

An Evaluation of a Non-contact Biomotion Sensor with Actimetry

Niall A. Fox, *Member, IEEE*, Conor Heneghan, *Member, IEEE*, Monica Gonzalez, Redmond B. Shouldice, *Member, IEEE*, Philip de Chazal *Member, IEEE*

Abstract— Actimetry is a widely accepted technology for the diagnosis and monitoring of sleep disorders such as insomnia, circadian sleep/wake disturbance, and periodic leg movement. In this study we investigate a very sensitive non-contact biomotion sensor to measure actimetry and compare its performance to wrist-actimetry. A data corpus consisting of twenty subjects (ten normals, ten with sleep disorders) was collected in the unconstrained home environment with simultaneous non-contact sensor and ActiWatch actimetry recordings. The aggregated length of the data is 151 hours. The non-contact sensor signal was mapped to actimetry using 30 second epochs and the level of agreement with the ActiWatch actimetry determined. Across all twenty subjects, the sensitivity and specificity was 79% and 75% respectively. In addition, it was shown that the non-contact sensor can also measure breathing and breathing modulations. The results of this study indicate that the non-contact sensor may be a highly convenient alternative to wrist-actimetry as a diagnosis and screening tool for sleep studies. Furthermore, as the non-contact sensor measures breathing modulations, it can additionally be used to screen for respiratory disturbances in sleep caused by sleep apnea and COPD.

I. INTRODUCTION

SLEEP assessment can be based on many different types of signals. Existing methods to measure these signals, including polysomnography (PSG), actigraphy, and sleep diaries. PSG, the gold standard for sleep assessment, may be impractical for some applications, particularly for usage in the home. It can be both intrusive and expensive.

Actimetry is a mature technology, developed over the last 25 years [1], [2], [3]. An actimeter is a wearable motion sensing and data logging device that records the motion data continuously for days, weeks, or even longer. The actimetry monitor is generally placed on the non-dominant wrist, leg, or sometimes the trunk. The digitized actimetry signal can be processed on a computer and used to diagnose and monitor sleep disorders such as insomnia [2], circadian sleep/wake disturbance [1], and periodic leg movement (PLM). Actigraphy is not considered to be as reliable as full PSG studies for the diagnosis of sleep disorders, but due to its ability to record continuously for long periods of time, its convenience and its low-cost, it is a very useful screening device. It is considered more reliable than patient sleep logs.

A brief description of actimetry technology is given here.

Dr. N. Fox, Dr. P. de Chazal, Dr. R. B. Shouldice and Prof. C. J. Heneghan are with BiancaMed, NovaUCD, University College Dublin, Belfield, Dublin 4, Ireland. Corresponding author.

Dr Monica Gonzalez is with the Sleep Disorders Unit, Hospital Universitario Marques de Valdecilla, Santander, Spain.

The reader is referred to [1] for a more detailed state of the art. A sensitive linear accelerometer is employed to capture movements. The movement is bandpass filtered (typically 0.25 to 2-3Hz). This eliminates very slow movements and fast human movements such as shivers and involuntary tremors. Voluntary human movements rarely exceed 3-4Hz.

The motion is transduced into an analog electrical signal and digitized. The movement counts are accumulated over an epoch, the length of which is generally user programmable. The analog signal can be digitized using three methods, a) time above a threshold, b) number of zero crossings, or c) digital integration. The time above threshold method accumulates the amount of time the analog signal is above a pre-determined threshold during the epoch. An example threshold might be 0.2g ($g=9.8 \text{ m/s}^2$). Two issues with this method are, (a) that there is a saturation effect because the signal amplitude above the threshold is ignored and, (b) movement acceleration is not measured.

The zero crossings method counts the number of times that the actimetry signal level crosses the zero line during an epoch. Three issues with this method are that, (a) movement amplitude is not captured, (b) movement acceleration is not measured, and, (c) it is susceptible to large invalid count readings due to high frequency artifacts. The digital integration method samples the analog actimetry signal at a high rate. The area under the curve is then calculated. Both amplitude and acceleration information is captured. The digital integration method has been found to outperform the time above threshold and zero crossing methods for identifying movement.

Actigraphy is often reported as counts but it is important to stress that different hardware devices and different actimetry algorithms can produce very different counts for the same actimetry. Thus, a direct comparison between ActiWatch actigraphy and actimetry derived from the non-contact sensor is difficult. An alternative method is to compare the temporal location of actimetry. This would allow the capture of false positives and false negatives.

There has been a lot of interest recently in the detection of vital signals using non-contact radar technology. Non-contact sensors can monitor respiratory, movement, and even cardiac signals in an un-intrusive manner [4], [5]. Non-contact sensors offer a number of advantages over existing technologies 1) there is no contact with the subject 2) the cost of the sensor is very low and 3) the sensors are very portable.

II. METHODS

A. Test Corpus

Simultaneous actimetry and non-contact sensor recordings were recorded for twenty subjects consisting of twelve females and eight males, with a mean age of 46.7 years (SD 21.3). Nine of the subjects were classified as healthy. For the other eleven subjects, six had severe sleep apnea, two had moderate sleep apnea, one had chronic obstructive pulmonary disease (COPD), one had childhood obesity, and one suffered from insomnia. The recordings were made in the unconstrained home environment under the supervision of Dr Monica Gonzalez of the Sleep Disorders Unit, Hospital Universitario Marques de Valdecilla, Santander.

TABLE 1: DETAILS OF THE SUBJECTS IN THE TEST CORPUS.

Record Number	Age (years)	Sex	Health Status	Length (hours)
1	36	F	Healthy	8.04
2	29	F	Healthy	8.33
3	67	F	Moderate Sleep Apnea	7.67
4	30	F	Healthy	4.38
5	49	M	Healthy	6.89
6	30	F	Healthy	7.36
7	31	F	Healthy	6.11
8	79	F	COPD	7.53
9	8	F	Childhood Obesity	8.06
10	23	F	Healthy	8.84
11	34	F	Healthy	8.74
12	30	F	Healthy	7.56
13	34	M	Moderate Sleep Apnea	6.33
14	69	M	Severe Sleep Apnea	6.72
15	79	F	Insomnia	8.19
16	58	M	Severe Sleep Apnea	8.02
17	49	M	Severe Sleep Apnea	8.16
18	51	M	Severe Sleep Apnea	7.82
19	77	M	Severe Sleep Apnea	7.92
20	72	M	Severe Sleep Apnea	7.97

B. Actimeter: ActiWatch

The Actiwatch (registered trademark of Mini Mitter Company [6]) is a long-term activity monitoring device. It is cordless, and data is transferred to the PC via a close proximity RF link. The Actiwatch contains a sensor capable of detecting acceleration in two planes. It is sensitive to 0.01g, and integrates the degree and speed of motion and produces an electrical current with varying magnitude. An increased degree of speed and motion produces an increase in voltage. The watch converts this signal and stores it as activity counts. The maximum sampling rate is 32 Hz. For this study, the watch was placed on the non-dominant wrist and set to record the number of activity counts during 15 second intervals (epochs).

C. Non-contact Sensor

The non-contact sensor employed in this study is a patented multi-channel biomotion sensor [7]. It employs 5.8GHz Doppler radar using a patented modulation system

that limits both the maximum and minimum range. The baseband signal is filtered using an analog active filter with bandwidth (0.05- 1.6) Hz. The emitted power is very low - less than 10mW. The sensor range can be adjusted between 1m and 3m so that external movements can be rejected.

D. Non-contact Sensor Data Logger

The design of the non-contact biomotion logger shares some of the benefits of existing actimeters. These include convenience of use, light weight, portability, cheap, low power usage, non-intrusive, and the capacity to record for several days or even for weeks.

The data logger, which was developed by BiancaMed, incorporates all of the aforementioned characteristics. It can be mains or battery powered. It is a standalone device which records data from an internal non-contact sensor to an SD flash card for easy transfer to a PC for analysis. It is capable of logging continuously for weeks with standard off-the-shelf SD cards (upto 4GB), as used in digital cameras. It contains an independent battery-powered clock which tags the movement data with accurate time information and digitizes the sensor channels at 50Hz with 10-bit resolution.

Figure 1 depicts the data logger. The user places it no more than 1 meter from the bed, between 0.25 to 0.5 meters above the height of the mattress, and facing towards the torso of the subject. For the detection of movement (actimetry), positioning of the logger has been found not to be crucial. For detection of breathing, the data logger is more sensitive to positioning however, experiments show that if placed within the above limits, good signals are obtained.



Fig. 1. Shown is the BiancaMed data logger unit. The dimensions are length 116mm, width 70mm, and height 36mm.

E. Non-contact to Actimetry Mapping

The mapping from the non-contact sensor to actimetry is carried out as follows:

1) The first stage is a digital band pass filter with passband (1.5, 4.6) Hz, stopband (0.7, 4.9) Hz, 3dB passband, and stopband attenuation of 50dB; implemented as a 7th order Butterworth filter. This filter attenuates the breathing frequencies, thus emphasizing the movement frequencies (the top and centre axes of Figure 5, show the raw- and filtered- non-contact sensor data respectively).

2) The respiration signal is then removed with a sort filter.

3) Finally, the signal is thresholded and summed into non-overlapping two second bins to give an actimetry count. The two second epochs can then be downsampled to the appropriate epoch and compared with wrist based actimetry.

Due to varying clock offsets between the ActiWatch and data logger, the actimetry and non-contact sensor recordings were aligned manually. After alignment, the signals were truncated so that only data that were recorded simultaneously were retained. The length of each aligned and truncated set of recordings is given in Table 1. The average length is 7.53 hours with an aggregated length of 151 hours across all 20 recordings.

F. Performance Measure

The performances measures are epoch based. The actimetry counts were aggregated into 30 second epochs for both the ActiWatch and the non-contact actimetry. For each epoch, counts greater than one were quantised to one and a comparison made between the quantised counts of the Actiwatch and the non-contact sensor, i.e., the comparison measures the accuracy of temporal activity location, rather than magnitude of the actimetry.

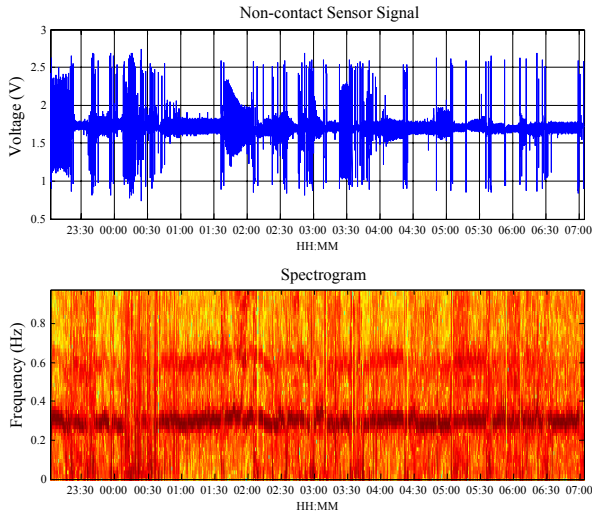


Fig. 2. The top axis is a non-contact sensor overnight recording for record Number 1. The spectrogram shown on the lower axis is based on 30 second windows with 29 seconds overlap. The top axis clearly shows movement (high amplitude sections). The bottom axis shows frequency of breathing during non-movement sections.

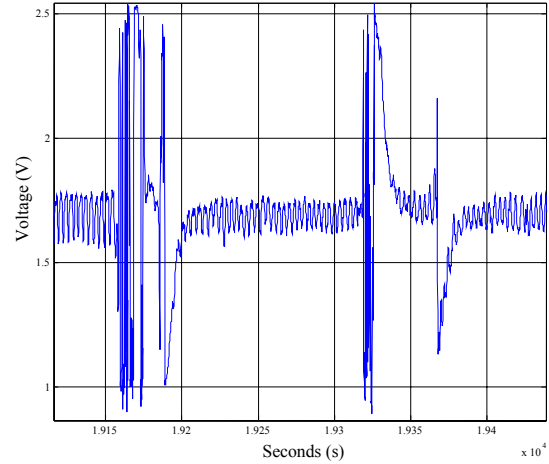


Fig. 3. Shown is approximately 300 seconds of the non-contact sensor signal (from record Number 1) with periods of breathing and movement.

Table 2 shows the four possible states that can arise when comparing the reference epoch (ActiWatch actimetry) with the non-contact actimetry epoch. TN, FN, FP, and TP refer to true negative, false negative, false positive, and true positive respectively. The sensitivity (the probability that an epoch with actimetry is detected by the non-contact actimetry mapping) is defined as:

$$Sensitivity = \frac{TP}{TP + FN},$$

and the specificity (the probability that the an epoch without actimetry is labeled the same by the non-contact actimetry mapping) is defined as:

$$Specificity = \frac{TN}{TN + FP}.$$

TABLE 2: THE FOUR POSSIBLE COMPARATIVE STATES THAT CAN ARISE BETWEEN ACTIWATCH ACTIMETRY AND NON-CONTACT ACTIMETRY, BASED ON QUANTISED EPOCH ACTIMETRY COUNTS.

		Non-contact Actimetry	
		0	1
ActiWatch	0	TN	FP
Actimetry	1	FN	TP

III. RESULTS

An exemplar non-contact sensor recording is provided in Figure 6 with the corresponding non-contact actimetry signal and ActiWatch actimetry. It can be seen that the non-contact and ActiWatch actimetry agree very well in temporal location and also in magnitude. Table 3 gives the sensitivity and specificity for each of the twenty comparisons of the non-contact with ActiWatch actimetry.

TABLE 3: SHOWN ARE THE EPOCH BASED PERFORMANCE MEASURES FOR EACH OF THE RECORDINGS.

Record Number	TP	FN	FP	TN	Sen (%)	Spec (%)
1	64	13	107	783	83	88
2	54	35	68	845	61	93
3	94	34	329	465	73	59
4	47	3	81	396	94	83
5	75	16	26	711	82	96
6	18	37	32	798	33	96
7	97	73	59	506	57	90
8	191	67	97	550	74	85
9	85	18	136	729	83	84
10	150	5	152	755	97	83
11	106	13	528	404	89	43
12	33	7	26	842	83	97
13	35	6	361	360	85	50
14	59	15	71	663	80	90
15	408	54	431	91	88	17
16	43	5	72	844	90	92
17	87	20	229	645	81	74
18	155	46	384	355	77	48
19	179	38	265	470	82	64
20	208	8	284	458	96	62
mean	109	26	187	584	79	75

IV. DISCUSSION

Across all twenty subjects, the mean sensitivity and specificity were 79% and 75% respectively. The non-contact sensor monitors motion over all of the body will thus registers more motion than a single non-dominant wrist positioned ActiWatch. This may explain the lower mean specificity value. To test this, a further study will be carried out where several ActiWatches are employed to capture movement from different regions of the body.

The sensor proved to be very reliable, convenient and non-invasive. There were no signal quality or equipment set up issues. None of the subjects reported being disturbed by the sensor.

The specificity for Record 15 was very low (17%). This subject suffered from insomnia and exhibited high levels of movement throughout the nights recording with a total of 462 Actimetry events. The high number of true positive events (408) shows that, even though for this particular record the specificity was low, the non-contact sensor is still useful for the diagnosis of sleep insomnia.

The sensitivity for Record 6 was low (33%). On visual inspection of this record, the non-contact to Actimetry mapping failed to identify Actimetry events even though there was clear evidence of movement in the raw non-contact signal. Thus, further refinement of the non-contact to Actimetry algorithm may yield higher performance.

The results of this study show that the non-contact sensor can reliably quantify actimetry. Thus, established actimetry based sleep algorithms can be deployed on non-contact based actimetry data and, for example, sleep efficiency can be estimated. A full PSG was not carried out for this study, and hence expert annotated EEG based sleep staging was

not possible. Due to the lack of expert sleep staging, the sleep efficiencies from the Actiwatch- and non-contact-actimetry were not compared at this time.

Figure 3 above shows that the non-contact sensor can reliably measure the breathing signal. Figure 2 gives a spectrogram of an overnight non-contact sensor signal and the breathing frequencies of approximately 0.3Hz (18 breaths per minute) are clearly visible. Additionally, Figure 4 shows a sample non-contact breathing signal taken from a subject with mild sleep apnea. The modulations in the breathing signal due to apnea are evident and this shows that the non-contact, can not only be used as an actimeter, but also can be employed to automatically screen for respiratory disturbances during sleep such as occurs during sleep apnea and COPD [8].

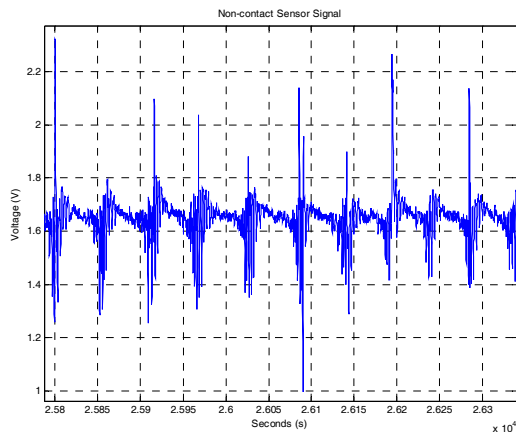


Fig. 4. Shown is approximately six minutes of the non-contact sensor breathing signal taken from record Number 3 (the subject has moderate sleep apnea). The modulations in breathing signal are evident.

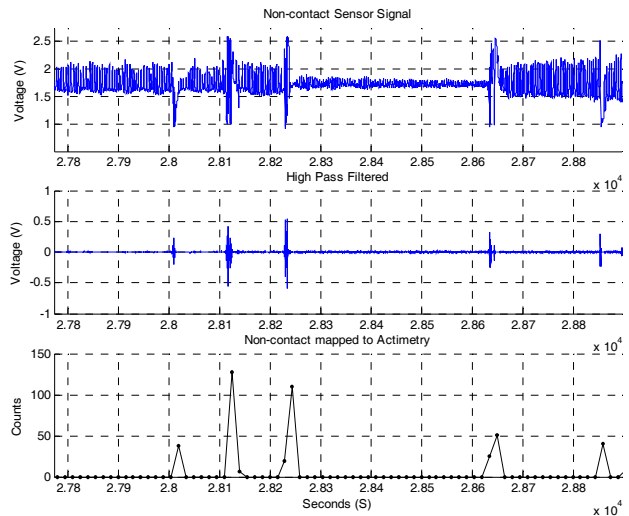


Fig. 5. Sample section of a non-contact sensor signal with the mapping to actimetry. The top axis is the raw non-contact sensor signal. The centre axis is the filtered signal. Note that the breathing frequencies have been removed. The bottom axis shows the resulting actimetry counts from the mapping.

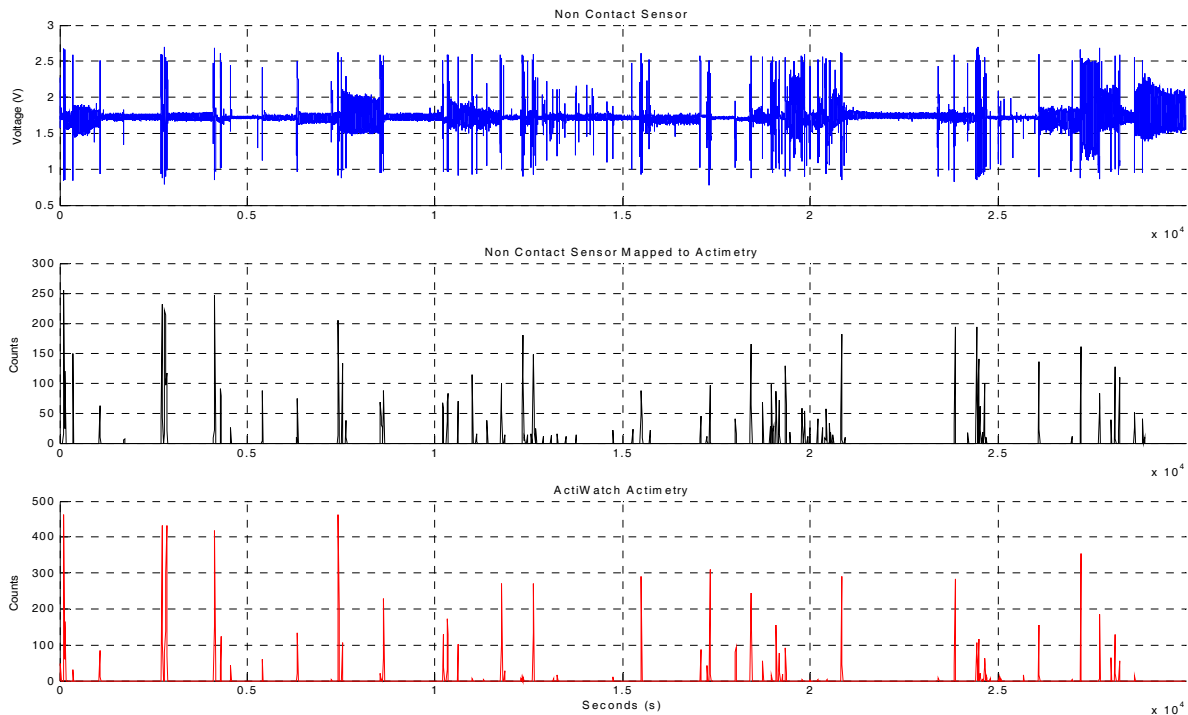


Fig. 6. Shown is the non-contact sensor recording for Record Number 2 (top axis) with the actimetry recording on the bottom axis. The signals have been aligned and truncated. The middle axis shows the non-contact signal mapped to actimetry.

V. CONCLUSION

It has been shown that non-contact based actigraphy can capture equivalent information to that of standard wrist based actigraphy. Furthermore, the non-contact biomotion sensor is a richer source of physiological information. Actigraphy is a single modality signal, whereas, the non-contact biomotion sensor can capture both actigraphy and respiration information. Further development of the non-contact sensor will provide it with the ability to capture cardiac information.

The non-contact sensor also proved to be highly convenient and unobtrusive.

Other future work includes the recording of a full PSG in conjunction with the non-contact sensor over a large subject set and quantifying the accuracy with which the non-contact sensor can measure breathing and breathing modulations. Also, the efficacy of a non-contact sensor based automatic apnea/hypopnoea index (AHI) scoring algorithm [9] will be evaluated in comparison with expert determined AHIs.

ACKNOWLEDGEMENTS

The authors would like to thank the volunteers who took part in this study.

REFERENCES

[1] S. Ancoli-Israel, R. Cole, C. Alessi, M. Chambers, W. Moorcroft, C.P. Pollak, "The role of actigraphy in the study of sleep and circadian rhythms," *Sleep* vol. 26, no. 3, pp. 342-392. May 2003.

[2] K. L. Lichstein, K. C. Stone, J. Donaldson, S.D. Nau, J.P. Soeffing, D. Murray, K. Lester, N. Aguiard, "Actigraphy Validation with Insomnia," *Sleep* vol. 29, no. 2, pp. 232-239. 2006.

[3] E. J. W. Van Someren, "Actigraphic Monitoring of Movement and Rest-Activity Rhythms in Aging, Alzheimer's Disease, and Parkinson's Disease," *IEEE Trans. Rehabilitation Engineering*, vol. 5, no. 4, pp. 394-398 Dec. 1997.

[4] Y. Xiao, J. Lin, O. Boric-Lubecke, V.M. Lubecke, "Frequency-Tuning Technique for Remote Detection of Heartbeat and Respiration Using Low-Power Double-Sideband Transmission in the Ka-Band," *IEEE Trans. Microwave Theory and Techniques*, vol. 54, no. 5, pp. 394-398, pp. 2023-2032, May 2006.

[5] B. Lohman, O. Boric-Lubecke, V. M. Lubecke, P. W. Ong, and M. M. Sondhi, "A digital signal processor for Doppler radar sensing of vital signs," in Proc. 23rd IEEE Annu. Eng. Med. Biol. Soc. Conf., 2001, vol. 4, pp. 3359-3362.

[6] Mini Mitter Company, Inc. Actiwatch 16/Actiwatch 64/Actiwatch-L Activity Monitors. Instruction Manual, 1999.

[7] T.E. McEwan. "Differential Pulse Radar Motion Sensor." U.S. Patent 5966090, Oct. 12, 1999.

[8] V. Kapur, D.K. Blough, R.E. Sandblom, R. Hert, J.B. de Maine, S.D. Sullivan, and B.M. Psaty. "The medical cost of undiagnosed sleep apnea," *Sleep*, vol. 22, no. 6, pp. 749-755, 1999.

[9] P. de Chazal, C. Heneghan, E. Sheridan, R. Reilly, P. Nolan, M. O'Malley, "Automated Processing of the Single Lead Electrocardiogram for the Detection of Obstructive Sleep Apnea," *IEEE Trans. Biomedical Engineering*, vol 50, pp. 686-696. Jun 2003.