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NIGHT-Care: a passive RFID system for remote monitoring and control of overnight living environment

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Abstract

An Ambient Intelligence platform, *NIGHTCare*, for remote monitoring and control of overnight living environment is here proposed. The platform, entirely based on RFID passive technology is able to recognize nocturnal behaviors and activities, generates automatic alarms in case of anomalous or pathological events and support diagnostics. The results of a complete test in real scenario are presented, together with a numerical assessment of electromagnetic safety issues.

Selection and Peer-review under responsibility of the Program Chairs.

Keywords: Pervasive Healthcare, RFID, human monitoring system

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1. Introduction

Health improvement is maybe the primary challenge the OECD (Organization for Economic Co-operation and Development) countries are asked to face in the next future. The demographic development, the progressive increase of the percentage of elderly people, the growth of chronic degenerative diseases following the current lifestyles (smoking, obesity, and inactivity) contribute toward the need of innovative healthcare paradigms, based on decentralized, pervasive and patient-centric approaches. Engineering and Medical technologies have the opportunity to share expertise and efforts to effectively implement the concept of Pervasive Healthcare [1], e.g. a multidisciplinary system where environment, persons, and even their implanted medical devices are continuously

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and remotely monitored in order to have every time and everywhere information about their condition and state. Promising solutions could come from the recent progresses of Radio Frequency Identification (RFID) passive technology. Together with its ID code widely used for logistics, an RFID tag is in fact able to carry information about the tagged object such as its physical state and its evolution along with time, without any specific embedded sensor, through low-level processing of received and backscattered electromagnetic signals [2]. This family of “transparent” and non-intrusive devices could offer great advantages in pervasive healthcare: one or more battery-less RFID sensor tag could be permanently integrated into everyday objects and clothes at the purpose to monitor the subject from different perspectives. The sampling of behavioural parameters, such as activity detection and classification, and the monitoring of human interaction with the objects and the surrounding environment is a suitable application of RFID systems, very recently demonstrated in [3,4].

Sleep is definitively one of the most important behavioural parameters since sleep disorders could sensibly affect the quality of life, leading to daytime sleepiness, spread weariness and even moodiness. Furthermore, especially for weak subjects such as elderly, children and neurologic patients, the night could be a source of many dangerous events (falls, disorientation, nighttime wandering) that call for early detection and prompt actions. These requirements are even more pressing in case of alone-living subjects or inside hospitals and nursing houses, where many patients need to be contemporarily monitored all along the night by sustaining high personnel costs.

Typical remote monitoring platforms comprise audio/video recording systems and active sensors directly connected to first-aid remote centres. However, cost, complexity and intrusiveness have limited up to now their widespread diffusion and social acceptance by the end users.

This paper describes a passive RFID platform, hereafter denoted as *NIGHTCare*, for monitoring people during the night. The NIGHTCare platform deploys miniaturized wearable tags (WT) properly integrated into clothes, conventional ambient tags (AT) dispersed in the environment, a long-range UHF RFID reader, a physical-layer software engine for real-time processing and a web-based graphical processor with warning modules (even accessible through smartphone or any portable device). By processing the electromagnetic signals arising from the interaction between the subject and surrounding environment, the system detects and reports the presence or the absence of the user in the bed, his jerky movements and his motion patterns, accidental falls, prolonged absence from the bed and prolonged periods of inactivity (caused for example by fainting, unconsciousness or even death). Finally, in addition to the generation of automatic alarms to operators, families, or toward first-aid remote centers, the system is able to produce reports and large scale aggregated statistics, useful for the formulation of diagnosis, for the follow-up of therapies and not least for behavioural and clinical studies.

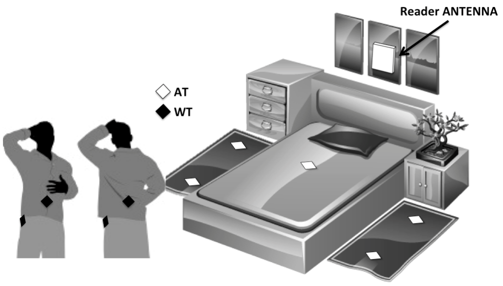


Fig. 1 NIGHTcare: Ambient intelligence system aimed to take care of the night sleep involving RFID tags placed over the body (WT: wearable tags) and in the surrounding environment (AT: ambient tags). A long-range UHF-RFID reader, properly placed in proximity of the bed, scans the environment and interrogates the tags.

2. Description of the System

A passive RFID system is composed of one or more digital devices called *tag*, embedding an antenna and an IC-chip with a unique identification code (ID), and a radio scanner device, called *reader*. Fig. 1 shows a representation of how the RFID technology is employed in the NIGHTCare system. The patient, lying on the bed, wears four wearable RFID tags properly sewn into his night-suit at the level of abdomen, back, left and right hip. A conventional dipole tag is placed underneath the mattress, such to be completely shadowed by the body all along the night regardless the position assumed by the user. One or two other conventional tags are positioned at each side of the bed, eventually hidden by carpet such to mitigate their visual impact. The radio scanner device is placed in correspondence of the headboard, properly tilted and lifted in order to uniformly cover the entire bed and the floor surrounding it.

The response of the tags to the reader's query is subjected to an *ambient modulation,* in the sense that the strength of the backscattered field is modified by the proximity of the human body with the tags themselves. Moreover, in case of specific body-environment configurations, a tag may be fully shadowed by the sleeper so that it will not be able to reply the reader's interrogation. For example, if the subject lies on the bed, the tag under the mattress is totally shielded and it will not respond while the others on the floor are free to communicate. Vice-versa if the subject falls. The activity of the sleeper during the night may be therefore recognized by processing the signals received from the tags. More in details, the IDs of the responding tags can be used to recognize the status of the sleeper (whether he is in the bed, he is fallen down or instead he is outside), while the processing of the strength (RSSI levels) of the electromagnetic fields that are reflected by the responding tags and are hence detected by the reader, can be used to extract information about motion and about specific postures during the sleep.

Being the tags totally battery-less, the RFID link is intrinsically weaker than that of active systems: to be activated, the tags need to receive the right amount of power from the reader and hence the antennas of the wearable and ambient tags play a key role in the overall performance of the platform. A low-gain tag antenna could prevent the tag to be activated and consequently the reader would be unable to receive any backscattered signals, hence impairing the possibility of real-time monitoring.

A minimum read range of three meters is requested for all the passive tags, in order to achieve a compliant illumination of a single bed and of the near surroundings, while preserving a safe distance between the reader antenna and the patient. The maximum read range r_{MAX} can be well approximated by the Friis equation:

$$r_{MAX} = \frac{4\pi}{\lambda}\sqrt{\frac{P_{EIRP}\eta\widehat{G_T}}{P_{chip}}}$$

Where P_{EIRP} is the power emitted by the reader (fixed to the maximum value of 3.2W by the European Regulation) η is the polarization mismatch between the antennas of reader and the tag, P_{chip} is the minimum power required to activate the IC and finally $\widehat{G_T}$ is gain of the tag antenna reduced by the mismatch with the IC.

2.1. System elements

1) The wearable RFID tag (WT): is a miniaturized UHF-RFID layout, already proposed by the authors in [5]. The lightweight and the small sizes (35mm×45mm×2mm) make this tag suitable to be integrated into plasters, wristbands or various clothes. The tag is folded over a 2mm-thick polymeric *Polyethylene* substrate having dielectric properties ($\varepsilon = 2.3$, $\tan\delta = 2\text{x}10^{-4}$); the RFID microchip transponder is the Impinj Monza 4 with power sensitivity $P_{chip} = -17.5$dBm. The estimated free-space maximum read range is almost 5m (Fig.2) at the European frequency 868MHz.

2) The Ambient tag (AT): is a commercial AD-843 inlay with external size of 94mm x 38 mm [6] suitable to be placed on the bed and ground thanks to its proven good performances in a wide range of applications. The measured free space maximum read range is greater than 5m in the European 868MHz frequency.

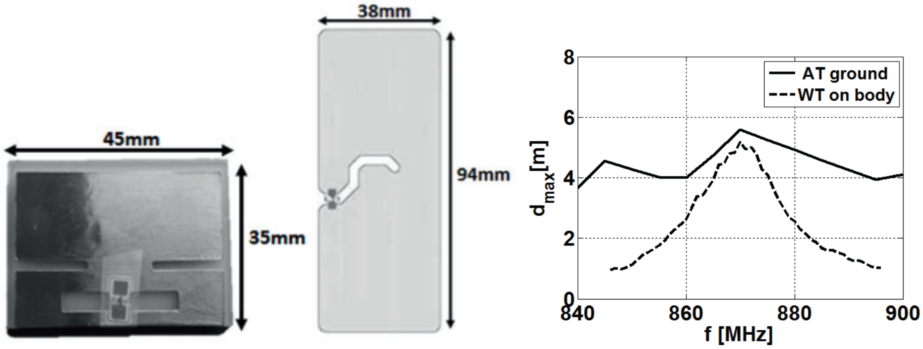


Fig. 2 Top view of the RFID miniaturized wearable tag and of the conventional environmental tag, together with their estimated maximum read range along broadside direction .

3) The reader: is the CAEN ION equipped with a broadband linear-polarized Stacked Planar Inverted-F Antenna (SPIFA) over Teflon substrate, having external size of 130mm × 200mm × 12mm and maximum simulated gain evaluated at 868MHz along the broadside direction equal to 5.8dB. The 3dB-beamwidth of the antenna (85° and 108° for the H-plane and the E-plane respectively) is compatible with a uniform illumination of the environment.

2.2. Safety Compliance Issues

The compliance of the NIGHTCare platform with radio-emissions regulations and human safety has been specifically investigated by means of numerical electromagnetic simulations with the tool FEKO [7] at the purpose to estimate the electromagnetic field in the whole environment and the power absorbed by the sleeper's body. In its basic configuration (Fig.3), the model comprises the reader antenna (by means of its radiation pattern), the floor, the bed and the patient, here emulated by considering an anthropomorphic homogeneous phantom ($\varepsilon r = 41.5$, $\sigma = 0.94$S/m, $\rho = 1000Kg/m^3$).

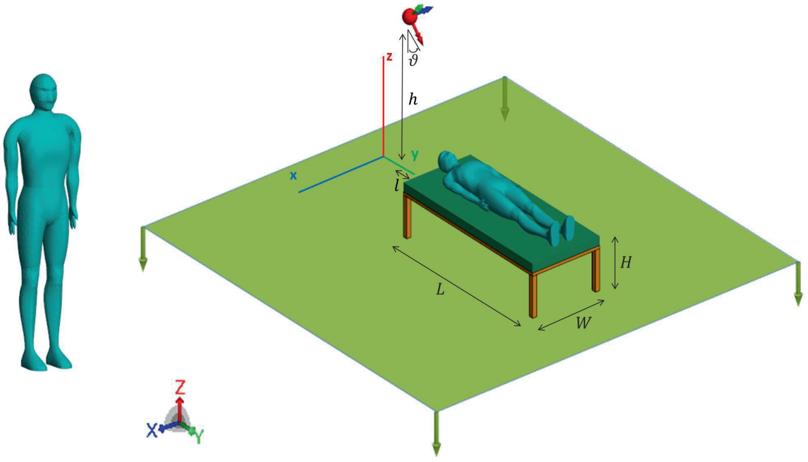


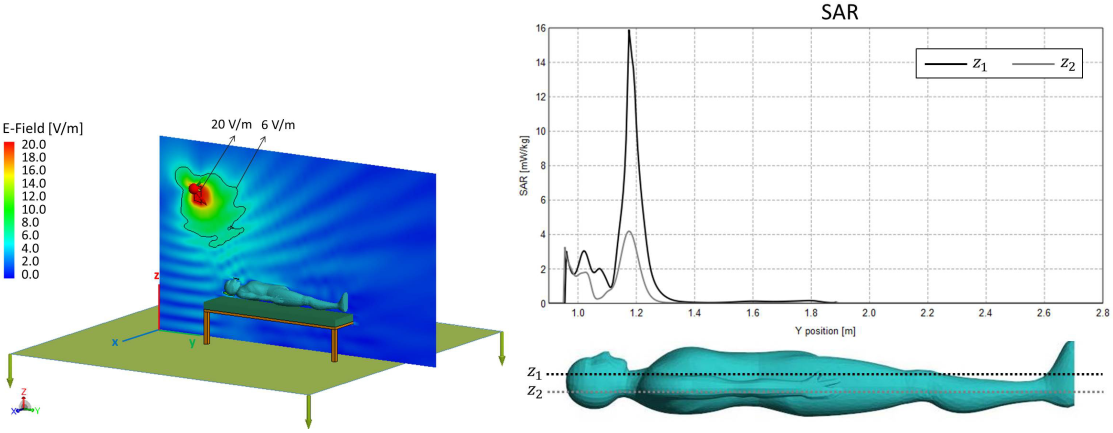
Fig. 3 Numerical Model of the NIGHTcare platform comprising the reader antenna, the bed and the human phantom. Geometrical parameters: L=190cm, W=80cm, H=52cm, h=180cm, l=40cm, $\vartheta = 45°$.

Constraints over electromagnetic field exposure and power absorbed by the human tissues are imposed by the European Recommendations [8]. In particular, the emitted field is required to be less than $E_0 = 1.375\sqrt{f}$, i.e. about $41\mathrm{V/m}$ in Europe where f=866MHz. The Specific Absorption Rate (SAR)

$$SAR(r) = \frac{\sigma(r)|E(r)|_{rms}{}^{2}}{\rho(r)}$$

averaged on the entire body needs to be less than $\mathrm{SAR}_{b,max}$=0.08W/Kg and the SAR averaged over 10g of tissue less than $\mathrm{SAR}_{10,max}$ =2W/Kg. Even more restrictive constraints may be found in some Countries, as in the case of Italy where E_0 = 6V/m.

Fig. 4a shows the field produced by a reader antenna placed at *h*=180cm from the floor, *l*=40 cm from the bed, with a tilt of 45° and emitting 3.2W EIRP with a duty-cycle of 0.2, corresponding to a single interrogation per second. The system is completely compliant even with the more restrictive EM exposure limits, since in close proximity of the sleeper the field is lower than 4V/m. The duty-cycle could be even further reduced in accordance with the characteristics of the user and the monitoring requirements. Fig.4b finally shows the estimated SAR profiles inside the body. The averaged values SAR_b =0.6mW/Kg and SAR_{10} =4mW/Kg (expected to arise in correspondence of the upper portion of the body) are greatly below the exposure limits.



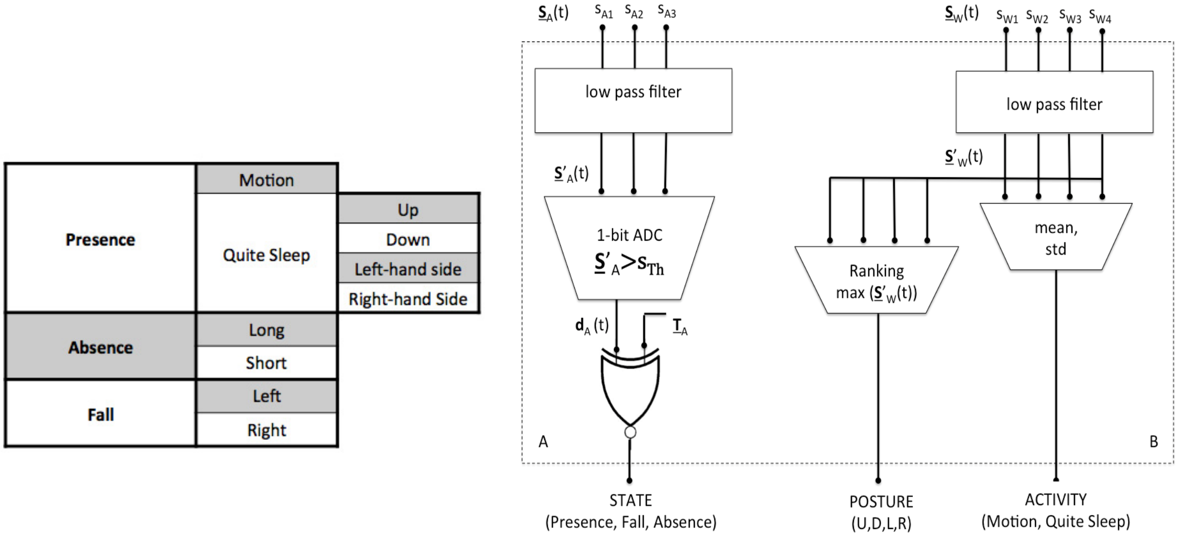
a) b)

Fig. 4 a) Numerical estimation by Feko of the field distribution in a conventional sleeping room with a reader antenna placed 1.5m far from the body, emitting 3.2W EIRP with a duty cycle d=0.20 (an interrogation per second). b) Calculated values of SAR along the sagittal plane of the body

3. Signals and Processing Algorithm

The detection algorithm can be logically divided into two parts, one for the detection of the user state, e.g. his presence/absence from the bed, and a second one for the estimation of his activity, e.g. movements, quite sleep and corresponding postures (see Fig.5). The former relies on the analysis of the signals coming from the ambient tags $\underline{\boldsymbol{S}}_A = [s_{A1}(t), s_{A2}(t), s_{A3}(t)]$, while the latter depends on the signals from the wearable tags $\underline{\boldsymbol{S}}_W = [s_{W1}(t), s_{W2}(t), s_{W3}(t), s_{W4}(t)]$. The two sub-algorithms are not totally independent, since at the end of the process the final results are properly crossed such to validate the inferred states and solve possible ambiguous cases. A high-level description of the proposed detection algorithm is given by the flow chart sketched in Fig.5.

RFID backscattered signal is characterized by low values (~ -50dB) and high fluctuations, mainly due to the receiver internal noise, the limited stability of its components and above all the non-stationary communication channel. Therefore, the raw data $\underline{\boldsymbol{S}}_{\boldsymbol{A}}(t)$ and $\underline{\boldsymbol{S}}_{\boldsymbol{W}}(t)$ need to be preprocessed before feeding the event-detection algorithm by low-pass filtering. Furthermore, since the interrogation protocol could randomly fail because of environmental interferences and collisions, missed readings are dropped out the useful time series, as in the case of *on the floor* tags, whose response to the reader query is strongly related to the user's fall detection (false positive events detection).



Presence	Motion	
	Quite Sleep	Up
		Down
		Left-hand side
		Right-hand Side
Absence	Long	
	Short	
Fall	Left	
	Right	

Fig. 5 Left) Classification table of the NIGHTcare platform. Right) High-level flow chart of the detection algorithm

After the preprocessing block, the averaged signals from the ambient $\underline{\boldsymbol{S}}_{\boldsymbol{A}}{}'$ undergo a 1-bit A/D conversion, whose threshold values (stored in a vector $\underline{\mathrm{s}}_{\mathrm{Th}} = [\, \mathrm{s}_{\mathrm{Th1}}\,, \mathrm{s}_{\mathrm{Th2}}, \mathrm{s}_{\mathrm{Th3}}\,]$) are properly set according to the personal monitoring requirements and to the different users' categories. Finally, a *XNOR* gate is applied to the digital signals $d_A(t)$ such to retrieve the user's state. The reference *XNOR* input is a [3×4] matrix T_A containing the only four meaningful combinations among the 2^3 available ones, e.g. *Presence, Absence, Left-fall, Right-fall*. The *Long-Absence* state is finally appointed when the Absence condition lasts for a period longer than the physiological one set for the user.

The detection of the activity relies instead on the analysis of the analog signals $\boldsymbol{S'}_W(t)$ coming from the wearable tags $\boldsymbol{S}_W(t)$ and processed by the initial block. The discrimination between *motion* and *quite sleep* is firstly performed by analyzing the signals' standard deviation; then if the subject is in the rest condition, his posture is retrieved by applying a simple maximum-value rule: the tag that has the maximum RSSI value is the closest to the reader antenna and, since the subject wears a tag on each side of the body, the position can be univocally retrieved.

The detected status and posture of the sleeper is both stored in the database and visualized in real-time on mobile and fixed platforms. If a dangerous event is detected, an audiovisual alarm is automatically generated and the critical event occurrence stored (see Fig.6).

The algorithm is also capable to count the events and perform statistics on the user's state, e.g. how many time he left the bed in the night, the number of movements and the time percentage for each position, as shown in the next experimental session.

It is worth noticing that it is possible to infer the patient states presence, absence and fall, even by using the only ambient tags. Whether collecting information about the posture and the movement of the sleeper was not required, the platform could be hence sensibly simplified.

Fig. 6 Real-time visualization of the NightCare system on mobile platform

4. Experiments

A realistic experimental session has been performed during three nights by monitoring an elder subject (age 95) inside a nursing home. The subject was not fully aware of all the functionalities of the system, ensuring a natural and not-biased behaviour during the three experiments.

Fig.7 top shows the NIGHTcare responses over one of the three nights. The detected profile has been validated by the annotations about the activity kindly provided by the lady the morning after. The patient went to bed around 22.15 and slept approximately until 5.00 in the morning, with a short absence around 1.00 am, probably for going to bathroom. The sleep was peaceful, with only 12 small movements detected over the entire night and a quite constant posture: the patient rarely changes her position during the night, due to the slowness and difficulty in movement that is typical of the advanced age. Finally, the sleep appears well reproducible throughout the course of the three nights, as clearly demonstrated by the aggregated data about the body posture and the movements on Fig.8 (middle and bottom). Each night, the lady went to bed between the 22.15 and the 22.30 and slept until 5.15-5.30 in the morning. She went to the bathroom around 1.00am and took approximately 5-10 minutes to come back to the bed.

5. Conclusions

The results presented in the paper demonstrated that by combining together wearable tags and ambient tags it is possible to develop a fully passive RFID system to remote monitoring the state of children, disabled and elderly people during the night. The platform is completely compliant with the EM exposure limits and hence it is suitable to be installed in both domestic and hospital environments.

By considering the advantages of RFID passive sensors, it is possible to envisage a further improvement of the platform by providing the same infrastructure also with wearable temperature sensor tags at the purpose to detect and follow fever events, as well as humidity sensor tags under the mattress to monitor incontinence and finally miniaturized tags placed over medicines and food to enrich the patients' behavioral analysis.

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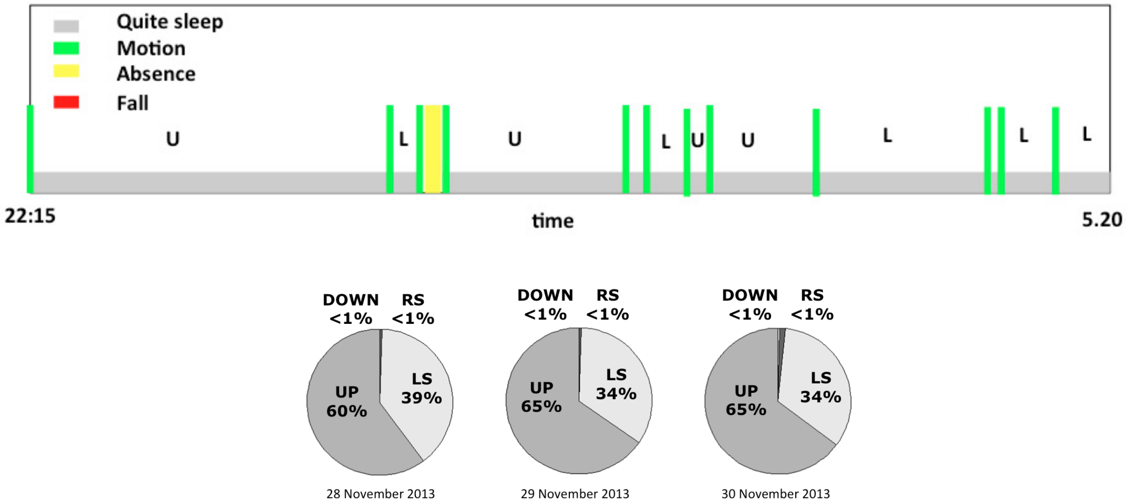

Night	Time	Absence	Number of movements
I (28 nov)	22:34 – 5:25	1 (1:00 - 1:10)	about 14
II (29 nov)	22:18 – 5:19	1 (00:51 – 1:00)	about 12
III (1 dic)	22:18 – 5:24	3 (22:32 – 22:40) (1:17 – 1:23) (4:56 – 5:02)	about 17

Fig. 7 Top) Trace of the NIGHTCare platform as recorded November 29th 2013. For each quite sleep condition, the different body postures have been classified (U: up, L: Left-hand side). Middle and Bottom) Aggregated statistics on the body posture and the movements

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