The SenseWear™ Armband as a Sleep Detection Device

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Abstract – Among sleep researcher and clinicians, there is a need for a cost-effective and easy-to-use tool that can obtain objective, accurate and reliable sleep data in a free-living environment to assist in the screening, diagnosis and treatment of sleep disorders. BodyMedia's SenseWear Armband which addresses this need, utilizes a 2-axis accelerometer, heat flux sensor, a galvanic skin response sensor, skin temperature sensor and near-body ambient temperature sensor to gather data leading to the calculation of various sleep parameters. This paper outlines our studies which demonstrate how the SenseWear Armband differentiates sedentary activities from sleep and has accuracy rates for sleep onset, wake and total sleep that are comparable to some existing sleep detection devices while addressing their limitations.

Index Terms-- SenseWear Armband, sleep, wake sensor array, actigraphy, activity assessment, contextual detection, free-living environment, accuracy, wearable computer.

BACKGROUND

Sleep disorders are extremely common. Increasingly they are being recognized by the health profession as detrimental to one's health and quality of life. It is reported that 33% of the U.S. adult population experience occasional bouts of insomnia while 9% to 12% experience insomnia on a chronic basis (Ford 1989, Mellinger 1985 and Gallup 1991). However, it is estimated that only 10% of those individuals suffering from common sleep disorders, such as obstructive sleep apnea, have been identified, diagnosed and treated. Clearly, there is a need for increased lay and professional awareness about the importance of proper sleep and its relationship to daytime performance and excessive sleepiness.

While polysomnography (PSG) is the currently accepted standard for the diagnosis of some sleep disorders, it is not always affordable and accessible due to the size of the equipment, cost, and use in laboratory settings. Furthermore, insurance companies cover only a few sleep disorder diagnoses by polysomnography such as sleep apnea and periodic limb movement. In response, a variety of more affordable and portable devices have been developed to detect obstructive sleep apnea but many have severe limitations. As a result there are few dependable options for monitoring an individual's sleep over time apart from actigraphy and sleep logs.

It has been suggested that portable sleep monitors such as wrist actigraphy can be useful in assessing hypersomnias, circadian wake/sleep disorders, parasomnias and periodic movements in sleep, and, perhaps, are most beneficial in assessing longitudinal changes in sleep and monitoring responses to treatment (Sadeh 1995 and Chambers 1994). However, there are significant differences between various instruments and there have been calls for standards regarding reliability, validity, ruggedness and artifact rejection.

Wrist actigraphy has proved useful in sleep research in terms of providing accurate data about total sleep time and sleep efficiency, provided it is coupled with manual entry of in and out-of-bed times.

Agreement rates with PSG are in the 80-95% range for wake/sleep detection (See Appendix 1), but actigraphy is only marginally acceptable when attempting to measure the exact time that an insomniac is asleep. Some of the artifacts that plague the use of actigraphy include: 1) overestimation of total sleep time in psychophysiological insomnia because the patient is lying quietly in bed while awake, 2) underestimation total sleep time in patients with sleep state misperception because of restlessness and increased movement within sleep, and 3) overestimating total sleep time when the patient has actually taken the actigraph off (Sadeh 1995) or is quiet or sedentary during the day.

DESCRIPTION OF THE SENSEWEAR ARMBAND

The BodyMedia SenseWear Armband utilizes a proprietary multi-sensor array including a 2-axis accelerometer, heat flux sensor, galvanic skin response sensor (GSR), skin temperature sensor, and a near-body ambient temperature sensor. The SenseWear Armband also offers the option of heart rate detection through the use of most commercial chest straps such as a Polar Heart Rate Monitor. The following is a brief description of each sensor and its function in the device. More detailed specification can be found in the paper "Characterization and Implications of the Sensors Incorporated into the SenseWear Armband for Energy Expenditure and Activity Detection".

1) The accelerometer in the SenseWear Armband is a 2-axis micro-electro-mechanical sensor (MEMS) device that measures motion. By taking into account acceleration due to gravity, our algorithms can also predict the context in which the armband is being worn such as getting in and out of bed and lying down.

2) The proprietary heat flux sensor in the armband is a robust and reliable device that reflects a measure of the amount of heat being dissipated by the body. The sensor uses very low thermally resistant materials and extremely sensitive thermocouple arrays. It is placed in a thermally conductive path between the skin and the side of the armband exposed to the environment. A high gain internal amplifier is used to bring the signal to a level that can be sampled by the microprocessor located in the SenseWear Armband.

3) Skin temperature is measured using a highly accurate thermistor-based sensor located on the backside of the armband near its edges and in contact with the skin. Continuously measured skin temperature is reflective of the body's core temperature activities.

4) The near-body ambient temperature sensor measures the air temperature immediately around the wearer's armband. This sensor also uses a highly accurate thermistor-based sensor and directly reflects the change in environmental conditions around the armband; for example, walking out of an air-conditioned building on a hot day.

5) Galvanic skin response (GSR) represents electrical conductivity between two points on the wearer's arm. The SenseWear Armband GSR sensor includes two hypoallergenic stainless steel electrodes integrated into the underside of the armband connected to a circuit that measures the skin's conductivity between these two electrodes. Skin conductivity is affected by the sweat from physical activity and by emotional stimuli.

6) The SenseWear Armband houses a custom receiver board to receive the pulses transmitted by a heart beat detection chest strap. The receiver board includes a free-running 8kHz timer derived from the crystal controlled microprocessor clock that is accurate down to 50 beats per minute

7) The functionality of the SenseWear Armband can be expanded with the SenseWear Transceiver. This tiny programmable module can be integrated into digital products such as a pulse oximeter to enable 2-way communication with the SenseWear Armband.

POSTULATE

As suggested above, in developing the SenseWear Armband, we were particularly intrigued by the notion that the SenseWear Armband's sensors may be an ideal combination of physiologic data collectors with respect to sleep parameters. Our multi-axis accelerometer is similar to an actigraph except for the fact the SenseWear is worn on the upper arm as opposed to the wrist thereby, minimizing the extraneous movement noise associated with small movements of the wrist. In addition, because it employs a dual axis accelerometer, the SenseWear Armband produces valuable information about the user's body position (i.e., lying down versus sitting) thus enhancing the prediction of activity states that are important with respect to sleep.
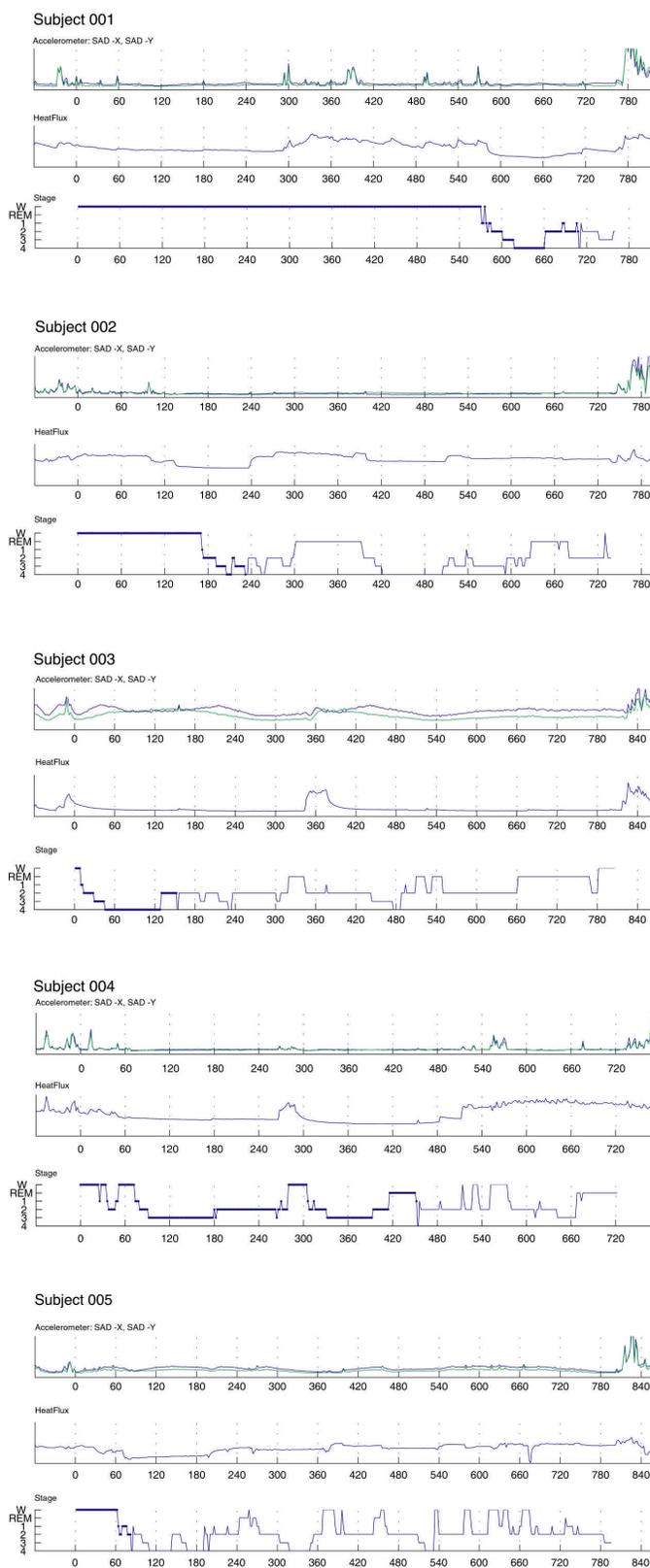
Furthermore, our unique sensor array allows for a greater breadth of physiological observations compared to an actigraph. In turn, we anticipated that our sleep algorithms would not be based solely upon acceleration like the actigraph, but incorporate data from the multiple sensors to enhance accuracy. Our unique heat flux sensor may enhance the sensitivity of detecting sleep latency/onset, which appears to be related to a decline in core body temperature. The GSR may be beneficial in differentiating the lack of temperature regulation that occurs with REM sleep. The ability to determine heart rate variability may be useful in distinguishing REM from non-REM sleep. This creates the potential for being able to measure some of the multiple other parameters of full polysomnography.

Finally, the sensor array only logs data when worn on the body and accurately identifies and shuts off within one minute when the armband is off body. This feature addresses one of the major limitations of actigraphs cited earlier.

PRELIMINARY STUDY

To explore the possibility of the SenseWear Armband as a sleep detection device, we collected data of normal individuals wearing the SenseWear Armband in a sleep laboratory while being monitored with the SensorMedics digital sleep system.

The initial preliminary data acquisition included ten subjects with a history of normal sleep. The sleep studies were scored by a sleep technician and reviewed and interpreted by a board certified sleep physician.

The following is a summary of the key findings from this preliminary sleep laboratory study:

1. The SenseWear Armband's accelerometer reflected almost all of the subject's movements during sleep when compared to simultaneous review of the digital polysomnographic data, as well as, a videotape recording of a subject's sleep.

2. The heat flux sensor recording frequently demonstrated a drop with the onset of sleep. This may reflect the well known circadian regulation of sleep onset, which is marked by a drop in body temperature. Most heat loss occurs through the head, hands and feet. As a consequence, the arm skin temperature falls and therefore, the difference between the arm skin temperature and the ambient environment will be decreasing at the time of sleep onset. Therefore, the heat flux that the SenseWear Armband is measuring on the arm will be decreasing. Note: mjs #2 laying quiet and awake—the heat flux did not drop with circadian timing but rather at sleep onset around 4am.

3. Unsandwiching of the SenseWear during sleep appears to result in a rise of heat flux as does removal of covers

4. The heat flux frequently rises after a period of REM but not consistently

FORMAL STUDIES

Encouraged by the results of our preliminary studies which supported the feasibility of using the SenseWear Armband as a sleep detection device, we began two formal studies, free-living and sleep laboratory, to gather data for the creation and validation of a sleep algorithm. The following sections describe the methodology used for data collection in these two studies, the strategy used for development of the sleep algorithm, results obtained and discussion.

FREE-LIVING STUDY

We collected data of free-living subjects wearing the SenseWear Armband during times including IN and OUT-of-bed to measure SenseWear Armband detection as compared with the subject's diary of activities. We had 15 subjects who recorded 266 sleep sessions in a free-living environment.

FORMAL SLEEP LABORATORY STUDY – NORMAL SUBJECTS

To extend our investigations of the validity, reliability and consistency of the SenseWear Armband measurements of sleep onset, body movements/restlessness and awakenings, we developed a formal protocol that received IRB approval and was conducted at the Western Pennsylvania Hospital Sleep Laboratory in Pittsburgh, Pennsylvania.

Protocol Summary:

This study was done by performing standard nocturnal poly-somnography with video monitoring in the Western Pennsylvania Hospital Sleep Laboratory on ten volunteers who considered themselves to be normal sleepers. They were simultaneously wearing the BodyMedia SenseWear Armbands.

Methods:

All subjects wore the SenseWear Armbands, one on each arm, for at least 1-hour prior to sleep, during sleep, and for 1-hour after awakening. All subjects were advised not to wear any perfume or other chemicals on the skin of the arms where the armbands were placed. All subjects simultaneously underwent a standard nocturnal polysomnography (PSG) with video monitoring in the Sleep Laboratory. Each PSG was scored by a sleep technician in 30-second epochs and reviewed and interpreted by the same board certified sleep physician (MS).

The scored polysomnographic data of the SensorMedics System was then synchronously plotted in minute epochs against the prediction of sleep produced by the algorithms from the SenseWear Armband data (described below). One subject's data was not used because of technical difficulties. Two of the remaining 9 subjects recorded data from only their left arm. These were analyzed separately because of possible differences in data collection, which may have occurred due to alteration in sensor orientation that results when the armband is worn on different arms.

DEVELOPMENT OF A SLEEP ALGORITHM

Data sets were built with positive examples of sleep obtained from normal and sleep disordered individuals wearing the SenseWear Armband during a PSG sleep study. All data was gathered on the right upper arm. The data sets were also interlaced with many negative examples of sleep, mainly wakeful but sedentary activities such as reading a book or watching TV gathered from individuals wearing the SenseWear Armband in a free-living environment. These negative examples were included because they provided us an opportunity to distinguish sleep from other restful activities.

Raw data, along with certain derived measures, gathered from all the sensors in the SenseWear Armband were utilized in creation of the sleep algorithm. Due to their proprietary nature, details regarding the specific data channels and derived measures will not be presented in this paper.

Models were built and evaluated using a two-stage process. First, an artificial neural network (ANN) was used to develop a probability model for the data. A training data set was then passed through the ANN to generate a set of predictions. This set of predictions was then put through another process to find the optimum combination of threshold and voting scheme using a fixed true negative value of 95%. The true negative value of 95% was selected since the ultimate goal of the sleep prediction algorithm was for it to be applied to data gathered by a wearer using it 24 hours per day. Under such circumstances it becomes critical to be at least 95% accurate in predicting "wake." The cost of selecting a high true negative (wake) accuracy is a somewhat decreased true positive (sleep) accuracy.

The data was separated randomly into 4 sets for the purpose of cross validation. Using the first 3 sets, a temporary model algorithm was trained on one data set and then tested against the other two data sets resulting in a cross validation table of true positives (accuracy predicting sleep). Subsequently, a final model was constructed training on data from all three sets. Parameters were found and this model was fixed as the sleep prediction algorithm. It was subsequently applied to a 4th data set, containing one quarter of our data selected at random, and including free-living data. The results on this 4th data set were in line with the cross validation. As such, the results on this set reflect the results that would be obtained on other unseen data.

In a similar fashion, an algorithm was developed for the free-living detection of IN and OUT of bed.

Results:

The overall accuracy of predicting IN and OUT of bed for the free-living contextual studies was 93.2%. The average error rates are summarized in Table 2.

TABLE 2 - SenseWear Armband's Accuracy in Predicting Free-Living Participant Logged Sedentary Activities

Sedentary Activity	Average Error (minutes)
Getting into bed	1.0
Getting out of bed	1.0
Single Sleep Session (average session – 379 minutes)	20

Applying the algorithm to SenseWear Armband data collected from PSG recorded sleep data and self-logged sedentary activities, the overall agreement was 91.9%. The true negative identification of wakefulness was 92.8% and the true positive identification of sleep from sedentary activities was 87%.

The formal Sleep Laboratory Study PSG demonstrated a minute-by-minute agreement with the SenseWear Armband of 85.3. As can be seen in Table 3, the overall prediction of sleep was 99.1%. The overall minute-by-minute prediction of wake was 50.5%

Of the 7 subjects who recorded their SenseWear Armband data from the right arm, the sleep onset latency error average was 8.3 minutes. The final awakening error average was 2.1 minutes.

The 2 subjects with left arm data had similar results. Minute-by-minute of the SenseWear Armband's prediction of sleep was 93.3% concordant with PSG. The wake prediction was 44.8% concordant. The sleep onset latency error average was 6.5 minutes and the final awakening error average was 7.0 minutes.

TABLE 3 - Western Pennsylvania Sleep Lab PSG Study – SenseWear Armband Accuracy Data

Data Collection	Subjects	Minute-By-Minute True Positive (sleep)	Minute-By-Minute True Negative (wake)	Onset Error, Minutes, Average	Wake Error, Minutes, Average
West Penn	7	99.1%	50.5%	8.3	2.1
West Penn *left arm data collection*	2	98.3%	44.8%	6.5	7.0

Further analysis of the 7 subjects wearing the SenseWear Armband on the right arm, demonstrated that in sleep stages III, IV, and rapid eye movement sleep (REM), the SenseWear Armband prediction of "sleep" was 100%. It gave a true positive prediction of "sleep" equal to 98.9% in stage II sleep, and 94% in stage I sleep (See Table 4).

TABLE 4 - Western Pennsylvania Sleep Lab PSG Study – SenseWear Armband Sleep Predictions by Sleep Stage

Sleep Stage	True Positive Prediction of sleep	Minutes of Data in Set
1	94.0	117
2	98.9	1090
3	100.0	344
4	100.0	290
(REM) 5	100.0	347

Summary graphs of SenseWear Armband and PSG for each study subject are presented in Appendix 2.

DISCUSSION

The above results demonstrate that the SenseWear Armband is very good in predicting "sleep", demonstrating a concordance with polysomnographic measured sleep that is at least comparable to other modalities such as actigraphy and sleep logs (Usui 1998 & 1999, Sadeh 1994, Cole 1992, Jean-Louis 2001, Reid 1999), while also addressing some of the problems with actigraphy such as knowing when it is off the body.

The SenseWear Armband demonstrates a higher concordance with the PSG for sleep and a lower concordance for short periods of wakefulness during sleep. This difference reflects the fact that the initial algorithm was built on a prediction of sleep probability over a 29-minute window. That is, it was based on the 14 minutes prior to and 14 minutes post the minute in question. However, during the process of algorithm development, once the optimum threshold was delineated, a vote of greater then 9 minutes was all that was required in the prediction algorithm. As a result, detection of wake episodes less then 10 minutes is limited. While this limitation probably has little significance for the consumer who rarely recalls awakenings of less then 10 minutes the next morning, it will be addressed in subsequent efforts to refine the algorithm to enhance the SenseWear Armband's capability as a screening, diagnostic and monitoring tool for researchers and clinicians.

This limitation must also be taken into account when evaluating the SenseWear Armband's ability to distinguish sleep from sedentary free-living activities as logged by study participants. Specifically, the algorithms minute-by-minute prediction of wakefulness over a wide

range of routine activities was 98.6% and sedentary activities were correctly identified as wake 95% of the time. This demonstrates that the SenseWear Armband is at least comparable to actigraphy in its ability to distinguish quiet wakefulness and sedentary activities from sleep.

Detection of brief awakenings and arousals are important in diagnosing disorders such as sleep apnea and periodic movements of sleep. However, these are medical conditions that are currently routinely evaluated in a sleep laboratory. Unfortunately, the large numbers of individuals who may want to monitor or improve their sleep, or who suffer from insomnia, do not have the resources of a sleep laboratory to help them due to cost or reimbursement limitations. To address this issue, we will be refining the algorithm and developing a movement index, as a corollary to an arousal index on a polysomnogram, to help further characterize the sleep recorded by the SenseWear Armband and give a measure of restlessness or sleep fragmentation. This may also compensate for the SenseWear Armband limitations detecting short awakenings during sleep as noted above.

CONCLUSION

The studies we have conducted over the past year provide strong support for the notion that the SenseWear Armband has considerable potential to become an accurate and reliable free-living sleep detector. From our studies we feel the key benefits of the SenseWear Armband include:

- Its accuracy for detection of sleep onset, wake and total sleep time is comparable to existing ambulatory sleep detection devices
- Its multiple sensor array accurately differentiates sedentary activity from sleep
- Its capabilities address many of the limitations of actigraphy

Further studies and algorithm development are in progress to improve our ability to detect brief arousals and interruptions that occur during sleep. This will enhance the SenseWear Armband's capability to become an even more accurate measure of "sleep", but also sleep quality and wakefulness.

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Appendix 1 – A review of the reliability studies with modern actigraphy – from Sadeh et. al.

STUDY[a]	SAMPLE[b]	Sample Size	AGE	S/W[c]	SEF[c]	DUR[c]	COMMENTS[d]
Kripke (3)	N	5	NA	NA	0.98	0.95	
Mullaney (4)	N	53	18-66 yr	96.3	0.81	0.9	HS TST
	P	32	18-66 yr	91.6	0.95	0.82	HS TST
Webster (5)	N	14	College	93.9	NA	NA	AS IDT
	N + P	14	College	93.4	NA	NA	AS IDT
Sadeh (6)	N	13	20-76 yr	90.2	0.91	NA	AS
	SAS	25	20-76 yr	85.7	0.63	NA	AS
	INS	16	20-76 yr	78.2	0.79	NA	AS
	C/P	13	3-13 yr	89.9	0.81	NA	AS
Sadeh (7)	N + P/C	11	12-48 mo	85.3	NA	NA	AS
Hauri (8)	INS	36	24-69 yr	82.1	NA	NA	AS
Cole (11)	N + P	51	NA	88.0	0.82	0.90	AS SLT
Sadeh (12)	N	36	10-25 yr	91.2	NA	NA	AS
Sadeh (13)	N	41	Newborn-12 mo	95.3	NA	0.95	AS

[a]Studies are identified by the first author's name. Only papers published in peer-reviewed journals are included.
[b]Sample: N = normal individuals; SAS = sleep apnea patients; INS = insomniacs; C = children and infants; P = heterogeneous group of patients
[c]Measures: S/W = minute-by-minutes agreement for sleep-wake scoring; SEF = correlations between PSG and actigraphic-based sleep efficiencies or sleep percentages; DUR = duration of sleep
[d]Comments: HS = hand scoring; AS = automatic scoring; TST = total sleep time was used because statistics for SEF were not available; SLT = sleep latency was used because sleep duration was not available; IDT = including daytime scoring; NA = not applicable or not available.

APPENDIX 2

I.   MODEL ANALYSIS AGAINST PSG SLEEP MODEL "2002_04_10"
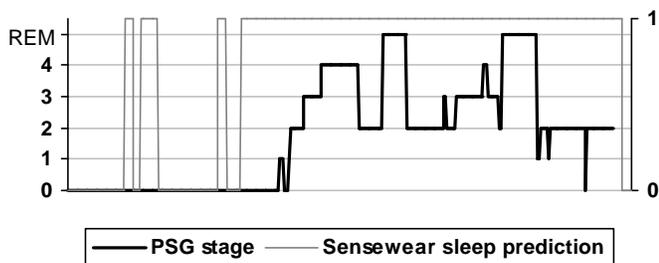
Key: PSG Stage

Left Axis: 0 is wake, then sleep stages 1 - 4 & REM. Sensewear sleep prediction
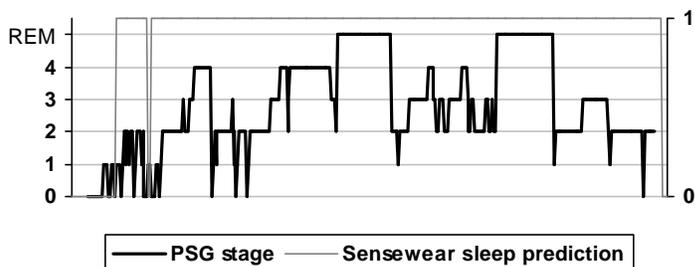
Right axis: Sleep or wake.
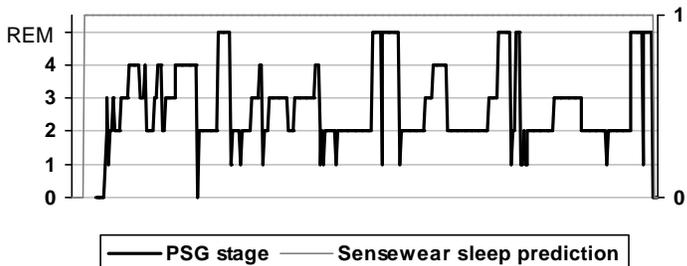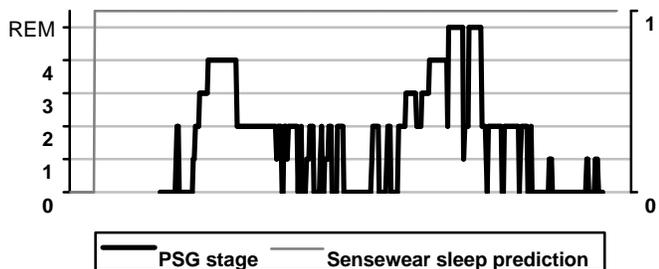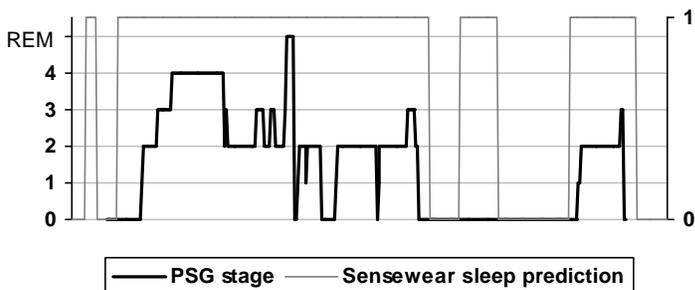
West Penn data collected from the right arm

WP04

| PSG stage | Sensewear sleep prediction |

WP01

| PSG stage | Sensewear sleep prediction |

WP05

| PSG stage | Sensewear sleep prediction |

WP02

| PSG stage | Sensewear sleep prediction |

WP06

| PSG stage | Sensewear sleep prediction |

WP03

| PSG stage | Sensewear sleep prediction |

WP07

| PSG stage | Sensewear sleep prediction |

West Penn data collected from the left arm

These subjects were not included in the algorithm development process.

WP08

| PSG stage | Sensewear sleep prediction |

WP09

| PSG stage | sensewear sleep prediction |