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Ambient intelligence in the bedroom

Dorien Van Deun[1], Tim Willemen[1,2,3], Vincent Verhaert[1], Bart Haex[1,4], Sabine Van Huffel[2,3], Jos Vander Sloten[1]

[1]Department of Mechanical Engineering, Biomechanics Section, KU Leuven, 3001 Leuven, Belgium
[2]Department of Electrical Engineering, ESAT-STADIUS, KU Leuven, 3001 Leuven, Belgium
[3]iMinds Research Institute, Medical Information Technologies
[4]IMEC, 3001 Leuven, Belgium

Over the past 10 years, ambient intelligence has infiltrated our lives in the form of various home applications, enabled by the ever decreasing size and cost of computing technology. While in transport and industry its presence has become second nature, some areas have remained fairly untouched. Our bedroom is one of these areas, despite the fact that we spent almost a third of our lives accommodating it. Since our bedroom hosts the beginning and end of our daily activities, it needs to assist us in the recovery and preparation of respectively our past and future daily activities. Therefore it holds an enormous opportunity for ambient intelligence applications, which do exactly what is needed: sensibly assisting the user, learning his or her preferences, and reacting to his/her mood and needs. In this chapter we will outline the different ways of assisting the user in his or her intelligent bedroom: ways to monitor health, improve both physical and mental recovery during the night by automatically optimising the sleep environment (smart body support and temperature control), as well as automate a number of tedious tasks which reoccur at every start and end of the day.

Ways to monitor health

Since we spent almost a third of our lives in bed, it presents an enormous opportunity for general health monitoring. During the past decade, numerous methods and techniques have been developed to record vital body parameters such as respiratory and cardiac activity from within or around our bed. Some methods directly measure electrical activity of the heart, while others focus on the mechanical activity of both heart and lungs. The main idea is however to perform all measurements off-body, e.g. without attaching sensors directly to the skin. This will make sure that subjects are not disturbed before and during their sleep, both physically and mentally. Physical disturbance can occur due to skin irritation on places where sensors were attached, or the presence of wires connecting the sensors to a registration or transmitting device. Mental disturbance on the other hand can be due to the person being aware that he or she is being measured, or to the nuisance of attaching the sensors before being able to go to sleep.
Once heart and breathing rate are acquired, heart and breathing rate variability analysis (i.e. temporal changes in heart and breathing rate analysed in both time and frequency domain (Cardiology Task Force, 1996)) can lead to information regarding cardiac health, stress and sleep quality. The latter two are based on research that links the variability within heart and breathing rate to the sympathetic and parasympathetic variations within the autonomic nervous system (Somers et al., 1993). Based on this link, differences in stress level of a person can be received (Hall et al., 2004), his/her sleep pattern can be analysed (Willemen et al., 2013) and possible sleep disorders can be detected (Stein et al., 2012).
In this subchapter on health monitoring, we will first discuss how respiratory and cardiac activity can be registered off-body from within or around our bed, after which we will go into more detail on the relevant information that can be extracted from these signals and how this information can be used.

Off-body registration of respiratory and cardiac activity

As described in literature, *electrical* activity of the heart can be registered by placing textile electrodes into the bed sheets (Peltokangas et al., 2012; Devot et al., 2007) (Figure 1). Similarly to how a standard electrocardiogram (ECG) is obtained, it registers the voltage difference between the different electrodes that are in contact with the subject's body. Wearing pyjamas will of course limit the possible body contact area with the electrodes embedded in the bedding textile, making the registration difficult. Although these textile electrodes can also be implemented in pyjamas themselves, it violates the idea of having all sensors off-body, since you would have to put on these pyjamas every time, and worry about issues like battery status and a wireless communication link.

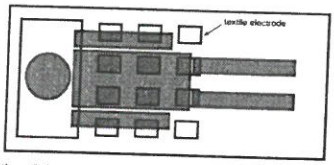


Figure 1: Off-body detection of electrical activity from the heart (Peltokangas et al., 2012; Devot et al., 2007).

Mechanical activity of heart and lungs leads to subtle body motions. Respiration causes obvious thorax and abdominal movement, whereas the pulsation of blood with every heart beat gives a small but detectable oscillation of the body due to conservation of momentum,

$$\vec{p}_{t_1} = \vec{p}_{t_2}$$
$$t_1 : \vec{p}_{t_1} = \vec{0}$$
$$t_2 : \vec{p}_{t_2} = m_{blood}\vec{v}_{blood} + m_{body}\vec{v}_{body}$$

With $\vec{p}$ the momentum at timestep 1 and 2 (t_1 and t_2), m the mass and $\vec{v}$ the velocity. The registration of the latter is formerly called a ballistocardiogram (BCG) (Braunstein et al., 1953).

This movement is different from the movement we can feel when placing our hand on our chest, the so-called seismocardiogram, which is a direct result of the contraction of the heart. The ballistocardiogram reflects purely the movement of the blood. To better understand its principle, we can compare it to the recoil when firing a gun (Figure 2). When someone shoots a bullet out of a gun, due to conservation of momentum the gun will experience a recoil opposite to the direction of the bullet.

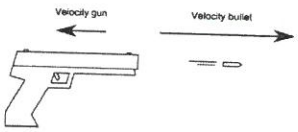


Figure 2: Recoil of a gun, comparable to the recoil the body experiences in the ballistocardiogram.

In the case of the ballistocardiogram, the blood would be the bullet, and the human body would be the gun. At Every heartbeat, blood is ejected from the heart through the aorta, first moving a bit upwards, after which it moves down towards our digestive system and our legs. Due to these movements, our body will experience a consecutive down- and upward recoil with every heartbeat, after which the oscillation is absorbed (e.g. within the mattress material). Figure 3 shows an examplary fragment of a registered ballistocardiogram that lasts eight seconds, in this case measured with a pressure sensor connected to a volume of air which was placed underneath the thorax of the subject. On top the combined respiration and heart beat signal is shown, whereas below the band filtered individual signals are presented, containing about two and a half respiration cycles and seven heart beats.

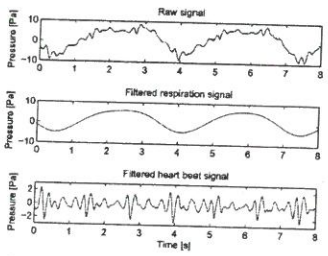


Figure 3: Example eight-second fragment of a registered ballistocardiogram.

Existing methods that are able to measure this mechanical activity can be divided into several categories. A first category uses Doppler radar aimed at the chest area (Guohua et al., 2007). A second category uses load cells inside the four bed legs, detecting changes in the centre of mass of the bed plus sleeper (Brink et al., 2006), or accelerometers in one or more of the bed legs to detect repetitive vibrations coming from this mechanical activity (Nukaya et al., 2012). A third category uses sensor pads placed below, within or on top of the mattress, positioned at the chest area. These sensor pads work either electronically (capacitive, piezoresistive, piezoelectric) (Alihanka et al., 1981), mechanically (pressure variations in a fluid, accelerometers) (Shin et al., 2010; Heise et al., 2010) or optically (reflective changes due to bending of optical fibers) (Bruser et al., 2012). A last category places the same kind of sensor pads underneath, within or upon the pillow (Zhu et al., 2006). Figure 4 visualizes the most commonly used method (third category), with a sensor pad placed underneath the chest area.

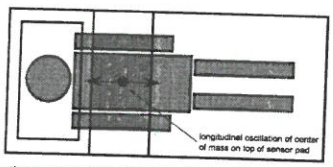


Figure 4: Off-body detection of mechanical activity from the heart (Alihanka et al., 1981; Shin et al., 2010; Heise et al., 2010; Bruser et al., 2012).

Numerous algorithms of different complexity have been developed for extracting the heart rhythm from the BCG signal. A first category uses characteristic features of the general BCG complex shape to determine the heart beat locations, either using thresholds or using machine-learning mechanics such as clustering (Bruser et al., 2011; Rosales et al., 2012; Heise et al., 2013). Sometimes these features are first enlarged by applying a differentiation or squaring filter (Mack et al., 2009; Kortelainen et al., 2007). A second category tries to determine the heart beat locations via correlation to either a BCG complex template constructed from a training set (Jansen et al., 1991), or to the previously detected heart beat cycle (Friedrich et al., 2010; Bruser et al., 2011). Multiple algorithms have also been combined for improved robustness (Sprager et al., 2012; Bruser et al., 2011; Friedrich et al., 2010; Bruser et al., 2013).
Although currently existing algorithms are able to successfully segment almost all individual heart beat cycles, they still experience difficulties in localizing the exact positions of the heart beat locations. This exact detection is important for heart rate variability analysis where the exact variations in time difference between the sequential heart beats are crucial. The main reason for these difficulties is the large variations in BCG complex shape, not only between registration methods, sleeping postures (due to differences in contact surface) and subjects (due to differences in cardiac strength, rhythm and exterior anatomical differences), but also over the respiration cycle (due to changes in cardiac filling of the left and right ventricle). Nevertheless, given the large surge of interest in BCG research during the last decade, and the current state of the art, these difficulties will most probably be overcome in the coming years.

Extraction of relevant information

Demographics show that nowadays up to 24 % of the population is faced with regular sleep problems (National Sleep Foundation, 2012), due to e.g. insomnia (the inability to initiate and maintain sleep), obstructive sleep apnoea syndrome (OSAS; upper airway collapse during sleep), an increased stress level or a mere lack of sleep hygiene. This percentage seems to be raising every decade, inversely correlated with the ever decreasing average amount of sleep we get due to our highly active lifestyles (on average we sleep one hour less than 100 years ago). Therefore, it is not surprising that the importance of sleep is being emphasized more and more every year, next to the other important health pillars of healthy food and sufficient activity. Given the general trend of people becoming more proactive in following up on their own and their family member's health status, people want to follow up quality of sleep as well.
Sleep can roughly be divided into two main states, labelled Rapid-Eye-Movement (REM) and Non-REM (NREM (N1-N2-N3)) sleep, which alternate in cycles of about 90 minutes (Rechtschaffen et al., 1968). Figure 5 shows an example of a hypnogram from a healthy sleeper, with five alternating sleep cycles of NREM sleep and REM sleep. NREM sleep, especially deep sleep (N3), is more prominent during the first hours of sleep and is essential towards physical

recovery (Haex, 2004; Adam et al., 1984). REM sleep, linked to dreaming and more prominent during the last hours of sleep, acts towards the recovery of our mental state (Meerlo et al., 2009).

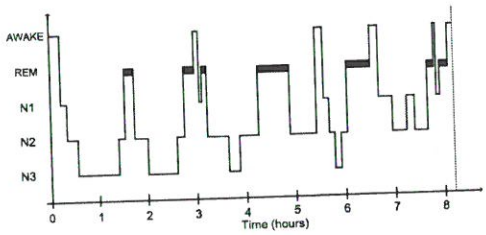


Figure 5: Example of a healthy hypnogram with 5 alternating cycles of NREM sleep (N1-N2-N3) and REM sleep.

Polysomnography (PSG) (Iber et al., 2007) is currently the gold standard in detailed sleep analysis. It requires however extensive amounts of on-body sensors (electroencephalogram for brain activity, electro-oculogram for eye activity, electromyogram for muscular activity, etc.), making the method costly and disturbing, and thus ruling out long-term monitoring. Actigraphy (ACT) (Morgenthaler et al., 2007) on the other hand, which makes solely use of movement information (accelerometer worn as a wrist band) to differentiate between Wake and Sleep, is both cheap and user-friendly, but unfortunately lacks both detail (such as the REM-NREM distinction) and accuracy (Paquet et al., 2007; Buickaert et al., 2010). For this reason, sleep quality estimation using cardio-respiratory variability analysis suits perfectly to fill the gap between PSG and ACT, since it still has decent accuracy (Willemen et al., 2013) while being much more user friendly than PSG because of its unobtrusive character.
Deep sleep (N3) is characterized by a low variation in heart and breathing rate, while higher variation indicates light sleep (N1) or REM sleep. Furthermore, sudden raises in heart rate indicate periods of awakenings. This is certainly the case when followed by a period with a higher variability in inspiration and expiration lengths, since this reflects a more conscious control of our breathing. During sleep, we breathe unconsciously, leading to more regular breathing intervals. Longer periods of immobility also point towards deep sleep (N3), whereas periods with large movement activity point towards wake and periods with repeating small movement activity (so-called twitches) points towards REM sleep (Willemen et al., 2013).
When we cut in our sleep time, we mainly reduce the amount of REM sleep we get since it is more prominent during the last hours of sleep. This thus reduces our mental recovery window. Increased amounts of stress, mood disorders and cognitive dysfunction are all linked to this reduction in REM sleep (Meerlo et al., 2009). When increased amounts of REM sleep are perceived towards the beginning of the night, it is a clear sign for a present or upcoming depression. When for older persons significant changes in sleep pattern are measured (mainly with regard to when they go to bed and when they get up again), it is often a sign of upcoming dementia or Alzheimer's disease (Moe et al., 1995). Highly irregular breathing and moments of absent breathing could point towards a sleep disorder like Obstructive Sleep Apnoea, which has an incidence rate that increases with age (Lee et al., 2008) and can have a serious impact on cardiovascular health.
Besides purely monitoring our sleep quality on a day-by-day basis to look for imminent disease, depression or possible sleep disorder, the monitoring system can also give recommendations on whether and how we have to reduce our stress level when we go to bed (detected in our heart rate variability pattern), or how to improve our sleep hygiene for obtaining better sleep (for example by drinking less caffeine and alcohol, or by making time for 30 minutes of relaxation before going to bed to be able to fall asleep more rapidly). Most of us are not aware that some of our activities or customs can have a significant impact on our sleep. By logging our activities and customs next to the day-by-day monitoring of our sleep, we can learn which ones affect our sleep in a negative way and should thus be avoided to improve our overall sleep quality. Information overload should however be prevented. We don't want to become so aware of our sleep, that it starts to have a detrimental effect. We all have experienced these situations where we truly want to fall asleep, but we fail to succeed in doing so because we are giving too much attention to it. The same principle applies here: obtaining the best quality of sleep should not become a competition. The system of monitoring, reporting and recommending should work in an empowering and not overpowering way.

Information-Based Adaptation
Besides reporting sleep quality to the user, information on sleep and sleep distribution can also be applied during the night itself. In order to influence and improve sleep quality, the bed and other bedroom properties could be adapted continuously to best fit our current sleep status. We do not need a 70 or 80 dB alarm to wake us up, for example, if we would already be lying awake in our bed; some soft music, and (gradually) turning on the lights would have the same effect. On the other hand, if we are still in deep sleep, and we definitely need to wake up at a particular time, increasing the volume higher than the standard 70 dB might help those of us who tend to sleep firmly. Further on, in the evening, a colder room (but warmer bed sheets) will get us all comfortable in bed, while in the morning a warmer room (but colder bed sheets) could help us to get from underneath our blankets more easily (which will be described in more detail in the next subchapter).
When we want to put on some light during the evening or night, it is often better to have a lower intensity of light than during the day to prevent significant suppression of the hormone melatonin which is produced during darkness and helps to regulate and promote sleep (McIntyre et al., 1989). In the morning, this depends on whether we want to wake up quickly or slowly, (probably depending on whether we need to go to work). Also the colour spectrum of the light can be adapted to our mood (Küller et al., 2006). If we are stressed in the morning (measured through heart rate variability monitoring from within our bed), some extra green and blue might help us relax. If we are just tired, some red and violet might give us the adrenaline boost we need to get ourselves going. If in the evening we arrive laughing to our bedroom, some yellow might improve our mood even more.
This active adaptation of our bedroom is a topic that, amongst others, will be further discussed in the next section, which focuses on how to improve our physical and mental recovery during the night.

Improving recovery during the night by optimising sleep conditions

Both physical and mental recovery occur during sleep, which can be seen as a muscle and brain relaxation state. While mental processing occurs during REM-sleep, physical recovery of our body is mainly situated during deep sleep (N3), also called slow wave sleep (SWS). To optimize physical recovery the bedding system plays a central role as it functions as a support to the human body. At present, more and more research is focusing on filling the knowledge gap related to the impact of the sleep surface on general sleep quality and other sleep related factors such as sleep architecture and body movements. For example, it has proven that applying ergonomic design principles can affect actual sleep (Van Deun et al., 2012). The same applies for bedroom and bed temperature. Since sleep occurs during the circadian phase of decreased heat production and increased heat loss (Van Someren et al., 2006), the major sleep period occurs during the decrease of core body temperature (CBT) in the circadian rhythm. Moreover, the ease of falling asleep is related to skin temperature at the extremities, such as hands and feet, and can be optimised to reduce sleep onset time or nightly awakenings. (Marotte and Timbal, 1982, Van Someren, 2006).
This subchapter will focus on optimization of body support and temperature during sleep, which are both subject-dependent and therefore require feedback control loops to be able to be used in (future) bedroom environments.

Body support optimization

Ideally, the body is supported in a way that allows the muscles to relax and intervertebral discs to recover from daily activities in which the spine is nearly continuous loaded (Nachemson and Elfström, 1970; Leblanc et al., 1994). From an ergonomic point of view, such optimal support during sleep refers to aligning the spine towards its reference shape, which is comparable to the shape while standing but with a slightly flattened lumbar lordosis due to the changed working axis of gravity (Dolan et al., 1988). The shape can be referenced to as the S-shape that would appear in a condition of weightlessness. Bed properties that provide this optimal support are both posture- and person-dependent. For instance, in most subjects lateral, frontal and posterior body contours differ, which results in a different spinal alignment when changing sleep posture (Gracovetsky, 1987; Verhaert et al., 2011; Haex, 2004).
To account for these variable conditions, a new approach in the development of state-of-the-art bedding systems consists of monitoring movement and sleep posture changes based on mattress indentation data (Verhaert et al., 2011). In addition, the combination of mattress indentation measurements with personalized digital human models (Van Deun et al., 2013) allows estimating spinal alignment during sleep in an unobtrusive way (Verhaert et al., 2011b). this methodology was applied by Verhaert et al. (2013) to control mechanical bed properties (stiffness) of a sleep system during the night. Furthermore, follow-up studies by Van Deun et al. explored the influence of such an *active bedding system* (designed to continuously optimize spinal alignment) on objective and subjective sleep parameters. Overnight experiments in a dedicated sleep laboratory were performed in order to look at sleep macrostructure, body movements and subjective sleep parameters. The following paragraphs will dive deeper into the different aspects that are needed in state-of-the-art bedding systems to continuously and automatically optimize body support.

Mattress indentation measurements
The ability to instrument the bedding system has raised interest in studying body movement or monitoring sleep postures (Lu et al., 1999; Adami et al., 2010; Harada et al., 1999; Brink et al., 2006; Hoque et al., 2010). Mattress indentation measurements provide useful information to assess movements and sleep postures. Examples of a lateral (left) and supine (right) sleep posture are presented in Figure 6. Moreover, since mattress indentation provides direct information on how the mattress surface is deformed, these measurements offer valuable insight in the deformation of the body (once the body itself is characterized in terms of shape and weight distribution, which is discussed further on). As opposed to pressure mapping, indentation measurements provide more appropriate information to assess spinal alignment during the night because of the direct link to body indentation. As an example, a person having wide and heavy shoulders will sink deep into the mattress when lying in a lateral sleep posture. A pressure recording of that person can be difficult to interpret because the measured pressure heavily depends on the soft tissue around his/her shoulder. More soft tissue better distributes pressure and would thus result in lower peak pressure.



Figure 6: Example of mattress indentation measurements for right lateral (left) an supine (right) sleep postures.

According to Verhaert et al. (2012) movements and postures can be easily detected usir. mattress indentation measurements integrated in a bedding system. Sensitivity for posture recognition (supine, left lateral, right lateral and prone postures) varies between 83.6% and 95.9%. Movement detection shows a sensitivity of 91.2% in this study. Also so-called intermediate sleep postures have been recently studied. These postures show a combination of lateral and prone or supine sleep positions. An example is a subject lying in a lateral sleep posture according to his hip orientation while his shoulders are turned towards the mattress, and thus rather resemble a prone posture (Figure 7). Such in-between postures cause spinal torsion and thus should be avoided. Due to large interpersonal differences, they are more difficult to identify using static classification methods.

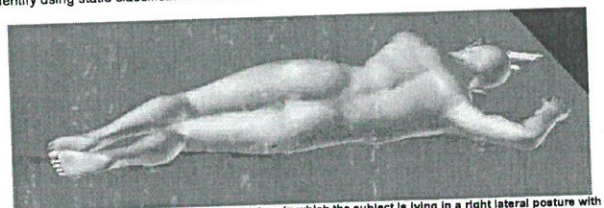


Figure 7: Example of an intermediate sleep posture in which the subject is lying in a right lateral posture with it shoulders turned towards the mattress.

Digital human modelling

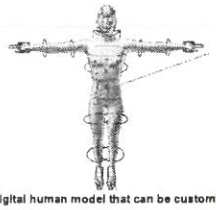


Figure 8. Example of a digital human model that can be customized (www.blender.org)

Human avatars, here defined as human mesh models having an underlying skeleton to enable posing of the mesh, are commonly used in modelling purposes such as modelling work space environments. The use of a *customized* human model (e.g. Figure 8) is of large importance in individualizing sleep ergonomics. It can be used to quantify body support (Verhaert et al., 2012), which is depending on a subject's anthropometric characteristics. In modelling sleep ergonomics, the need for a *personalized* human avatar is two-fold. First of all, it can be used to classify a the sleep posture or even track it during the night, for example by means of a particle filter which can be used when static posture recognition algorithms fail in recognizing so-called intermediate postures. This fail is mainly due to the fact that most recognition algorithms do not incorporate individualized anthropometric information. Secondly, when looking at body support – or specifically spinal alignment –, a digital human model is necessary to assess the spine shape of a person when lying on a sleep system in a specific posture. Therefore, only a customized human avatar can be used that takes into account the person-specific anthropometrics (such as sagittal and coronal body shapes, length and preferably also weight distribution) in order to calculate the shape of the spine.

Anthropometric information on the human body can be derived both manually (using caliper and tape) and automatically. Automatic methods include information from camera images such as contour information (Van Deun et al., 2013) and depth and colour information (e.g. from Microsoft Kinect (Wijckmans et al., 2013)). Also 3D full body scanners can be used to generate complete 3D information but such scanners are much more expensive compared to camera information. More recently, mattress indentation measurements are used to generate customized human avatars. As opposed to camera images or body scanners, mattress indentation measurements also provide information on the weight distribution of the body since heavy body parts will sink deeper into the mattress. Therefore, these measurements are preferably used for digital human modelling in sleep ergonomics.

Most of the presented techniques will use a 3D base model (mesh model) of the human body that is adapted to the measured information, resulting in a customized model. Adaptation of the mesh can be performed by morphing, a technique in which vertices are repositioned along a (linear) deformation path between two extreme target positions, called morph targets (Volz et al., 2007; Klette and Zunic, 2004).

In order to use the human model for spine shape estimation, body weight needs to be distributed to the different body parts in accordance to mattress indentation measurements.

Smart control of spinal alignment

The combination of mattress indentation measurements with customized information on the human body allows for estimating the shape of the spine unobtrusively, as shown by Verhaert et al. (2012). When incorporated into the bedding system, this allows for continuous follow-up of the spine shape during the night.

We can go one step further by introducing active components into the bedding system resulting in a so-called *active or smart bedding system*. Actuators are used to control the stiffness of the bedding system in different comfort zones as to create a non-homogeneous stiffness distribution. The necessary stiffness distribution is depending on both the person's anthropometric characteristics and the sleep posture in which he or she is lying. As a consequence, a smart bed also has a posture recognition algorithm incorporated, as described before. Furthermore, unobtrusive evaluation of the spine shape is used as input to a controller to regulate the stiffness of the comfort zones. A schematic representation of this control loop is presented in Figure 9.

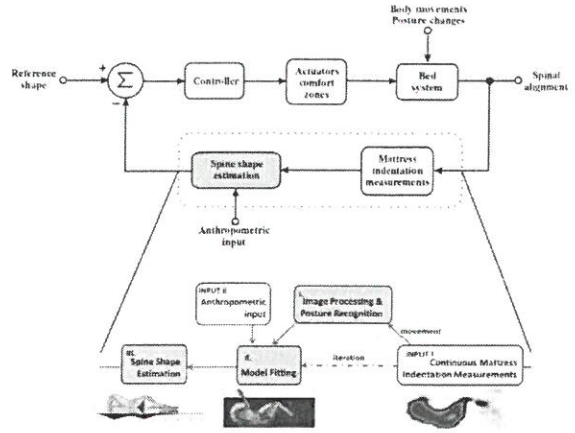


Figure 9: Schematic representation of a control loop that optimizes spinal alignment by controlling stiffness actuators in different comfort zones. Adopted from Verhaert et al. (2013).

A reference shape of the spine is used as input and refers to the optimal shape the spine would have in an unloaded condition. The reference shape is comparable to the spine shape while standing, however with a flattened lordosis since no gravity is working in the longitudinal direction when sleeping. Based on the difference between the reference and the estimated spine shape, a controller alters the stiffness in the different comfort zones of the bed resulting in a change in mattress indentation measurements and spinal alignment. This loop is continued until spinal alignment is similar to the optimal (reference) condition. Every time the sleeper changes posture, the stiffness distribution is optimized.

The effect of smart body support on sleep, sleep-related parameters and recovery

Overnight experiments have been performed to evaluate the effect of an optimized body support – provided by a smart bed - on both objective and subjective sleep parameters using polysomnographic recordings and questionnaires respectively. Van Deun et al. (2012) used the previously described bedding system during overnight sleep experiments in a dedicated sleep laboratory. Subjective results show a significant positive effect on both sleep and daytime quality after sleeping on an active bedding system. On the other hand, movement and sleep posture information – as retrieved from mattress indentation measurements – show no significant difference when the bedding system was not altering its stiffness distribution. Objective measurements on sleep parameters retrieved from a polysomnographic recording have shown that optimal body support during the night increases the amount of deep sleep, also called slow wave sleep (SWS). Since SWS is essential for physical recuperation (Shapiro et al., 1981) during the night, sleeping on a smart bed that provides optimal body support will result in a positive restorative effect on your body. This allows to (physically) recover from daily activities during the night. Mental recovery, on the other hand, mostly occurs during REM-sleep, which was not significantly altered.

Smart control of neck extension in OSA patients

For specific groups of people, such as patients suffering from obstructive sleep apnoea (OSA) syndrome, body support control or temperature control are not the prior focus to improve sleep. In 80% of the cases OSA is associated with more and longer apnoea's or hypopnea's in a supine sleep posture. The same relation applies to snoring. Therefore, sleep optimization (and improved recovery associated with it) during the night can be achieved by controlling the cervical position when sleeping in a supine posture. For example, it has been proven by Choi et al. (2000) and Jan et al. (1994) that the resistance of the upper airway is reduced when the head is extended. As mentioned before, bedding systems exist that can detect the supine sleep posture and, when necessary, alter the stiffness distribution. Such systems can be used in OSA sufferers or snorers to increase head or neck extension by increasing the stiffness at the shoulders and upper body regions in order to enable a better air flow.

Temperature optimization

Bedroom and bed temperature play a key role in optimising sleep by influencing sleep onset latency, nightly awakenings and sleep depth. Sleep onset closely follows the maximal rate of decline in Core Body Temperature (CBT) and maximal heat loss during the evening (Figure 10). This decline triggers sleep initiation and may facilitate entries into deeper sleep stages (Murphy and Campbell, 1997). The probability to wake up, on the other hand, increases during the early morning rise in CBT (Figure 10). As opposed to CBT, temperature of the skin extremities shows an inverse rhythm, i.e. skin temperature peaks during the habitual sleep period (Marotte and Timbal, 1982, Van Someren, 2006). Skin temperatures at the extremities such as hands and feet increase (e.g. prior to sleep onset) because of peripheral vasodilation, ending up cooling down your core body (Magnussen, 1939; Kleitman et al., 1948). Under normal conditions the nocturnal increase of skin temperature is further amplified by postural change (Tikuisis and Ducharme, 1996; Kräuchi et al., 1997)or a warm microclimate resulting from insulated bedding (Goldsmith and Hampton, 1986; Muzet et al., 1984; Okamoto et al., 1997).

In general it is suggested that a rapid decline in CBT increases the likelihood of sleep initiation and may facilitate entries into deeper sleep stages (Murphy and Campbell, 1997).

The effect of skin temperature on sleep and recovery

The above findings have already been used and studied in attempts to improve sleep and sleep onset by steering the skin temperature. For example, warming skin temperature in a direct or indirect manner prior to sleep has been shown to speed up sleep, resulting in a decreased sleep onset time as confirmed by Kräuchi et al. (1999) and Gradisar and Lack (2004).

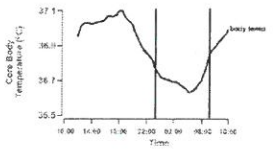


Figure 10: Body temperature and its relation to sleep in adults. Normal sleep occurs between 23:00h and 07:00h.

Moreover, mildly increased skin temperature (0.4°C) at the extremities was shown to increase the time spent in deep sleep (slow wave sleep) by Raymann et al. (2008). However, one should be careful with warming because a too warm skin during sleep initiation might induce arousals and elevation of the core body temperature (Raymann et al., 2007a; 2007b). This elevation of CBT, in turn, can lead to more nocturnal awakenings and decreased sleep. The same applies when the CBT is too low (below the thermoneutral zone).

Based on the aforementioned evidence it is thus of utmost importance to limit thermal manipulations to the proximal and distal *skin* area, i.e. the area normally covered by bedding, without interfering with core body temperature and without interfering with normal room temperature. The magnitude, body location and timing of the skin temperature manipulation are also of large importance for its application to improve sleep. Results of a study by Raymann et al. (2008) indicated that a thermal sleep treatment should aim at individualized and time-of night-dependent control of skin temperature within the small range of reported skin and bed temperature microclimates during sleep (Goldsmith and Hampton, 1968; Muzet et al., 1984; Okamoto et al., 1997). Ideally, bed microclimate temperature should be kept, on average, above 33.5 and 33.2 °C for young adults and elderly (with out sleep complaints) respectively. It is not advised to simply apply heating blankets, which warm up both the skin and core body. Moreover, the warming then occurs without knowledge about the actual body temperatures, which may become high and adversely affect sleep (Fletcher et al., 1999) such as by activating heat stress responses.

The effect of room temperature on sleep

Finally, when speaking of room temperature optimisation, the ideal case consists of starting the night with a slightly lower room temperature (e.g. around 18°C) which enables the core body to lower temperature by losing heat. During actual sleep, room temperature could be slightly increased in order to minimize any thermoregulatory efforts to maintain a stable body temperature during the night. This optimal temperature range is called the thermal neutral zone, in which the body's heat production is in equilibrium with the rate of heat loss to the environment. A normal range for a sleeper varies between 18°C and 22°C. If the room temperature becomes too hot or too cold, you are more likely to wake up during the night. Furthermore, the comfort

level of the room temperature can specifically affect REM sleep since it is generally more vulnerable to temperature-related disturbance (Muzet et al., 1983). The ideal room temperature is subject-dependent, as was the optimal skin temperature, but also the amount of insulation plays a central role. As an example, worse sleep has been reported with a bedroom air temperature of 30℃, as compared to 18 and 23℃ (Fr eedman and Roehrs, 2006). REM sleep is then decreased, as did deep sleep (slow wave sleep) but to a lower extent.

Smart control of temperature

For bedroom applications at home, a system can be developed that is integrated in the bedding system itself which measures skin temperature and/or humidity as well as room temperature and controls the bed microclimate and bedroom temperature in feedback control loops (such as described before for body support). Unobtrusive temperature sensors, such as for example iButton devices, can be integrated in the blankets. The use of iButtons for temperature monitoring have been validated for home monitoring purposes by van Marken Lichtenbeld et al. (2006). Also the mattress can be equipped with temperature and humidity sensors. In the case where skin temperature should be increased, the sleep microclimate can be optimised by heat insulation (such as additional cloths or bedding) or warming up the bed using an electrical blanket. In the latter it is important to switch off heating during actual sleep to prevent interference with core body temperature. Another way is to use body heating such as a warm bad or a sauna prior to bedtime. Early morning awakenings, on the other hand, can only be tackled using an electrical blanket having a delayed start. Lowering the microclimate temperature can be achieved by systems that use a temperature controlled fluid or air flow integrated in a blanket or in the bedding system itself. Bedroom temperature can be more easily controlled using an air conditioning installation or the like.

Automating tedious tasks which reoccur every day

Everyone will recognize that moment when you just crawled underneath the warm blankets of your bed, and it suddenly hits you that you forgot to turn off the lights in the kitchen, still have the manual override of the central heating on or forgot to lock the door. Or you just think you forgot. What if a central computer would know that everyone is up in his bed, and would just do this automatically for you so you never have to worry about this anymore? And this is just the beginning. We can all come up with numerous tedious tasks we lose time on every single day. It would be so much better if the central heating would turn on half an hour before our alarm clock would go off, that a warm bath would already be waiting in the bathroom, and a hot coffee with toast would be ready in the kitchen when we get downstairs.

While we don't mind technology aiding us in trying to find balance in our lives, we still like to believe we are in control of everything happening around us, at least in our own home. Some decisions should not be made without us being aware. After all, most people don't like or even fear the prospect of being controlled by technology. Especially when we take into account that more complex systems are also more vulnerable to malfunction.

On the other hand, it is also important for ambient technology not to work disruptively. If it decides to interact with us, it should try to do so in a way which is seamlessly interwoven with our lives. It should be aware of the context of the situation before reporting, and not interrupting our present activity. Since we spend most of the time in our bedroom sleeping, we don't want to be awoken every time our ambient intelligent bedroom decides to, for example, increase the heating or change the back support from within the mattress. This is one of the main differences with other applications of ambient intelligence, namely the fact that we are not conscious.

Therefore, to solve this problem, and help people get comfortable with this unconscious interference, every decision the system makes should be nicely fitted into a report which is viewable for the user at any time. This way, people can build up their trust within the system, and truly experience how their intelligent bedroom transforms them into a healthier person.

Conclusion

In this book chapter, an overview was given on the current status of ambient intelligence for bedroom applications and its perspective to the future. We tried to give insight in the possibilities of ambient intelligence in the bedroom, as well as the current status of the technology and algorithms making it all possible. A focus was given on different aspects ranging from monitoring sleep and general health in our bedroom, towards automatically controlling body support and temperature during sleep. The combination of both health monitoring and environmental control in an intelligent and efficient way can prove of great benefit for all of us. Moreover, upcoming and state-of-the-art technology will enable a rapid growth of these applications in our future bedrooms.

The majority of this chapter was focused on research performed within our biomechanics division and we hope that it will lead to numerous useful applications.

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