hold the temperature for another 1.5 hours. After the cycles are complete, the chamber returns to 25° C. Total time in chamber was 3.5 hours. During testing, SenseWear Armband channels 0, 1, and 2 were set to record at 1 sample per minute and the CUI program was set to send continuous data packets to the SenseWear Armband via the cradle.

There were no noted errors during these environmental lab tests. The SenseWear Armband collected and recorded data as expected. There were absolutely no breaks in the continuous data packets being sent, even at extreme ranges. The listed temperature range for the device is 0° C to 45° C. The device exceeded our listed specifications.

An additional submersion test was performed on the SenseWear unit to test for waterproofing. The test was at 1.5 meters underwater. The SenseWear unit used was installed with a bare board and 1 ounce of Dri-Rite compound with a moisture indicator. This test showed some slight moisture leakage in the area around the stainless steel heat flux sensor cap. Subsequently, the shapes of the parts in the involved area were corrected to create a better seal. While the unit is currently not rated as such, its seal approximates waterproof quality.

IV. IN-HOUSE STUDIES OF THE SENSOR ARRAY

A variety of probative studies have been conducted to validate each of the individual sensors that are incorporated into the SenseWear Armband sensor array. The results of some of these studies have been described earlier in the characterization of each sensor. Other aspects of these studies are currently being analyzed and edited. Upon completion of this process they will be included in a future version of the paper.

V. CONCLUSION

The SenseWear Armband has incorporated a unique array of physiologic sensors that position it to become a more accurate and reliable device for detection of physical activity and energy expenditure then any current monitor on the market. The use of this multiple sensor array in conjunction with simple body measurements including gender, age, height and weight allow for accurate calculations of energy expenditure across a full range of daily activities. This capability makes the SenseWear Armband a powerful tool for researchers, clinicians and consumers who are interested in monitoring energy balance so they can more effectively manage weight.

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