Actuation and intervention principles of a smart bed to improve quality of sleep

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Actuation and intervention principles of a smart bed to improve quality of sleep

A thesis submitted to attain the degree of
DOCTOR OF SCIENCES of ETH ZURICH
(Dr. sc. ETH Zurich)

presented by
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Prof. Dr. Robert Riener, examiner
Prof. Dr. Kenneth Hunt, co-examiner

2017
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Preface

The work presented in this thesis was fully conducted at the Sensory-Motor Systems Lab at ETH Zurich in collaboration with the Institute of Pharmacology and Toxicology at the University Zurich. The work presented in chapter 4 was developed in collaboration with Elite SA (Aubonne, VD, CH). The scientific investigations reported in chapter 2 and chapter 3 were conducted in close collaboration with Dr. Ximena Omlin. Parts of the introduction and chapter 2, are based on a publication with a shared first-authorship:


Part of the introduction and chapter 3 are based on following scientific articles that have been accepted for publication, are under review, or are in preparation:

- X. Omlin, F. Crivelli, M. Näf, L. Heinicke, P. Achermann and R. Riener, “Effect of rocking movements on sleep and memory performance”, *under review*
- X. Omlin, F. Crivelli, L. Heinicke, M. Näf, P. Achermann and R. Riener, “Cardiorespiratory adaptations to vestibular stimulation during sleep”, *in preparation*

In order to reduce the overlap with the PhD thesis of Dr. Omlin, this thesis focuses on the technical setups and on the evaluation of function and applicability of the developed approaches. Complementary information about methods and results of the sleep study are reported in the appendices. Most details concerning the conducted study have been omitted and can be found in Dr. Omlin’s PhD thesis and in the publications mentioned above.
Acknowledgements

These years at the SMS-Lab have been a great and unforgettable experience at both a professional and a personal level. First of all I would like to thank my main supervisor Prof. Robert Riener, for giving me the possibility to join the Lab and to work on this great project. You always believed in me and in our work and you have been a fundamental guide and support during my whole PhD. A special thank goes to Dr. Peter Wolf, who with his suggestions and support contributed significantly to my work, particularly during the preparation of this thesis. A big thank goes then to the people who worked with me in the Somnomat project starting from Ximena Omlin, who has been a competent, motivated, and supportive companion. I am glad I had the chance share this great experience with you. Thanks also to Lorenz Heinicke who helped me in developing the rocking beds and provided a fundamental support during the studies as well as guaranteeing a great and fun working environment. A special thank goes also to the new members of the Somnomat team Rachel van Sluijs and Dr. Elisabeth Wilhelm, who I shared the last part of my period with, who supported me during the last steps of my PhD, and who will continue our work. I would like to thank also Michael Herold-Nadig, Alessandro Rotta, and Marco Bader who contributed to the design and construction of the experimental setups. A particular thank you goes to Georg Rauter, Nicolas Gerig, and Amir Sarabadani, for the numerous interesting and productive discussions and for the important suggestion and help they gave me. Thank you to Diana and Sabina for their precious admin support. Finally, I want to thank all SMS members who guaranteed a wonderful working environment. A special thank goes also to all the students I supervised during the past years and who contributed to the development of the project: Lorenz, Vidya, Steve, Yvonne, Eduardo, Lukas, Paul, Adrian, Matthew, Manuel.

After the SMS Lab I would like to thank Prof. Acherman, for his great support and help during the whole period spent at the sleep laboratory. My profound thank goes to Francois Pugliese and Sania Markic from Elite SA, for the great and productive collaboration developed within the Somnomat project. Thank you for believing in our work and supporting our project. A special thank goes to Prof. Kenneth Hunt who agreed to co-supervise my PhD and showed great interest in our idea and great support during the past years.

The path who conducted to this great achievement was rich of positive and unforgettable experiences, however it presented also difficult periods. Thus, I would like to thank the closest persons in my life who accompanied me, understood me, and helped me during this journey starting from my girlfriend Charlotte, my parents Ercole and Raffaella, my brothers Martino and Filippo, and my grandparents Carla and Giannetto. A big thank you to all of you.
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<td>AHI</td>
<td>Apnea hypopnea index</td>
</tr>
<tr>
<td>B</td>
<td>Baseline condition</td>
</tr>
<tr>
<td>BMI</td>
<td>Body mass index</td>
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<tr>
<td>C1</td>
<td>Movement condition until sleep onset</td>
</tr>
<tr>
<td>C2</td>
<td>Movement condition 2h after light off</td>
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<tr>
<td>CAVE</td>
<td>Cave augmented virtual environment</td>
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<td>CI</td>
<td>Confidence interval</td>
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<td>CL1</td>
<td>AdaBoost standard</td>
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<td>CL2</td>
<td>AdaBoost with Gaussian-based adaptive normalization</td>
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<td>CL3</td>
<td>AdaBoost with quartiles-based adaptive normalization</td>
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<td>CL4</td>
<td>Fixed threshold with Gaussian-based adaptive normalization</td>
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<td>CL5</td>
<td>Fixed threshold with quartiles-based adaptive normalization</td>
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<tr>
<td>CPAP</td>
<td>Continuous positive airways pressure</td>
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<tr>
<td>DOF</td>
<td>Degree of freedom</td>
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<tr>
<td>ECG</td>
<td>Electrocardiography</td>
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<td>EEG</td>
<td>Electroencephalography</td>
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<tr>
<td>EMG</td>
<td>Electromyography</td>
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<tr>
<td>EOG</td>
<td>Electrooculography</td>
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<tr>
<td>ETH</td>
<td>Swiss Federal Institute of Technology</td>
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<tr>
<td>FF</td>
<td>Feedforward</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
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<td>HRV</td>
<td>Heart rate variability</td>
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<td>ILC</td>
<td>Iterative learning controller</td>
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<tr>
<td>IMU</td>
<td>Inertial measurement units</td>
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<tr>
<td>$LA_{eq}$</td>
<td>Equivalent continuous A-weighted sound pressure level</td>
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<tr>
<td>M^3-Lab</td>
<td>Multimodal motion synthesis lab</td>
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<td>MSLT</td>
<td>Multiple sleep latency tests</td>
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<tr>
<td>N1</td>
<td>Sleep stage N1</td>
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<tr>
<td>N2</td>
<td>Sleep stage N2</td>
</tr>
<tr>
<td>N3</td>
<td>Sleep stage N3</td>
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<td>NREM</td>
<td>Non-rapid eye movement sleep</td>
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<td>OSAHS</td>
<td>Obstructive sleep apnea hypopnea syndrome</td>
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<tr>
<td>P0</td>
<td>Bed configuration “FLAT”</td>
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<tr>
<td>P1</td>
<td>Bed configuration “HEAD UP”</td>
</tr>
<tr>
<td>P2</td>
<td>Bed configuration “TRUNK UP 4.8 deg”</td>
</tr>
<tr>
<td>P3</td>
<td>Bed configuration “TRUNK UP 21 deg”</td>
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<td>PD</td>
<td>Proportional-derivative</td>
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<tr>
<td>PI</td>
<td>Proportional-integral</td>
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<tr>
<td>PSG</td>
<td>Polysomnography</td>
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<td>Description</td>
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<td>PT</td>
<td>Positional therapy</td>
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<tr>
<td>r³</td>
<td>Reconfigurable Rope Robot</td>
</tr>
<tr>
<td>REM</td>
<td>Rapid eye movement sleep</td>
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<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>SD</td>
<td>Standard deviation</td>
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<td>SI</td>
<td>Snoring index</td>
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<td>SMS</td>
<td>Sensory-Motor Systems Lab</td>
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<td>SNR</td>
<td>Signal to noise ratio</td>
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<tr>
<td>SO</td>
<td>Slow oscillations</td>
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<tr>
<td>SWA</td>
<td>Slow wave activity</td>
</tr>
<tr>
<td>SWS</td>
<td>Slow wave sleep</td>
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<tr>
<td>TBT</td>
<td>Tennis balls therapy</td>
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<tr>
<td>UARS</td>
<td>Upper airways resistance syndrome</td>
</tr>
<tr>
<td>VAD</td>
<td>Voice activity detection</td>
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<td>WHO</td>
<td>World Health Organization</td>
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Abstract

Good sleep hygiene is a key factor in health and well-being. Perturbed sleep and sleep disturbances can have serious consequences on almost every aspect of a person’s life. Scientific studies suggest that between 33% and 50% of the population is permanently or occasionally affected by sleep disturbances. Thus, identifying an effective approach to promote sleep and to enhance sleep quality could have a huge impact on a significant part of the population. Moreover, the widespread occurrence of sleep-related disturbances among the general population create a very appealing potential market for a new commercial solution to improve sleep quality.

Vestibular stimulation, and particularly rocking movements, seems to be an effective approach to promote sleep. Although rocking movements are widely applied on a popular level, the link between rocking movements and sleep is still poorly understood from a scientific point of view. Thus, further research is needed to understand how rocking movements modulate sleep and how they can be effectively applied to improve sleep quality.

Snoring is one of the most common sleep disturbances and studies suggest that up to 44% of men and 28% of women snore. Snoring can have a severe impact on numerous health and social aspects of both the snorer’s and his/her bed partner’s life. Sleeping posture has been shown to have a significant influence on snoring and sleep disturbed breathing. Elevating head and trunk has been observed to reduce disturbed breathing in subjects with mild to severe obstructive sleep apnea hypopnea syndrome. Moreover, positional therapy, which consists of methods to prevent the subject assuming the sleeping posture associated with increased snoring, has been suggested as a simple and effective approach to reduce snoring.

Within the Somnomat project we decided to investigate the development of a smart bed designed to interact with the subject to improve sleep quality in a non-pharmacological manner. This bed includes sensors to monitor the state of the subject lying on it, a computer program to analyze the acquired information in real-time and to estimate proper intervention, and a set of actuators to transmit it to the subject. This PhD thesis developed and explored two main aspects of a future smart bed: the use of vestibular stimulation to improve sleep quality and the concept of human-in-the-loop control implemented in a smart bed to monitor snoring activity and automatically apply a postural intervention to reduce snoring. Accordingly the conducted work can be divided into two parts characterized by the following objectives: Part I describes the development of actuated platforms providing vestibular stimulation and the investigation of the impact of different kinds of vestibular stimulation on human sleep. Part II focused on the development and the evaluation of a human-in-the-loop controlled smart bed, automatically detecting and classifying snoring sounds and consequently adapting the mattress shape to actively influence the subject’s sleeping posture and to reduce snoring.

The first part resulted in three actuated platforms enabling vestibular stimulation while lying on a mattress. In the first experimental setup a tendon-based robot was developed and applied to explore the effects of rocking movements along six different axes (longitudinal, lateral, and vertical translation; longitudinal and lateral swing-like rotation; rotation on the vertical axis) on relaxation. The conducted exploration showed that none of the chosen rocking movements affected relaxation, however, comfortable kinds of rocking movements were identified. These rocking movements were implemented in two rocking beds to further explore the impact of vestibular stimulation on sleep. The rocking beds were applied with 18 healthy human subjects. Each subject had to choose the preferred movement among five different directions (longitudinal, lateral, and vertical translation;
longitudinal and lateral swing-like rotation) and one out of two amplitude/frequency combinations. Most of the subjects perceived the chosen movements as comfortable and relaxing and preferred the nights with movements compared to the night without. However, quantitative analysis based on polysomnography recordings showed no effects of rocking movements in promoting sleep. Neither the provided movements nor the entire setup had any disrupting effects on sleep, i.e. normal and healthy sleep was observed for all subjects in all experimental conditions. The choice of the actuation components and the mechanical design, including high quality transmission and sound damping and absorbing elements, were optimized in order to minimize the acoustic impact of the beds. A control strategy, which relied on low control gains and on a model based feedforward compensation of gravity, inertia, and friction, allowed smooth movements and pleasant stimulation. The rocking beds have been shown to be compatible with the physiological recordings and with the requirements of the sleep laboratory. Thus, the developed rocking beds provide a valuable setup for future investigations.

The smart bed developed in the second part of the project was tested for function and applicability in a proof of concept experimental phase. The system was applied during nocturnal sleep with one regular snorer (four nights without intervention and three nights with closed-loop head and trunk elevation). Snoring activity was detected and analyzed based on a classifier designed to adapt online in order to recognize repetitive patterns in the microphone recordings. The classification algorithm first identified all acoustic events with intensity and duration compatible with snoring sounds. Then, the characteristic of an average snoring sound was calculated from a buffer of previously detected events. Finally, the events which deviated the most from average snoring, were discarded and classified as non-snoring. Different approaches were evaluated based on the data acquired during the experimental phase and the most promising approach showed classification accuracy of 80% (specificity=84%, sensitivity=80%). These results should be further validated with different subjects and different environmental conditions. The subject did not report any discomfort or negative effects. In the first two intervention nights, neither sleeping posture nor snoring activity were clearly affected. However, a greater elevation angle tested during the third night caused cessation of snoring in four out of the six times an intervention occurred. Therefore, an intervention with a reasonable elevation angle should be further investigated with a greater number of subjects and experiment nights.

The experimental setups for sleep research developed during this thesis now offer three valuable test benches to further explore and develop the concept of a smart bed and open up new opportunities for fundamental research on sleep.
Überblick


Der erste Teil führte zur Entwicklung von drei aktuirten Plattformen, die die Stimulation des sensorischen Gleichgewichtssystems einer liegenden Person ermöglichen. Im ersten Versuchsaufbau wurde


Die im Rahmen der vorliegenden Arbeit entwickelten Versuchsaufbauten für die Schlafforschung stellen drei wertvolle Prüfstände zur Erforschung und Weiterentwicklung des Konzeptes “smart bed” dar. Zudem eröffnen sie neue Möglichkeiten in der Grundlagenforschung zum Thema Schlaf.
1 Introduction

1.1 Background and literature review

1.1.1 Sleep

This section presents a summary of the review presented by Dr. Ximena Omlin who collaborated with the author of the present dissertation on the same project. Following paragraphs report only the most important concepts, for a deeper introduction about the physiology of sleep and the vestibular system please refer to [2].

Sleep as a key factor for a healthy life

Sleeping is more than simply not being awake, it is an active and regulated state that is crucial for day-time functioning and well-being [4]. We sleep for around one third of our life; nevertheless despite the progress scientists have made in studying and characterizing the physiological process of sleep, the fundamental question “why do we sleep?” remains unanswered [5]. Concerning the brain, it is suggested that sleep has a primary function, having a strong impact on mental performance and promoting brain plasticity, synaptic reorganization, and learning [5, 6, 7, 8, 9].

Although sleep plays a fundamental role for health and well-being and sustains both cognitive function and physical performance [10, 11], achieving restorative sleep is often a problem. Studies suggest that between 33% and 50% of the population is permanently or occasionally affected by sleep disturbances including: difficulties falling asleep or maintaining sleep, insomnia or non-restorative sleep [12]. The number of reported sleep related complaints is also increasing [13]. The importance of a healthy sleep is motivated by the consequences of a bad sleep-hygiene [14]. Sleep deprivation and sleep disorders have a negative impact on mood [15], cognitive performance, and motor function [16] and can interfere with almost every important area of function, including work, family, and social life. Furthermore, sleep disorders are associated with increased risk of cardiovascular diseases and obesity [17, 18]. Thus, finding an effective treatment is of great interest for a significant part of the population.

Sleep medications such as benzodiazepines have been shown to be an effective short-term treatment for insomnia [19], by reducing sleep latency and wake time after sleep onset, and by increasing total sleep time [20]. However, reduced efficacy after continuous treatment and the risk of addiction suggests that pharmacological interventions are not suitable for long-term use [19, 21]. Non-pharmaceutical approaches seem to be similarly effective and, at the same time, suited to longer-term use [19]. Such alternative therapies include relaxation techniques, stimulus control therapy, cognitive-behavioral therapy, and sleep hygiene rules, which can help improving sleep onset latency, sleep efficiency, and sleep quality [19, 22]. Relaxation techniques such as soothing sounds and music, and warm feet appear to be commonly used also by healthy subjects when having problems falling asleep [23, 24]. Rocking movements also seem to have a great potential in promoting sleep and our daily life is full with examples. Rocking babies to help them relaxing or falling asleep has been used for centuries [25, 26]. Not only babies but adults as well seem to be sensitive to rocking; it’s in fact common to easily begin to doze on moving cars and rattling train or to relax on a rocking
chair or in a swinging hammock. However, although such examples are widely applied on a popular level, from a scientific point of view the link between rocking movements and sleep is still poorly understood [26, 27, 28].

Sleep architecture

Wakefulness and different stages of sleep are associated with characteristic physiological states. According to the present gold standard, these states are measured by applying polysomnography (PSG), which includes electroencephalography (EEG), electromyography (EMG) and electrooculography (EOG). Sleep is typically classified in two states: rapid eye movement sleep (REM) and non-rapid eye movement sleep (NREM) sleep [1] (Figure 1.2). During a sleep episode, REM and NREM sleep alternate cyclically with a period of ca. 90-100 minutes (approximately 4-6 NREM-REM cycles, Figure 1.1).

According to the new scoring rules, NREM sleep (75-80% of sleep time) is further divided in sleep stages N1, N2, and N3. Sleep stages N1 and N2 correspond to the transition from waking to deep sleep and are defined as light sleep. Sleep stage N3 represents deep sleep and is also defined as slow wave sleep (SWS). The transition between wakefulness and sleep stage N1 is marked by decreased EEG alpha waves (8-13 Hz), low-voltage mixed frequency EEG, and slow rolling eye movements [29, 30]. The beginning of sleep stage N2 is defined as sleep onset and is characterized by the appearance of sleep spindles and K-complexes [29, 30]. Sleep spindles consist of 0.5-1 s spindles shaped EEG oscillations (12-14 Hz). K-complexes are represented by a sharp negative wave followed by a positive wave, both lasting more than 0.5 s [29, 30, 31]. Delta waves (0.5-4 Hz) appear in small amounts in sleep stage N2 and progressively increase during the transition to deep sleep until becoming dominant in sleep stage N3 [29, 30]. Sleep stage N3 is characterized by high-amplitude slow wave activity, low muscle tone, and no eye movements [29, 30]. REM sleep (20-25% of sleep time) is associated with low-amplitude desynchronized and mixed-frequency EEG, atonia of skeletal muscle groups, and the typical rapid eye movements [29, 30]. The distribution of REM and NREM sleep stages across a sleep period is defined “sleep architecture” and is usually visualized with a hypnogram (Figure 1.1).

Rocking movements and sleep

The effect that rocking movements seem to have on sleep might be associated with direct or indirect links between sensory systems and sleep-wake centers in the brain [26]. However, the underlying mechanisms involved in such processes remain unclear and little research has been conducted investigating the interaction between sleep and the vestibular system [26, 27, 28, 32, 33, 34, 35].

Most of these studies have analyzed whether the vestibulo-ocular reflex pathway’s response to vestibular stimuli differs between sleep and wakefulness and whether it is influenced by the process of sleep [32, 33, 34, 35]. These investigations have shown that vestibular stimulation influences the vestibulo-ocular response during REM sleep and the occurrence of REM during NREM sleep [27, 32, 33, 34, 35]. The first scientific indication of the potential of vestibular stimulation in promoting sleep was shown in [36] where a significant decrease in active sleep ratio and an increase in quiet sleep ratio, were observed in infants exposed to vestibular stimulation (15 min of sinusoidal vestibular stimulation over a 2-week period) with respect to the control group [30].

The first study with adults was published by Woodward et al. [27] in 1990. The investigation aimed to evaluate the effects of vestibular stimulation, provided in the form of a parallel swing movement (longitudinal direction, amplitude=3.2 cm, frequency=0.42 Hz, maximal velocity=8.4 cm/s, maximal acceleration=22.1 cm/s², negligible vertical acceleration), on nighttime sleep parameters and daytime sleep tendency. Eight healthy subjects underwent one adaptation night
1.1 Background and literature review

Figure 1.1: Hypnogram. Hypnogram, power density and slow wave activity time course for an exemplary study night. Top: Hypnogram with sleep stages (W: waking, REM: REM sleep, N1-N3: NREM sleep stages). Scoring was performed on 20-s epochs according to AASM scoring rules [1]. Center: Power density spectrum between 0.75-20 Hz. Bottom: Time course of slow wave activity (0.75-4.5 Hz, artefacts removed).
Figure 1.2: Sleep and wake classification. EEG, EOG and EMG recording during wake and sleep. a: Sleep spindle, b: K-complex, c: slow oscillation. Sleep stages N1-N3 are denoted according to AASM scoring rules [1]. Source: [2]
followed by two consecutive nights with either “movement” or “stationary” conditions. The same protocol was repeated after 5-10 days testing the other condition. The sleep stage N2 percentage was significantly lower and the REM density index (eye movements per epoch) significantly higher in the nights with movement compared to the nights without [27]. However, the only significant effect observed on sleep latency is decreased mean sleep latency between the first and second night with movements in contrast to the increase observed in the stationary condition [27]. Following the night-time study, multiple sleep latency tests (MSLT) have been performed through the course of one day with 5 naps in a bed that is either moving or stationary. The same protocol was repeated another day for the remaining condition. No significant effects were found, however a tendency to reduced MSLT latency was observed for the movement condition [27]. Despite the lack of significant results, based on the tendency observed in the MSLT and the reduced sleep latency in the second motion night, the authors concluded that rocking movements might have a potential for helping inducing sleep [27].

A second study was published by Bayer et al. [26] more than 20 years later in 2011, where the effects of rocking movements on an afternoon nap were investigated in 10 healthy subjects. Similarly to Woodward et al. [27] vestibular stimulation was provided by using an actuated parallel swing (lateral parallel swing, sinusoidal motion, amplitude=5.25 cm, frequency=0.25 Hz, maximal velocity=8.25 cm/s, maximal acceleration=12.95 cm/s², negligible vertical acceleration). During the study, each subject underwent two sessions of a 45 min afternoon nap, one with and one without rocking, presented in randomized order at least one week apart from each other. It was found that rocking accelerated sleep onset by shortening of sleep stage N1 and reduction of stage N2 latency (calculated from first N1 epoch) [26]. The authors also reported an effect of rocking on deep sleep, with an increase of sleep stage N2, slow oscillations (SO), and spindle activity [26]. A possible explanation proposed by Bayer et al. was that rhythmic rocking may affect synchrony of brain activity within thalamo-cortical networks, which could facilitate sleep onset and promote the maintenance of sleep [26]. For subjects reported to be more relaxed during the rocking condition, it was also proposed that sleep onset could have been accelerated due to a feeling of enhanced relaxation [26].

Vestibular stimulation can also be applied via electrical stimulation of the vestibular system. This different method was used by Krystal et al. [28] to study whether vestibular stimulation could be used to treat transient insomnia. Almost 200 healthy subjects underwent a 4h phase advance protocol as a model of transient insomnia. The study started with a baseline night of 8h sleep starting at the usual bedtime, followed by the treatment night. During the treatment night, bedtime was anticipated by 4h with respect to the baseline and the subjects received either vestibular stimulation via bipolar electrical stimulation or placebo treatment for the first measurement hour. No significant difference in sleep latencies and architecture was observed between sham and vestibular stimulation. However, when only a subset of subjects with difficulties with falling asleep during daytime (MSLT sleep latencies >14 min) was considered, a tendency towards shorter sleep onset latency was shown for the condition with vestibular stimulation. As reported by the authors, these results suggest that vestibular stimulation has a potential to treat transient insomnia, which should be further investigated [28].

In summary, present knowledge strongly suggests that vestibular stimulation has the potential to promote sleep onset and enhance sleep quality. However, little research exists and the few published investigations present great differences concerning methods, characteristics of the chosen stimulation and outcome measures. Because of these differences it is difficult to compare between the results and identify the underlying mechanisms describing the link between vestibular stimulation and sleep as well as to find potential applications. Particularly, there is currently a lack of knowledge concerning the importance of stimulation parameters such as type and length of the stimulation or the direction and the characteristics of the provided movements. In the conducted studies, it appears that the choice of those parameters was mainly motivated by practical reasons and applicability. The two investigations involving real rocking differed in movement direction.
1 Introduction

(longitudinal movements used in [27] vs. lateral movements used in [26]) and in applied amplitudes and frequencies. However, both studies applied similar sinusoidal trajectories provided with a parallel swing and both trajectories present similar acceleration and velocity profiles. Thus, there is no information about how the effects on sleep differ between different kinds of vestibular stimulation and, for example, whether a hammock-like rotational motion or a purely translational rocking would be more effective than a parallel swing to promote relaxation and sleep.

1.1.2 Snoring

The physiology of snoring.

A problem commonly linked to sleep disturbances is snoring. According to literature, between 25% and 44% of men and between 15% and 28% of women snore [37, 38] and among the general population complaints of bed partner disturbances caused by snoring are common [38].

The snoring sound results from tissue vibrations in the upper airways, generated by turbulent airflow while breathing when asleep. The turbulences are due to improper breathing caused by narrowed or obstructed airways that can be influenced by structural characteristics, medical and health conditions, alcohol, cigarettes, or medication as tranquilizers [39]. Narrowed airways can be due to structural reasons as swelled tonsils, abnormal tissue characteristics of soft palate, ovula, and tong base. They are furthermore affected by the sleeping position of the snorer, i.e. the effect of gravity on the soft and floppy tissues [39].

More or less serious health problems are associated with different levels of snoring. The first level of snoring is called primary snoring. It is caused by mild resistance in the upper airways and is not associated with any medical condition, sleep disturbance, or sleep disturbed breathing. The second level of snoring is related to upper airways resistance syndrome (UARS). Even though no standards exist for a clear diagnosis, literature refers that UARS is characterized by repetitive increased upper airway resistance that cause brief EEG arousals (2-14 s) but without either apnea or oxygen desaturation [40]. UARS is defined as a sleep disturbed breathing and is associated to excessive daytime sleepiness and hypertension [40]. The third level of snoring is associated with obstructive sleep apnea hypopnea syndrome (obstructive sleep apnea hypopnea syndrome (OSAHS)): The high resistance in the upper airway causes a reduction in (hypopnea) to the complete cessation (apnea) of breathing during sleep. These episodes cause hypoxia and, consequently, frequent arousals and fragmented sleep resulting in many severe consequences for the patient health [41] (see following section). OSAHS can vary from mild to severe depending on the occurrence of apneic and hypopneic episodes. Such occurrences are measured by the apnea hypopnea index (AHI), which reports the number of apnea and hypopnea events occurring during 1 hour of sleep [41]. Another type of sleep apnea is the central sleep apnea. This sleep disturbed breathing is characterized by events with a total absence of respiratory effort. Because central sleep apnea is not associated with snoring, it has not been further considered in the present work. The different types and characteristics of sleep disturbed breathing are summarized in Table 1.1.

Consequences of snoring and OSAHS on both snorers and bed partners

Also in absence of OSAHS, primary snoring and UARS can perturb sleep, influencing sleep efficiency and wakefulness time after sleep onset [42], and may cause daytime fatigue and sleepiness with substantial health consequences [43, 44, 45, 39]. The negative effects of snoring become more severe with increased level of snoring. Vibrations associated with snoring have been reported to progressively cause nerve damage that may lead to an impaired upper airway patency [46]. A study on rats showed that vibrations generated in the upper airway during snoring are transmitted to
1.1 Background and literature review

Table 1.1: Sleep disturbed breathing. Classification and definitions of abnormal sleep related breathing events.

<table>
<thead>
<tr>
<th>Definition</th>
<th>Description</th>
</tr>
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</table>
| Increased Upper Airways Resistance (IUAR) | Classification rules [40]:  
• Increasingly negative inspiratory esophageal pressure combined with decreased oronasal airflow  
• Absence of apnea or oxygen desaturation |
| Hypopnea                       | Classification rules [1]:  
• Event duration > 10 s  
• ≥ 50% drop in airflow amplitude with 3% oxygen desaturation from pre-event baseline  
• ≥ 30% drop in airflow amplitude with 4% oxygen desaturation from pre-event baseline or event associated with arousal  
• Conditions satisfied for > 90% of the event duration |
| Apnea                          | Classification rules [1]:  
• Event duration > 10 s  
• ≥ 90% Drop in airflow amplitude  
• Conditions satisfied for > 90% of the event duration |

Types of sleep apnea [1]:  
• **Obstructive**: associated with continued or increased inspiratory effort (during whole event)  
• **Central**: absent inspiratory effort (during whole event)  
• **Mixed**: absent (first portion of the event) followed by resumption of inspiratory effort (second portion of the event)  

| Apnea Hypopnea Index (AHI) | Number of apnea and hypopnea events occurring during 1 h of sleep [11]. |

the carotid artery and may result in direct vibratory injury to the artery. Thus, it is possible that non-apneic snoring also represents its own vascular risk [47, 48]. Furthermore, Schoebel et al. [49] suggests that snorers may have a reduced parasympathetic tone. Even in its mild form, where the medical problems linked to snoring are limited or absent, snoring can become a significant social problem for the snorer and a sleep problem for the bed partner [37]. It has been proven that both the quality of sleep of the bed partner and the quality of life of both the snorer and the bed partner can be improved by reducing snoring [37, 38].

However, snoring is often only an indicator of more severe sleep related breathing disorders such as OSAHS [50]. Studies report that OSAHS interests 2-4% of middle-aged adult population [51, 52, 53]. Hagander et al. [46] speculate that early treatment to reduce snoring could prevent OSAHS in predisposed subjects. If left untreated, OSAHS can have serious consequences and can lead to various health problems such as: headaches, disrupted sleep, hypoxemia, daytime fatigue, and sleepiness, impaired daytime neuropsychological functions (including executive, attention, learning, and memory functions), affective dysfunctions and depression, poor performance in everyday activities, such as at work and school, motor vehicle crashes [52], and academic underachievement in children and adolescents [39, 54]. Additionally to the problems related to a disrupted sleep and hypoxemia, heavy snoring and OSAHS are associated with higher risk of cardiovascular diseases such as high blood pressure, stroke, heart failure, irregular heartbeats, heart attacks, diabetes, worsening of attention deficit hyperactivity disorder, carotid atheroscle-
Introduction

Sleep apnea is associated with important socio-economic costs. Sassani et al. estimated that the annual cost of OSAHS-related car collisions corresponds to: $15.9 billion, 810'000 collisions, and 1'400 fatalities, which could be reduced by $11.1 billion, 500'000 collisions, and 1'000 fatalities with effective treatment of all drivers affected by OSAHS, without considering the others economic, medical and social benefits of treating OSAHS. Only in the USA, undiagnosed and untreated sleep apnea is estimated to generate $3.4 billion in additional medical costs.

Different treatments to reduce snoring and treat OSAHS

Several treatments exist to reduce snoring including both non-surgical and surgical approaches. First, simple behavioral changes such as avoiding sleeping in supine position, avoiding alcohol, losing weight and quitting smoking can lead to a significant reduction of snoring. When behavioral changes are not effective some dental devices such as mandibular advancement devices, mandibular reposition appliances or oral appliances exist. These devices are designed to reposition the jaw in order to reduce narrowing of the airways. Mandibular advancement devices showed positive effects in reducing snoring and AHI and may help primary snorers or individuals with mild OSAHS. However, various side effects have been noticed such as discomfort and pain in the teeth or facial musculature and in the temporomandibular joint, irritations, excessive salivation or mouth dryness, bite change, and temporomandibular disorders. Moreover, long-term use of mandibular advancement devices may cause dental morphology changes. Investigations report varying compliance (4-82 %) where discontinuation may be due to a lack of perceived effectiveness. Tongue retaining devices work similarly to mandibular advancement devices by holding forward the anterior part of the tongue. However both popularity and evidence of effectiveness of this alternative method are low.

Snoring caused by narrowed, swollen or obstructed nasal passages can be reduced by applying nasal devices or steroid sprays and decongestants. These approaches are particularly effective in people who only snore occasionally, in the presence of allergies, colds, and upper airway infections. Achuthan et al. conducted a systematic review of pharmacological treatments for primary snoring including: serotonergic drugs, nasal lubricants and homeopathic medications, pseudoephedrine and domperidone, corticosteroids, surfactant, and botulinum toxin. This investigation reported that because of limitations in the conducted drug trials, side effects and lack of information about the long-term use of such therapies, there is currently no evidence supporting a pharmacological treatment for primary snoring.

An effective treatment for subjects suffering from snoring and OSAHS is the application of the continuous positive airways pressure (CPAP) device, which provides a constant increased air pressure preventing airways collapsing and narrowing during breathing. CPAP treatment has been shown to be efficacious in reducing snoring, AHI, and sleepiness as well as improving life quality and cognitive function and is the most effective treatment for OSAHS. However, despite its effectiveness CPAP treatment encounters low compliance. This may be due to the bulky, noisy, and cumbersome characteristic of CPAP devices, to negative social factors, and to numerous reported side effects which include: discomfort, claustrophobia, skin abrasions and irritations, irritated eyes, dry nose and mouth, nosebleeds, sore gums or lips, chest discomfort, nasal congestion and irritation or dryness of the nasal and pharyngeal membranes, sneezing, gastric and bowel distension, sinus and ear infections.

Many other more or less “exotic” treatments and products exist. The result of these alternative approaches is very subjective and no scientific data or proof is available on the effectiveness or eventual side affects of these approaches.
Finally, various surgical options can reduce snoring. Some interventions are designed to reduce obstructions and narrowing in the airways such as nasal surgery to improve a narrow nasal passage, shrinking of turbinates, correction of deviated septum, and removal of polyps. Other operations aim to reduce vibrations induced in the palate and uvula by scarring, stiffening or removing parts of the involved tissues. Surgical treatments are generally effective in reducing snoring as well as improving sleep quality of the bed partner \[37\], studies show a short-term snoring reduction in 75-100% of patients. But such effectiveness seems to progressively decrease over the years after surgery \[59\]. Moreover, as in any other situation, no surgery is without risks \[59\] and surgical interventions are invasive, expensive, and lead to a permanent alteration of the anatomical characteristics of the patient.

It has been proven that sleeping posture can have a big influence on many snorers. The majority of non-apneic snorers, as well as mild to moderate OSAHS patients, snore while sleeping in one particular position (usually supine). Abnormal breathing, snoring, apneas, and hypopneas are significantly reduced when such position is avoided (usually sleeping on one side) \[61, 62, 63, 64, 57, 65, 66\]. These subjects are defined positional snorers. Also head and trunk inclination seem to have an effect on snoring and sleep disturbed breathing. Sleeping with head and trunk in upright position has shown positive effects in reducing AHI in some OSAHS patients \[67, 68, 69\]. These two types of postural interventions, i.e. head and trunk elevation and positional therapy, will be examined in depth in the next sections.

### Upper body elevation

Head inclination and trunk elevation seem to have an impact on snoring and disturbed breathing. A possible explanation is that sleeping with upright inclination with respect to the horizontal affects the effect of gravity on the upper airway caliber and on the posterior displacement of the tongue, reducing risk of obstructions \[67\]. A study involving 13 obese (113-197% of ideal body weight) male subjects with moderately severe OSAHS (AHI>35 /h) compared supine with upright sleep, with head and trunk reclined at 60 deg to the horizontal. The two conditions, one after the other, were tested in each subject during one night of polysomnography. The conditions’ order was alternate between the subjects. Significant reduction of obstructive apnea as well as significant improvement of gas exchange was observed in upright compared to supine sleep position. Two subjects who had shown complete reversal of OSAHS at 60 deg were retested with lower inclination angles and also showed improvement at 20 and 40 deg. These results suggests that upright posture could be a simple and effective solution to reduce sleep disturbed breathing in obese patients with moderately severe OSAHS, however, compliance and long-term efficacy should be further investigated \[67\].

A randomized crossover investigation was conducted by Skinner et al. \[69\] to compare the effectiveness in treating OSAHS of a shoulder-head elevation pillow compared to nasal CPAP. The study involved 14 overweight (body mass index (BMI) range: 25-54) subjects with mild-moderate OSAHS (AHI 10-60 /h). The used pillow was designed to elevate the subject trunk at 60 deg with respect to the horizontal. Upright sleep was reported as successful (AHI<10/h) in four subjects, partially successful (10/h<AHI<16/h) in three subjects, and a failure in the remaining seven subjects, while nasal CPAP was reported as successful in 12 subjects and partially successful in one subject. Self-reported compliance was significantly higher with the elevation pillow compared to nasal CPAP. Despite the variable results, and a clearly higher efficacy of nasal CPAP, the satisfactory outcome in a limited number of subjects and the good compliance suggest that elevated body posture could be a beneficial treatment to reduce OSAHS is some individuals, particularly for patients who are intolerant of nasal CPAP \[69\].

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\[\text{Note of the author: Skinner et al. \[69\] reported an inclination of 60 deg that does not seem to correspond neither to the picture reported on the paper nor to similar pillows founded on the market. An inclination of ca. 30 deg appears more reasonable and consistent with the pictures and with the dimensions of the pillow reported in the paper.}\]
While some positive effects have been shown for patients ranging from mild to severe OSAHS, no information have been found on the impact of head and trunk elevation on primary snoring. Being a simple and unobtrusive approach, upright sleep may be of particular interest in treating primary snoring and mild OSAHS, where because of the limited severity of their condition the subjects may be more reluctant to adopt other treatments such as surgery and CPAP. Some side effects linked to continuous elevated posture such as back pain have been reported [69]. These adverse effects may be limited by elevating the user head and trunk only when needed, by controlling the shape of the mattress. Such automated approaches may allow minimizing the interference with comfort and user’s sleep habits and should be further investigated.

Positional therapy to reduce snoring

The term positional therapy (PT) was coined in 1991 by Cartwright et al. [70] with the definition of “preventing patients to sleep in the worst sleeping position”, i.e. sleep position associated with worse snoring. The worst sleeping position is usually, but not necessarily, the supine position [71]. This approach can represent an effective, simple, and inexpensive intervention to reduce abnormal breathing and snoring in from 56% to 87% of the subjects [57, 45]. In positional OSAHS patients, positional therapy has been shown to be effective as either an alternative or complementary approach to traditional (CPAP) therapy [57]. Moreover, significantly better self-reported compliance with positional therapy with respect to CPAP has been shown [71].

Traditional positional therapy: The tennis balls therapy

The first historical appearance of applied positional therapy has been found in military documents from the American War of Independence (1775-1783) and World War I (1914-1918). It is reported that during these conflicts, soldiers were instructed to attach small cannon balls to the back of the uniforms or to sleep wearing their backpack in order to avoid the supine position. The goal was to reduce snoring sounds that could reveal their position to the enemy [71]. Since then this type of traditional positional therapy, also called tennis balls therapy (TBT), has been implemented in various passive devices such as belts or t-shirts with rigid bodies (such as tennis balls) mounted on it to make it uncomfortable to lie on the back. Globally, tennis ball therapy has shown positive effects in avoiding supine position and reducing snoring and AHI [71]. However, discomfort, backache, sleep arousals as well as ineffectiveness and no improvement in sleep quality or daytime alertness associated with tennis balls therapy resulted in low compliance and, consequently, poor long-term efficacy of such treatment [71, 45, 72].

An alternative approach: Active tools to provide positional therapy

With the progress of sensing and computing technology, an alternative implementation of positional therapy was developed. Such an approach includes a system to monitor the sleeping posture of the user and a closed-loop strategy that triggers some stimulation (e.g. vibration, sounds, electrical stimulation...) on the user when the forbidden posture is detected. The stimulation should disturb the user enough to induce him to change posture or, in extreme cases, wake him up.

A pioneer in this field was R. Cartwright who in 1985 published the first scientific paper presenting an active device able to trigger an auditory alarm if supine position was detected for longer than 15 s [73]. Following this preliminary study, such alternative form of positional therapy has been greatly developed and the same principle has been implemented in devices, which use vibrations and electrical stimulation instead acoustic alarms. The effectiveness of these approaches was investigated in various scientific publications and patents describing devices to actively train the user to avoid supine position continue to be filed until nowadays [71].
This new generation of positional therapy devices seems to successfully prevent the users from lying supine, thus avoiding compromising sleep quality and efficiency [71]. Both sleep in supine position and AHI were significantly lower when such devices were used [71, 74]. Additionally to their efficacy, higher short-term compliance was shown with the active devices with respect to tennis balls therapy [59]. However, despite these promising results, little knowledge exists about long-term efficacy and compliance [59, 71]. Van Maanen et al. [74] reported that total sleep time was significantly reduced when a vibrating device taped to the neck of the subjects was used to provide active positional therapy [74]. The used apparatus, provides a gradually increasing vibration 10 s after supine position is detected, to induce the user to change posture [74]. This result suggests that the positional therapy intervention could cause undesired sleep arousals and that the subjects may woke up before changing their sleeping position. This could have a counterproductive disrupting effect on sleep and should be avoided. Particularly, the approach presented in [74] and other similar devices act indistinctly when supine position is detected, independently whether the user is snoring or not. The disruptive effect of positional therapy could be minimized by triggering the intervention only when also snoring or sleep disturbed breathing are detected.

Summarizing, there is evidence suggesting positional therapy as an effective approach to reduce both non-apneic snoring and treat OSAHS patients. Recently, a new category of active devices improved compliance and reduced disruptive effect on comfort and sleep with respect to traditional treatments such as tennis balls therapy. However, triggering acoustic and vibratory stimulation may not only prevent supine position but also cause arousals and disrupt the user’s sleep. Thus, alternative designs and interventions that are more compatible with a natural sleep environment should be investigated. A possibility would be to integrate both sensing and actuation into the bed structure, avoiding that the user has to wear any device. Additionally, monitoring of snoring activity and disturbed breathing would allow intervening on the subject only when needed, minimizing the side-effects of the treatment. Within our project we are developing such ideas by implementing positional therapy into an adjustable smart bed able to monitor and detect snoring sounds and automatically adjust the shape of the mattress to influence the sleep posture of the user. This concept is further explored in the following section.

1.1.3 Smart systems and sleep

The idea of a smart bed

“Smart systems incorporate functions of sensing, actuation, and control in order to describe and analyze a situation, and make decisions based on the available data in a predictive or adaptive manner, thereby performing smart actions. In most cases the “smartness” of the system can be attributed to autonomous operation based on closed loop control, energy efficiency, and networking capabilities.” (Cited from Wikipedia: “Smart System”)

Automation refers to a system with some degree of autonomy, where the operations are automatically controlled by algorithms. With the development of computers, automation progressively diffused among almost every process of our life starting from the control of complex power plants, space- and aircraft machines, manufacturing firms and assembly line, and moving closer and closer to our daily activities. Today, technological progress combined with a facilitated access to it (e.g. lower prices, trends) has populated our world with smart systems designed to interact with human users. This field is growing concerning both research and commercial applications. Such growth has experienced an important acceleration with the advent of the smartphone that has boosted both development and application of mobile technology. In fact, within a smartphone computational power, connectivity, and portability have been successfully combined into a single and compact device that has become part of our routine. Based on collecting and sharing information and the experiences of millions (or billions) of users in real-time, mobile computing technology has
revolutionized many fields such as communication, way to travel, to choose restaurants and hotels, video games, education, finance... Additionally, the smartphone has promoted the development of numerous software applications as well as mobile sensors designed to monitor the state of the user and to interact with them.

One example of this trend is the health app for iPhone (Apple, Cupertino, CA, USA) allowing continuous tracking of the user’s activity such as steps, walking distance, stairs and offering statistics and plots. Additionally to the automatic monitoring of daily activity, the same app allows to manually insert data about nutrition, medical condition, body structure, sleep habits, and so on. Finally, by coupling the iPhone with the Apple Watch (Apple, Cupertino, CA, USA), the monitoring of biometric data such as heart rate can be included. This complete tracking of one’s state should help the user to better know, control, and improve their own health condition. This is only one example of many of a smartphone’s applications, smart watches, wrist bands, wearable sensors, and other portable sensing devices available on the market. These products developed for various medical, wellness, fitness, and sport applications form the emerging and growing field of mobile health [75]. The progress of mobile health is supported by both a growing number of publications and a dramatic increase in funding during the past decade as well as a great expected growth in the global market (from $1.5 in 2012 to $21.5 billion expected for 2018) [75]. The main promises of this new technology are: improving the accessibility and the convenience of health care, bringing clinic/hospital monitoring and diagnosis to the home, allowing continuous monitoring of patients during daily life, allowing remote accessibility and sharing of info and data [75]. Additionally, the popularity of these applications may promote an increase in user sensitivity and consideration of their own health and a healthy lifestyle (e.g. apps to track physical activity, to track sleep habits, to control nutrition and body weight, to quit smoking...). As an important element of a healthy life, sleep is also a factor in this phenomenon and the number of applications and tools to track sleep habits and enhance sleep is growing. The increasing popularity and success of sleep related consumer technology suggests as well that sleep and its importance are gaining more and more consideration among the common population [3]. However, the main problem of most of available devices and methods, in mobile health in general but particularly in sleep related applications, is the lack of evidence and high-quality research supporting reliability and efficacy of the proposed approaches, from both a technical and medical point of view [75] [3] [76].

Within our project we want to follow this emerging and promising field of research by developing a smart bed to monitor the state of the user and automatically interact with them by providing a closed-loop controlled intervention aiming to improve sleep quality. A smart bed involves: a controller, a set of actuators, a plant to be controlled that in our case is the human, a sensing system, and a software to process and analyze the measured signals (Figure 1.3). First, the estimated state of the user is compared to the reference values, which correspond to the desired state the user should be brought to (e.g. reference value=“no snoring” state). The controller is composed by a set of rules, which are applied to the difference between reference and estimated state. The output of the control algorithm is a command corresponding to the desired activation to be sent to the actuators. Based on the received activation command, the actuated bed applies the desired intervention to the human. The sensing system is composed of a set of sensors used to acquire quantitative information about the state of the human while lying in the bed and during sleep. A processing and analysis software completes the feedback modality of the system, extracting from the measured raw signals an estimation of the user’s state.

As opposed to many of the existing approaches, our goal is to provide strong scientific evidence supporting both the reliability and efficacy of the developed technology. In contrast with simple smartphone apps and wearable devices, a smart bed would allow integration of both sensing and actuation technology within the sleep environment (e.g. bed frame, mattress, pillow...) minimizing any interference with comfort, sleep habits, and natural conditions. At the same time, a whole bed allows implementation of dedicated hardware and full control of certain aspects such as sensor locations and configurations, guaranteeing higher reliability of the system. The closed-loop feature
1.1 Background and literature review

Figure 1.3: Control flow-chart of a smart bed. The chart visualizes the closed-loop principle of a general smart bed including: a controller to compare the reference with estimated state and compute a command for the desired intervention; a set of actuators to provide the intervention to the user; a set of sensors to measure quantitative signals describing the state of the user; a processing and analysis software to extract from the raw signals an estimation of the user’s state.

of the smart bed allows application of the adequate treatment only when needed, minimizing disturbances due to undesired interventions or interventions applied when non necessary. This could improve user compliance, which is a key factor of an efficacious treatment [59].

Review of consumer technology and smart systems in sleep

The idea of developing a smart platform able to interact with the user’s sleep is not new and some examples exist in published scientific literature, filed patents, and commercial products. Similarly to the example of mobile health, consumer technologies applied to sleep and referring to various sleep related problems or conditions have been growing and are gaining more and more popularity among the general population. These technologies present various features such as sleep education, self-guided sleep assessment, sleep or wake induction, as well as entertainment, social connection, and information sharing [3]. This section presents a review of the most interesting examples classified in three categories: smartphone’s apps, wearable platforms, and embedded platforms.

Smartphone apps

In 2015 the Apple App Store (Apple, Cupertino, CA, USA) alone offered more than 500 sleep related applications, and hundreds of similar apps were available for Android and Microsoft platforms [3]. As confirmation of the success of these applications, one of the top five paid apps for iPhone in 2014 was Sleep Cycle, an app to track sleep and providing a smart alarm feature, claiming to optimally wake up the user when they are in light sleep [3].

Most smartphone apps rely on the sensing capability of a smartphone and assess sleep and sleep related patterns based on: questionnaires, accelerometer and inertial measurement units (IMU), and microphone. Questionnaires include: first, digital version of standard methods used to assess sleep and sleep disorders such as the Epworth Sleepiness Scale [77], the Berlin Questionnaire [78] or the STOP BANG questionnaire [79]; second, any questionnaire recording qualitative and subjective information about sleep and sleep habits (e.g. health app for Apple iPhone).

Accelerometer and IMU sensors can be used to quantitatively track the activity of the user (i.e. actigraphy) and to monitor the sleeping posture of the user. Actigraphy is the main sources used by most of the apps to infer wakefulness and sleep and, in some cases, even to distinguish between sleep stages. However, actigraphy has been shown to be effective only in detecting sleep, while poor performance was found concerning detection of wake episodes and resolving sleep structure.
Moreover, significant differences were found between standard actigraphy performed by the Actiwatch (Cambridge Neurotechnology Ltd, Cambridge, UK) and data recorded by an iPhone, suggesting that placing a smartphone in the user’s bed as proposed by many apps is not an acceptable screening solution \[76\]. Thus, available knowledge suggests that actigraphic-based sleep analysis is not reliable and should only be used to give a qualitative feeling about own sleep \[76\].

Audio recordings can be a reliable method to identify sleep disturbed breathing and snoring. For this purpose, numerous apps allow acoustic overnight recording, samples of healthy and disturbed breathing for comparison, time courses of acoustic intensity for visual inspection, noise disturbance counters to count noisy events overcoming a predefined intensity threshold, as well as various analysis and classification of the recorded acoustic patterns. Smartphones provide good quality audio recordings. However, it is difficult for the average user without medical training and experience to identify eventual disturbances; moreover, validity and reliability of these automatic classification and diagnosis methods have not been proved yet \[76\].

Based on the sensing capability described above, smartphone apps offer various features, which can be classified in three main categories. The first features category consists of monitoring and tracking sleep by collecting quantitative and qualitative information about sleep habits and sleep variables meant to be used by the user to better know their own condition and eventually identify sleep related disturbances. A second group of apps, as Sleep Cycle introduced above, offer a smart alarm. Such apps claim to be able to distinguish “light” from “deep” sleep and to use this information to optimally wake up the user when in “light sleep”. Of particular interest is the closed-loop modality of these apps. However, as previously mentioned, none of the existing apps have been proven to be reliable in extracting sleep architecture from the available recordings, thus the efficacy of those approaches is questionable \[76\]. Moreover, these methods find little support in literature and no studies have analyzed the impact these consumer smart alarms have on performance or mood \[3\]. The third category includes apps to implement active postural intervention similarly as introduced in section 1.1.2. All these systems are based on similar approaches: as soon as snoring sounds are detected, the apps produce some kind of acoustic sounds or vibrations to induce the subject to change his sleeping position or to wake up. Based on our knowledge, most of the existing systems and devices present only a counter of “noisy events” based on simple thresholding of the energy of the acoustic recordings \[76\]. With such an approach it is not possible to distinguish between an actual snoring event and another sound with similar intensity. Generally, no scientific evidence confirming the reliability of the systems and no details concerning the applied methods and algorithms are provided \[76\] \[80\]. Moreover, the performance of such apps and their detection algorithms strongly depends on the hardware characteristics of the smartphones (e.g. microphones and sound cards) and on other varying factors such as position of the smartphone with respect of the user, different users, and environmental conditions \[76\].

Summarizing, many apps (the most relevant ones are summarized in Table 1.2) aiming to track sleep, to help identify sleep disorders or to enhance sleep exist. However, most of these approaches present lack of scientific proof and documentation, limited and unreliable sensing capability and high performance variability depending on smartphone’s type, type of user, and environmental conditions. Thus, except for simple digital implementation of validated questionnaires, none of the remaining apps has been proven to be effective and reliable \[76\].

<table>
<thead>
<tr>
<th>Name</th>
<th>Sensing</th>
<th>Open-loop Features</th>
<th>Closed-loop Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleep Cycle</td>
<td>• Accelerometer: user activity</td>
<td>• Tracking of “sleep trend”</td>
<td>• Smart alarm (to wake up the user when he’s in light sleep)</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th><strong>Sleep Bot</strong></th>
<th><strong>Accelerometer:</strong> user activity</th>
<th><strong>Microphone:</strong> ambient sounds, sleep talking, snoring</th>
<th><strong>Tracking of “sleep cycles”</strong></th>
<th><strong>Tracking of sleep pattern, habits, and statistics</strong></th>
<th><strong>“go to bed” reminder</strong></th>
<th><strong>Smart alarm</strong></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th><strong>Sleep as Android</strong></th>
<th><strong>Accelerometer:</strong> user activity</th>
<th><strong>Microphone:</strong> snoring</th>
<th><strong>Tracking of “sleep cycles”</strong></th>
<th><strong>Tracking of sleep pattern, habits, and statistics</strong></th>
<th><strong>Possible integration with additional HW (e.g. Pebble, Android wear, Philip’s HUE)</strong></th>
<th><strong>Snoring detection and “anti-snoring” intervention</strong></th>
<th><strong>Smart alarm (with mental or physical engagement to stop it)</strong></th>
</tr>
</thead>
</table>

| **Sunriser** | **-** | **-** | **-** | **-** | **Wake up the user accordingly to geographical position** | **-** | **-** |

| **Entrain** | **-** | **-** | **-** | **-** | **Pre-trip preparation encouraging exposure to sun light to reduce jet lag** | **-** | **-** |

| **Go! To Sleep** | **Questionnaires** | **-** | **Tracking and scoring of sleep habits** | **-** | **-** | **-** | **-** |

| **Stop snoring** | **Microphones:** snoring | **-** | **-** | **-** | **Anti-snore postural intervention (ring tones)** | **-** | **-** |

| **SnoreClock** | **Microphones:** snoring | **-** | **-** | **-** | **Tracking of snoring activity** | **-** | **-** |

| **Table 1.2: Smartphone’s apps.** Examples of sleep and snoring related smartphone’s apps. The reported features are based on the available device documentation and on the review presented by Ko et al. [3]. All references are reported in the appendices (section A.1.1, Table A.1). |

**Wearable Platforms**

Wearable platforms feature sensors integrated in clothing or to be worn by the user in portable devices such as bracelets or watches. As opposed to simple smartphones, such devices allow measurement of movements, activity, biometric information, and physiological variables directly on the user’s body. Such increased sensing capability guarantees, compared to smartphones, higher measurement precision and reliability as well as a broader spectrum of physiological data such as: heart rate, electrocardiography (ECG), respiration, skin temperature, perspiration, and even brain activity. Moreover, these devices are based on dedicated hardware that, with respect to smartphone apps, result in less variability and higher robustness among different users, conditions, and environments. However, having to wear sensors and electronics may cause discomfort [3] and negatively affect the user’s habits and sleep.
Similarly to smartphone’s app, some wearable watch-like devices implement active postural intervention. All found approaches are based on the same principle described above: acoustic recordings are automatically analyzed in real-time and as soon as snoring sounds are detected the device produces acoustic sounds, vibrations, or electrical stimulation to induce the user to change his sleeping position or to wake up. As for smartphones’ apps, no scientific evidence supporting efficacy and reliability of the proposed approaches has been provided so far. Another closed-loop feature proposed by some of the found devices is the smart alarm, which bases on sleep stage monitoring to optimally wake up the user from light sleep. However, whether such smart alarm principle is effectively able to improve the subjective experience of awakening is little supported by current literature. Particularly, no studies analyzed the effect of existing consumer smart alarms on performance and mood [3]. Most of wearable devices provide only monitoring and analysis features. Based on biometrical variables and questionnaires, these devices offer actigraphy and tracking of sleep structure, sleep habits, ECG and heart rate, sleep posture, movements, and snoring activity. This information should help the user better knowing and controlling own sleep condition, avoiding bad habits, and identifying eventual sleep disturbances.

Summarizing, this class of tools (the most relevant examples are summarized in Table [1,3]) seems to provide reliable and robust monitoring of biometric and sleep related parameters. However, their closed-loop capability is nowadays limited to smart alarms and anti-snore postural intervention and in both cases there is no scientific evidence supporting the proposed approaches. Particularly, because of their wristbands or watch-like shape, they can only interact with the user through audio, vibratory, or electrical stimulation.

<table>
<thead>
<tr>
<th>Name</th>
<th>Sensing</th>
<th>Open-loop Features</th>
<th>Closed-loop Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>FitBit (clip-on, wristbands, smartwatches, jewelry)</td>
<td>• Motion • Biometric sensors</td>
<td>• Actigraphy • Sleep tracking and sleep efficiency estimation • Long-term trends (inspection and visualization)</td>
<td>• Smart alarm (vibration)</td>
</tr>
<tr>
<td>Jawbone UP (clip-on or wristband)</td>
<td>• Motion • Biometric sensors</td>
<td>• Actigraphy • Tracking of “light” and “deep” sleep</td>
<td>• Smart alarm (vibration)</td>
</tr>
<tr>
<td>Apple Watch</td>
<td>• Motion • Biometric sensors</td>
<td>• Actigraphy • HR tracking</td>
<td>-</td>
</tr>
<tr>
<td>Android Wear</td>
<td>• Motion • Biometric sensors</td>
<td>• Actigraphy • HR tracking</td>
<td>-</td>
</tr>
<tr>
<td>Microsoft Band</td>
<td>• Motion • Biometric sensors</td>
<td>• Actigraphy • HR tracking</td>
<td>-</td>
</tr>
<tr>
<td>Mimo Baby Monitor (bodysuit)</td>
<td>• Accelerometer • Body temperature • Respiration</td>
<td>• Online biometric monitoring</td>
<td>-</td>
</tr>
</tbody>
</table>
1.1 Background and literature review

Table 1.3: Wearable devices. Examples of sleep and snoring related wearable devices. The reported features are based on the available device documentation and the review presented by Ko et al. [3]. All references are reported in the appendices (section A.1.1, Table A.2).

**Embedded platforms**

The third category includes systems where technology has been integrated into elements of furniture that are commonly part of the sleep environment such as beds, mattresses, blankets and bed sheets, or pillows. Similarly to smartphones apps and wearable devices, such platforms to monitor and influence sleep are becoming more and more popular. With respect to previously presented mobile devices, embedding sensors and actuators in the normal sleep environment may reduce disrupting effects on comfort and natural sleep habits. Moreover, it allows dedicated solutions (e.g. dedicated hardware, optimized sensor position...), which could improve function and reliability of the system [3].

The first example is the Sleep Number® x12 bed (Figure 1.4) developed by Select Comfort Corp. (Minneapolis, MN, USA). The x12 is an actuated bed including adjustable mattress firmness (provided by a series of inflatable cushions integrated into the mattress), adjustable head and foot position, and massage stimulation. The bed can be connected to a WLAN, accessed from a tablet or a smart phone, and is controlled with a remote control allowing voice commands. The most interesting function is the *intelligent sleep tracking*. Sensors integrated in the mattress allow measurement of the mean respiration rate, mean heart rate, and movements of the user. The software monitors the sleep patterns (e.g. hours and quality of sleep) and suggests the optimal settings for the adjustable mattress. Additionally, when the bed partner snores, the user can use the remote control to activate a snoring reduction feature, which elevates the snorer head by 5 deg. This change should help to clear the upper airways and alleviate snoring. The x12 is the only actuated bed implementing an anti-snore feature. However, the proposed approach to reduce snoring requires the partner to wake up and actively trigger the bed and neither automatic monitoring of snoring activity nor closed-loop control of the intervention are included.

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*This is what is claimed by the developers. No scientific evidence about the reliability of such measurement is
A second intelligent bed available on the market is the Sleep Smart® (Figure 1.5) developed by Kingsdown Inc. (Mebane, NC, USA). Based on the recordings provided by sensors integrated into the bed, the system monitors and learns the sleep patterns of the user night by night. The acquired information is used to automatically adjust the mattress support to the anatomical characteristics and sleep behavior (sleep position and movements) of the user. Such adaptation is performed by controlling six air chambers integrated in the mattress. The monitoring system performs in real-time, allowing set up of a physiological alarm (smart alarm), which should wake up the user at the optimal time. The bed also includes an anti-snore modality, probably in form of trunk elevation as presented proposed by the Sleep Number® x12. However, no details on the characteristics of such interventions were found.

Another approach is based on an inflatable pillow (Snore Activated Nudging Pillow, Figure 1.4) produced by Hammacher Schlemmer (New York, NY, USA). This pillow uses a microphone to sense sonar vibrations associated with snoring. When snoring is detected, it inflates an internal bladder that raises the depth of the pillow to induce the user to adjust the head or the body position. This pillow bases on microphones recordings to automatically detect snoring sounds. However, being a simple pillow the action of the system is limited to influencing the head elevation and not the position of the whole body.

In addition to these smart-systems, the market offers many examples of beds, couches, and armchairs providing vibratory or oscillatory stimulation claiming to help relaxation and promote sleep. As presented in section 1.1.1 vestibular stimulation and particularly rocking motion may be beneficial in promoting sleep onset and enhancing sleep quality. Of particular interest is Sway (Klafs GmbH and Co. KG, Freiburg im Breisgau, D; Figure 1.7) a wellness bed designed to enhance power napping by gently rocking the user along a pendulum trajectory (pendulum length=7.5 m, amplitude=11.5 cm, frequency=0.19 Hz (period=5.4 s)). The company reports a study conducted by the Fraunhofer Society (Fraunhofer Society, Munich, D) showing a faster relaxation in the form of faster reduction of heart rate variability (HRV) with rocking condition compared to no movements. However, no further details are available supporting the scientific reliability of such a study. Moreover, based on our knowledge, none of these beds implement any kind of “smart feature” such as monitoring or closed-loop modalities.
1.1 Background and literature review

Figure 1.5: Sleep Smart. A) Adjustable mattress. B) Independent control of three support zones. C) Trunk elevation modality. D) Smartphone App providing both control and analysis tools. Source: kingsdown.com

Figure 1.6: Snore activated Nudging Pillow. Left: Normal condition. Right: “Nudging” condition. Source: www.hammacher.com
In summary, embedded platforms present great advantages with respect to mobile technologies in terms of smartphones and wearable devices. Integrating sensors and actuators within the bed may increase functionality and reliability as well as allowing unobtrusive solutions compatible with a natural and comfortable sleep environment. Moreover, a whole actuated bed allows expansion of the spectrum of interventions, which could be provided to the user such as active adjustment of the mattress shape, vibratory massages, rocking movements, and other kinds of vestibular stimulation. These features may substantially increase the system’s effectiveness in influencing sleeping posture and enhancing sleep quality.

1.2 Aim and structure of the thesis

The final objective of the project is to develop a smart bed able to interact with the user to promote relaxation and enhance sleep quality in a non-pharmacological way. The work presented in this thesis covers the first steps towards such ambitious goal and has been developed along two parallel paths, exploring two main aspects of the smart bed idea: first, the actuation principle of the smart bed and the intervention to be provided to the user; and second the concept of human-in-the-loop and closed-loop control of the bed.

Vestibular stimulation in the form of rocking movements was suggested as a potentially effective non-pharmacological treatment to promote relaxation and sleep onset and to improve sleep quality. Smooth and slow rocking movements appear compatible with a natural and comfortable sleep environment. Also from a technical and practical point of view an actuated rocking mechanism could be well suited to the characteristics and the requirements of healthy sleep. For these reasons, we decided to consider vestibular stimulation, and particularly rocking movements, as the best candidate for the actuation principle of the smart bed. However, despite many practical examples of sustaining the positive impact of vestibular stimulation on relaxation and sleep (e.g. rocking babies into sleep, falling asleep faster on moving cars and trains, relaxing in rocking chairs or swinging hammock), from a scientific point of view few studies have been conducted and the underlying mechanisms linking vestibular stimulation and sleep are still poorly understood. Particularly, there is no knowledge on how the effects on relaxation and sleep differ between different types of rocking

Figure 1.7: Sway rocking bed. Left: The bed in trunk elevation configuration. Right: The rocking mechanism. Source: www.klafs.ch
1.2 Aim and structure of the thesis

movements and what is the importance of stimulation parameters such as direction, frequency and amplitude. Thus, further investigations are required to both better understand this phenomenon and identify effective and successful applications. In order to enable the desired investigation, an actuated bed was needed to move a sleeping human subject along various, adjustable trajectories. This need motivated the first aim of the thesis:

**Aim I: Development of a robotic bed-platform providing vestibular stimulation and investigation of the impact of different kinds of vestibular stimulation on human sleep.**

The conducted work is reported in chapters 2 and 3, where two robotic approaches to investigate the influence of rocking movements, first on relaxation and then on sleep, are presented and discussed. This part of the project, and particularly the studies reported in chapters 2 and 3, was conducted in strict collaboration with another PhD student. Details and complementary information can be found in the PhD dissertation of X. Omlin [2].

The second part of the project focuses on the closed-loop modality of the smart bed idea and presents a first functional implementation of the smart bed. The bed presented in this thesis focuses on the problem of snoring. The chosen approach was based on the principle that snoring relates to sleeping posture and, consequently, it could be reduced by properly influencing the posture of the snorer. Particularly, our smart bed is equipped with microphones to acquire acoustic recordings overnight. The microphones recordings are analyzed on-line by a computer program, which detects, classifies, and analyzes acoustic patterns associated to snoring. Depending on the measured snoring activity, the computer program controls the actuators of the adjustable bed to influence the sleeping posture of the user.

Snoring is a common sleep related disturbance and can have a severe impact on numerous health and social aspects of the snorer’s life. Sleep posture has been shown to have an important influence on snoring and sleep disturbed breathing. A reduction of disturbed breathing was observed in subjects sleeping with head and trunk in elevated position with respect to horizontal. However, continuous elevated posture could cause back pain. This adverse effect may be limited by elevating the user’s head and trunk only when needed, by controlling the shape of the mattress during the night. Avoiding the sleeping posture associated with worse snoring (positional therapy), which is usually the supine position, was suggested as a simple and effective approach to reduce snoring. Traditional positional therapy, such as wearing special belts and t-shirts to make it uncomfortable to lie in supine position, were reported to be uncomfortable, disrupting the user’s sleep and resulting in poor long-term compliance. Better compliance was shown for active positional therapy devices, monitoring the user’s posture and triggering acoustic alarms, vibrations or electrical stimulation when the “forbidden” position is detected. Those tools appear to be less disturbing than the traditional approach while effective in preventing supine position and reducing snoring and abnormal breathing. However, the interventions used to induce a change in sleeping posture may cause undesired arousals reducing total sleep time. As for the head and trunk elevation, also for positional therapy, triggering the intervention only when actual snoring is detected may reduce adverse affects.

These two postural interventions, head and trunk elevation and positional therapy, were suggested as promising treatments to reduce snoring. Compared to the existing approaches, implementing these two methods in a smart bed could improve both functionality and comfort. The smart bed integrates both sensing and actuation technology within the bed frame, minimizing disrupting interference with a natural sleep environment. Additionally, it allows direct influence of the user’s sleep posture by controlling the whole mattress shape. Finally the closed-loop feature of the smart bed allows applying the desired treatment only when needed. This could reduce disturbances due to undesired interventions or interventions applied when non necessary. This motivates the second aim of the thesis:

**AIM II: Development and evaluation of a human-in-the-loop controlled smart bed, automatically...**
detecting and classifying snoring sounds and consequently adapting the mattress shape to actively influence the user’s sleeping posture and reduce snoring.

The conducted work is presented in chapter 4. Chapters 5 and 6 present overall conclusions and outlook unifying the two parts of the thesis and discussing the next steps towards the final goal of the project. Additional completing material is added in the appendices at the end of the document.
2 The M$^3$ setup, a robot to study the effects of rocking on relaxation

2.1 Introduction

Present knowledge strongly suggests that vestibular stimulation has the potential to promote relaxation, facilitate sleep onset, and enhance sleep quality. However, previous studies did not consider the importance of stimulation parameters such as direction and characteristics of the provided movement and, apparently, the experimenter chose those parameters mainly motivated by practical reasons and applicability. The two investigations involving real rocking differ in amplitudes, frequencies and movement direction (longitudinal parallel swing [27] vs. lateral parallel swing [26]). However, both studies applied similar sinusoidal trajectories provided with a parallel swing and both trajectories have similar acceleration and velocity profiles (Table 2.1). Thus, there is no information about how the effects on sleep differ between different kinds of vestibular stimulation and, for example, whether a hammock-like rotational motion or a purely translational rocking would be more effective than a parallel swing to promote relaxation and sleep.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Kind of trajectory</th>
<th>Amplitude [cm]</th>
<th>Frequency [Hz]</th>
<th>Max vel. [cm/s]</th>
<th>Max acc. [cm/s$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woodward et al.</td>
<td>longitudinal parallel swing</td>
<td>3.2</td>
<td>0.42</td>
<td>8.4$^*$</td>
<td>22.1$^*$</td>
</tr>
<tr>
<td>[27]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bayer et al. [26]</td>
<td>lateral parallel swing</td>
<td>5.25</td>
<td>0.25</td>
<td>8.25$^*$</td>
<td>13.0$^*$</td>
</tr>
<tr>
<td>Sway</td>
<td>7.5 m pendulum</td>
<td>11.5</td>
<td>0.19$^*$</td>
<td>13.7$^*$</td>
<td>16.4$^*$</td>
</tr>
</tbody>
</table>

$^*$ Calculated from the given parameters.

1 Klafs GmbH and Co. KG, Freiburg im Breisgau, D; Figure 1.7

Table 2.1: Movement parameters. Table summarizing the trajectory parameters used in literature and commercial products.

The first part of our project was dedicated to exploring this still poorly understood field, by investigating the impact of different kinds of vestibular stimulation on relaxation. Bayer et al. [26] suggested that relaxation could play a role in the facilitated transition from waking to sleep, which was observed in presence of rocking movements. Therefore, selecting stimulations perceived as comfortable and relaxing could be essential in order to achieve the strongest effect on sleep. Moreover, compared to a sleep study, focusing on relaxation significantly reduced study complexity and execution time and allowed testing a greater number of different motion parameters. Relaxation is associated with a decreased activity of the sympathetic nervous system [81] and can be assessed by using physiological signals such as heart rate, heart rate variability, respiration frequency and EEG signals [82, 83]. The physiological responses to a decreased activity of the sympathetic nervous system are a decrease in heart rate and respiration frequency as well as an increase in heart rate variability [84, 85]. In the EEG, an increase in alpha (8-12 Hz) and theta (5-8 Hz) activity are mainly used as an indicator of relaxation [86, 87].
To systematically evaluate which kind of movements have an influence on relaxation, a device able to provide a wide range of controlled and repeatable movements was needed. Some systems, such as actuated beds or robotic platforms, are already commercially available, but none of the existing devices fulfilled all the requirements needed to perform such a study. On the one hand, existing actuated beds provide only limited predefined movements; on the other hand, the available 6 degree of freedom (DOF) robotic platforms, suitable for carrying the payload of a human body such as those used in cars or flight simulators, are too noisy or not smooth enough to be applied in relaxation or sleep studies. Thus, we developed a new robotic device, which allowed movement of a platform with size of a standard single bed along 6 DOF, with adjustable parameters (e.g. amplitudes and frequencies).

The developed device was applied to study the effect of three rotational and three translational movements on human subjects, with the aim of identifying the most comfortable and relaxing movement. Relaxation was assessed by physiological recordings including EEG, ECG, and respiration frequency as well as through a questionnaire (7-point scale). If the potentially beneficial effects of vestibular stimulation are due to a specific movement, greatest changes in relaxation are expected for these particular stimulation parameters. Knowledge about such specific stimulation parameters could be used, in a later state, to promote sleep in an optimal way.

In addition, the developed setup was evaluated with respect to robot performance, acoustic noise, safety, and comfort. Such analysis represented a fundamental step in order to identify the optimal actuation design to allow, in a later phase, study of the influence of vestibular stimulation on sleep.

### 2.2 Setup

#### 2.2.1 Requirements and architecture

As a main requirement, the robotic device had to include a platform with dimensions of a standard single bed (90 x 200 cm) allowing the subject to lie comfortably in supine position. Furthermore, the system had to be able to carry a payload up to 105 kg (90 kg subject, 15 kg measurement equipment). This payload limit was defined because of the technical characteristics of the chosen approach.

The actuation system had to be able to move the platform along parametrizable trajectories in 6 DOF. In order to allow a wide range of movements, the workspace of the system was limited only by safety and technical requirements. For safety reasons the acceleration threshold was set to 3 m/s$^2$ for x and y translations, 1.5 m/s$^2$ for z translation and 25 deg/s$^2$ for rotations. Because of technical and spatial considerations the range of motion was set to ±0.5 m for x, y and z translations, and ±30 deg for yaw rotation, while a reduced workspace of ±10 deg was chosen for pitch and roll rotation as larger amplitudes might be too disturbing for the subjects (Figure 2.1).

In order to not affect relaxation of the subjects in a negative way, the system had to satisfy certain requirements concerning acoustic noise level, light condition and comfort. In absence of clear information about the influence of acoustic noise on relaxation, the guidelines for an acoustic noise level compatible with a healthy sleep environment were taken into account. Griefahn [88] suggested that during sleep continuous background noise level should not exceed 40 dB and intermittent noise should not exceed a level of 10 dB higher than the background noise. The World Health Organization (WHO) recommended an equivalent continuous A-weighted sound pressure level ($L_{Aeq}$) of 30 dB and maximal level of 45 dB inside a bedroom [89]. To avoid substantial biological effects on sleep, in a more recent report, the WHO set the threshold for the outside noise level during night to 30 dB [90]. Considering that the setup was applied in a relaxation study, and not with sleeping subjects, the highest acceptable limit for continuous background noise level was
2.2 Setup

set to 45 dB.

A continuous monitoring system was implemented in order to guarantee safety for the subject, the experimenters and the hardware. The architecture of the setup is visualized in Figure 2.2.

![Figure 2.1: Movement axes. Coordinate system defined with respect to the human body.](image)

![Figure 2.2: Experiment setup. Flow chart visualizing the architecture of the experiment setup.](image)

2.2.2 M³-Lab and Somnomat platform

A tendon-based parallel robot, the r³-system [91], was previously developed as the haptic system of a M³-Lab [92, 93]. The is a simulation environment designed as a cave augmented virtual environment (CAVE) system [94], which can be used to render audio, visual and haptic feedback [92, 93] (Fig. 2.3). However, only the haptic interface was used for this setup.

The r³ was reconfigured in order to fulfill the requirements regarding DOFs and dynamics of our project. The main advantage of the chosen approach was the large workspace, which allowed a wide range of 6 DOF trajectories to be performed. This is crucial when testing a large range of movement parameters, in order to find the best movement to promote relaxation and, in a later phase, sleep.

The CAVE had a size of 7.2 x 5.6 x 5.2 m and was delimited by a large frame construction made of modular aluminum profiles (Bosch Rexroth, Lohr a. M., Germany). For the Somnomat setup,
seven motorized winches of the r³-system were fixed to the ground outside of the CAVE. To actuate the system, lightweight ropes were attached to a bed-platform (the Somnomat platform) and led over a pulley system mounted on the large frame construction to the motorized winches (Figure 2.3). The seven ropes were used to control position and orientation of the bed-platform within the CAVE workspace. The bed-platform was constructed with lightweight aluminum profiles (Bosch Rexroth, Lohr a.M., Germany) and carried a standard wooden slatted frame with a mattress on top as well as the physiological measurement devices (section 2.3, Figure 2.4). The total weight of the bed platform without payload was approximately 63 kg. In addition to the seven actuated winches of the r³-system, the bed-platform was connected to two counterweight sets to compensate the high static load. The use of lightweight ropes allowed reduction of the weight and the inertia of the moving components and minimization of the force errors due to the ropes' oscillations [91]. Additionally, by placing the motorized winches far away from the bed-platform, the influence of the motor noise on the human lying on the platform was reduced. The position of the pulley system and the fixation points on the platform were identified by applying a rope robot synthesis algorithm, in order to fulfill the workspace requirements (section 2.2.1) [95].

Figure 2.3: The M³ setup. Left: The Somnomat bed platform. Right: Drawing of the M³-Lab showing the large frame construction and the bed platform connected to the seven tendons of the r³-system.

2.2.3 Actuation

Each motorized winch was driven by a 2 kW AC-brushless servo motor (AKM53G, Danaher, Pennsylvania, USA). A custom made winch (Ertalon, highly wear-resistant polyamide) with a diameter of 75 mm was directly coupled to the motor shaft (Figure 2.4). To satisfy the conditions lightweight, low work strain and high stiffness, a 4 mm synthetic rope of Dyneema (D-Pro, Liros, Berg, Germany) was chosen. To meet the requirements, a tackle (Rescue, Petzl, France) was mounted on each tendon to double the robot’s forces. With the chosen configuration, each axis had a continuous payload of 262 N and a peak payload of 790 N. Normally-closed electromagnetic braking systems (Robastop, Chr. Mayr GmbH + Co. KG, Mauerstetten, Germany) were mounted on each drive train. During operation, the brakes were kept electronically open. A more detailed description of the drive trains can be found in [91, 93]. The ropes were guided into the CAVE via a pulley system mounted on the frame (Figure 2.4). The safety was guaranteed by redundant measures implemented at mechanics, electronics and software level. In any potentially dangerous situation, the brakes mounted on the drive trains were closed to block the ropes.
2.2 Setup

Figure 2.4: Actuation system. A) Motorized winches used to actuate the tendon-based robot. B) Pullies system used to guide the ropes from the winches to the bed platform. C) Tendon connection to the platform. D) Measurement devices mounted on the platforms.
2.2.4 Sensing

For monitoring and control purpose, angular position of the motors and rope forces were measured. Position was monitored by high-resolution encoders (17-bit BISS-encoder) mounted on each motor. The forces were measured using linear force sensors (Transmetra GmbH, Neuhausen, Switzerland) mounted between the ropes and the platform (Figure 2.4). To evaluate the accuracy of the robot, the pose of the bed platform was measured with an opto-electronic motion tracking system (QTM, Qualisys AB, Gothenburg, Sweden). With this system, the position of 4 markers placed on the platform frame were recorded using 10 motion capture cameras mounted on the frame of the CAVE. The platform pose was calculated from these marker positions via post-processing using MATLAB/Simulink® (MATLAB R2009b, MathWorks, Natick, MA, USA). This position was not used for control but only for evaluation purposes.

2.2.5 Control

The device was controlled using MATLAB/Simulink® combined with an xPC real-time target computer. A model-based proportional-derivative (PD) position controller was used to control position and orientation of the bed-platform in task-space. The controller was composed of 3 components: a physical based feedforward (FF) part, the PD position controller, and an iterative learning controller (ILC). The FF term included a model of drive trains’ inertia and friction and a dynamic model of the bed-platform. The output of the controller was a command wrench, defining force and torque to be applied to the platform. The rope force vector in the joint space was calculated in real-time from the command wrench using a quadratic programming optimization, which minimized the rope forces and guaranteed mathematical continuity avoiding jumps in the desired values. A complete mathematical description of the control model can be found in [93]. A kinematic model linked the joint space with the Cartesian task space. The position of the bed-platform in task space was calculated using a physical-based forward kinematic model, from the angular position of the motors measured in joint space. A detailed explanation of the forward kinematic can be found in [96].

![Control flow chart](image)

**Figure 2.5: Control flow chart.** Flow chart visualizing the strategy implemented to control the \( r^3 \) to move the Somnomat platform along the desired trajectories.

2.2.6 Tuning and optimization

Starting from reasonable values based on the analysis of the system, the control parameters were manually adjusted according to 2 major objectives: first, minimize undesired and disturbing movements felt by a human subject lying on the platform; second, guarantee the repeatability of the
stimulations i.e., the same conditions for different subjects characterized by diverse mass and mass distribution. After an initial tuning process based on the minimization of the absolute position error, the parameters were further adjusted during a test session based on the feedback provided by a subject lying on the bed-platform.

Absolute accuracy of the system was sacrificed in order to reduce noise, vibrations and stick-and-slip phenomena. The resulting controller was tested for payloads of diverse mass and mass distribution and optimized for 80 kg payload. For lighter subjects additional mass was placed on the platform.

### 2.3 Experimental phase: Effects of rocking on relaxation

#### 2.3.1 Aim of the study

The M³ setup was applied to investigate the effect of six different kinds of rocking movements on relaxation. The aim of the conducted study was the identification of the most comfortable and relaxing movement. Assuming that the beneficial effects of vestibular stimulation are associated with a specific movement direction, such particular stimulation parameters is expected to show the greatest changes in relaxation.

#### 2.3.2 Subjects

Twenty-five healthy subjects (17 male, age: 23-47 years (mean: 27.5 years)) without history of neurological disorders or diseases of the vestibular system participated in the study. To analyze test-retest stability 7 subjects (all male) were measured twice. The subjects were all right handed, non-smokers with no sleep deprivation and regular sleep for 3 days prior to the study. In addition, subjects did not consume any medication or caffeine for 4 hours prior to testing. The study was approved by the Institutional Review Board of the ETH Zurich and performed in accordance with the standards for research involving human subjects defined by the Declaration of Helsinki [97].

#### 2.3.3 Movements

The Somnomat setup allowed a large range of motions, though not all were suitable for promoting relaxation. Important for the feasibility of our study was the selection of motions, which were relaxing and comfortable, and did not induce motion sickness. For this selection, a pilot study with four subjects was performed [98]. Translational and rotational sinusoidal trajectories along the 3 body axes were applied to the subjects lying in the bed-platform. Furthermore, combination of motions resulting in trajectories with more than 1 DOF were tested. Movements were presented in random order. In previous studies, investigating the effect of vestibular stimulation on sleep, low stimulation frequencies between 0.25 and 0.42 Hz were arbitrarily chosen [27, 26]. In order to perform a comprehensive investigation, we also included higher frequencies to test their effect on relaxation and motion sickness.

The movements were, therefore, performed with frequencies of 0.3, 1, and 2 Hz. Depending on the frequency, the amplitude ranged from 0.01 m and 0.5 deg (2 Hz) to 0.4 m and 10 deg (0.3 Hz) [98]. The rotation axis was set at different positions along the bed, as well as 2 m above the center of the bed. A questionnaire (7-point scale) was used to assess how pleasant and relaxing each movement was perceived to be by the subjects and if the movement induced motion sickness.
In this pilot study, best ratings concerning relaxation and comfort were observed for a movement frequency of 0.3 Hz. For translations, low amplitudes around 0.2 m were preferred by the subjects and for rotations, a rotation axis in the middle of the body or 2 m above the center of the bed. Combinations of different axes had a higher potential to induce motion sickness than movements with only one DOF.

Based on the results of the pilot study, six different movements were chosen for this study: translations along X, Y, and Z axis with a sinusoidal trajectory characterized by amplitude of 15 cm and frequency of 0.3 Hz; roll rotation (rotation axis parallel to X axis, 2 m above the platform), pitch rotation (rotation axis parallel to Y axis, 2 m above the platform) and yaw rotation (rotation axis parallel to z axis, located in the center of the platform) with a sinusoidal trajectory characterized by an amplitude of 6 deg and frequency of 0.3 Hz (Figure 2.1).

2.3.4 Protocol

Subjects were lying in the bed-platform in a supine position with closed eyes. The session consisted of three baseline measurements where no movement was performed, and six conditions with movement. Baseline measurements took place at the beginning, in the middle and at the end of the session. The conditions with movement were divided into two blocks: a set including the three rotational movements and a set including the three translational movements. The blocks and the movements within each block were randomized. Each baseline measurement and each condition with movement lasted 5 min. This duration was chosen to keep the total duration of the experiment short (as lying for a long time could influence subjects’ physiological condition) but at the same time to ensure physiological adaptation to the movement stimuli. The questionnaire was assessed during short breaks (3 min) after each baseline measurement and movement condition (Figure 2.6).

2.3.5 Physiological recordings and data analysis

All physiological signals were recorded with the biosignal amplifier g.USBamp (g.tec medical bioengineering, Graz, Austria). The signals were filtered with a hardware bandpass filter of 0.01-100 Hz and a 50 Hz notch filter. A sampling frequency of 512 Hz was used. Synchronization between robot and physiological recording was guaranteed by a 1-bit digital signal sent from the $r^3$-system and acquired by the amplifier. To minimize the occurrence of artifacts in the physiological recordings due to the movement of the platform, the measurement system was mounted on the platform.

EEG was measured with the active electrode system g.GAMMAsys (g.tec medical bioengineering, Graz, Austria). Electrodes were placed, according to the International 10-20 system, at 14 locations (Fz, F3, F4, F7, F8, C3, T7, T8, P1, P2, P7, P8, O1 and O2). The electrodes were re-referenced to the linked mastoids (LM). All channels were low-pass filtered with a cutoff frequency of 40 Hz. EOG was measured with 2 electrodes placed near the corner of each eye and used for artifact removal. The EEG data were visually inspected for artifacts, which were removed manually using
the MATLAB toolbox EEG Lab [99]. Waking EEG alpha power (8-12 Hz), alpha peak power (the power around the highest peak (± 2Hz) in the 8-12 Hz range), and theta power (5-8 Hz) were calculated using a Fast Fourier Transform (FFT) routine (MATLAB) with Hanning window and averages over 2 s epochs. Test-retest stability was investigated for the alpha power of the O1-LM of seven subjects measured twice (rho values from Spearman’s rank correlation).

ECG was recorded with an electrode placed 2 cm below the right clavicular between the first and second ribs, an electrode placed at the fifth intercostal space on the midaxillary line on the left side of the body, and a ground electrode on the right acromion. Mean heart rate was calculated using the NN intervals (interval between normal-normal beat). To assess HRV in the time domain, the standard deviation of NN intervals (SDNN) and the square root of the mean squared differences of successive NN intervals (RMSSD) were calculated. Furthermore, HRV in the frequency domain was determined based on the low-frequency band (LF: 0.04 Hz-0.15 Hz) and the high-frequency band (HF: 0.15 Hz-0.4 Hz). Cubic spline interpolation was used to convert the NN intervals into an instantaneous time series with a constant sampling frequency. Welch’s method of modified periodograms was used to estimate the power spectral density [100]. Respiration was recorded with a thermistor flow sensor (Thermistor Flow Sensor, S.L.P. Inc., St. Charles, Illinois, USA) placed beneath the nose. Respiration frequency was estimated with spectral analysis using a Fast Fourier Transform routine (MATLAB) with a Hanning window and averages over 60 s epochs.

2.3.6 Questionnaire

A questionnaire was designed to assess how relaxing each movement was perceived to be by the subjects and if the movement induced motion sickness. The questionnaire consisted of five questions:

- Q1: “How comfortable was the movement?”

- Q2: “Did you feel any dizziness, nausea, or discomfort?”

- Q3: “How well were you able to relax during the movement?”

- Q4: “How high is the probability that you would fall asleep/drowse off during this movement (over a longer period)?”

- Q5: “How sleepy do you feel at the moment?”

Subjects answered using a 7-point scale, 1 corresponding to “not at all” and 7 to “very”. To assess relaxation and sleepiness, the mean across Q1, Q3, Q4 and Q5 was calculated for each subject. Motion sickness values were calculated from Q2. The intra-subject test-retest stability (rho values from Spearman’s rank correlation) was calculated from the ratings of seven subjects measured twice.

2.3.7 Statistical analysis

Physiological variables and questionnaire data were statistically tested with a univariate general linear model followed by post hoc tests in SPSS (SPSS Inc., Chicago, Illinois, USA). A Tukey correction was used to correct for multiple comparisons. The conditions with movement were compared among each other and to baseline measurements. The significance level was set at p<0.05.
2.3.8 Robot performance

Trajectories

In addition to investigating the effects of the provided movements on relaxation, the conducted study allowed evaluation of the function and the applicability of the developed setup. The quality of the movements was evaluated by analyzing the measured and reference pose \( p \in \mathbb{R}^6 \) (i.e. 3D position and orientation) of the bed-platform. The performance of the control strategy and the robot accuracy were evaluated by comparing the estimated pose \( p_{ji}^m \), i.e., the platform pose calculated by the \( r^3 \)-system based on the forward kinematics, with the reference values \( p_{ref}^{ji} \) across all subjects \( i \) for each trajectory \( j \) (eq. 2). Repeatability of the robot was evaluated by comparing the estimated pose \( p_{ji}^m \) for each subject \( i \) with the mean estimated trajectory averaged across all subjects \( \bar{p}_j \) for each trajectory \( j \) (eq. 3, 4). The reliability of the estimation of the platform pose was verified by comparing the values computed by the \( r^3 \) \( p_{ji}^m \) with the pose measured by the motion tracking system \( p_{ji}^{QTM} \) (eq. 5). This validation was carried during a test session, by executing all study trajectories \( j \), with a human subject (75 kg) lying on the platform.

\[
E_{acc}^j = \frac{1}{N_j} \sum_i \frac{1}{N_k} \sum_k |p_{ref}^{ji}(t_k) - p_{ji}^m(t_k)| 
\]

(2.1)

\[
E_{rep}^j = \frac{1}{N_j} \sum_i \frac{1}{N_k} \sum_k |p_{j}(t_k) - p_{ji}^m(t_k)| 
\]

(2.2)

\[
\bar{p}_j(t_k) = \frac{1}{N_j} \sum_i p_{ji}^m(t_k) 
\]

(2.3)

\[
E_{rel}^j = \frac{1}{N_k} \sum_k |p_{ji}^{QTM}(t_k) - p_{ji}^m(t_k)| 
\]

(2.4)

The evaluation results \( \bar{e}^x \) and \( \sigma_e^x \) (eq. 6, 7) are the mean and standard deviation of the error values \( E_j^x \), respectively, averaged over all tested trajectories \( j \).

\[
\bar{e}^x = \frac{1}{N_j} \sum_j E_j^x 
\]

(2.5)

\[
\sigma_e^x = \sqrt{\frac{1}{N_j} \sum_j (E_j^x - \bar{e}^x)^2} 
\]

(2.6)

Acoustic Noise Level

The acoustic noise level was measured by a Sound Level Meter (2230 Sound Level Meter, Brüel & Kjaer Sound & Vibration Measurement A/S, Naerum, Denmark) in a test session for all the 6 study trajectories and for a baseline condition with the platform kept at a constant position. Noise was measured on the bed-platform at the position of the subject head. For each condition, the mean (\( LA_{eq} \)) as well as maximum (\( LA_{max} \)) and minimum (\( LA_{min} \)) noise levels in dB were measured during 60 s.
2.4 Results and discussion

2.4.1 Evaluation of the robot performance

Accuracy of position estimation approach

The reliability of the approach implemented to estimate the platform pose was verified by applying the method explained in section 2.3.8. The results averaged over the six movement conditions show a mean position error of 0.48 cm (SD: 0.03 cm) and a mean orientation error of 0.33 deg (SD: 0.06 deg).

The evaluation performed using the motion tracking system showed high precision of the pose estimation approach (maximal position error of 0.51 cm and maximal orientation error of 0.42 deg). The precision of the pose estimation depends on the measurement of the rope length and the precision of the positioning of deflection units and tendon connection points. This result verifies the reliability of the implemented approach. This approach allows precise estimation of end-effector pose within the workspace using a simple configuration, characterized by sensors mounted at the motor so that payload and the dynamics of the moving system are not affected. Such a satisfactory result is reached when the positioning of the tendon deflection and connection points is known with a precision of about 1 cm. This allows for fast and easy robot reconfiguration, without jeopardizing the performance of the system.

Robot accuracy and performance of the position controller

The robot accuracy was evaluated by comparing the estimated pose with the reference values (section 2.3.8). The estimated pose deviates from the reference trajectory by a maximal value of 3.14 cm, (mean: 1.12 cm; SD: 0.79 cm) and a maximal orientation error of 0.63 deg (mean: 0.28 deg; SD: 0.16).

This low trajectory accuracy was due to the chosen control strategy. For the purpose of the study, the absolute accuracy was less important than the way motion was perceived by the subject and the ability to provide the same stimulation to all subjects. Thus, the configuration used in the study was a compromise between accuracy and performance of the robot. An “aggressive” controller was effective in improving absolute accuracy but this strategy was discarded because it generated undesired vibrations.

Major problems were encountered when slow movements (translational velocities below 0.12 m/s) were performed. The reason of this behavior was probably imprecise modeling of the transition from static to dynamic friction combined with stick-and-slip phenomena.

Improving the physical-based model through precise identification of the robot friction may allow enhancement of the performance at low speed. The precision could be increased by improving the model-based feed-forward term of the controller, making it more adaptable to various characteristics of the subjects (e.g., diverse mass and mass distribution). Another improvement could be obtained by integrating a sensor to directly measure accelerations and orientation of the bed platform and the human body. Such non-collocated additional sensors will provide a measurement of higher derivatives of platform position and its orientation independently of the r³-system, which may improve the performance by compensating disturbances due to unmodeled dynamics. Moreover, acceleration is what was really perceived by the subject and, due to the influence of the mattress, the motion of the human body parts do not necessarily correspond to the motion of the bed-platform. Thus, instead of controlling the pose of the platform, additional sensors could...
help to monitor and control the body accelerations, representing the stimulation that is actually perceived by the human subject.

Repeatability

The repeatability of the robot was evaluated by comparing the estimated pose for each subject with the mean trajectory averaged across all subjects (section 2.3.8). For each subject the estimated pose deviated from the averaged trajectory by a max value of 0.94 cm (mean: 0.48 cm; SD: 0.23 cm) and a maximal orientation error of 0.31 deg (mean: 0.15 deg; SD: 0.07 deg).

Despite the low absolute accuracy, the results showed a similar performance across all tested subjects. This ensured that all subjects received equivalent stimulation. In addition to the control strategy, placing additional mass on the platform in order to have a constant payload of approximately 80 kg was proven to be a simple adjustment to help such performance repeatability across the different subjects. However, an improvement of the controller to allow compensation for the differences in the payload mass and mass distribution would be more practical and efficient.

Acoustic impact

During motion the measured mean noise level ($L_{A_{eq}}$) was 45.1 dB (SD: 0.4 dB) ($L_{A_{max}} = 46.6$ dB (SD: 0.5 dB); $L_{A_{min}} = 44.0$ dB (SD: 0.3 dB)), while during the baseline condition was 43.7 dB (SD: 0.1 dB) ($L_{A_{max}} = 44.6$ dB (SD: 0.5 dB); $L_{A_{min}} = 42.7$ dB (SD: 0.1 dB)).

As this study aimed in investigating relaxation and not sleep, an average noise level around 45 dB was acceptable. The main noise contribution resulted from the fans used for cooling the electronics of the robot. Such monotonous background sound was independent on the movement condition; thus, the influence on the present study results was considered as negligible.

However, in order allow a sleep study the noise impact of the system should be reduced to 30-35 dB, as suggested for the maximal limit of a healthy sleep environment. It would be very critical to fulfill these requirements without major adaptation of the $r^3$-system. Thus, an alternative actuation design is suggested for future studies focusing on human sleep.

2.4.2 Effects of rocking movements on subjects and physiological recordings

The data was tested for an order effect, to detect changes due to the order of the conditions. Order effects were not found in any of the questionnaires or physiological parameters.

Brain activity

As EEG is very sensitive to artifacts, especially due to motion, the signal quality was analyzed in detail to ensure that the acquired signals can be used for further analysis. The frontal electrodes were often affected by eye movements triggered by the vestibular stimulation. These eye movements would influence the spectral analysis; hence, the frontal electrodes were excluded from the analysis. The signal quality of the remaining electrodes was, with a percentage of artifact free data ranging from 93.3% (SD: 6.4%) to 97.7% (SD: 2.9%), high and appropriate for further analysis. Furthermore, the power density spectrum exhibited the characteristics of EEG activity
during relaxation (with closed eyes), with high values for alpha activity (8-12 Hz) and a typical alpha peak around 10 Hz (Figure 2.7).

However, in all derivations no significant changes in alpha power, alpha peak power and theta power were observed when comparing the conditions with movement among each other and to baseline measurements. Test-retest stability of alpha power (O1-LM) was high (range for \( \rho \): 0.79-0.98) in the seven subjects measured twice.

Although EEG measurements did not reveal differences between the conditions, it was demonstrated that data acquisition with this setup fulfilled the required signal quality for EEG analysis. In average over all conditions, 95.5\% of the data could be used for analysis. The power density spectrum of the recorded EEG data equates to brain activity during relaxation; therefore, movements appear not to affect the signal quality with the current setup. The high test-retest stability also confirms this observation. However, the EEG variables showed no differences concerning relaxation between conditions with movement compared to the baseline measurements without movement, as well as between the different conditions with movement. Hence, no recommendation, about which movement is most effective to induce relaxation, can be derived from the EEG recordings.

A possible explanation for these findings could be the duration of the different conditions. 5 minutes of a particular movement are possibly not sufficient to measure the potential effect of vestibular stimulation on promoting relaxation. Studies reporting a change in alpha and theta activity, due to different relaxation techniques, used longer conditions up to 30 min \[86, 87, 101\]. However, the condition length is often connected to the relaxation techniques used in the study (such as meditation, breathing techniques etc.), which are not comparable with vestibular stimulation. Bayer et al. \[26\], who investigated the effect of rocking movements during a nap, reported a latency to sleep stage N1 of 7.75 (±1.48) minutes in their study. As our study protocol was more comparable to the nap study protocol rather than to the relaxation studies using relaxation techniques, a condition of 5 minutes was chosen. In our opinion, this condition length provided enough time for physiological adaptations but was short enough to avoid subjects falling asleep and to keep the total data collection time as short as possible. However, the condition duration was an estimation, due to the fact that no comparable study protocol has been previously used, and might not been best suited to measure changes in relaxation due to vestibular stimulation.
Cardio-respiratory signals

Heart rate, as well as HRV (SDNN, RMSSD, LF/HF) showed no significant difference between the conditions with movement and baseline measurements. The ECG signal was not affected by the setup or motions. Therefore, no artifact removal was necessary and all data could be used for analysis.

Respiration frequency was significantly lower in all baseline measurements (median: 0.183-0.233 Hz) compared to the conditions with movement (median: 0.283-0.300 Hz) (Fig. 2.8). The different movement conditions did not differ. Due to irregular breathing patterns six subjects had to be excluded from the analysis.

The ECG signal quality was, as expected, not affected by the setup or the applied motions. However, respiration was influenced by the movements as it was found that subjects increased their respiration frequency compared to baseline measurements without movement. Furthermore, it appeared that the respiration frequency during the conditions with movement (median: 0.283-0.300 Hz) adapted towards the movement frequency of 0.3 Hz.

That vestibular stimulation can lead to an increase in respiration was observed previously [102][103][104]. Stimulation of the vestibular system can elicit respiratory changes due to the activation of the vestibulo-respiratory reflex, which provides adjustments in respiration and airway patency during movements and postural changes [105]. The increase in respiration frequency could therefore be mainly associated with the activation of the respiro-vestibulatory reflex and not with a decrease in relaxation (e.g., opposite effect) as no other physiological measurement showed differences compared to the baseline measurement. However, the activation of the vestibulo-respiratory reflex was shown for rotations and with amplitudes of over 60 deg, which are much higher amplitudes than tested in the current study.

Furthermore, the adaptation of the respiration frequency towards the movement frequency could be of interest regarding relaxation. Respiration techniques are widely used to reduce stress and induce relaxation [106], which could influence sleep as relaxation can have a promoting effect on sleep onset [107]. Additionally, it was reported that deep and slow breathing influences autonomic
and pain processing [108] and reduces blood pressure [109, 110]. Therefore, it would be interesting to investigate, if subjects would also adapt to slow movements by altering their respiration and decreasing their respiration frequency.

However, only further investigations evaluating the effect of other motion frequencies may provide clear insight in the relationship between vestibular stimulation and respiration.

### Questionnaires

A trend ($p = 0.057$) toward higher relaxation was found for movement along the z-axis (median: 4.67; confidence interval (CI): 4.33-5.67) compared to the roll-axis (median: 4.33; CI: 3.67-5.00). Between the other movement conditions the values for relaxation did not differ (Figure 2.9). Motion sickness and discomfort values did not differ between the movement conditions (median: 1 (in all conditions)).

![Figure 2.9: Relaxation. Boxplot of normalized relaxation values (Z-transformation) of all movement conditions. For details with respect to boxplots see Figure 2.8.](image)

Although the different movement axes did not alter the physiological responses of the subjects, it appears to have an influence on their subjective perception of relaxation. Movements along the Z-axis appear to be most promising to promote relaxation. However, differences in the ratings were found only in the conditions which were perceived as the most (Z-axis) and least (roll-axis) relaxing. Furthermore, the variability of the ratings was very high among the different subjects. Hence, it is assumed that there is not one specific movement, which is most relaxing, rather it is very individual. These findings show that individual movement preference should be taken into account, when investigating rocking movements and their potential to promote relaxation or sleep, which was not considered until now. Intra-subject test-retest stability was weak and only significant in 2 subjects. However, the sample size was small (n=7). Further investigation with a higher number of participants is needed to address the question whether subject’s perception of the movement can change over days, or whether a more detailed questionnaire would be better suited to assess the perception of relaxation.

### 2.5 Conclusions and outlook

An actuated 6 DOF device, fulfilling all safety-related and technical requirements to investigate the effect of vestibular stimulation in human subjects, was successfully developed and tested.
The applied movements were reported to be relaxing and no problems with motion sickness or discomfort were observed. Physiological recordings including EEG were of good quality and applicable for data analysis. However, no changes were found in EEG and ECG variables due to the movement. This finding might be explained by the short condition duration of 5 min. Though, respiration frequency was influenced by the movement. Movements along the Z-axis appeared to be the most promising to promote relaxation based on the questionnaire. However, individual movement preference should be taken into account, when investigating rocking movements and their potential to promote relaxation or sleep.

The evaluation of the robot’s performance showed that the influence of low absolute position accuracy on the conducted study was only marginal. In fact, the analysis of trajectories repeatability showed that the provided stimulations were similar for all tested subjects. This assured the reliability of the study results. However, it was not possible to completely avoid undesired oscillations and vibrations. At low speeds, these disturbances become more dominant and strongly affected the perception of the movement. This could be improved by including additional sensors or by modifying the control strategies (e.g., controlling velocities and accelerations) and enhancing the physical-based model describing the robot. However, the characteristics of the tendon-based robot did not allow meeting the requirements of a sleep study. Particularly, the smoothness of the motion and the perception of the trajectories by the subjects should be improved. Additionally, the acoustic impact of the powerful electronics of the \( r^3 \)-system would need major adaptation in order to meet the limitations imposed for a healthy sleep environment. For these reasons we concluded that the tendon-based approach provided a powerful test-bench to investigate the influence of a wide range of different kinds of vestibular stimulation on relaxation, but was not suited to be applied for human sleep.

This first phase of the project allowed important knowledge and experience to be gained, which were applied to design and develop a second device to explore the influence of rocking movements on sleep (chapter 3).
3 Two actuated beds to study the effects of rocking on human sleep

3.1 Introduction

About 33% of the general population presents insomnia symptoms [12]. Sleep disturbances such as insomnia increase risk of cardiovascular diseases and obesity [13,14], have a negative impact on mood, cognitive performance and motor function [15] and have an important economic cost (92.5-107.5 billion dollars annually in the USA [111]). A promising non-pharmaceutical approach to improve sleep quality is vestibular stimulation. Many examples in daily life suggest a relationship between vestibular stimulation and facilitation in falling asleep. People tend to fall asleep easily while traveling by train or by car. Parents help babies to fall asleep by rocking them in their arms or in a cradle. Moreover, many people like to relax or fall asleep in a hammock or in a rocking chair. In spite of the fact that vestibular stimulation such as rocking movements are widely applied to promote relaxation and sleep, from a scientific point of view this phenomenon remains unclear. Only a few studies have been conducted, where the effect of the provided vestibular stimulation on sleep was analyzed based on physiological measurements including brain activity (EEG). Both studies suggested a facilitated transition between wakefulness and sleep and to deeper sleep stages [26,27]. However, in both studies the characteristics and the direction of the chosen movements were not particularly motivated. Bayer et al. [26] used a bed rocking along the lateral axis (amplitude = 5.3 cm, frequency = 0.25 Hz), while Woodward et al. [27] applied a longitudinal rocking movement (amplitude = 3.2 cm, frequency = 0.42 Hz). Thus, despite the promising results of these studies, the relationship between vestibular stimulation and sleep remains unclear. Particularly, there is no information concerning how the effect differs between diverse kind of movements and about the importance of parameters such as directions, amplitude, and frequency. Thus, with our project we wanted to explore how different kinds of rocking movement affect sleep onset and the process of sleep, aiming to identify which stimulation is best to promote relaxation and sleep. In order to enable such investigation, an actuated bed was needed to move a sleeping subject along various, adjustable rocking trajectories.

In the first phase of the project, a tendon based parallel robot, the M3 setup, was used to explore the effects of different kind of rocking movements on relaxation (chapter 2). The preliminary investigations suggested 1-DOF trajectories as the most promising in promoting relaxation without inducing motion sickness or dizziness. A study was conducted to analyze the effects of rocking movements along six different axes (vertical, lateral, and longitudinal translations, lateral and longitudinal swing-like rotation, yaw rotation; Figure 2.1). No significant differences between the conditions resulted from the analysis of EEG and ECG features. The questionnaires suggested the vertical translation as the most promising in promoting relaxation, but no significant differences supported this tendency and the variability of the ratings was very high between the subjects. Based on these results, it was not possible to identify one particular motion as the most promising to promote relaxation for all subjects. However, based on the experiments conducted with the M3 setup, the movement frequencies and amplitudes most suitable for relaxation and sleep could be identified. Particularly we decided to consider only 1 DOF movements with frequencies and amplitudes that did not exceed the values used in the relaxation study (amplitude=0.15 m, frequency=0.3 Hz).
The experience gained during the first phase of the project was applied to design and develop the second version of our experiment setup to investigate the effects of rocking movements on human sleep. The new devices, the Somnomat rocking beds, consisted of two beds enabling to move sleeping subjects along five different directions: longitudinal, lateral, and vertical translations; lateral and longitudinal swing-like rotations. The two rocking beds were applied in a sleep study, which aimed at analyzing the effects of rocking movements on 18 healthy subjects. This chapter presents in detail the design of the Somnomat beds and provides an evaluation of technical performance and applicability with human subjects. Details of the conducted study and an extensive discussion of the results are reported in [2].

3.2 Setup

3.2.1 Requirements and architecture

A device was needed to rock sleeping subjects along different directions, with adjustable amplitudes and frequencies. The available systems that could be used to perform the desired task could be divided into two groups. The first group included some commercial moving beds such as simple passive hanging or rocking beds and hammocks, vibrating beds or chairs, and a few actuated rocking beds. The second group included some complex robots such as Stewart platforms, commonly used in flight or drive simulators or positioning systems (e.g. antenna, military applications, etc.), enabling 6 DOF trajectories, fast dynamics, and high payloads. On the one hand, the beds belonging to the first group provided only passive motion or one actuated axis, limiting the range of movement that could be tested. On the other hand, the second group was comprised of bulky, highly complex, noisy, and commonly expensive systems that hardly satisfy the requirements of a sleep study. Because none of the available approaches was suited to our investigations, we decided to develop two novel actuated beds, dedicated to the investigation of the effect of different rocking movements on sleep. Sleep and sleep research imply strict constraints and complex conditions. In order to guarantee applicability in sleep studies, the new setup was designed and developed based on the following requirements:

- **Requirement 1:** The robotic device had to include a platform of the size of a standard single bed (90 x 200 cm) allowing the subject to lie comfortably in a supine position.
- **Requirement 2:** The device had to include a stable moving structure, sustaining a standard slatted frame, a mattress, and an adult human subject up to 100 kg, resulting in a total moving mass up to 200 kg.
- **Requirement 3:** An actuation system was needed to move the platform along the desired trajectories (Figure 3.1).
- **Requirement 4:** The whole device had to be transportable, easy to install, and to be placed in a normal private bedroom or in the room of a standard sleep laboratory.
- **Requirement 5:** To allow relaxation and sleep, the system had to satisfy requirements concerning acoustic noise level and comfort. For a healthy sleep environment, Griefahn [3] and the World Health Organization (WHO) [39, 40] recommend a threshold of a continuous background noise level between 30 and 40 dBA.
- **Requirement 6:** Another important requirement was the quality and the smoothness of the trajectories. Parsons [112] showed a median sensitivity threshold of approximately 1 cm/s² root mean square (RMS) amplitude for whole-body vibration with frequencies between 2 Hz and 100 Hz. Because of this high sensitivity, in order to guarantee a pleasant and
comfortable movement, any trajectory disturbances such as unexpected vibrations, jumps, or jerks disrupting the motion smoothness had to be minimized.

- **Requirement 7**: During the sleep study, standard PSG recordings (EEG including EOG and EMG, ECG and respiration) had to be performed to assess sleep characteristics. Artifacts in the recorded physiological measurements induced by the electromagnetic actuators and other electrical components had to be avoided.

- **Requirement 8**: Finally, safety of the subjects and the research staff had to be guaranteed in order to apply the device in a study involving healthy human subjects.

Five different rocking directions were chosen to be implemented in the new setup: three translations along the three body axes (longitudinal (X), lateral (Y), and vertical (Z)) and two swing-like rotations (lateral (roll) and longitudinal (pitch)) (Figure 3.1). This choice was made by combining the results of the first investigation phase with spatial, practical, and technical requirements. The sixth direction used in the relaxation study, rotation about the vertical axis (yaw), was excluded because it was the only movement where different accelerations were applied to different parts of the body. In order to optimize movement performance and minimize design complexity, two different beds have been developed: one for the three linear translations (Somnomat bed A, Figure 3.2) and one for the swing-like rotations (Somnomat bed B, Figure 3.7). The detailed description of the devices is presented in section 3.2.2 and 3.2.3.

![Figure 3.1: Body coordinate frame. Blue: longitudinal (X), lateral (Y), and vertical (Z) translations. Red: Lateral (Roll) and longitudinal (Pitch) swing-like rotations.](image)

### 3.2.2 Somnomat bed A: Translational rocking

**Design and actuation**

The rocking bed A was a serial kinematic system that could be divided into four stages (Figure 3.2).

Starting from the bottom, the first stage was the base frame. Four wheels mounted on the base allowed the whole platform to be easily moved and positioned when unblocked, and provided a stable stand when blocked, respectively. The second stage was mounted on a set of linear guides (Haudenschild AG, Altendorf, Switzerland) allowing vertical translation with respect to the base. The actuation was provided using a brushless 3-phase synchronous AC servomotor (TPM010 dynamic, Wittenstein AG, Igersheim, Germany) including a low-backlash planetary gear-head \((i = 31)\) mounted on the base driving a high quality tooth-belt system (Poly Chain GT
Two actuated beds to study the effects of rocking on human sleep

Figure 3.2: The Somnomat rocking bed A. Left: Bed configured for translations along X-axis and along Z-axis. Right: Bed configured for translation along Y-axes.

Carbon Belt, Gates, Denver, USA). Four gas springs (pre-loaded with a force of 425 N, Bansbach easylift GmbH, Lorch, Germany) were used to compensate the static load of the moving platform (stages 2-4) and part of the payload (Figure 3.3). The third stage was mounted on two linear guides (Flexi-Line, Nadella GmbH, Nufringen, Germany) placed atop the second stage. The two guides allowed the third stage to translate horizontally with respect to the second stage. The horizontal motion was actuated by an electromagnetic direct linear actuator (PS01-48x360F-C, LinMot, Spreitenbach, Switzerland) mounted between stages 2 and 3 (Figure 3.3).

Figure 3.3: Mechanical design of the Somnomat bed A.

The fourth stage, the bed frame, was coupled with the third stage via a passive rotary joint. This joint allowed the bed frame to be rotated with respect to stages 1-3. During the motion, the bed frame was fixed to stage 3 with a constant angle equal to 0 or 90 deg. Such rotation allowed the orientation of the subject to be changed with respect to the translation axes. Hence, the subject could be moved along both the longitudinal and lateral body axes using the same actuator (Figure 3.4). The bed frame included support frame, slatted frame, and a viscous-elastic mattress (Viscopedic,
Elite SA, Aubonne, Switzerland), which reduced eventual vibrations and disturbances perceived by the subject lying on it. All frames were mainly constructed using aluminum profiles (Assembly Technology, Bosch Rexroth, Lohr am Main, Germany) providing high mechanical performance and modularity.

![Actuator direction](image)

**Figure 3.4:** Two stimulation directions with one actuator. The bed frame of the two Somnomat platforms can be turned 90 deg from position A to position B. This allows the subject to be moved along two different directions using only one actuator.

### Sensing

The horizontal position and velocity were sensed based on a resolver integrated in the motor. The current demanded by the motor was measured as an indication of the force applied by the motor. Similar to the vertical motion, the angular position of the motor was measured based on the motor resolver and the motor torque was measured based on the current supplied to the motor. All signals were digitized by the motor drives and acquired on the control program through EtherCat communication protocol (EtherCAT Technology Group, Nuremberg, Germany). In addition, an IMU (YEI Technology, Portsmouth, USA) was mounted on the bed frame to measure accelerations and angular velocities independently from the motor and closer to the subject. Position and velocity sensed on the linear motor and horizontal acceleration provided by the IMU were fused using a Kalman Filter to reduce measurement noise and improve the estimation of the horizontal velocity. A magnetically operating position sensor (55100 Mini Flange Mount Hall Effect Sensor, Hamlin, USA) was mounted on both vertical and horizontal mechanisms, to detect the middle point of the trajectory. This additional sensor allowed to detect the absolute middle position of each actuated axis, and was used to monitor the correct functioning of the device.

### Control

The control program was implemented in MATLAB/Simulink® (Matlab 2013b, MathWorks, Natick, USA) and ran on a real-time xPC Target PC.

**Horizontal motion**

The horizontal motor was controlled using a linear proportional-integral (PI) velocity controller combined with a model based FF term to compensate friction and inertia. The proportional and the integral gains were not constant but calculated as a linear function of the magnitude of the reference
velocity. This allowed the “aggressiveness” of the controller to be increased at low speeds improving the precision and the smoothness at the turning points, as well as reducing the aggressiveness at higher speeds, to limit undesired ripples and vibrations. The friction compensation model consisted of two different linear models of dynamic friction, one for positive and the second for negative velocities, respectively. Smooth transition between the two models was guaranteed for low velocities ($v < \varepsilon$) using a $7^{th}$-order polynomial function. No compensation of the static friction was performed. Inertia compensation was calculated based on payload and reference acceleration. The same control strategy was applied for both the X and Y axis, while the friction model, control gains, and tuning parameters were identified and adjusted separately.

*Figure 3.5: Controller X and Y. Flow chart visualizing the control strategy used to control the horizontal motion (X and Y) in the Somnomat bed A.*

**Vertical motion**

The vertical motion was controlled similarly to the horizontal one, using a linear PI velocity controller combined with a model based FF term to compensate friction, inertia, and static load. In this case, proportional and integral gains of the PI controller were constant. Inertia compensation was calculated based on payload and reference acceleration. In addition to the friction model, where the same approach as used for the horizontal axes was applied, the controller of the Z axis included FF compensation of the weight of the platform and of the forces introduced by the gas springs.

*Figure 3.6: Controller Z. Flow chart visualizing the control strategy used to control the vertical motion (Z) in the Somnomat bed A.*
3.2 Setup

3.2.3 Somnomat bed B: Swing rocking

Design and actuation

The second bed, the Somnomat rocking bed B (Figure 3.7) presented a similar design as bed A but had only one DOF. The bed could be divided into three stages: basis, stage 2, and stage 3 (including bed frame, slatted frame, and mattress).

![Somnomat bed B: Roll](image1)

![Somnomat bed B: Pitch](image2)

Figure 3.7: The Somnomat rocking bed B. **Left:** Bed configured for swing-like rotation along roll-axis. **Right:** Bed configured for swing-like rotation along pitch-axis.

The base frame was analogous to bed A (see previous section). The second stage was mounted on two curved guides (Curviline, Haudenschild AG, Altendorf, Switzerland) allowing a swing-like rotation with respect to the base (Figure 3.8). Two different guides were used, allowing movement along an arc trajectory with a radius of either 2 m or 4 m. Actuation was provided by the same brushless 3-phase synchronous AC servomotor (TPM010 dynamic, Wittenstein AG, Igersheim, Germany) used in bed A, including a low-backlash planetary gear-head ($i = 31$) mounted on the base driving a high quality tooth-belt system (PowerGrip HTD, Gates, Denver, USA) (Figure 3.8). Similar to bed A, the bed frame, including slatted frame and mattress, was coupled to stage 2 using a passive rotary joint, which allowed changing the orientation of the subject with respect to the actuated axis (Figure 3.4).

Sensing

As in the Somnomat bed A, the angular position of the motor was measured based on the motor resolver and the motor torque was measured based on the current supplied to the motor. All signals were digitized by the motor drives and acquired on the control program through EtherCat protocol. A same magnetically operating position sensor used in bed A was mounted on the mechanism to detect the middle point of the trajectory. This additional sensor allowed to detect the absolute middle position and was used to monitor the correct functioning of the device.

Control

The rocking bed B included the same actuator and a similar belt transmission principle as used for the vertical axis of bed A. Thus, a similar control strategy was applied. The controller included a linear PI velocity controller combined with a model based FF term to compensate friction, inertia, and static load. As for the Z axis, also in bed B a standard approach with constant proportional
and integral gains was chosen. Inertia compensation was calculated based on payload and reference acceleration. Friction was modeled and compensated in the same way as previously described for bed A. In addition, the effect of gravity was modeled and compensated.

![Figure 3.8: Mechanical design of the Somnomat bed B.](image)

**Figure 3.9: Controller roll and pitch.** Flow chart visualizing the control strategy used to control the swing-like motion (roll and pitch) in the Somnomat bed B.

### 3.2.4 Communication and electronics

The communication between the xPC Target, actuators, and sensors was based on the EtherCAT communication protocol. Additional inputs and outputs signals were managed using I/O Beckhoff EtherCAT Terminals (Beckhoff, Verl, Germany) integrated in the EtherCAT network. Only the IMUs used in bed A were directly connected to the xPC target through a serial communication board. For each bed, other than the actuators all electronic components contributing to the overall acoustic noise impact of the system were placed inside an electric cabinet, which could be located in another room, away from the bed.
3.3 Experimental phase: Applicability and impact of the rocking beds

Safety

A protective net was mounted around the bed platform (Figure 3.10). This barrier prevented the sleeping subjects for falling off the bed or getting caught between moving parts while rocking movements were performed. Automatic monitoring of measured signals and control commands was implemented in the control program in order to guarantee the safety of the subject, the staff, and the hardware components in case of software failures. Redundancy was provided by additional monitoring of I/O motor signals performed directly on the motor drives. Finally, an independent loop included a watchdog checking the communication with the xPC target and a set of emergency stop buttons placed on the bed platforms and in the control room, were the experiments were directed from (Figure 3.10). Any detected failure triggered an emergency stop by switching off the motor power supply and stopping the motion.

![Figure 3.10: Safety measures.](image)

Figure 3.10: Safety measures. Protective net preventing the sleeping subject for falling off the bed or getting caught between moving parts. Emergency stop buttons to cut the motor power and immediately stop the motion.

Shielding

In order to avoid electromagnetic interference in the recorded physiological signals, an aluminium plate was mounted below the mattress, in the area corresponding to the upper half of the body of the lying subject. This shield was electrically insulated from any conductive part of the bed structure and was connected to the ground of the amplifier used to acquire the physiological signals.

3.3 Experimental phase: Applicability and impact of the rocking beds

3.3.1 Aim

The two Somnomat rocking beds were developed to be applied in sleep research. The experimental setup used in a scientific study could significantly influence the results of the conducted investigations, particularly when a sensitive process such as human sleep is involved. In order to prove
the reliability of the conducted study, the performance and applicability of the rocking beds were analyzed and discussed. The analysis involved two distinct experimental phases: a series of tests conducted prior to the sleep study, and the sleep study itself.

The first experimental phase aimed to evaluate applicability of the rocking beds and to define the details of the experimental setup to be used during the sleep study. First, the beds were set up at the sleep laboratory to prove that size and logistic requirements were compatible with the characteristics of the lab. Furthermore, motion quality and acoustic impact of the rocking beds were analyzed in order to define which range of movements were suited to being applied during the sleep study. Finally, the rocking beds were tested in combination with the physiological measurement devices used at the sleep laboratory to exclude disrupting effects on the recorded data due to either movements or electromagnetic interference.

The second experimental phase aimed to evaluate the impact of both the used devices and the chosen rocking movements on human sleep and on sleep environment. Therefore we evaluated safety, comfort and compatibility with a natural sleep environment, acoustic impact, quality of the provided rocking movements, and compatibility with the PSG measurements. The evaluation was based on the data acquired during a sleep study where the two rocking beds were applied with 18 healthy human subjects. An extensive description of this study and the complete analysis of the effects of the provided rocking movements on sleep and on the physiological state of the subjects is presented in [2].

3.3.2 Applicability

Experimental setup

The whole experimental phase was conducted in a sleep laboratory at the University of Zurich. The Somnomat rocking beds were set up in two rooms of the sleep lab. Each room was compatible with a standard bedroom with respect to size and furnishings and was acoustically insulated from the rest of the lab. The control PC, xPC target, and the electronic cabinet were placed in the corridor and wired to the platform inside the experiment room (Figures 3.12 and 3.13). The
experiments were conducted from a control room, located outside the sleep lab. The rocking beds were controlled from the control room, through a laptop remotely connected to the control PC. When the bed was moving, the experiment was visually monitored by means of IR cameras located in each experiment room (Figure 3.13).

The sleep lab was equipped with a measurement system to acquire and monitor polysomnographic recordings during the experiments. Physiological recordings were acquired through polygraphic amplifiers Artisan (Micromed, Mogliano, Veneto, Italy) mounted on each rocking bed. The recordings were acquired, monitored, and stored in the control room using the software Rembrandt DataLab (Version 8.0; Embla Systems, Broomfield, CO, USA).

![Experiment room](image1.png)
![Control room (monitoring)](image2.png)
![Corridor (electronics and PCs)](image3.png)

**Figure 3.12: Experiment setup.** *Left:* Rocking bed B placed in the experiment room at the sleep laboratory. *Right top:* The experiment and the rocking bed were monitored and controlled from the control room. *Right bottom:* Electronics components and PCs were located in the corridor to minimize acoustic disturbances during the experiment.

### Performance and range of motion

To avoid disrupting effects on relaxation, which may negatively influence sleep onset and sleep, subjects lying in the rocking beds should perceive the movements as pleasant and comfortable. Thus it was important that the motions appeared smooth and that disturbances such as ripples, jumps, jerks, and undesired vibrations were minimized along with the overall acoustic impact of the system.

The performance of the rocking was quantified based on the absolute error between reference velocity and velocity calculated based on the measured motor positions. These metrics reflected the capability of the rocking bed to track the desired trajectory profiles. The evaluation was performed using sinusoidal trajectories with a fixed linear amplitude of 15 cm and maximal linear velocity varying from 5 cm/s to 20 cm/s. These trajectories were chosen within the range of movements identified as the most promising in promoting relaxation (chapter 2). The same trajectories were tested for all five movements axes, with the same payload of 90 kg. To simplify the comparison between the different movement directions, for the Somnomat bed B (i.e. for roll and pitch axes) the trajectory velocity is reported as the magnitude of the platform’s velocity tangential to the curved trajectory, while the amplitude corresponds to the arc length of the curved trajectory.
The acoustic impact of the platforms was evaluated by measuring the A-weighted $L_{A_{eq}}$ at the subject head position using a Sound Level Meter (Real Time Octave Band Analyser type 114, Norsonic, Lierskogen, Norway). Analogously to the analysis of the motion quality, the acoustic measurements were performed for each motion axis for the same set of sinusoidal trajectories with a constant payload of 90 kg on the platform. For each trajectory the sound level was averaged over 10 s and each measurement was repeated three times.

**Compatibility with physiological recordings**

To identify potential interference in the recorded physiological signals, the following test was performed. Grass electrodes were placed on the skin of a ready to cook chicken analogously to how they are usually applied on the head of the human subject to record EEG. The electrical characteristics of the chicken skin are similar to the characteristics of the human subject. Combined with the absence of any electrical activity, this condition provided a clean reference signal. On such a low noise reference signal, eventual artifacts and disturbances could be easily identified.

### 3.3.3 Applicability and effects on human subjects and sleep

**Subjects**

The study involved eighteen healthy subjects (male, right handed, age: 20-28 years, mean: 23.7 years). Each subject had to first undergo telephone and questionnaire screening to exclude sleep disorders, irregular sleep wake rhythm, diseases of the vestibular system, and neurological, psychiatric or acute/chronic internal diseases. Subjects with excessive daytime sleepiness and excessive susceptibility to motion sickness were also excluded. Additional inclusion requirements were: non-smokers, free of drugs and medication, normal sleepers, and moderate alcohol and caffeine intake. A screening night was conducted prior to the study to verify sleep quality, sleep efficiency (>80%)
and the absence of sleep disorders. The study was approved by the Institutional Review Board of the ETH Zurich and was performed in accordance with the standards for research involving human subjects defined by the Declaration of Helsinki [97].

**Movements**

Vestibular stimulation was applied using the Somnomat rocking beds A and B (section 3.2). The kind of movement was chosen by the subject prior to the first experimental night. This avoided using a movement perceived as uncomfortable. Furthermore, assuming that the effect of vestibular stimulation on sleep is influenced by relaxation, the greatest impact would be expected when a movement perceived as pleasant and relaxing is applied. The subjects had to choose first, between 5 movement directions (X, Y, Z, roll, and pitch) and second, between two frequencies: a “fast” (0.24 Hz) and a “slow” one (0.16 Hz). The amplitude of the two trajectories were calculated in order to guarantee the same maximal velocity (0.1 m/s) for both movements. This resulted in 0.066 m and 0.1 m amplitude for the fast and the slow frequency, respectively. Each movement was tested for 2 min, while the subjects lay in bed in a darkened room with closed eyes. Movement directions and frequencies were applied in randomized order. During a short break after each movement the subjects gave feedback and ranked the movement on a scale from 1 to 5 (1=best liked movement, 5=least liked movement).

**Protocol**

Subjects who successfully passed the screening phase spent three experimental nights in the sleep lab (Figure 3.14).

The experiment included one night without movement (baseline condition (B)) and two nights with vestibular stimulation (movement condition until sleep onset (C1); movement condition 2 h after lights off (C2)). The order of the different experimental conditions was randomized. In condition C1 vestibular stimulation was provided from lights out to sleep onset In condition C2 vestibular stimulation was provided for the first 2 h after lights out. To ensure that same level of acoustic noise level was present in all conditions, the bed noise was pre-recorded and played back for the first 2 h after lights out for condition B and from sleep onset till 2 hours after lights out for condition C1. Noise playback matched movement direction and frequency selected by the subjects. Both the acoustic noise level of the moving bed and the pre-recorded noise playback were below 35 dB. Subjects were not informed about the order of the randomized conditions. The only information given to the subject shortly (5 min) prior to lights out was whether vestibular stimulation was applied or not. This protocol was chosen to minimize subjects’ potential bias (expectations) towards the experimental conditions, which could have had an influence on the process of falling asleep as well as the subjective rating of sleep quality. After the last experimental night subjects were asked to compare night with against nights without movements, and state which condition they preferred.
During each experiment night the physiological state of the subject and sleep parameters were assessed based on polysomnographic recordings and declarative memory task. The experimental setup is summarized in the flow chart visualized in Figure 3.15.

**Figure 3.15: Control chart.** The flow chart summarizes the experiment setup. The chosen reference trajectory was fed to the controller of the rocking bed, which actuated the platform in order to provide the desired condition to the subject. Polysomnographic recordings including EEG, EMG, EOG, ECG, and respiration were performed to allow quantitative assessment of sleep parameters.

**Measurements**

Brain and cardio-respiratory activity were continuously recorded throughout the entire 8 hour sleep period with a polygraphic amplifier Artisan (Micromed, Mogliano, Veneto, Italy) and the software Rembrandt DataLab (Version 8.0; Embla Systems, Broomfield, CO, USA).

EEG (according to the 10-20 system: F3, F4, C3, C4, P3, P4, O1, O2, A1, A2, referenced to Cz), submental EMG, and EOG signals were sampled at 256 Hz. Sleep stages were visually scored on a 20-s epochs basis according to standard criteria [1]. Frequent arousals are a signal of poor sleep quality. Arousals are usually found together with movements. Epochs scored as artifacts are usually associated with movements. Thus an indication of disturbed sleep was calculated as the percentage of epochs scored as artifacts. Additional indication of disrupted sleep was calculated from the occurrence of changes between wake, sleep stage N1 (N1), sleep stage N2 (N2), sleep stage N3 (N3), and REM. Both these two features were calculated from the hypnogram data resulting from the manual scoring of the PSG recordings. ECG recording was performed with one electrode placed 2 cm below the right clavicula between the first and second ribs, the second one placed at the fifth intercostal space on the midaxillary line on the left side of the body. Sampling frequency of the ECG recorded signals was 64 Hz. Analysis was based on heart rate, mean heart rate, and HRV features. Respiration was recorded using two respiration belts (EPM Systems, Midlothiana, USA): one placed around subject’s chest and the other around the abdomen. Analysis was based on respiration frequency features. Sleep in general is assumed to favor memory consolidation [113, 114, 115, 116]. To investigate whether vestibular stimulation plays a role in this process, a declarative memory performance was assessed with a word-pair learning task [117, 118].

Additional information about the physiological recordings, declarative memory task, and about the performed data and statistical analysis are reported in the appendix (section [B.1]). A complete description of the conducted sleep study is presented in [2].
3.4 Results and discussion

3.4.1 Applicability of the rocking beds

Experimental setup

The two platforms were successfully set up in a sleep laboratory, fulfilling all requirements concerning size and transportability. The technical characteristics of the two platforms are summarized in Table 3.1. The architecture of the experimental setup (Figure 3.13) allowed minimization of any interference with the experimental room and with the subjects. Placing the electronic cabinet, the control PC and the xPC target in the corridor outside the experimental room guaranteed a quiet and natural sleep environment inside the room. The complete experiments could be controlled from the control room located outside the sleep lab avoiding any potential disturbance during the study. The safety of the beds has been evaluated and approved by the Institutional Review Board of the ETH Zurich for application in a sleep study involving healthy human subjects. Continuous visual monitoring and full control of the devices was guaranteed for the operating staff in the control room. Additionally, an emergency stop switch was located in the control room to directly stop the bed motion in case of need.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Bed A</th>
<th>Bed B</th>
<th>Roll / Pitch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [cm]</td>
<td>227</td>
<td>227</td>
<td>227</td>
</tr>
<tr>
<td>Width [cm]</td>
<td>100 / 176</td>
<td>100</td>
<td>126 / 100</td>
</tr>
<tr>
<td>Height [cm]</td>
<td>126</td>
<td>156</td>
<td>108</td>
</tr>
<tr>
<td>Tot. mass (no payload) [kg]</td>
<td>200</td>
<td>200</td>
<td>145</td>
</tr>
<tr>
<td>Moving mass [kg]</td>
<td>67</td>
<td>121</td>
<td>75</td>
</tr>
<tr>
<td>Max payload (static) [kg]</td>
<td>253</td>
<td>199</td>
<td>505</td>
</tr>
<tr>
<td>Max actuator force [kN]</td>
<td>1.02</td>
<td>3.33</td>
<td>3.33</td>
</tr>
<tr>
<td>Max lin. velocity [cm/s]</td>
<td>210</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 3.1: Characteristics of the Somnomat rocking beds.

Performance and range of motion

Motion performance was evaluated by analyzing the absolute errors between reference trajectory and the values calculated based on the motor resolver ($e_{vel} = v_{ref} - v_{meas}$, Figure 3.16). Each trajectory was tested for 5 min. Absolute linear velocity errors $|e_{vel}|$ were below 0.91 cm/s for pitch and roll ($|e_{vel,axi}| = \text{mean (standard deviation)}$: $|e_{vel,roll}| = 0.14 (0.1)$ cm/s; $|e_{vel,pitch}| = 0.13 (0.1)$ cm/s), below 1.24 cm/s for Z ($|e_{vel,Z}| = 0.29 (0.18)$ cm/s), and below 3.56 cm/s for X and Y ($|e_{vel,X}| = 1.10 (0.80)$; $e_{vel,Y} = 0.93 (0.67)$ cm/s).

Small ripples during the motion and little jerks in the conversion points were noticed as perturbations of the trajectories’ smoothness. The controllers were tuned to try to minimize the impact of these disturbances. The tuning process was performed manually, starting from control parameters identified on a dynamic model of the system to guarantee stability and the desired bandwidth. A first tuning process allowed to improve the ability of the rocking bed to track reference position and velocity. Then, the controllers where further adjusted based on the feedback of a test subject, in order to improve the perceived smoothness when lying on the mattress. The human senses the linear accelerations and angular velocities through the vestibular system as well as vibration and pressure between the body and the mattress through the mechanoreceptors located in the skin.
Thus, we are not able to measure our absolute position in space or notice small deviations from the desired trajectories but we are very sensitive to small jerks and discontinuities. The final phase of the tuning process based on subjective feeling and perception was crucial to obtain the pleasant and comfortable motions required to perform the study.

The best performance was observed for roll and pitch axes, where the motion appeared smooth and almost ripple-free (Figure 3.16). The vertical motion presented higher jerk in the conversion points, probably caused by damping and stick-and-slip caused by the four gas springs (Figure 3.16). The highest perturbations were observed for the horizontal translations X and Y (Figure 3.16). This was due to difficulty in driving the linear motor along smooth trajectories at slow speeds. Even though the errors were significantly higher compared to the other axes, when lying in the platform the perception of the motion remained pleasant. This was qualitatively evaluated based on a person lying on the platform during the tuning phase. Increased perceived smoothness and reduction of disturbances such as ripples and jerks could be achieved by further developing the control strategies. Possible adaptations consist of improving the friction model to be used in the FF compensation as well as including an adaptive algorithms to learn and compensate unmodeled disturbances in periodical trajectories. However, the conducted analysis showed that satisfactory motion quality was achieved for all five axes and that, within the tested range, the two rocking beds were suited to application in a sleep study with healthy human subjects.

As expected, the acoustic noise level highly depended on the maximal velocity reached during the sinusoidal motion (Figure 3.17). The main sources of such noise were the carriages moving on the
3.4 Results and discussion

Rails and the gear boxes of the rotary motors. In trajectories with a maximal linear velocity below 15 cm/s, maximal continuous acoustic noise of approximately 40 dBA was fulfilled. However, a qualitative evaluation based on subjective perception of acoustic noise, suggested that in a very quiet environment such as the sleep lab ($L_{eq}$ with no motion of ca. 25 dBA), acoustic noise above 30-35 dBA could already be perceived as disturbing. Based on this result, the workspace considered as applicable for a sleep study was reduced to trajectories with maximal velocities below 10 cm/s.

![Averaged acoustic noise level](image)

**Figure 3.17: Acoustic impact.** A-weighted equivalent continuous sound level $L_{eq}$ measured without motion (device on) and during four representative trajectories (linear amplitude $a = 15$ cm, max linear velocity $v_{max} = \{5, 10, 15, 20\}$ cm/s), for all movement axes X, Y, Z, roll, and pitch.

Based on these results, sinusoidal movements with a maximal velocity of 10 cm/s were identified as suitable to be applied in the sleep study. Within such ranges the rocking beds guarantee good motion quality in terms of smoothness and absence of undesired disturbances (based on subjective feedback reported during the tuning phase), as well as low acoustic impact, compatible with a natural and healthy sleep environment. These limitations were strictly related to the technical characteristics of the rocking beds and a larger suitable range of motion could be allowed by different mechatronical components or designs. For example, a reduction of the acoustic noise generated by the moving carriages would allow consideration of higher rocking velocities. The two trajectories chosen for the conducted sleep study were sinusoidal movements with frequency 0.24 Hz and amplitude of 6.7 cm and frequency of 0.16 Hz and amplitude of 10 cm, respectively. These trajectories fulfilled the performance and acoustic requirements and appeared promising for further investigation. The chosen movements presented similar parameters (e.g. frequency, amplitude, maximal acceleration, and maximal velocity) compared to previous studies ([27, 26]) and to the commercially available rocking bed Sway (Table 3.2). The trajectories used in the relaxation study (chapter 2) were significantly faster and were considered “too aggressive” to be applied in a sleep study.

**Compatibility with physiological recordings**

Placing the Grass electrodes on the skin of the ready to cook chicken showed that no interference was present for axes Z, roll, and pitch axes while very small disturbances in a range of 1-2 $\mu$V were observed in the X and Y axes.

The aluminium shielding plate mounted under the mattress (Figure 3.11) proved to be effective in avoiding electrical artifacts in the EEG signal caused by the powerful AC servomotor used for
### Table 3.2: Movement parameters

Table summarizing and comparing the trajectory parameters used in research or implemented in commercial systems.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Kind of trajectory</th>
<th>Ampl. [cm]</th>
<th>Freq. [Hz]</th>
<th>Max vel. [cm/s]</th>
<th>Max acc. [cm/s²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woodward et al. [27]</td>
<td>longitudinal parallel swing</td>
<td>3.2</td>
<td>0.42</td>
<td>*8.4</td>
<td>*22.1</td>
</tr>
<tr>
<td>Bayer et al. [28]</td>
<td>lateral parallel swing</td>
<td>5.3</td>
<td>0.25</td>
<td>*8.2</td>
<td>*13.0</td>
</tr>
<tr>
<td>Sway²</td>
<td>7.5m pendulum</td>
<td>11.5</td>
<td>*0.19</td>
<td>*13.7</td>
<td>*16.4</td>
</tr>
<tr>
<td>Relaxation study (chapter 2)</td>
<td>translation (X, Y, Z)</td>
<td>15.0</td>
<td>0.30</td>
<td>28.3</td>
<td>53.3</td>
</tr>
<tr>
<td>Relaxation study (chapter 2)</td>
<td>2m pendulum (roll, pitch)</td>
<td>20.9</td>
<td>0.30</td>
<td>39.5</td>
<td>74.4</td>
</tr>
<tr>
<td>Sleep study</td>
<td>translation 1 (X, Y, Z)</td>
<td>10.0</td>
<td>0.16</td>
<td>10.1</td>
<td>10.1</td>
</tr>
<tr>
<td>Sleep study</td>
<td>translation 2 (X, Y, Z)</td>
<td>6.6</td>
<td>0.24</td>
<td>10.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Sleep study</td>
<td>4m pendulum 1 (roll, pitch)</td>
<td>10.0</td>
<td>0.16</td>
<td>10.1</td>
<td>10.1</td>
</tr>
<tr>
<td>Sleep study</td>
<td>4m pendulum 2 (roll, pitch)</td>
<td>6.6</td>
<td>0.24</td>
<td>10.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

* Calculated from the given parameters.

² Commercial rocking bed (Klafs GmbH and Co. KG, Freiburg im Breisgau, D; Figure 1.7).

For the relaxation study, the motion parameters are as follows:

- **Ampl.** (Amplitude): The maximum displacement from the equilibrium position.
- **Freq.** (Frequency): The number of cycles per unit time.
- **Max vel.** (Maximum velocity): The maximum speed achieved.
- **Max acc.** (Maximum acceleration): The maximum rate of change of velocity.

These parameters are crucial for understanding the effects of rocking on human sleep, as they help in designing suitable sleep environments for better health outcomes.
3.4 Results and discussion

the Z, roll, and pitch axes. The disturbances observed for X and Y axes were probably caused by the cables of the electrodes moving through the permanent magnetic field of the linear motor providing horizontal actuation. These disturbances were significantly lower than the usual range of a human EEG signal and could be considered negligible when brain activity is present. Thus, the rocking beds proved to be compatible with the measurements devices used in the sleep lab to record the physiological activity of the subjects.

3.4.2 Impact on human subjects and sleep

Subject preferences and subjective perception

A preference for swing movements was observed as 12 out of 18 subjects selected either pitch, or roll axis. Furthermore, the majority of the subjects (n=12) decided upon a low stimulation frequency of 0.16 Hz rather than the high frequency of 0.24 Hz. Most subjects (n=12) preferred a condition with movement compared to the baseline (Figure 3.18).

![Figure 3.18: Selection of movement parameters. Left: Subjects selection of movement axes. Center: Subjects selection of movement frequency: “slow trajectory” (frequency=0.16 Hz, amplitude=0.1 m), “fast trajectory” (frequency=0.24 Hz, amplitude=0.066 m). Right: Subject preference among condition with and without motion.](image)

Based on the subjects’ feedback recorded with questionnaires, all tested movements were perceived as comfortable and relaxing. No occurrence of motion sickness was reported in any of the subjects during the motion selection procedure or during the experimental nights. Moreover, the majority of the subjects preferred sleeping with movements over sleeping without. This was in line with the findings of Bayer et al. [26] where a clear preference towards naps with movement was reported. The subjects’ preference for the conditions with movements confirms that the Somnomat rocking beds were able to provide a pleasant rocking motion as well as guaranteeing a comfortable sleep environment.

Preference for the low stimulation frequency could be influenced by subjects’ precaution not to disrupt sleep by a motion being perceived as too fast, although movements in both frequencies exhibited comparable velocities. However, the generally positive rating assigned to the motions suggests that subjective preferences were the main factor for movement selection rather than discomfort or dislike of some motions.

Although the relaxation study described in chapter 2 showed a tendency towards higher subjective relaxation and comfort for the vertical movement (Z-axis), motion preferences were different in the conducted sleep study. Swing motions were clearly preferred to translations and the Z-axis was
the least selected one. A reason for this finding might lie in the unfamiliarity of vertical rocking. Subjects might tend to select movements which are known from experience rather than unfamiliar movements. Swing movements could appear more familiar due to experiences relaxing or falling asleep on a boat or in a hammock or even as a baby in a rocking cradle. However, these selection factors might be more relevant for subjects, when selecting a movement to be applied during a whole night of sleep than during a short time of relaxation. In addition, the swing trajectories applied with the Somnomat beds were characterized by longer radius \( R = 4 \) m compared to the motion used in the relaxation study \( R = 2 \) m, chapter 2 and presented considerably higher velocities and accelerations (Table 3.2). Furthermore, the quality of the movements used in the sleep study was significantly improved compared to the first M³-Setup. These aspects could have influenced subjective perception and preference and could explain the different results between the two investigations. Moreover, the two rocking beds (Bed A: translations; bed B swing-like rotations) differed in actuation principles and mechanical design. These differences resulted in the slightly different motion performance shown in the previous section (section 3.4.1). Such differences combined with the bulky structure of bed A, considerably bigger than bed B, could have influenced the choice of the subjects.

Effects of rocking movements on sleep and physiology

Physiological recordings were not affected by either the rocking beds or the vestibular stimulation as no artifacts or disturbances were observed during the conditions with movements. This allowed sleep architecture to be assessed and sleep parameters to be based on standard approaches such as manual scoring and spectral analysis. The shield implemented in the two beds successfully prevented artifacts and electrical interference due to the beds’ actuators. Mounting the physiological amplifier directly on the moving platform of the beds allowed artifacts due to the motion of the electrode cables to be avoided.

The analysis of brain activity showed no changes in sleep architecture in the presence of vestibular stimulation. Respiration and ECG recordings showed normal sleep stage dependent characteristics of respiration frequency, heart rate and HRV. However, conditions with vestibular stimulation showed no difference in heart rate, HRV or respiration frequency compared to the condition without stimulation. Performance in declarative memory was found to be improved after sleep, in line with results of previous studies 119, 120, 121, 122 overnight. However, overnight memory improvement exhibited similar gains in all three conditions, leading to the conclusion that vestibular stimulation did not have additional beneficial consequences on memory.

During the scoring of the PSG recordings, epochs characterized by a sudden increase in high-frequency activity related to movements or muscular activity were classified as artifacts and excluded from the analysis. Usually, this signal pattern is found when arousals occur. Therefore, comparing the number of artifacts epochs and the occurrence of sleep stage changes between nights with and without motion, could indicate whether vestibular stimulation influenced sleep in a negative way. The total number of artifact epochs and sleep stage changes were calculated from sleep onset to 2 h following lights off. Neither the number of artifact epochs (B: mean: 40.11 (SD: 21.32); C1: 36.28 (16.38); C2: 31.90 (13.50)) nor the number of sleep stage changes (B: 24.39 (12.65); C1: 26.17 (18.98); C2: 28.83 (23.48)) differed significantly between conditions. These results suggests that vestibular stimulation had no negative impact on sleep continuity either while it was applied (comparison between condition B and C2) or after it was stopped (comparison between condition B and C1) 123. This is in agreement with the analysis of sleep architecture, which showed no significant differences in sleep onset latency, in wake after sleep, or in time in the different sleep stages between conditions with and without rocking motion.

In summary, none of the analyzed physiological features and sleep parameters significantly differed between conditions with and without rocking movements. Our study did not show any improvement
of sleep quality nor any indication of better sleep in presence of vestibular stimulation. However, neither disturbances nor negative effects on sleep were observed when rocking movements were applied using the Somnomat rocking beds; and all subjects showed healthy and good sleep in all tested conditions. This confirms the applicability of the approach showing that neither the rocking beds nor the provided movements disturb sleep. The reason for the lack of positive effects could be due to the studied population, composed of young and healthy “good sleepers”. Different results could be achieved when considering a population characterized by reduced sleep efficiency such as the elderly.

All details concerning data and statistical analysis as well as the complete report and discussion of the results of the conducted sleep study are presented in [2].

### 3.5 Conclusions and outlook

Two rocking beds have been designed and developed to be applied in sleep research to rock sleeping human subjects along five different movement axes (three translations and two swing-like rotations). A first evaluation phase conducted to analyze function and performance, proved the applicability of the beds with healthy humans and compatibility with the requirements of sleep studies. The devices are approximately the size of a hospital bed and could be successfully transported and placed in a standard bedroom. The beds guaranteed comfort and provided smooth and pleasant movements. Slow sinusoidal trajectories characterized by maximal linear velocity below 10 cm/s ensured a low acoustic impact compatible with the guidelines for a healthy sleep environment. No electromagnetic interferences with physiological measurement devices nor particular artifacts due to the bed movements were observed. Standard polysomnographic recordings could be performed during rocking.

The two beds were successfully applied to study the effects of rocking movements on 18 healthy human subjects. Most of the subjects preferred the conditions with motion compared to the one without, confirming the comfortable and pleasant characteristics of the chosen movements. Swing-like rotations were clearly preferred to translations and slow movements were preferred to fast movements. These results suggest that the range of possible movements to be considered for further investigations could be further reduced. However, technical reasons such as the differences in actuation principles and motion performance between translation and rotation axes could have influenced the choice of the subjects. Thus, this aspect combined with the subjectivity observed in the motion selection process should be considered in future studies.

Despite the fact that movements were subjectively preferred to the baseline without motion, vestibular stimulation had no effects on any of the analyzed physiological features. However, as well as no positive effects on sleep quality, neither negative effects nor disturbances were observed in the presence of rocking movements, and healthy and good sleep was observed for all subjects in all tested conditions. This confirms the applicability of both the rocking beds and the provided movements.

Even though all requirements were successfully fulfilled, the main limitations of the developed beds were the acoustic noise and the smoothness of the movements. In a quiet environment such as the sleep lab, each small noise becomes audible and could potentially influence relaxation and sleep. In the conducted study, this aspect was solved by playing back the previously recorded noise of the moving bed, when no motion was present. This guaranteed that same acoustic environment among different conditions. However, alternative designs to reduce the needed actuation power and to avoid rails and fast spinning wheels could allow reduction of the acoustic impact of the device and should be considered in future studies. Similarly, when being rocked in a very quiet environment we are very sensitive to any ripple, vibration, and, particularly, to any discontinuity
perturbing the monotonous smoothness of the motion. Thus, in order to exclude the presence of undesired disturbances affecting the relaxation and the results of the study, in future investigations extreme care should be dedicated to the choice of mechanical components and control strategies. For example, by avoiding continuous changes in the motion direction of the actuator (e.g. by applying a crank mechanism) the quality of the turning points could be significantly improved. Guaranteeing smooth change of directions was indeed the most critical and difficult task, and abrupt turning points could severely affect the comfort and pleasantness of the motion.

The results of the conducted study did not show any influence on sleep due to the chosen vestibular stimulation. Consequently, we could neither confirm the role of vestibular stimulation in promoting relaxation and sleep, nor identify the influence of motion parameters such as direction, frequency, and amplitude. However, the rocking beds developed within this project now offer an effective and powerful tool which can be applied to further investigate this phenomenon.
4 A smart bed to influence sleeping posture and snoring

4.1 Introduction

Snoring is a very common problem and affects up to 44% of men and 28% of women [37, 38]. Snoring, along with sleep disturbed breathing, can have disruptive consequences on sleep and is associated with numerous health and social problems for both the snorer and the bed partner [42, 43, 44, 45, 16, 37, 52, 53, 55, 50, 57, 51, 58]. Thus, such conditions should not be underestimated and an efficacious treatment could considerably improve the snorer’s life quality (additional background information on snoring is presented in 1.1.2).

To treat snoring one can choose between various approaches such as simple behavioral changes (e.g. losing weight and stopping smoking) [59, 60], various nasal and dental devices to influence shape and position of upper airways during the night [39, 60], nasal sprays and other pharmacological treatments [44], positional therapy to avoid supine position [71, 45, 72], upper body elevation [67], continuous positive air pressure (CPAP) devices, various methods based on alternative and Chinese medicine [39], or surgery to modify tissue characteristics and shape of the upper airways. Some of the existing approaches have been proven to be effective. However, users’ long-term compliance is low and most of the approaches have been reported to interfere with comfort and natural sleep. In particular, most existing approaches consist of temporary or permanent intervention adopted to reduce snoring a priori, acting on the user during the whole period of sleep, whether he or she is snoring or not.

Head and trunk elevation (or upright sleep) has shown some positive effects in reducing sleep disturbed breathing in cases ranging from mild to severe obstructive sleep apnea hypopnea syndrome OSAHS [67, 69]. However, little research has been done and, as shown by Skinner et al. [69], the results varied significantly between the tested subjects. As head and trunk elevation is a very simple and unobtrusive method, it should be further investigated. Particularly, the impact of upright sleep on primary snoring (e.g. in absence of OSAHS) has not yet been investigated. Side effects such as back pain may be limited by elevating the user’s head and trunk only when needed. Thus, automatically controlling the shape of the mattress during the night may allow minimization of the interference with comfort and the user’s sleep habits and increase user compliance.

Positional therapy, i.e. inducing the user to avoid the sleeping posture (usually supine) associated with worse snoring, has been suggested as a simple and effective approach to reduce both non-apneic snoring and treat OSAHS [70] [57] [45]. Recently, active devices able to monitor the user’s posture and provide positional therapy in an interactive way, have shown improved compliance and reduced disruptive effect on comfort and sleep with respect to traditional tennis ball therapy [71]. However, only triggering acoustic and vibratory stimulation on a wearable device when lying supine may also cause arousals and disrupt the user’s sleep [74]. Thus, alternative designs and interventions that are more compatible with a natural sleep environment should be investigated.

Within our project we decided to implement these two principles of postural intervention, i.e. trunk elevation and positional therapy, into a smart system, or a smart bed, able to monitor and detect snoring sounds and automatically adjust the shape of the mattress to influence the
sleeping posture of the user. Integration of sensors and actuators within the bed structure allows hardware characteristics and configuration to be controlled along with guaranteeing unobtrusive solutions compatible with a natural and comfortable sleep environment. Differently from mobile technologies, a fully actuated bed allows active adjustment of the mattress shape while the user sleeps on it (see section 1.1.3 for further details about smart system and applications on sleep). These functions may substantially increase the system’s effectiveness in influencing sleep posture compared with simply triggering acoustic, vibratory or electrical stimulation. Additionally, by continuous monitoring of the snoring activity, a smart bed would be able to intervene only when the user snores, minimizing the disruptive effect on sleep and avoiding affecting the user’s habits and comfort when no action is needed.

The platform chosen to implement the smart bed was an adjustable bed, featuring motorized change of mattress shape and vibratory stimulation underneath the head and foot area. The closed-loop modality was realized by equipping the bed with microphones and interfacing the bed with a computing unit running the control algorithms. First, this chapter presents the design of the smart bed including a detailed description of each hardware and software component. Then, a proof of function investigation was conducted on one regular snorer during seven nights (four without and three with postural intervention). Based on the data acquired during this investigation, a complete evaluation of the technical function of the smart bed and the applicability of the chosen approach is reported and discussed.

4.2 Setup

4.2.1 Requirements and architecture

The developed smart bed included: a controller to compare reference with current snoring activity and compute a command for the desired postural intervention; the adjustable bed to provide the intervention to the user; microphones to record snoring sounds; and the processing and analysis software to extract quantitative information on the user’s snoring activity from the raw acoustic recordings in real-time (Figure 4.1).

![Figure 4.1: Smart bed architecture.](image)

The design approach and the components of the smart bed have been chosen in order to fulfill the following requirements:

- **Requirement 1**: A comfortable and natural sleep environment during a whole night sleep;
- **Requirement 2**: Safety of the user during a whole night sleep;
- **Requirement 3**: The smart bed has to be equipped with an actuation system enabling influence of the sleeping posture of the user;
• **Requirement 4:** The smart bed has to be equipped with a monitoring system, allowing automatic quantification of the snoring activity in real-time;

• **Requirement 5:** Autonomous operation, i.e., postural intervention is controlled in a closed-loop manner, based on the output of the monitoring system.

The complete software has been implemented using MATLAB/Simulink® (R2014b, MathWorks, Natick, MA, USA).

### 4.2.2 Intervention and actuation

#### Adjustable bed

The main body of the system consisted of an adjustable bed (Ambience E-Motion, Elite SA, Aubonne, VD, CH; Figure 4.2), which was designed, developed and commercialized by Elite SA. This bed was equipped with four motors to adjust the position of head, back, legs, and feet of the user. Additionally, two vibro-motors located below the mattress area corresponding to the head and the feet provided massage and vibratory stimulation. The bed fulfilled high standards in terms of comfort, support, and thermal regulation. Thus, guaranteeing a comfortable and natural sleep environment for the user has been fulfilled (requirement 1). The actuation system allowed adaptation of the mattress shape as well as providing vibratory stimulation while the user is asleep. These features could potentially be used to influence the sleep posture of the snorer in an interactive way without waking up the subject. Additionally, the user is not forced to wear a device which may negatively influence comfort or interfere with natural sleep habits.

Serial communication protocol between the control laptop and the actuation system of the adjustable bed allowed reading the state of the bed in real-time as well as controlling the four motors and the two vibro-motors.

#### Intervention

With the chosen adjustable bed, two different strategies to influence the snorer’s posture could be applied:

• **Elevating head and trunk:** The actuators of the adjustable bed slowly change the mattress shape and lift the upper body of the snorer, influencing the effect of gravity on the upper airways (“direct influence”);

• **Inducing a posture change:** This approach is based on the concept of Positional Therapy. The actuators of the adjustable bed slowly change the mattress shape to a configuration that should be perceived as uncomfortable combined with vibratory stimulation. This condition should induce the subject to change their posture, e.g. by turning from supine to one side (“indirect influence”).

Studies suggest that both approaches could have a positive effect in reducing snoring and disturbed breathing (for details see section 1.1.2). However, little is known about what intervention parameters would be most effective and how an adjustable bed could be used for this purpose. Moreover, the effect of such a postural intervention controlled in closed-loop has not been yet investigated. The setup developed within the present thesis offers a wide spectrum of parametrizable postural interventions including different shapes of the mattress, different inclinations and elevations of head and trunk, and different vibration pattern.
4.2.3 Sensing

Microphones

Unobtrusive recording of snoring activity is commonly achieved by relying on microphones. Microphones being integrated within the sleep environment guarantee a minimal intrusion to the user and their sleep habits. The reliability of this method is proven by numerous existing applications in consumer technology [3] as well as in scientific literature [124]. Also medical devices used for home analysis of snoring and sleep disturbed breathing such as NOX-T3™ (Nox Medical, Reykjavik, Iceland) or Emblettas” (Embla, Broomfield, CO, USA) rely on microphones recordings. To guarantee a complete and reliable medical analysis, these devices include also physiological recordings such as breathing effort and airflow. Microphones require very little power and are cheap, simple, and small, which are fully compatible with both a natural sleep environment and the economical requirements of a commercial bed, made for home use. Microphones can be easily integrated into and hidden in the bed frame, without interfering with any aesthetic requirements of a high quality bed.

The implemented setup included small electret condenser microphones (POM-3535L-3-R, Pui audio, Dayton, USA). The recorded signals were first amplified, digitized and finally acquired on the control laptop through USB connection.

Microphone, electronics, and cabling were inserted in an aluminium profile mounted on the bed frame (Figure 4.3). The mounting support allowed the microphones to be positioned above the users' head, offering protection to the circuitry, as well as guaranteeing aesthetic compatibility with the environment.
Microphone placement

Two microphones were symmetrically mounted on the bed frame above the middle line of each side of the double bed, faced toward the center of the pillow area of the snorer and the bed partner, respectively (Figure 4.4). Two is the minimum number of microphones allowing discrimination of which side of the bed the noise is originating from. Source localization was computed by comparing the spectral energy of the signals provided by the two microphones (section 4.2.4).

Microphone calibration

In order to guarantee reliability of signal processing and classification algorithms and, particularly, the signal comparison used in the source localization approach, the two microphones were calibrated based on a reference signal. A Precision Acoustic Calibrator (CAL200, Larson Davis, PCB Piezotronics div., Depew, NY, USA) generating a 1 KHz signal at 94 dB was used. To avoid a ceiling effect a custom made acoustic damper was applied to the calibrator to reduce the signal’s amplitude to approximately 76 dB.

4.2.4 Snoring detector

The snoring detector algorithm included a set of operations to extract a quantitative measurement of snoring activity from the raw acoustic recordings. This process was divided into six steps:

- Filtering: Learning and removal of background noise;
- Events detection;
- Source localization;
4 A smart bed to influence sleeping posture and snoring

Figure 4.4: Microphone location. Microphone support mounted on the experiment setup. Because only one adjustable-bed is used, the second microphone has been placed at the position corresponding to the bed partner, according to the size of a double bed.

- Feature extraction;
- Classification;
- Quantification of snoring activity (snoring index)

The snoring detector was designed and optimized in order to guarantee: Real-time execution, adaptation to different snorers and different environment, and robustness in distinguishing snoring events from other acoustic happenings. A simple strategy resulting in “cheap” computation was preferred, in order to avoid complex, time consuming, and computationally expensive training procedures. In addition, a computationally cheap approach would facilitate the transition to a small computation unit that could be integrated in a future commercial version of the smart bed. Each step of the snoring detector is presented in details in the following sections. A complete description of the implemented algorithms is presented in appendix C.2.

Filtering: Learning and removal of background noise

The first step of the algorithm consisted of filtering the raw signal and removing the background noise. The raw signal \( y(t) \) recorded with the microphones can be modeled as the sum of the target signal \( s(t) \) and the background noise \( n(t) \) (additive noise). Assuming that the background noise remains stationary, its spectral characteristic could be estimated from the frames without particular acoustic activity (e.g. snoring, speech, noisy events). An estimation of the target signal \( \hat{s}(t) \) was then obtained by subtracting the estimate of the background noise spectrum from the noisy raw signal (spectral subtraction). The method proposed was based on the theory presented by Boll et al. [125] and was adapted from the MATLAB/Simulink® implementation of A. Behboodian [126].
4.2 Setup

Events detection

The second step consisted of identifying the fragments of the raw signal corresponding to acoustic events, distinguished from the background. Acoustic events were detected when the spectral energy of the signal overcame a defined threshold. After thresholding, the signal was reprocessed in order to: first, find the real boundaries of the event; second, merge the events that are too close to each other to be two distinct snoring episodes (distance between events < 0.2 s); and third, discard the ones that are too short or too long (event length > 3.5 s or event length < 0.2 s) be associated with snoring [124]. The algorithm was based on the approach presented by Dafna et al. [124], which was further developed and adapted to enable the real-time execution.

Source localization

The snoring detector was designed to be applied on a double bed, where up to two persons can sleep and snore at the same time. This condition required the algorithm to be able to identify from which side of the double bed the snoring sounds are coming from. The localization of the snoring source was performed by comparing the spectral energy of the signal recorded by the two microphones mounted on each side of the double bed (section 4.2.3).

Features extraction

To identify snoring among all detected acoustic episodes, each event was described by a set of quantitative features. Based on literature, 126 mathematical features were initially considered (Table [C.1]), describing 25 time related characteristics (i.e. periodicity, duration, energy) and 101 spectral characteristics (i.e. spectra models, bio-characteristics frequencies, dynamic frequency) of the detected event [124]. The features were calculated in a 24s-window surrounding the event (12 s preceding and following the event). The number of features used in the final implementation of the snoring detector were first reduced based on the computational requirements, removing all the features too computationally expensive to be calculated in real-time (section 4.2.5). Then, the feature space was further minimized through a training process, in order to optimize the classification performance based on experimental data (section 4.2.5).

Classification

In the final step of the snoring detector, the algorithm based on the feature vector $x_k$ to classify the event $k$ into “snoring” or “non snoring”. Recalling the general requirements of the snoring detector, real-time execution of the classification step had to be guaranteed with limited computational power. Additionally, the classifier had to adapt to different snorers and sleep environments without requiring expensive and complex training processes. Particularly, this adaptation had to be performed without requiring further manual labeling and supervised training.

Observing and analyzing the conditions characterizing a normal sleep environment, the following assumptions could be made:

- “Snoring” events occur repeatedly during the night;
- “Snoring” events are similar between each other (e.g. similar intensity, duration, periodicity);
- “Non-snoring” events are less frequent and occur sparsely during the night;
“Non-snoring” events can be very different between each other (e.g. very different intensities, duration, frequency distribution).

Based on these assumptions a potentially effective strategy is learning the characteristics of a repetitive pattern online. Assuming that the most repetitive acoustic events are associated with snoring, the classifier adapts online, learning to recognize the snoring events. The main limitations of the approach appear when no snoring occurs or in presence of other repetitive events (e.g. loud cars regularly passing by, regular alarm-like sounds). Absence of snoring was addressed by setting a low limit to the adaptive threshold (see event detection algorithm, section C.2), preventing the algorithm from adapting to very low intensity acoustic events. Additionally, snoring activity was detected only in the presence of repetitive snoring (section 4.2.6), thus isolated false positives had no effect on the function of the system. Repetitive patterns presenting similar duration and periodicity as snoring are very unlikely in a normal sleep environment and were not considered in this first implementation.

Based on this idea two classification approaches were explored: adaptive boosting (AdaBoost) and a simple logic binary classifier based on fixed thresholds and adaptive normalization. Both these approaches presented simple implementation and low computational cost. In both cases, two distinct parts composed the classifier: an adaptive part and a pre-identified model (Figure 4.5). The adaptive part was updated at each iteration. This allowed the algorithm to learn the characteristics of the repetitive patterns online. The model was identified offline based on manually labeled training data. Based on this principle, five classifier designs were explored, the details are presented in the following sections.

**Figure 4.5: Classifier design.** The flow chart visualizes the two parts of the classifier: the adaptive normalization and the pre-identified model.

*AdaBoost standard (CL1)*

AdaBoost (Adaptive Boosting) is the most common boosting algorithm [127]. Boosting bases on the principle that a combination of multiple base or weak classifiers results in better performance compared to each single weak classifier. This guarantees good results also when each weak classifier is only slightly better than random [127]. The final classification rule is obtained as a weighted linear combination of the weak ones, where the weights $\alpha_m$ are optimized on a training dataset.
4.2 Setup

Classifier design CL1: Standard AdaBoost (based on [127])

1. Initialization: All weighting coefficients $w_n^{(1)}$ are initially set to $w_n^{(1)} = 1/N$, where $N$ is the number of data points.

2. Base classifiers: $M$ base classifiers are fit to the training data to minimize the weighted error $J_m$

$$J_m = \sum_{n=1}^{N} w_n^{(m)} I(y_m(x_n) \neq t_n)$$

(4.1)

where the indicator function $I(y_m(x_n) \neq t_n)$ is equal to 1 when $y_m(x_n) \neq t_n$ and to 0 otherwise and $t_n$ is the reference label. $y_m(x_n)$ is the label predicted by the $m^{th}$ weak classifier and is calculated as follows

$$y_m(x_n) = \begin{cases} 1 & \text{if } d_m x_{n,i} \geq d_m t_h, \\ -1 & \text{otherwise} \end{cases}$$

(4.2)

where direction $d_m = \{-1, 1\}$, threshold $t_h$, and feature index $i$ correspond to the classification rule that minimizes $J_m$. A weight $\alpha_m$ is calculated for each base classifier as a function of the resulting classification error $\epsilon_m$

$$\epsilon_m = \frac{J_m}{\sum_{n=1}^{N} w_n^{(m)}}$$

(4.3)

$$\alpha_m = \ln \left( \frac{1 - \epsilon_m}{\epsilon_m} \right)$$

(4.4)

The weighting coefficients $w_n^{(m)}$ are finally updated, amplifying the misclassified data points.

$$w_n^{(m+1)} = w_n^{(m)} \exp(\alpha_m I(y_m(x_n) \neq t_n))$$

(4.5)

3. Online classification: The final classification prediction is given by the sign of the weighted sum of the $M$ weak classifiers

$$y_{pred,k}(x_k) = \text{sign} \left( \sum_{m=1}^{M} \alpha_m y_m(x_k) \right)$$

(4.6)

AdaBoost with adaptive normalization (CL2 and CL3)

One limitation of the classical AdaBoost approach is that the thresholds of the weak classifiers are optimized on the training set. A change in the signal (e.g. different snorer) can influence the value of the features and considerably affect the classification performance. This problem was solved by training the classifier to identify the features that differ the most between the classes, independently from their absolute value. This was achieved through an adaptive normalization step. The algorithm was based on the assumption that the occurrence of “snoring” is much higher than the occurrence of other acoustic events. Moreover, “snoring” events present similarities between each other, while “non snoring” events could include many different acoustic episodes.

Based on this assumption, a model of the snoring event can be learned from a sufficiently big set (or buffer) of detected events. The model is thus calculated and updated online by analyzing the sample distribution of the features extracted from $N$ events or data points. Two different analysis
approaches were tested: first, the normalization parameters $\mu$ and $\sigma$ were extracted from a Gaussian model fitted on the features’ distributions (CL2); second, $\mu$ and $\sigma$ were calculated from the quartiles (i.e. 25%, 50%, and 75% percentiles) of the features’ distributions (CL3). The performance of the first method depends on how well the real distributions approach a Gaussian shape. The second model does not depend on the shape of the distribution, but detects and discards the data points considered as outliers.

Classifier design CL2 and CL3: AdaBoost with adaptive normalization

1. Normalization parameter: The normalization parameters are calculated from the training dataset $X_{\text{train}} = x_1, \ldots, x_N$ based on the features’ distribution. Two normalization approaches were investigated:

   A) Gaussian model (CL2): The normalization parameters $\mu$ and $\sigma$ are extracted from a Gaussian model fitted to the features’ distribution:

   \[
   g_m(x) = \frac{1}{\sigma_m \sqrt{2\pi}} \exp\left(-\frac{1}{2} \left( \frac{x_m - \mu_m}{\sigma_m} \right)^2 \right)
   \]

   where $\mu = (\mu_1, \ldots, \mu_M)^T$ (4.8)

   \[
   \sigma = (\sigma_1, \ldots, \sigma_M)^T
   \]

   B) Quartiles-based normalization (CL3): The normalization parameters are calculated based on the quartiles of the features’ distribution:

   \[
   \mu = \text{median of } X_{\text{train}}
   \]

   \[
   Q1 = \text{first quartile (25% percentile) of } X_{\text{train}}
   \]

   \[
   Q3 = \text{third quartile (75% percentile) of } X_{\text{train}}
   \]

   \[
   \sigma = \frac{Q3 - Q1}{2}
   \]

   The normalized dataset $\tilde{X}_{\text{train}}$ is so obtained as

   \[
   \tilde{x} = \frac{x - \mu}{\sigma}
   \]

   where $\mu$ and $\sigma$ are two M dimensional vectors containing the normalization parameters for all M features.

2. After normalization the AdaBoost classifier is trained as shown in the standard AdaBoost (CL1), steps 1.-2.

3. Online classification: Before applying the classifier, the features vector $x_k$ is normalized analogously to step 1. To enable online execution of the algorithm, the features’ distributions are calculated from a circular buffer $X_{\text{buff},k} = (x_k - N_{\text{buff}} + 1, \ldots, x_k)$ storing $N_{\text{buff}}$ feature vectors corresponding to the $N_{\text{buff}}$ previously detected events. The online normalization parameters $\mu_k$ and $\sigma_k$ are then calculated as in step 1. The final label prediction is given by the sign of the weighted sum of the M weak classifiers applied to the normalized features vector $\tilde{x}_k$

   \[
   y_{\text{pred},k}(\tilde{x}_k) = \text{sign} \left( \sum_{m=1}^{M} \alpha_m y_m (\tilde{x}_k) \right)
   \]

   where buffer length $N_{\text{buff}}$ and classifier complexity $M$ are design parameters, which have to be defined during the training phase based on experimental data.
Fixed threshold with adaptive normalization (CL4 and CL5)

In a second approach, a simple threshold based binary classification was implemented. The classification rule assigned the label based on the distance of the feature vector from the modeled “snoring” event. The parameters of the classification rule were identified as described in the previous section, by analyzing the features’ distribution among a buffer of \( N \) previously detected events. As for the AdaBoost with adaptive normalization, two different strategies were evaluated: the Gaussian model (CL4) and the quartile-based model (CL5).

**Classifier design CL4 and CL5: Fixed threshold with adaptive normalization**

1. **Normalization parameter:** The normalization parameters are calculated from the training dataset \( X_{\text{train}} = (x_1, \ldots, x_N) \) based on the features’ distribution. Two normalization approaches have been investigated:

   A) **Gaussian model (CL4):** The normalization parameters \( \mu \) and \( \sigma \) are extracted from a Gaussian model fitted to the features’ distribution:
   
   \[
   g_m(x) = \frac{1}{\sigma^m \sqrt{2\pi}} \exp\left\{ -\frac{1}{2} \left( \frac{x_m - \mu_m}{\sigma_m} \right)^2 \right\} 
   \]
   
   \( \mu = (\mu_1, \ldots, \mu_M)^T \) \hspace{1cm} (4.17)
   \( \sigma = (\sigma_1, \ldots, \sigma_M)^T \) \hspace{1cm} (4.18)

   B) **Quartile-based (CL5):** The normalization parameters are calculated based on the quartiles of the features’ distribution:
   
   \( Q1 = \text{“1st quartile (25% percentile) of } X_{\text{train}}” \) \hspace{1cm} (4.19)
   \( Q2 = \text{“median (50% percentile) of } X_{\text{train}}” \) \hspace{1cm} (4.20)
   \( Q3 = \text{“3rd quartile (75% percentile) of } X_{\text{train}}” \) \hspace{1cm} (4.21)
   \( \mu = Q2 \) \hspace{1cm} (4.22)
   \( \sigma = \frac{Q3 - Q1}{2} \) \hspace{1cm} (4.23)

   The normalized dataset \( \hat{X}_{\text{train}} = (\hat{x}_1, \ldots, \hat{x}_N) \) is so obtained as
   
   \[
   \hat{x}_n = \frac{x_n - \mu}{\sigma} \quad \text{with} \quad n = 1, \ldots, N 
   \]
   where \( \mu \) and \( \sigma \) are two \( M \) dimensional vectors containing the normalization parameters for all \( M \) features.

2. **Online classification:** Before applying the classifier, the features vector \( x_k \) is normalized analogously to step 1. To enable online execution of the algorithm, the features’ distribution is calculated on a circular buffer \( X_{\text{buff},k} = (x_k, x_{k-N_{\text{buff}}+1}, \ldots, x_k) \) storing \( N_{\text{buff}} \) features vectors corresponding to the \( N_{\text{buff}} \) previously detected events. The online normalization parameters
\( \mu_k \) and \( \sigma_k \) are then calculated as in step 1. The final label prediction is obtained as follows:

\[
c(\tilde{x}_k) = \frac{1}{M} \sum_{m=1}^{M} I(\tilde{x}_k \leq \varepsilon)
\]

(4.25)

\[
y_{\text{pred},k}(\tilde{x}_k) = \begin{cases} 
1 & \text{if } c(\tilde{x}_k) > \delta \\
-1 & \text{otherwise}
\end{cases}
\]

(4.26)

where the buffer length \( N_{\text{buff}} \), the feature number \( M \), and the thresholds \( \varepsilon \) and \( \delta \) are design parameters, which have to be defined during the training phase based on experimental data.

### 4.2.5 Classifier training

**AdaBoost-based classifiers (CL1, CL2, and CL3)**

The AdaBoost model composed of thresholds \( \mathbf{th} = (th_1, ..., th_M) \), directions \( \mathbf{d} = (d_1, ..., d_M) \), coefficients \( \mathbf{\alpha} = (\alpha_1, ..., \alpha_M) \) and complexity \( M \) (i.e. the number of weak classifiers) was obtained through a training and optimization process performed on a set of manually labeled experimental data (supervised training). The standard AdaBoost training method [127] was applied to all three variations of the AdaBoost classifiers. The buffer length \( N_{\text{buff}} = 500 \) of the online adaptive normalization step was chosen based on a qualitative analysis of the classifier behavior.

---

**AdaBoost (training and model identification)**

1. **Training and validation** For \( n = 1, ..., N \)
   a) Main dataset partition in “training/validation” and “testing” sets:
      \( X_n^A = \) “all recordings but \( n \)”;
      \( X_{\text{test}}^n = \) “recording \( n \)”;
   b) **Cross-validation** For \( k = 1, ..., K \)
      - Subset partition in “training” and “validation” sets:
        \( X_{\text{train}}^{n,k} = 75\% \) of “snoring”+75\% of “non snoring” events in \( X_n^A \), randomly sampled without repetition;
        \( X_{\text{val}}^{n,k} = \) remaining 25\% of events;
      - For model complexity \( m = 1, ..., M \)
        **Training**: Identify each AdaBoost model \( \text{model}_{n,k,m} \) on the training set;
        **Validation**: Calculate the classification performance by applying the obtained \( \text{model}_{n,k,m} \) on the validation set;

2. Analysis of the classification performance resulting from the training phase and identification of the model complexity \( m_{\text{test}} \), which guarantees maximal averaged performance \( \bar{p}_{\text{max}} \) (see following section classification performance);

3. **Testing** For \( n=1, ..., N \)
4.2 Setup

a) Re-Training: Retrain the Adaboost model on the whole dataset $X_n^A$ using complexity $m_{best}$;

b) Testing: Apply the obtained model on the testing dataset $X_n^{test}$;

4. Analysis of the classification performance resulting from the testing phase. Summarizing the results in the confusion matrix.

Fixed threshold-based classifiers (CL4 and CL5)

To reduce the classifier’s complexity, to improve its performance, and to avoid over-fitting, a feature selection algorithm was applied to reduce the features space. Features selection was conducted in two steps: first, the features were ranked based on ANOVA F-test statistics; second, a forward selection was performed on the sorted features to find the number of features resulting in highest classification performance [124].

The first step is defined as a parametric univariate filter [128], and is based on one-way ANOVA F-test statistics to quantify the efficacy of each feature in distinguishing between the two classes. Such efficacy is given by the F-score value, which represents the ratio between explained variance (or inter-class variance) and unexplained variance (or intra-class variance). High F-scores indicate high variance between the different classes and low variance within the same class, and correspond to features well suited to distinguishing between the two classes. The snoring detection was designed only to distinguish between “snoring” and “non snoring”. While the “snoring” class referred to a particular event with particular characteristics, the “non snoring” class could include many different acoustic events and thus it could be characterized by high intra-class variance. Thus, F-score was calculated considering only the “snoring” class. With this adjustment, the approach evaluated how a feature was effective in distinguishing “snoring” from the rest, without penalizing the F-score when very high variance was observed in the “non-snoring” class. The features were finally ranked from highest to lowest F-score. The detailed algorithm is presented in the appendix (section C.3). The classifier parameters $\delta = 1.5$ and $\epsilon = 0.5$ and the buffer length $N_{buff} = 500$ of the online adaptive normalization step were chosen based on a qualitative analysis of the classifier behavior.

In the second step, the performance of the classifier was evaluated for the first $m$ features selected from the ranked features vector, for $m = 1, ..., M$ (where $M$ is the total number of features). The optimal feature number $m_{best}$ corresponds to the lowest complexity resulting in highest performance.

Fixed threshold (training and model definition)

1. **Training and validation** For $n = 1, ..., N$
   a) Main dataset partition in “training/validation” and “testing” set:
      $X_n^A$ = “all recordings but n”;
      $X_n^{test}$ = “recording n”;
   b) **Cross-validation** For $k = 1, ..., K$
A smart bed to influence sleeping posture and snoring

• Subset partition in “training” and “validation” set:
  
  \[ X_{n,k}^{\text{train}} = 75\% \text{ of “snoring”} + 75\% \text{ of “non snoring” events in } X_n^A, \text{ randomly sampled without repetition; } \]
  
  \[ X_{n,k}^{\text{val}} = \text{remaining 25\% of events}; \]

• Training: Features ranking based on their efficacy in distinguishing between “snoring” and “non snoring” events (see features ranking algorithm, section [C.3]).

• Validation for different model complexities \( m = 1, \ldots, M \):
  Validate classification performance by using only the first \( m \) features of the ranking obtained in the training phase;

2. Analysis of the classification performance resulting from the training phase and identification of the model complexity \( m_{\text{best}} \), which guarantees maximal averaged performance \( \bar{p}_{\text{max}} \) (see next section classification performance);

3. Testing For \( n=1,\ldots,N \)
   a) Re-Training: Recompute features ranking on the whole dataset \( X_n^A \);
   b) Testing: Apply the classifier on the test dataset \( X_n^{\text{test}} \) using the first \( m_{\text{best}} \) features of the ranking obtained in the re-training phase;

4. Analysis of the classification performance resulting from the testing phase. Summarizing the results in the confusion matrix.

Classification performance

The classification performance was calculated by comparing the reference labels (resulting from manual inspection of the microphone recordings) with the labels assigned by the classifier. The whole performance is completely described in the confusion matrix (Table 4.1 and Table 4.2). To enable the optimization process, the global classification performance was summarized in a single value \( \bar{p} \) obtained as the average of accuracy, sensitivity, and specificity.

<table>
<thead>
<tr>
<th>Predicted (rates)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ S ]</td>
</tr>
<tr>
<td>True</td>
</tr>
<tr>
<td>[ NS ]</td>
</tr>
</tbody>
</table>

ACC, GLOBAL, PREV

Table 4.1: Confusion matrix. General example of confusion matrix, all definitions are described in Table 4.2. The confusion matrix reports a comparison between manual labeling (True) and automatic labeling (Predicted) of “snoring” (S) and “non snoring” (NS) events. The confusion matrix reports the values normalized with respect to the total number of true “snoring” and “not snoring” events (see Table 4.2).
4.2 Setup

4.2.6 Controller

Snoring index

Snoring activity was quantified by the SI, i.e. the number of snoring events per unit of time. The snoring index $SI_k$ was calculated on the 2-minute time window preceding $t_k$ and updated every time step.

$SI_k = \sum_i I(t_{\text{event},i} > t_k - T_{\text{SI}})$

where $I(.)$ is the indicator function.

1. The snoring index $SI_k$ is calculated in the 2-minute time window ($T_{\text{SI}} = 120s$) preceding the current time $t_k$.

2. Measurement noise and jittering caused by misclassification are reduced by applying a low-pass moving average filter (filter window of 30 s).

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Total number of data points</td>
<td>$-$</td>
</tr>
<tr>
<td>TPR/SENS</td>
<td>True positive rate (sensitivity)</td>
<td>$\frac{TP}{TP+FN}$</td>
</tr>
<tr>
<td>FNR</td>
<td>False negative rate</td>
<td>$\frac{FN}{TP+FN}$</td>
</tr>
<tr>
<td>FPR</td>
<td>False positive rate</td>
<td>$\frac{FP}{TN+FP}$</td>
</tr>
<tr>
<td>TNR/SPEC</td>
<td>True negative rate (specificity)</td>
<td>$\frac{TN}{TN+FP}$</td>
</tr>
<tr>
<td>ACC</td>
<td>Accuracy (fraction of N)</td>
<td>$\frac{TP+TN}{TP+FP+TN+FN}$</td>
</tr>
<tr>
<td>PREV</td>
<td>Prevalence (number of “S” labels expressed in fraction of N)</td>
<td>$\frac{1}{N} \sum I(y_{\text{true}} = S)$</td>
</tr>
<tr>
<td>GLOBAL</td>
<td>Single value summarizing the global classification performance</td>
<td>$\frac{1}{4}(ACC + SENS + SPEC)$</td>
</tr>
</tbody>
</table>

Table 4.2: Confusion matrix definitions.

Control approach

A simple logic controller based on the state of the user was applied. The state of the user was set to “SNORING” or “NO SNORING” depending on the SI. A double threshold was used to prevent continuous jumps between the two states. Depending on the state of the user the bed was moved to a set of predefined configurations. In the experimental phase presented in section 4.3.
three bed configurations were chosen: “FLAT” (P0), “ELEVATION 1” (EL1), “ELEVATION 2” (EL2). Five minutes waiting time was set after each action, allowing the user to adapt to the new configuration. The reference position was sent from the control program to the low-level controller of the adjustable bed, which actuated the motors until the desired configuration was reached. The control algorithm is visualized in Figure 4.6.

4.3 Experimental phase: Proof of function and applicability

4.3.1 Aim

The smart bed was tested with one human subject to obtain a first insight into functioning, applicability, and effects of the developed approach. The first aim of the conducted investigation was proving function and applicability of the system when applied in realistic conditions, i.e. involving a human subject (regular snorer), application during a whole night’s sleep, intervention controlled in closed-loop. The second aim was collecting real data to tune and optimize the snoring detection algorithms and the control strategy. Finally, the conducted experiment aimed to provide a first impression about which effects the chosen postural intervention has on the subject. An evaluation of the subjects’ sleep was beyond the goals of the conducted experiments. Thus, no physiological measurements and no quantitative assessment of sleep characteristics were performed. This allowed minimizing the interference with natural sleep to be minimized.

4.3.2 Protocol and subject

The investigation was conducted with one single subject. The subject reported himself as a regular snorer, without knowledge of any particular sleep disordered breathing such as sleep apnea. A dedicated room was set up for the investigation at the SMS Lab at the ETH. No particular time constraints were imposed in order to respect the usual rhythm and habits of the subject. The main experimental phase included a total of six nights. The subject’s adaptation to the experimental environment, and evaluation of the experimental conditions (i.e. light, temperature, acoustic noise,...) were performed during the first four nights, when no intervention was provided. This first phase allowed collecting data and testing the performance of the snoring detection algorithm. After the adaptation phase, the closed-loop capability of the smart bed and the impact of the postural intervention were tested during two intervention nights. Based on the results observed during the two intervention nights, a seventh experiment night was performed using a different postural intervention. This additional night is discussed separately in section 4.4.5.

4.3.3 Intervention

During the intervention nights, the bed was controlled to three configurations “FLAT” (P0), “HEAD UP” (P1), “TRUNK UP” (P2), depending on the detected snoring activity (section 4.2.6, Figure 4.6). Configuration P0 corresponded to the normal flat mattress used in the nights without intervention. Configuration P1 implied maximal elevation of the head section of the adjustable bed. Configuration P2 corresponded to an elevation of the trunk section by approximately 4.8 deg (Figure 4.7).

In the additional experiment conducted during the seventh night, a greater trunk elevation intervention was tested. The same control approach and the same two-step strategy used in the previous two intervention nights were applied. Differently from the original intervention, the first
4.3 Experimental phase: Proof of function and applicability

Figure 4.6: Control algorithm. Visualization of the control strategy applied during the experimental phase presented in section 4.3. The bed is controlled to three pre-defined positions P0, P1, and P2 depending on the SI calculated online by the snoring detector. $TH_{up}$ and $TH_{down}$ defines the double threshold strategy: the user state is changed to from “NO SNORING” to “SNORING” when SI overcome $TH_{up}$ and is set back to “NO SNORING” when SI descend below $TH_{down}$. $t(P0)$, $t(EL1)$, and $t(EL2)$ refer to the elapsed time after the bed has been moved to P0, “ELEVATION 1”, and “ELEVATION 2” respectively.
step elevated the trunk by approximately 5 deg (corresponding to the second intervention step P2 of the first investigation) and the second step elevated the subject’s trunk by approximately 21 deg (P3). Table 4.3 summarizes the applied interventions.

<table>
<thead>
<tr>
<th>Measurement ID</th>
<th>Initial position</th>
<th>Elevation 1</th>
<th>Elevation 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>5, 6</td>
<td>Flat (P0)</td>
<td>Head elevation (P1)</td>
<td>Trunk elevation +5 deg (P2)</td>
</tr>
<tr>
<td>7</td>
<td>Flat (P0)</td>
<td>Trunk elevation (P2)+5 deg</td>
<td>Trunk elevation +21 deg (P3)</td>
</tr>
</tbody>
</table>

Table 4.3: Intervention. Details about the postural intervention applied during the main exploration (meas ID=5, 6) and in the single night extension test (meas ID=7).

Figure 4.7: Intervention. Bed configurations “FLAT” (P0), “HEAD UP” (P1), and “TRUNK UP” (P2) used in the main experimental phase (meas ID= 5, 6). Bed configurations “FLAT” (P0), “TRUNK UP” (P2), and “TRUNK UP 2” (P3) used in the additional experiment night (meas ID= 7).

4.3.4 Experiment setup

The experiment room consisted of a closed office with a big window, with size and characteristics compatibles with a normal bedroom (Figure 4.8). The room was adapted in order to meet temperature, acoustic, and light conditions of a natural and comfortable sleep environment. Shade and curtains guaranteed darkness and privacy during the whole duration of the experiment. The experiment was performed during the night, when no people were working in the lab or in the building. This guaranteed a quiet environment compatible with natural sleep conditions.

The experiment was performed using a single smart bed (section 4.2) equipped with two microphones. One microphone was placed above the subjects’ head and the second one in the position corresponding with the second side of a double bed (i.e. corresponding to the bed partner’s location). Comfort was guaranteed by a high quality mattress (Concerto, Elite SA, Aubonne, VD, CH). In order guarantee a natural condition and minimize interference with the subject’s habits, the subject was allowed to use his own pillow.

The measurement setup was completed by an USB IR camera and a Sound Level Meter (XL2 Acoustic and Audio Analyzer, NTI Audio AG, Schaan, Liechtenstein) to provide reference data (Figure 4.9). The IR camera was pointed to the bed and used to acquire information on sleeping posture, movements, and reaction of the subject to the provided intervention. The XL2 analyzer provided high quality audio recording, acoustic analysis tools, and absolute measurement of the sound level.

Being a commercially available product, neither the bed itself nor the actuation system presents any particular risk for the user. The only safety aspect to be considered was that the smart bed
4.3 Experimental phase: Proof of function and applicability

Figure 4.8: Experiment room. Experiment setup at the SMS Lab including the adjustable bed equipped with two microphones and the system PC running the snoring detection and the control algorithms. An IR camera and a Sound Level Meter were used to acquire reference acoustic recordings and to monitor the subject’s posture and behavior during the experiments.

Figure 4.9: Reference measurement devices. Left: XL2 Acoustic and Audio Analyzer. Right IR USB camera.
moves autonomously, while the subject sleeps. Thus, in order to prevent the user’s limbs from getting caught or squeezed between moving parts an elastic cover was placed above the moving structure and fixed on the bed frame.

4.4 Results and discussion

4.4.1 Manual scoring

Snoring

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
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<td>22:44</td>
<td>07:14</td>
<td>8.51</td>
<td>2.06</td>
<td>24</td>
<td></td>
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</tr>
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<td>07:10</td>
<td>7.38</td>
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<td>21</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>P1/P2</td>
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<td>07:14</td>
<td>7.68</td>
<td>3.54</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>P1/P2</td>
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<td>07:14</td>
<td>7.34</td>
<td>1.53</td>
<td>21</td>
<td></td>
</tr>
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<td>Mean</td>
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<td>2.06</td>
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</tr>
<tr>
<td>SD</td>
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<td>00:05</td>
<td>0.45</td>
<td>0.69</td>
<td>0.09</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4: Summary table. Experimental phase.

The acoustic recordings have been manually inspected to identify and report periods of snoring and other acoustic episodes (e.g. subject movements, vehicles). Because of the absence of information on respiratory activity, snoring has been scored only based on acoustic characteristics. This method allowed clear identification of periods of evident and loud snoring sounds. Standard scoring methods applied on a complete set of physiological recordings would significantly improve the quality of the results and is strongly suggested for future studies. However, for the proof of function presented in this thesis, the information guaranteed by acoustic recordings has been considered as sufficient. This allowed significant simplification of the measurement setup and minimization of the interference with comfort and natural sleep. Snoring occurred every night and particularly during the first half of the experiment time. Except for one night when the subject snored significantly more (46% of the experiment time), snoring appeared constantly in 21-24% of the experiment time (Table 4.4, Figure 4.10). Experimental time refers to the time from light off at night, to the subject’s wake up in the morning.

Sleeping posture

As widely discussed, sleeping posture has an important effect on snoring. Additionally, depending on the sleeping position of the subject, the same intervention could have different consequences. Thus, monitoring and analyzing the subject’s posture during the experiment was crucial. This information was obtained through manual inspection of the IR camera recordings. Because of technical issues, no camera recordings are available for two of the conducted experiments (experiment night 1 and 4), whose data are not included in the following analysis. During the remaining four scored nights, the subject slept mostly supine (mean=53%, SD=10%), followed by side sleep (mean=33%, SD=6%) and ventral position (mean=12%, SD=10%) (Figure 4.11). As expected, the subject snored almost only when sleeping supine (mean=90%, SD=8%, Figure 4.11).
4.4 Results and discussion

**Figure 4.10: Snoring time.** Comparison between snoring time and total experiment time. The plot visualizes the data for all six experiment nights divided into “NO intervention” and “intervention” conditions.

**Figure 4.11: Snoring and sleeping posture.** Time spent by the subject in the different sleeping postures. Each sleeping posture “supine” (red), “side” (green), and “ventral” (blue), is divided in “snoring” (dark) and “non snoring” (light) fractions. Recordings 2 and 4 have not been reported because of the missing camera recordings.
4.4.2 Evaluation of the snoring detector performance

Background noise removal

The spectral subtraction filter was very effective in removing the background noise from the signal and generated a significant increase in the signal to noise ratio (SNR) (Table 4.5, Figure 4.12). Particularly, the approach provided high damping of the “unvoiced frames” (i.e. portion of the signal characterized by background noise) with only little attenuation of the “voiced frames” (i.e. portion of the signal characterized by snoring or other noisy episodes). The progressive increase of SNR (before filtering) observable between measurement 1 and measurement 5 and 6 is due to a progressive improvement of the microphone mounting. Because no closed-loop intervention was applied during the first four nights, such hardware changes did not affect the results of the investigation.

<table>
<thead>
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<th>SNR after filtering [dB]</th>
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</thead>
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<td>13.64</td>
</tr>
<tr>
<td>2</td>
<td>-0.03</td>
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</tr>
<tr>
<td>3</td>
<td>0.31</td>
<td>10.02</td>
</tr>
<tr>
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</tr>
<tr>
<td>Mean</td>
<td>1.09</td>
<td>11.84</td>
</tr>
<tr>
<td>SD</td>
<td>1.14</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Table 4.5: Background noise removal. Signal to noise ratio (SNR) before and after background noise removal.

Figure 4.12: Background noise removal. Example plot showing a comparison between raw and filtered recordings acoustic recordings in presence of snoring.
4.4 Results and discussion

Classification performance

The data acquired during five experiment nights (measurement ID=2, 3, 4, 5, 6) were used to train and evaluate the five classification approaches presented in section 4.2.4. The first experiment night (measurement ID=1) was excluded because of high measurement noise due to the mounting of the microphones. The model parameters of each classification approach were optimized based on a training dataset. The performance of the resulting models was then evaluated on a test dataset, represented by one whole night recording not included in the training set. This approach allowed exploration of the robustness and the performance of the classifier when applied in real-time, and no data of the current night could be used for training. Moreover, testing the classification performance on one full night, and not simply on a pool of randomly chosen data points, allowed analysis of adaptation and learning capability of the implemented classifiers. The same procedure was repeated five times, iteratively selecting one different night as test set (see section 4.2.5 for details about the training process. For classifiers CL1, CL2 and CL3, at each iteration of the training phase, $M$ different AdaBoost models with complexity $m = 1, ..., M$ were identified on a fraction of the training set and evaluated on the remaining fraction. The procedure was repeated in a $k$-fold manner. This allowed analysis of how classification performance varied as function of the complexity, and identification of the optimal configuration. The approach implemented in classifiers CL4 and CL5 implied an adaptive normalization to be calculated online and fixed threshold parameters to be chosen a priori. The training phase was used to rank the features accordingly to their contribution in distinguishing “snoring” from “non snoring” events and, as for the AdaBoost approach, to analyze how the classification performance was influenced by the model complexity. In this case model’s complexity indicates the number of features selected for the classification process.

The results of the training phase are visualized in Figures 4.13-4.17 and in the corresponding confusion matrices Tables 4.6-4.10. For the classical AdaBoost classifier CL1, increasing the model complexity caused an improvement of accuracy and sensitivity accompanied by a progressive deterioration of specificity. This means that a highly complex model tends to classify most of detected events as “snoring”, progressively increasing the number of false positives. High values of accuracy also in the presence of low specificity, are due to the high prevalence of “snoring” data points (> 90%). The right-hand side of the confusion matrices report values normalized by the total number of the corresponding events, giving better information on the classification performance. Best global performance, calculated as the average between accuracy, sensitivity, and specificity, was obtained for complexity = 28 (global perf.=0.89 (0.02), accuracy=0.94 (0.01), sensitivity=0.96 (0.02), specificity=0.76 (0.08), Figure 4.13, Table 4.6). This optimal complexity was then used in the testing phase. The testing phase resulted in similar classification performance compared to the training phase (global perf.=0.87 (0.03), accuracy=0.93 (0.03), sensitivity=0.95 (0.02), specificity=0.74 (0.07), Table 4.6). This suggested high robustness of the approach when applied to new datasets (intra-subject robustness). However, because only one single subject was tested, no information on the inter-subject robustness of the classification approach is available.

In both AdaBoost methods combined with adaptive normalization CL2 and CL3, the classification performance seemed to stabilize above a complexity of approximately 15. CL2 showed higher capability of properly identifying “non snoring” events balanced by lower, and highly varying, accuracy and sensitivity (Figure 4.14). The opposite behavior was observed in CL3, which generally guaranteed better results compared to CL2 (Figure 4.15). Best global performance was observed for CL2 and CL3 with complexity equal to 4 (global perf.=0.83 (0.03), accuracy=0.84 (0.04), sensitivity=0.85 (0.05), specificity=0.80 (0.05)) and 25 (global perf.=0.88 (0.02), accuracy=0.90 (0.03), sensitivity=0.90 (0.03), specificity=0.84 (0.04)), respectively. These parameters were used in the testing phase. As opposed to the standard AdaBoost approach, higher variability in the results and a globally worse performance was observed in the testing phase when compared to the training phase (CL2: global perf.=0.73 (0.11), accuracy=0.72 (0.15), sensitivity=0.72 (0.16), speci-
**Figure 4.13: Training and testing CL1.** Classification performance calculated for classifier design CL1 (standard AdaBoost). The plot visualizes the results of the training phase as function of the model complexity. Accuracy (red), sensitivity (blue) and specificity (green) are reported as mean±standard deviation. Global performance is plotted in black. The * indicate the results of the testing phase.

**Table 4.6: Confusion matrix CL1.** Confusion matrix summarizing the performance of the classifier CL1 (standard AdaBoost) resulting from the training and testing procedure described in section 4.2.4. Best model complexity resulting from training: \( m_{opt} = 17 \). Each value is reported mean and (SD), calculated on the five different test datasets.
ficity=0.77 (0.03), Table 4.7; CL3: global perf.=0.79 (0.04), accuracy=0.79 (0.07), sensitivity=0.79 (0.09), specificity=0.78 (0.11), Table 4.8). This behavior was probably due to the normalization process (see section 4.2.4). During training, the normalization parameters were calculated on the whole training set, while when applied online, the normalization parameters were calculated on a buffer of 500 detected events, which was updated online. This probably caused an overfitting effect, deteriorating the classification performance when the classifier was applied on a new dataset (intra-subject robustness). However, because only one single subject was tested, no information on the inter-subject robustness of the classification approach is available.

![Figure 4.14: Training and testing CL2. Classification performance calculated for classifier design CL2 (AdaBoost with Gaussian-based adaptive normalization). The plot visualizes the results of the training phase as function of the model complexity. Accuracy (red), sensitivity (blue) and specificity (green) are reported as mean±SD. Global performance is plotted in black. The * indicate the results of the testing phase.](image)

<table>
<thead>
<tr>
<th>Predicted (rates)</th>
</tr>
</thead>
<tbody>
<tr>
<td>True</td>
</tr>
<tr>
<td>S</td>
</tr>
<tr>
<td>NS</td>
</tr>
</tbody>
</table>

Acc.=0.72 (0.15), Global perf.=0.73 (0.11), Prev.=0.91 (0.04)

Table 4.7: Confusion matrix CL2. Confusion matrix summarizing the performance of the classifier CL2 (AdaBoost with Gaussian-based adaptive normalization) resulting from the training and testing procedure described in section 4.2.4. Best model complexity resulting from training: $m_{\text{opt}} = 4$. Each value is reported as mean and standard deviation (in brackets), calculated on the five different test datasets.

In the classification methods CL4 and CL5, the training phase was used to first, rank the features from most to least effective in distinguishing “snoring” from “non snoring” events, and second, to analyze the influence of model complexity on the classification performance. In this case, complexity indicates the number of features used in the classifier. CL4 showed poor performance
Figure 4.15: Training and testing CL3. Classification performance calculated for classifier design CL3 (AdaBoost with quartiles-based adaptive normalization). The plot visualizes the results of the training phase as function of the model complexity. Accuracy (red), sensitivity (blue) and specificity (green) are reported as mean±SD. Global performance is plotted in black. The * indicate the results of the testing phase.

<table>
<thead>
<tr>
<th>Predicted (rates)</th>
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<th>NS</th>
</tr>
</thead>
<tbody>
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<td>0.21 (0.09)</td>
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<tr>
<td>NS</td>
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<td>0.78 (0.11)</td>
</tr>
</tbody>
</table>

Acc.=0.79 (0.07), Global perf.=0.79 (0.04), Prev.=0.91 (0.04)

Table 4.8: Confusion matrix CL3. Confusion matrix summarizing the performance of the classifier CL3 (AdaBoost with quartiles-based adaptive normalization) resulting from the training and testing procedure described in section 4.2.3. Best model complexity resulting from training: $m_{opt} = 25$. Each value is reported as mean and (SD), calculated on the five different test datasets.
Results and discussion

characterized by very low specificity. In practice, this method tended to simply classify most of
the events as “snoring”, resulting in ineffective distinguishing of the different acoustic episodes.
Specificity was already low with low complexity and it deteriorated further when complexity was
increased (Figure 4.16). In the training phase, best global performance was obtained consider-
ing only the first three features (global perf.=0.83 (0.03), accuracy=0.94 (0.01), sensitivity=0.98
(0.00), specificity=0.56 (0.07)). Similar performance was obtained when same model complexity
was applied on the test set (global perf.=0.83 (0.02), accuracy=0.93 (0.01), sensitivity=0.96 (0.02),
specificity=0.60 (0.07), Table 4.9). Better performance was observed in CL5, where the quartile-
based adaptive normalization was applied. During training, for low complexity (approximately
< 20) good results were achieved for all accuracy, sensitivity and specificity (Figure 4.17). When
complexity increased, specificity deteriorated progressively, showing a similar behavior as observed
for CL4. Best global performance was obtained with complexity equal to 17 (global perf.=0.88
(0.02), accuracy=0.91 (0.01), sensitivity=0.91 (0.02), specificity=0.81 (0.05)). Accuracy and sen-
sitivity decreased when such complexity was applied in the testing phase (global perf.=0.81 (0.06),
accuracy=0.80 (0.06), sensitivity=0.80 (0.07), specificity=0.84 (0.09), Table 4.10). However, the
global performance resulting from the testing phase remained at a satisfactory level and a good
balance between sensitivity and specificity was achieved.

Figure 4.16: Training and testing CL4. Classification performance calculated for classifier design CL4
(fixed threshold with Gaussian-based adaptive normalization). The plot visualizes the results of the training
phase as function of the model complexity. Accuracy (red), sensitivity (blue) and specificity (green) are
reported as mean±SD. Global performance is plotted in black. The * indicate the results of the testing
phase.

The results of the training phase showed the standard CL1 as the best AdaBoost-based classifier
and CL5 as the best of the proposed alternative approaches. CL5 performed as an outlier remover,
classifying as “non snoring” those events that were at the margin of the features’ distributions, and
deviated the most from the most frequent events. The training phase was only used to select the
most effective features and to evaluate the role of complexity. Assuming that snoring occurs re-
peatedly, this strategy has the potential to be more flexible in adapting to different kinds of snoring
(e.g. intensities, frequency distribution, periodicity) than the AdaBoost approach. In the latter
approach, the thresholds and weights (section 4.2.4) were defined based on the training approach
and were highly dependent on the training data. In conditions deviating from the training data,
Figure 4.17: Training and testing CL5. Classification performance calculated for classifier design CL5 (fixed treshold with quartiles-based adaptive normalization). The plot visualizes the results of the training phase as function of the model complexity. Accuracy (red), sensitivity (blue) and specificity (green) are reported as mean±SD. Global performance is plotted in black. The * indicate the results of the testing phase.

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<th>Predicted (rates)</th>
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<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>0.96 (0.02)</td>
<td>0.04 (0.02)</td>
</tr>
<tr>
<td>NS</td>
<td>0.40 (0.07)</td>
<td>0.60 (0.07)</td>
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</tbody>
</table>

Acc.=0.93 (0.01), Global perf.=0.83 (0.02), Prev.=0.91 (0.04)

Table 4.9: Confusion matrix CL4. Confusion matrix summarizing the performance of the classifier CL4 (fixed treshold with Gaussian-based adaptive normalization) resulting from the training and testing procedure described in section 4.2.4. Best model complexity resulting from training: $m_{opt} = 3$. Each value is reported as mean and (SD), calculated on the five different test datasets.

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<tr>
<td>S</td>
<td>0.80 (0.07)</td>
<td>0.20 (0.07)</td>
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<tr>
<td>NS</td>
<td>0.16 (0.09)</td>
<td>0.84 (0.09)</td>
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Acc.=0.80 (0.06), Global perf.=0.81 (0.06), Prev.=0.91 (0.04)

Table 4.10: Confusion matrix CL5. Confusion matrix summarizing the performance of the classifier CL5 (fixed treshold with quartiles-based adaptive normalization) resulting from the training and testing procedure described in section 4.2.4. Best model complexity resulting from training: $m_{opt} = 17$. Each value is reported as mean and (SD), calculated on the five different test datasets.
4.4 Results and discussion

the classification performance could be severely affected. This behavior was confirmed when the two trained classifiers were tested online with a human faking repeated snoring-like sounds. CL5 seemed to adapt quickly and start properly classifying repetitive snoring-like sounds, while the AdaBoost-based approaches tended to classify most of the event as non-snoring. The conducted analysis suggests the classifier design CL5 (fixed threshold with quartiles-based adaptive normalization) as the most promising approach. Further tests involving different subjects are needed in order to both prove the reliability of these preliminary results and test inter-subjects robustness of the snoring detector.

Feature selection

Due to the available computational power, not all features could be calculated in real-time. Thus, in a first step the most computationally expensive features were removed, reducing the feature space dimension to 44. The number of features was further reduced during the training phase, by selecting only the most effective ones. In the AdaBoost based approaches (CL1, CL2, and CL3) this selection was a direct consequence of the training process. An AdaBoost model is trained in order to identify, at each iteration, the best feature and the best threshold to properly separate the two classes. Thus, depending on the chosen complexity (i.e. the number of iterations or number of base classifiers, section 4.2.4), only a defined number of most significant features is used in the final model. Concerning methods CL4 and CL5, the features were first ranked based on the ratio between inter- and intra-class variability applying an adapted ANOVA F-Test (section 4.2.4). Then, depending on the chosen complexity \( m \) (i.e. the number of features used for classification), only the first \( m \) ranked features were selected. The two approaches gave different results (Table 4.11). However, we could identify a group of features characterized by both high F-score and AdaBoost ranking, which were selected for more than two different approaches. Being selected through different methods, emphasized the role of those features, at least for the investigated subject. Further studies involving different subjects and different environmental conditions (e.g. different bedrooms, different neighborhoods and locations) are required to verify the robustness of the snoring detector.

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</tr>
<tr>
<td>88</td>
<td>DFT (4 moments of freq. distribution)</td>
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</tr>
<tr>
<td>13</td>
<td>Zero crossing rate (ZCR)</td>
<td>1, 2, 2</td>
</tr>
<tr>
<td>71</td>
<td>8-subband frequency distribution</td>
<td>11, 3, 3</td>
</tr>
<tr>
<td>68</td>
<td>8-subband frequency distribution</td>
<td>3, 8, 7</td>
</tr>
<tr>
<td>2</td>
<td>Rhythm period ±12s</td>
<td>3, 2, 9</td>
</tr>
<tr>
<td>89</td>
<td>DFT (4 moments of freq. distribution)</td>
<td>21, 16, 10</td>
</tr>
<tr>
<td>19</td>
<td>Volume density rate (VDR)</td>
<td>5, 19, 12</td>
</tr>
<tr>
<td>16</td>
<td>SNR</td>
<td>6, 4, 13</td>
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<tr>
<td>6</td>
<td>12s after (event’s normalized area)</td>
<td>17, 24, 17</td>
</tr>
<tr>
<td>91</td>
<td>DFT (4 moments of ampl. distribution)</td>
<td>8, 2, 13</td>
</tr>
<tr>
<td>70</td>
<td>8-subband frequency distribution</td>
<td>26, 8</td>
</tr>
<tr>
<td>1</td>
<td>Rhythm period ±6s</td>
<td>17, 11</td>
</tr>
<tr>
<td>12</td>
<td>Duration trimmed (95%)</td>
<td>6, 16</td>
</tr>
<tr>
<td>8</td>
<td>12s area division</td>
<td>19, 10</td>
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<tr>
<td>15</td>
<td>Energy intensity</td>
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<tr>
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<td>Pitch intensity (FFT)</td>
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<tr>
<td>3</td>
<td>Rhythm intensity ±6s</td>
<td>10, 23</td>
</tr>
<tr>
<td>4</td>
<td>Rhythm intensity ±12s</td>
<td>2, 12</td>
</tr>
<tr>
<td>66</td>
<td>8-subband frequency distribution</td>
<td>4</td>
</tr>
<tr>
<td>86</td>
<td>DFT (4 moments of freq. distribution)</td>
<td>5</td>
</tr>
</tbody>
</table>
4.4.3 Real-time, closed-loop, and safety

The performed investigation offered proof of the real-time function of the approach. Particularly, the system was effective in acquiring and processing the acoustic recordings online, during the whole night (approximately 8h) without accumulating time delays. Raw and model data were successfully stored for offline analysis and inspection. The closed-loop modality of the smart bed was proven during two test nights. The system was able to recognize the periods of snoring and automatically change the bed configuration accordingly to the implemented control algorithm (Figure 4.6). The control software had no direct control of the actuators, but it could only send a motion command to the low-level controller of the bed. This was the same as moving the bed using the original remote control. Thus, eventual communication or calculation errors could only cause a wrong movement at the wrong time or lead to an undesired configuration, and had no influence on movement velocities, accelerations, boundaries or other potentially dangerous factors. No unexpected events were observed during the conducted investigation and the safety of the user was guaranteed during the whole experiment.

4.4.4 Effects of the intervention

General impact

An evaluation of the effectiveness of the provided intervention was beyond our objectives. However, testing the system with a human subject in realistic conditions allowed collection of a first impression and preliminary information on the general impact of the chosen intervention.

After each of the nights with intervention, the subject described the experimental condition as natural and comfortable and did not report any disrupting effect on sleep quality or undesired arousals due to the provided intervention. The motion was consciously perceived by the subject only if it occurred at the very beginning or at the very end of the night, when the subject was probably still falling asleep or in light sleep. Otherwise, based on the reported feedback, the intervention was not even perceived by the subject. This is a very important and promising result, suggesting that the adjustable bed could be used to provide a postural intervention on sleeping snorers without waking them up.
However, this evaluation was only based on the subject’s feedback and no quantitative assessment of sleep quality was performed. Arousal are usually found together with movements. More movements are also generally present when changes between sleep stages occur. Thus, frequent movements and changes of sleeping posture might be an indicator of arousals and disturbed sleep. The number of posture changes was extracted from the camera recordings and compared between conditions with and without postural intervention. No clear difference between the conditions was observed (Figure 4.18). Comparable amounts of movements among the different conditions suggested that the postural intervention did not clearly perturb sleep. This outcome was in agreement with the subjective feedback.

However, without EEG recordings is not possible to reliably assess sleep quality. The impact of postural intervention an sleep architecture and sleep parameters should be further investigated in future studies involving polysomnography recordings.

![Occurrence of movements and posture changes](image)

**Figure 4.18: Movements.** Occurrence of posture changes and movements during night.

### Effects of intervention on snoring

As only one subject was investigated, a descriptive analysis was conducted to obtain a first insight on the impact of the provided intervention on snoring (Figure 4.19). The data acquired during the first intervention night (measurement ID=5) showed that after both head and trunk elevation, the subject continued snoring or restarted shortly after the intervention. The second intervention night (measurement ID=6) showed mixed results. After three out of the five “head elevation” interventions (P1) the subject stopped snoring. In a fourth case the subject stopped snoring only after the second step “trunk elevation” (P2). While in one case neither of the two intervention’s steps had an effect on snoring. In some cases, it appears that even though snoring occurred, no intervention was immediately applied. This happened when the calculated SI (i.e. number of snoring events detected per unit of time, section 4.2.6) did not reach the defined threshold “TH<sub>up</sub>” (see control algorithm Figure 4.6). During the conducted investigation, the SI was calculated based on conservative parameters, in order to apply postural intervention only when loud and continuous snoring occurred. More data and further experiment nights could allow fine tuning of such parameters, optimizing the snoring detection performance.

The impact of the intervention was further analyzed by comparing the total amount of snoring and duration of snoring periods between nights with and without intervention. The total amount of snoring was similar among all experiment nights (21-24% of the experiment time) except for a significantly higher occurrence observed in the first intervention night (46% of experiment time, measurement ID=5, Figure 4.10). We do not expect the intervention to increase snoring, thus the observed difference was probably caused by non reported external factors such as the medical condition of the subjects or his behavior during the days preceding the experiment night. A potential effect of the postural intervention could be the reduction of long periods of continuous snoring. This aspect was investigated by analyzing how the duration of snoring periods was
Figure 4.19: Effects of postural intervention. The two plots visualize the two experiment nights with postural intervention (P1/P2). The blue areas indicate the period of snoring detected through manual inspection of the acoustic recordings. The red line shows the bed configuration. In green is reported the sleeping posture of the subject categorized in “supine”, “side”, and “ventral” sleep.

distributed among the experiment nights. Similar duration distribution was observed in experiment nights with and without intervention (Figure 4.20). However, long periods of continuous snoring (duration > 30 min) occurred more often during nights without intervention (n=4) compared to the nights when postural intervention was applied (n=1).

The varying results and the limited amount of data did not allow strong conclusions to be made on the effects of either head or trunk elevation on snoring. However some results are promising and should be further investigated. The main reason of the leak of a clear effect could be the little amplitude of the chosen intervention. The head elevation was barely noticeable and the trunk elevation condition lifted the subject’s upper body only by few degrees (4.8 deg). These interventions were chosen in order to limit the impact on the subject’s comfort, while mainly evaluating the technical function of the system. Existing literature reporting trunk elevation as successful in reducing sleep disturbed breathing involved higher tilt angles ranging from 20 to 60 deg [67, 69]. The use of bigger angles should be considered in a future study. A single night test exploring the effects of bigger elevation angles is reported in section 4.4.5.

Effects of intervention on sleeping posture

In addition to investigating the direct effect that head and trunk elevation had on snoring, the second principle at the base of the developed system was using the actuated bed to induce the snorer to change posture. Thus, the impact of the intervention on sleeping posture was analyzed.

The behavior of the subject after each of the 26 times the bed configuration was changed during the two intervention nights (measurement ID=5, 6) was analyzed. We observed that only in five cases did the subject change posture in the first five minutes after the intervention occurred and that in 14
4.4 Results and discussion

Figure 4.20: Duration of snoring periods. The plot visualizes the duration of snoring periods. Periods shorter than 5 minutes were not considered. The figure compares the four nights without intervention (green) with the two nights with intervention (red).

cases the subject did not change position at all, before the bed was moved to a different configuration (measurement ID=5: tot bed configuration changes=14, posture change <5min=1(7.1%), no posture change=8(57.1%); measurement ID=6: tot bed configuration changes=12, posture change <5min=4(33.3%), no posture change=6(50%); Figure 4.21). This result suggested that the provided interventions did not have any direct effect on the subject’s posture. However, this principle has to be further investigated in a study involving enough subjects and condition nights to allow a proper statistical analysis. Moreover, the mattress configurations chosen for the conducted investigation were not designed to induce a posture change. The use of different shapes (e.g. lowering head and trunk or creating a concave mattress shape to make sleeping supine uncomfortable) and the addition of vibratory stimulation could lead to different results and is strongly suggested for future studies.

4.4.5 Extended exploration: Increased elevation angle

The preliminary results reported in the previous section showed no evident effects on either snoring or sleep posture caused by the provided postural intervention. A possible reason for this lack of effect could be a too low elevation angle. To obtain a first insight on this hypothesis, greater elevation angles have been tested during one single night with the same subject participating in the previous experiments.

As observed during the previous investigation, most of the snoring occurred during the first part of the night. During the additional experiment night (measurement ID=7) the subject snored for 8.34 h, corresponding to 16% of the total experiment time (Table 4.12, Figure 4.22).

<table>
<thead>
<tr>
<th>ID</th>
<th>Intervention</th>
<th>Experiment</th>
<th>Snoring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Bed time [hh:mm]</td>
<td>Up time [hh:mm]</td>
</tr>
<tr>
<td>7</td>
<td>P2/P3</td>
<td>22:50</td>
<td>07:10</td>
</tr>
</tbody>
</table>

Table 4.12: Summary table. Extended exploration with increased intervention amplitude.

Observing the occurrence of sleeping postures, the subjects slept mainly in supine position (54%) when most of snoring occurred (63%). However, differently from the previous experiment nights,
Figure 4.21: Posture change after intervention. The plot visualizes in blue the elapsed time after each change of bed configuration (e.g. head elevation (P0), trunk elevation (P1), and bed back to flat (P2)) until the subject actively changes his posture. In red are marked the interventions when no posture change occurred before the following intervention or the end of the experiment.

Figure 4.22: Snoring time. Comparison between snoring time and total experiment time. The plot visualizes the data for all seven experiment nights divided into “NO intervention”, “P1/P2 intervention”, and “P2/P3 intervention” conditions.
37% of snoring occurred when the subject slept on the side (Figure 4.23). As for the previous experiment nights, the subject did not report any disturbance due to the postural intervention. Furthermore, despite the elevation angle being significantly higher, the subject did not remark on this difference with respect to the previous experiments. Frequent movements and changes of sleeping posture during night might be an indicator of arousals and perturbed sleep. The amount of posture changes was extracted from the camera recordings. The analysis showed that none of the applied interventions clearly affected the amount of posture changes and movements observed overnight (Figure 4.24). Also when greater elevation angles are used, the results agreed with the subjective feedback, describing the intervention as not disturbing. However, eventual effects of the postural intervention on sleep quality and sleep architecture should be further investigated in future studies involving EEG recordings.

![Snoring and sleeping posture](image)

**Figure 4.23:** Snoring and sleeping posture Time spent by the subject in the different sleeping postures. Each sleeping posture “supine” (red), “side” (green), and “ventral” (blue), it is divided in “snoring” (dark) and “non snoring” (hell) fractions. Measurements 1 and 4 have not been reported because of the missing camera recordings.

![Occurrence of movements and posture changes](image)

**Figure 4.24:** Posture changes and movements. Comparison of occurrence of posture changes and movements between conditions without intervention (measurement ID=2, 3), conditions with P1/P2 intervention (measurement ID=5, 6), and increased intervention P2/P3 (measurement ID=7).

The distribution of snoring periods duration showed a reduced occurrence of long periods of snoring, compared to the previously tested conditions (Figure 4.25). Particularly, only one period above 15 min, and no long snoring periods above 30 min occurred.
Further analysis was performed by observing how the subject’s behavior changed during the night. Particularly, we focused on how snoring activity and sleeping posture varied after each change of bed configuration (Figure 4.26). The bed was moved six times. During the first period of detected snoring, both interventions steps P2 and P3 were applied without apparent effect on snoring. However, in all remaining interventions, the subject stopped snoring right after the bed moved to P2. This results are very promising and suggest that the applied intervention was able to directly influence and reduce snoring. The interventions’ effects on snoring appear more clearly in night 7 compared to nights 5 and 6. This supports the hypothesis that higher elevation angle was needed to be able to effectively affect snoring activity. However, one single night provides only a first insight and the observed behavior has to be verified with further investigations. As observed in nights 5 and 6, in some cases, it appears that even though snoring occurred, no intervention was immediately applied. Analogously, as discussed in the previous section, higher sensitivity could be reached by adjusting the control parameters (section 4.4.4).

As observed in the previous experiment nights, no intervention effects on the sleeping posture were observed. The evolution of the subject’s posture during the experiment night showed no relation with the bed configuration (Figure 4.27). Out of the 11 changes in bed configuration which occurred during night 7, only one time did the subject change posture right after the motion, while eight times (72.7%) the subject did not move at all until another intervention occurred or the experiment ended.

Figure 4.25: Duration of snoring periods. The plots visualizes the duration of snoring periods. Periods shorter than 5 minutes have not been considered. The figure compares the four nights without intervention (green) with the two nights with intervention (red).
4.5 Conclusions and outlook

This chapter presented a smart bed to monitor snoring and apply a postural intervention aiming to reduce it. The system was based on the principle that snoring activity strongly depends on sleeping posture. Consequently, intervening on the user by influencing his sleep posture could be a simple but effective approach to reduce snoring. This idea was developed by designing and implementing a research version of such a smart system, which consists of a commercially available adjustable bed completed by two microphones, one for each side of the double bed, and one laptop, interfaced with the microphones and with the bed, running the monitoring and control software. The software algorithms performed by real-time processing and analysis of the microphone recordings, automatic detection of snoring events and quantification of snoring activity, and closed-loop control of the adjustable bed. The adjustable bed allowed adaptation of the mattress shape as well as vibratory stimulation. The system was developed to explore the use of postural interventions to influence sleeping posture and snoring, aiming to prove the applicability of such an approach and to acquire a first insight into the impact the proposed intervention has on the user. Particularly, the objective of the project was to develop and explore the closed-loop modality of the smart bed, which allows each intervention to be applied without either waking up the snorer or requiring the action of another person (e.g. the bed partner).

The adjustable bed and the mattress used for the smart bed were high quality, commercially available bedding products, fulfilling the requirement of a comfortable, natural, and healthy sleep environment.

The control software of the smart bed could only send a motion command to the adjustable bed, and did not have direct access to the actuators. This was the same as controlling the bed through the original remote control, avoiding unexpected behavior of the hardware, such as potentially

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Figure 4.27: Posture changes after intervention. The plot visualizes in blue the elapsed time after each intervention (e.g. trunk elevation +4.8 deg (P2), trunk elevation +21 deg (P2), and bed back to flat (P0)) until the subject actively changes his posture. In red are marked the interventions when no posture changes occurred before the following intervention or the end of the experiment.

In summary, the greater trunk elevation angle tested in night 7 resulted effectively in stopping snoring in four out of the six provided interventions. Particularly, snoring stopped because of the elevation intervention, independently from the sleeping posture of the subject. This results, combined with the absence of any observed or reported negative effects on comfort and sleep quality, represent a very promising result. However, a single night and a single subject are not sufficient to allow strong conclusions. As for the outcome of the previous six night, the observed results have to be confirmed with further investigations, involving both higher numbers of nights and different subjects.
dangerous velocities and accelerations, also in case of communication or calculation errors. Additionally, the actuated structure of the adjustable bed was covered with an elastic textile, in order to prevent the user’s limbs from being caught between moving parts. These measures guaranteed the safety of the user, also when asleep and nobody was actively monitoring the smart bed.

The actuation system of the adjustable bed allowed automatic modification of the mattress shape while the subject was asleep. The results of the proof of function investigation suggested that such intervention could be applied without waking up the subject and without affecting either comfort or sleep quality.

The use of microphones allowed real-time monitoring and quantification of snoring activity in a contact-less way, minimizing any interference with the subject’s habits and guaranteeing a natural sleep environment. The processing algorithms allowed identification and classification of the snoring sounds. Based on the data collected during the experimental phase, the classification approach was further developed and evaluated. Five different classifier designs were implemented and compared. All strategies satisfied the requirements of simplicity and low computational cost. The analysis conducted on the available data showed promising performance in means of accuracy, sensitivity, and specificity for all the different methods, with value ranges from 60% to 95%. Best results in terms of good balance between accuracy (80%), sensitivity (80%), and specificity (84%) were obtained with a simple binary classifier characterized by a fixed threshold and an adaptive normalization based on the quartiles of the features’ distribution. However, the adaptability and the generalization of the developed approaches have to be evaluated and verified with different users and different environmental conditions. Moreover, the reference information needed for the supervised training of the classifiers was based only on the manual scoring of the acoustic recordings. The reliability of the scoring process could be improved by applying standard medical approaches for the analysis of snoring and sleep disturbed breathing, based on physiological recordings such as respiration effort and airflow. Such a method is strongly recommended for future studies.

The closed-loop modality of the smart bed was been successfully tested during three nights. During all nights, the system was able to identify the periods of clear and loud snoring and autonomously adapt the mattress shape to two predefined positions: head elevation (P1), and trunk elevation to two different inclination angles (P2=4.8 deg and P3=21 deg). No disrupting effects on either comfort or sleep quality were reported by the subject. This promising result supports the applicability of the chosen approach. However, this outcome is based only on the subject’s feedback and should be verified in further studies implying quantitative assessment of sleep and sleep quality (e.g. based on polysomnography).

Investigating the effectiveness of the developed interventions was beyond the thesis objective. In this first proof of function it was shown that the postural interventions had few or no evident effects on snoring and no effect on sleeping posture. The absence of clear effects on snoring was probably due to the fact that in both head and trunk elevations, the change of the mattress shape was too small. Thus, the use of higher elevation angles was explored in a single additional night. During this additional test, the user stopped snoring after four out of the six postural interventions, which occurred during the night. Despite the amplitude of the intervention being considerably higher compared to the previous experiments, the subject did not report any negative effect on either comfort or sleep quality. This preliminary result was very promising and should be investigated in future studies, involving different subjects and a greater number of nights. As observed in the previous investigation, even the greater inclination angle had no effect on sleeping posture. All chosen interventions were not designed to induce the subject to change sleeping posture, thus the results are not surprising. Using different configurations (e.g. lowering head and trunk or creating a concave mattress shape to make uncomfortable sleeping supine) and combining vibratory stimulation could be more effective in inducing a posture change and should be investigated as well in future studies.

The developed smart bed fulfilled all requirements concerning comfort, safety and function. Tech-
4.5 Conclusions and outlook

The technical function and applicability were proven within a single-subject investigation. The conducted experiments gave some promising first results, which should be further investigated in a proper scientific study, involving different subjects and sleep environments.
4 A smart bed to influence sleeping posture and snoring
5 General conclusions

Novel actuated platforms to investigate the impact of rocking movements on relaxation and sleep: A first insight and a test-bench for future studies

A bed platform actuated by a tendon-based robot (the M³ setup) was designed, developed, and successfully applied to investigate the effects of rocking movements on relaxation in healthy human subjects.

The complexity and flexibility of the M³ setup allowed a wide spectrum of 6 DOF trajectories. However, the acoustic impact, the size, and the complexity of system made the platform better suited to be applied in nap or relaxation studies rather than being used with sleeping subjects. At low speeds, smooth and precise motions can not really be guaranteed with the M³ setup. Therefore, the setup is not applicable to investigate slowly rocking movements. This platform is better suited for applications involving faster dynamics such as studies on motion sickness.

The M³ setup was applied to analyze the effects of rocking movements along six different axes (longitudinal, lateral, and vertical translation; longitudinal and lateral swing-like rotation; rotation on the vertical axis) on relaxation. None of the chosen rocking movements affected relaxation. A possible explanation is that the intervention time of five minutes might have been too short to show clear changes in the observed EEG features. The questionnaires suggested vertical rocking as the preferred motion, however, the answers varied significantly between the subjects, weakening the reliability of such an outcome. These results allowed neither confirmation of the role of vestibular stimulation in influencing relaxation, nor identification of which kind of stimulation had the highest potential in promoting relaxation.

However, this first investigation phase allowed identification of 1 DOF trajectories with amplitudes and frequencies below 15 cm and 0.3 Hz respectively, as a promising range of motions to be further investigated.

The experience gained with the M³ setup was considered while developing the two Somnomat rocking beds. The two devices were designed and successfully applied to investigate the effects of rocking movements on human sleep. Safety, applicability, function, and performance were evaluated and proven for both devices, which now represent valuable test-benches for further studies.

With a size similar to an hospital bed, the two rocking beds could easily be transported and set up in a sleep laboratory or in the bedroom of a standard apartment. The acoustic impact and limited smoothness of the movements were significantly improved compared to the M³ setup. An optimized mechanical design, quiet components, and the placements of the noisy electronics in a cabinet separated from the bed, gave a guarantee that the acoustic impact was compatible with the requirements of a healthy sleep environment.

The Somnomat rocking beds were successfully applied with 18 healthy human subjects to investigate the influence of rocking movements on sleep. Each subject had to choose the preferred movement out of five different proposed directions (longitudinal, lateral, and vertical translation; longitudinal and lateral swing-like rotation) and one out of two amplitude/frequency combinations. Most of the subjects perceived the chosen movements as comfortable and relaxing and preferred the nights with movements compared to the night without. Only two subjects preferred the night
without motion. No cases of motion sickness were reported in any of the subjects. Moreover, the results of the sleep study showed that sleep variables such as sleep efficiency or number of arousals and wakefulness during the night were comparable between the nights with and without stimulation. Therefore, any disruptive effect on sleep due to either the use of the devices or the applied movements could be excluded.

Neither motion of the bed nor electromagnetic components had an impact on the performed physiological recordings. Artifacts caused by motion of the electrode cables were avoided by mounting the recording system directly on the moving platform, thus minimizing the motion of the cables. Interference due to the electromagnetic fields generated by the powerful actuators was successfully prevented by shielding the measurement devices. In conclusion, the absence of motion sickness and disturbing effects on sleep quality along with the compatibility with physiological recordings proved that both the rocking beds and the chosen movements could be successfully applied with human sleep.

Despite the positive feedback reported by the subjects, quantitative analysis based on polysomnography showed no effects of rocking movements in promoting sleep. The absence of positive effects on the analyzed sleep parameters could be due to the fact that the subject population was composed essentially of young and healthy good sleepers. The effects of vestibular stimulation could be more visible on subjects who in normal condition are characterized by reduced sleep quality and efficiency such as the elderly. Moreover, vestibular stimulation was provided only until sleep onset or during the first two hours of the experiment night; different results may be observed when rocking movements are present during the whole night.

Based on the these results it was not possible to identify which kind of stimulation has the highest potential in promoting relaxation and sleep and should be implemented in the smart bed. However, the conducted investigation allowed the identification of a promising range of motions. The movements used in the sleep study were in fact rated as pleasant by most part of the subjects. Moreover, neither the provided movements nor the entire setup had any disrupting effects on sleep and normal and healthy sleep was observed for all subjects in all experimental conditions. The absence of negative effects combined with the positive subjective feedback suggest that the chosen movements are applicable and should be further investigated in future studies. In addition, these results support the applicability of the whole experiment setup.

Finally, the conducted experiments provided knowledge about the kind of actuation principle and technical solutions to be implemented in a rocking bed. Particularly, the belt transmission system used for the swing-like movements, guaranteed both a simple and successful design, which could be considered for the future smart bed.

**A first implementation of the smart-bed to investigate the effect of postural interventions on snoring**

The second part of the project was dedicated to the development of a first device that includes all the features of the smart bed idea: real-time monitoring of the user state, closed-loop control of the system, intervention on the user.

Our first smart bed focused on the problem of snoring. As sleeping posture was proven to influence snoring and sleep disturbed breathing, our smart bed allowed a postural intervention to be performed automatically, without requiring any action of either the snorer or the bed partner. The function and the applicability of the smart bed were tested in a proof of function experimental phase, where the system was applied during nocturnal sleep with one regular snorer.

The closed-loop capability of the system was tested in three experiment nights, which showed that the bed was able to adapt the shape of the mattress based on the snoring activity measured on the
subject. During the first two intervention nights, in presence of snoring, the mattress shape was automatically adjusted to elevate first the head of the user by few degrees and then the trunk of the snorer by 4.8 deg. A third experiment night was conducted to explore the effects of a greater elevation angle (21 deg).

Applicability for both the smart bed and the chosen interventions was suggested by the absence of any negative effect on either comfort or sleep quality perceived and reported by the subject. In the first two nights, no evident effects have been observed on either sleeping posture and snoring activity. However, the greater elevation angle tested during the third night caused cessation of snoring in four out of the six times that an intervention occurred. A single subject test is not sufficient for a reliable outcome, however these results are promising and an intervention with a reasonable elevation angle should be further investigated with an higher number of subjects and experiment nights.

The conducted experiments proved that the developed setup fulfills all the requirements concerning function, comfort, and safety. The smart bed can now be applied in proper scientific studies to analyze the effects of closed-loop postural intervention on sleeping posture and snoring activity.

General outcome

The work presented in this thesis aimed to develop a smart bed to help people improving their sleep condition in a non-pharmacological way. The project was developed along two parallel paths exploring two main aspects of the smart bed. The first path focused on the development of actuated platforms enabling vestibular stimulation while lying on a mattress. By a tendon-based robot, comfortable types of rocking movements were determined. These rocking movements were implemented in two additionally developed platforms to further explore the impact of vestibular stimulation on sleep quality. This first exploration phase allowed testing and evaluating different actuation designs and technical approaches, providing a valuable test bench to optimize the technological strategies to be implemented in the smart bed. The second path focused on a concept of human-in-the-loop and closed-loop control of the smart bed. The system consisted of an adjustable bed equipped with microphones and a control software to automatically detect and classify snoring sounds and, consequently adapt the mattress shape to reduce snoring.

Based on the results obtained in this thesis it was not possible to identify which kind of vestibular stimulation has the highest potential in improving sleep quality and thus should be implemented in our smart bed.

However, the conducted work allowed identification of a promising range of movements perceived as relaxing and pleasant. Our experiments showed high variability in the subjects’ preferences, suggesting that identifying one particular movement direction, frequency, and amplitude suited to everybody would be very difficult. Swing-like movements were chosen by most of the subjects participating in the sleep study, however, the preferences did not clearly differ between lateral and longitudinal direction. In order to satisfy a larger group of users, a commercial rocking bed should probably include some flexibility and allow the customer to adjust the stimulation parameters. Particularly, turning the actuation axis with respect to the bed, as implemented in our rocking beds, is a simple solution, which could be considered for a future product to allow the user to choose the preferred movement direction. Moreover, at least the choice between a “fast” and “slow” stimulation should be provided to the user. The powerful actuators and the robust mechanical design chosen for the rocking beds are significantly over-sized when we consider the range of promising movements resulting from the experiments. Focusing on swing-like movements within such a promising range would allow a considerable reduction of the required motor power. In addition, swing-like movements could be provided based on rotary axes instead of carriages and guides; this alternative design could contribute to reduce both acoustic impact of the system as
well as to improve the smoothness of the trajectories.

With this project we made the first steps towards the development of a rocking features for the smart bed. However, these conclusions are based only on the subjective feedback and further studies are needed in order to provide quantitative evidence about the impact of rocking movements on sleep. Such scientific proof is needed if we want to provide to the user an effective tool to improve quality of sleep. Moreover, identifying and modeling the impact of vestibular stimulation on relaxation and sleep parameters is required if the stimulation want to be controlled in a closed-loop manner. The path to the integration of vestibular stimulation into the smart bed idea is still long, however this work allowed to build a strong basis ans to take the first steps toward this ambitious goal.

Focusing on snoring allowed us to considerably simplify the monitoring capability required for the smart bed. Indeed, while simple microphones could be applied to monitor snoring sounds, complex physiological recordings including brain activity are required to measure sleep in a reliable way. The chosen postural intervention (i.e. trunk elevation) represents, as vestibular stimulation, a simple approach, which could be easily integrated into a commercial product. The preliminary experiments conducted in this thesis suggest the applicability of the approach and showed first promising results. Further studies are now required to validate the effectiveness of the proposed postural intervention in reducing snoring as well as to prove the reliability of the snoring detection algorithms with different subjects and different environmental conditions.

Combining the two parts of our work, we conclude that the idea of a smart bed is applicable. We showed that both rocking movements and adjustment of the mattress shape can be applied without disturbing the sleeping subject. This gives us two intervention tools, which could be used in the smart bed to influence the subject’s sleep. This thesis presents the first steps towards the development of the smart bed and provides the tools and the know-how to further develop the actuation and monitoring technology of the smart bed as well as allowing fundamental research on sleep.
6 Outlook

Based on this thesis, three experimental setups for sleep research are now available: a tendon based robot allowing a bed platform to be moved along complex 6 DOF trajectories, two rocking beds to investigate the effects of rocking movements on human sleep, and a smart bed able to monitor snoring activity of the user and automatically adapt the mattress shape accordingly. Function, performance, and applicability of the developed devices were shown in studies with human subjects. These setups offer three valuable test benches to further explore and develop the concept of smart bed as well as open new opportunities of fundamental research on sleep.

The rocking beds can be applied to further investigate various aspects of the interaction between vestibular stimulation and relaxation or sleep. Particularly, subject populations presenting reduced sleep efficiency and quality such as the elderly may benefit more from rocking movements than young good sleepers. One of the initial objectives of our project was to systematically analyze the effects that different kinds of rocking movements have on relaxation and sleep; and to identify which stimulation has the highest potential in promoting relaxation and improving sleep quality. The limited number of movement conditions along with the limited number of subjects did not allow such systematic investigation. The conducted studies neither allowed confirmation of the role of rocking movements in promoting relaxation and sleep, nor identification of any influence on the analyzed sleep parameters due to the provided vestibular stimulation. The results of our investigations only suggest that the way different movements are perceived varies significantly between the subjects and no clear general preferences could be identified. The role of movement parameters such as direction, amplitude, and frequency should be further explored in future studies and the developed platforms can be applied to do so. These further investigations should allow us to finally identify and model the still unclear link between vestibular stimulation and sleep. Such a step forward would allow to focus the closed-loop approach, exploring how vestibular stimulation could be automatically modulated in order to influence sleep. In addition, the developed setups could be used to investigate different aspects linked to the vestibular system such as disorders of the vestibular system or motion sickness.

The smart bed developed in the last part of the thesis offers a functional experimental setup to investigate the influence of different kinds of postural interventions on sleeping posture, snoring, and sleep in general. In this thesis, only a single subject, proof of function test was conducted. The bed should now be tested with different subjects and in different environmental conditions to validate classification performance and generalization capability of the snoring detection algorithm as well as to evaluate the effects of the postural intervention, based on statistical analysis. The preliminary results presented in this thesis are only based on microphone recordings and subjective feedback. Future study should include physiological recordings in order to allow reliable assessment of snoring, sleep disturbed breathing, and sleep quality. In addition to head and trunk elevation, the smart bed allows other areas of the mattress (e.g. legs and feet) to also be moved as well as to provide vibratory stimulation. These features would allow investigating how the change of mattress shape combined with vibrations could be used to induce the user to actively change sleeping position.

In a further technological development of the smart bed the integration of additional sensors could be considered. The two microphones presently implemented in the system allow detection of only the side of a double bed where the snorer lies. Force or pressure sensors integrated into the mattress or mounted on the bed frame could provide additional information about the sleeping
posture of the user, which could be very useful to determine which postural intervention should be applied. In addition, accelerometers integrated in the mattress could provide sensing of the user movements, which could be used to get an insight about sleep and wake periods. Moreover, these additional sensors could allow monitoring of physiological signals such as respiration and cardiovascular activity. This could complete the monitoring features of the smart bed and be used to further develop the interaction with the user.

If the effectiveness of the approach will be confirmed by the future studies, a commercial version of the smart bed including closed-loop postural intervention to reduce snoring should be developed. Both the microphones system and the computation unit required to add the closed-loop feature to a standard adjustable bed would have a minimum impact on both aesthetic and cost of the bed. Thus, the “smartness” could be easily transferred from the research setup to a commercial version of the system. As snoring affects between one quarter and half of the common population, such a new bed would refer to a huge pool of potential customers. The modularity of the system would allow transfer of the closed-loop modality to different actuated or adjustable beds as well, e.g. vibrating mattress, cheaper adjustable beds with less DOF, different interventions such as lateral tilting. This would allow a wide spectrum of solutions, including different intervention types and price ranges, to be developed. These products would be able to address to different group of customers and gain larger portion of the market.
A Appendix chapter

A.1 Smart systems and sleep.

A.1.1 Review of consumer technology and smart systems in sleep: References

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Table A.1: Smartphone’s apps. References.
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Table A.2: Wearable devices. References.
B Appendix chapter 3

This section summarizes the details about the sleep study conducted with the Somnomat rocking beds presented in chapter 3. The following section is based on the PhD dissertation of X. Omlin [2], where all the details about the conducted investigation are reported.

B.1 Methods

B.1.1 Aim of the sleep study

Previous investigations regarding the effect of vestibular stimulation on sleep not only left open questions concerning stimulation axis and frequency (chapter 2) but also about stimulation duration. As it appears that mainly sleep onset is influenced, it is not clear whether vestibular stimulation also influences later sleep in a beneficial way. Bayer et al. [26] found in their 45-minute nap study that sleep spindle activity and SO were increased, especially in the second half of the nap. However, the nap protocol does not allow conclusions to be drawn about the further cause of this effect or the impact on regular sleep.

Sleep spindles and SO appear to play a crucial role in memory performance. Sleep in general is assumed to favor memory consolidation [113, 114, 115, 116]. Increasing sleep spindles and SO especially, seems to be related to an improvement in memory performance [129, 130, 131, 132, 133]. The mechanisms responsible for these memory benefits are still controversially discussed and not established yet (for a review see [113]). However, there is evidence linking increased SO and sleep spindle activity to an enhanced declarative memory performance. Hence, vestibular stimulation might have the potential to also alter memory performance by boosting SO and/or spindle activity [26, 134].

The regulatory processes of respiration and cardiovascular functions are crucial to maintaining ventilation, blood pressure and blood flow during sleep and are the consequences of carefully orchestrated changes in the central nervous system throughout different sleep stages [135]. Therefore, it is worthwhile to take a closer look at changes in the well-regulated cardio-respiratory system, which might be present when applying vestibular stimulation to promote sleep.

The effects of rocking movements on sleep were explored by first analyzing their possible potential to increase sleep spindles and SO, which might affect memory performance. In addition, we studied whether vestibular stimulation mainly affects sleep onset or whether a cumulative effect would be observed with longer stimulation duration. A further aim of the study was the investigation of possible changes in cardio-respiratory functions during vestibular stimulation, in particular, throughout the transitory phases of falling asleep as well as after sleep onset. It was of interest to analyze whether cardio-respiratory regulation responds differently to vestibular stimulation during NREM or REM sleep or to different stimulation frequencies. Knowledge about these processes can be essential to define optimal stimulation parameters in future applications. To take subjects’ individual movement preferences into account (chapter 2), subjects could select the motion to be used during the study, among a set of different movement directions and trajectory parameters.

The complete analysis of the effects of the provided rocking movements on sleep and on the
physiological state of the subjects is presented in [2].

B.1.2 Physiological recordings and data analysis

Brain and cardio-respiratory activity were continuously recorded throughout the entire 8 hour sleep period with a polygraphic amplifier Artisan (Micromed, Mogliano, Veneto, Italy) and the software Rembrandt DataLab (Version 8.0; Embla Systems, Broom field, CO, USA).

EEG

EEG (according to the 10-20 system: F3, F4, C3, C4, P3, P4, O1, O2, A1, A2, referenced to Cz), submental EMG, and EOG signals were sampled at 256 Hz. For further analysis the EEG signals were re-referenced to the mastoids (A1, A2). Analogue signals were filtered with a high pass filter (EEG: -3 dB at 0.15 Hz; EMG: 10 Hz; ECG: 1 Hz) and an anti-aliasing low-pass filter (-3 dB at 67.2 Hz). Sleep stages were visually scored on a 20-s epochs basis according to standard criteria [1]. Artefact removal was performed visually and by a semi-automatic detection algorithm [136]. EEG spectral power in specific frequency bands (delta: 0.75-4.5 Hz; theta: 4.5-9 Hz; alpha: 9-15 Hz; sigma: 11-15 Hz; beta: 15-25 Hz) was calculated based on spectral analysis performed with the FFT (Hanning window; averages over five 4-s epochs). Spindledetection was performed using the spindle detection algorithm according to Ferrarelli et al. [137, 138] for all artefact-free NREM sleep epochs. Detection of slow waves was performed using an algorithm previously described [139]. Frequent arousals are a signal of poor sleep quality. Arousals are usually found together with movements. Epochs scored as artifacts are usually associated with movements. Thus an indication of disturbed sleep was calculated as the percentage of epochs scored as artifacts. Additional indications of a disrupted sleep was calculated from the occurrence of changes between wake, N1, N2, N3, and REM. Both these two features were calculated from the hypnogram data resulting from the manual scoring of the PSG recordings.

ECG

ECG recording was performed with one electrode placed 2 cm below the right clavicula between the first and second ribs, the second one placed at the fifth intercostal space on the midaxillary line on the left side of the bod. Sampling frequency of the ECG recorded signals was 64 Hz. Heart rate and HRV were calculated in 17 subjects as data from one subject had to be excluded due to insufficient ECG signal quality. Mean heart rate was calculated based on the distances between consecutive R-R peaks (RR intervals). Data were oversampled to 1000 Hz using a cubic spline interpolation. HRV parameters were calculated according to the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology [140]. Data was processed using a moving 300 s windows with 280 s overlap. Spectral power calculations were performed in MATLAB using the plomb function. Power in the low frequency range (LF: 0.04-0.15 Hz) and high frequency range (HF: 0.15-0.4 Hz) were calculated and normalized to the total power (frequency range: 0.04-0.4 Hz) to determine the LF over HF (LF/HF) ratio. To analyse whether cardio-respiratory regulation responds differently to vestibular stimulation in different sleep stages, respiration, heart rate and HRV were calculated separately over all NREM and all REM sleep epochs. To investigate potential changes throughout the transitory phase of falling asleep as well as after sleep onset the 5 min prior to sleep onset (pre) were compared to the 5 min after sleep onset (post). Furthermore, to establish whether different stimulation frequencies influence cardio-respiratory variables in different ways subjects were divided in two subgroups according their movement frequency selection (subgroups: slow (0.16 Hz; n=12) and fast (0.24 Hz; n=5)).
B.1 Methods

Respiration

Respiration was recorded using two respiration belts (EPM Sytems, Midlothiana, USA): one placed around the subject’s chest and the other around the abdomen. Respiration signals were sampled at 64 Hz and filtered with a third-order Butterworth low-pass filter with a cutoff frequency of 5.4 Hz. Zero-phase digital filtering was performed by processing the data in both forward and reverse directions. Respiration frequency was calculated based on peak detection, by considering the periods of respiration as the times between two consecutive peaks. To compare respiration in different sleep stages, mean respiration frequency was calculated for each 20-s epoch using a 60 s moving window with an overlap of 40 s. Mean respiration frequency was calculated as the mean reciprocal value of the respiratory period \[141\]. To analyze variations of the respiratory signal the standard deviation of the respiratory periods was calculated (peak-to-peak variation).

Declarative memory task

Sleep in general is assumed to favor memory consolidation \[113, 114, 115, 116\]. To investigate whether vestibular stimulation plays a role in this process, a declarative memory performance was assessed with a word-pair learning task \[117, 118\]. Prior to sleep, subjects performed a word-pair memory task consisting of 40 semantically related word pairs, which were presented in randomized order. Three different word pair lists (randomized among the conditions) were used for the three measurement nights. At first, the subjects had to learn the word pairs. Then they were tested twice: immediately after learning (immediate recall) and after 8 hours of sleep in the morning (delayed recall). Word pairs were presented on a computer screen for 4 s each. During recall, subjects had to recall the second word after the first word of the pair was presented. There was no time limit to answer, but subjects were instructed to respond as fast as possible. After subjects entered the second word, the correct word pair was shown again for 2 s as feedback. The memory tasks were performed one hour before bed time (learning and immediate recall) and 30 min after waking up (delayed recall). Each correct word pair was scored with one point and correctly recalled word pairs containing mistakes (plural/singular form, spelling) with half a point. Overnight performance improvement was defined as the difference in correctly recalled word pairs between immediate and delayed recall. Initial acquisition rate, indicating how much of the individual learning capacity is already achieved in the immediate recall, was calculated as the performance in the immediate recall expressed as the percentage of the delayed recall performance \[119\].

B.1.3 Statistical analysis

Physiological recordings

All EEG features were statistically analysed using a univariate general linear model followed by post hoc LSD-tests. EEG features were defined in the model as dependent variable, condition as fixed effect and the factor subject as random effect. The conditions with movement were compared to each other and to baseline measurements. EEG data were analyzed for the entire night and the first 2 hours after lights out. The significance level was set at \(p < 0.05\). Analogously to the EEG features, statistical analysis of the number of artifact epochs and changes in sleep stages was performed using an univariate general linear model followed by post hoc least significant difference tests (LSD-tests). The number of artifact epochs or changes in sleep stages were defined in the model as dependent variable, condition as fixed effect and subjects as random effect. The significance level was set at \(p < 0.05\).

Respiration frequency, heart rate and HRV were statistically analysed using a univariate general
linear model followed by post hoc LSD-tests. To compare between conditions, respiration frequency, heart rate, and HRV features were defined in the model as dependent variable, condition as fixed effect and the factor subject as random effect. Differences in conditions were individually tested for NREM sleep, REM sleep, 5 min pre sleep onset and 5 min post sleep onset. Furthermore, differences in each condition between NREM sleep and REM sleep and between pre and post sleep onset were analysed. (NREM-REM sleep, pre-post sleep onset as fixed effect). In addition, subgroups (slow stimulation frequency, fast stimulation frequency) were compared. The statistical analysis was performed with the SPSS software (SPSS Inc., Chicago, Illinois, USA).

Declarative Memory task

Two out of the 18 subjects recalled all 40 word pairs correctly and were therefore excluded from the statistical analysis due to a ceiling effect. Statistical analysis was performed using a liner mixed model with random effects using the statistical software R [142]. Word-pair task performance measures (overnight memory improvement, immediate recall, delayed recall, initial acquisition rate) were entered into the model as dependent variable, the condition as fixed effect and the factor subject as random effect. To exclude effects of the word-pair task list version or the experimental night, interactions between these factors and the condition were tested. Correlations between sleep spindles, SO measures and word-pair task performance measures were calculated using Pearson’s correlation coefficient (two-tailed). EEG measures of the entire night as well as only the first two hours of the night were included in the analysis. The statistical analysis was performed with SPSS software (SPSS Inc., Chicago, Illinois, USA).

B.2 Results and discussion

B.2.1 Physiological recordings

Sleep architecture

All physiological recordings were of good signal quality. The shield implemented in the two beds successfully prevented artifacts and electrical interference due to the beds actuators. Mounting the physiological amplifier directly on the moving platform of the beds allowed avoidance of artifacts due to the motion of the electrode cables.

The analysis of brain activity showed no changes in sleep architecture in the presence of vestibular stimulation. Sleep latency, SWS latency and REM sleep latency were comparable among the conditions and did not reveal significant differences. Sleep efficiency, sleep stage N1, sleep stage N3 and time awake after sleep onset did not differ between the conditions when comparing the data over the entire night (8 hours) as well as during the first 2 hours after lights out. Only the amount of sleep stage N2 was significantly increased for C2 compared to B and C1 during the first 2 hours after lights out, but not for the entire night. In addition, when considering the first 3 hours after lights out, the differences in N2 sleep were no longer present (B: 79.61 ± 4.76 min; C1: 75.61 ± 4.14 min; C2: 77.11 ± 4.11 min). In contrast with the findings of Bayer et al. [26] the applied vestibular stimulation did not shorten sleep onset nor did it facilitate the transition to deep sleep. Sleep latencies (time from lights out until the first appearance of N2 sleep) and SWS latencies (time from sleep onset until first appearance of N3 sleep) did not exhibit any changes due to the vestibular stimulation. Also when calculating the N2 latency as the difference between first occurrence of N2 and first occurrence of N1, which was shortened in the study of Bayer et al. [26], no differences between the conditions appeared. A possible reason for these contradictory
findings might lie in the different sleep opportunities investigated. Bayer et al. [26] applied rocking movements during an afternoon nap whereas our study investigated vestibular stimulation during nocturnal sleep. In a population without sleep deprivation and with regular bed times, sleep pressure will be different for an afternoon nap compared to nocturnal sleep. As sleep pressure is higher prior to nocturnal sleep, sleep latency will be shorter and slow wave activity (SWA) higher compared to nap sleep. Furthermore, nap sleep exhibits often a reduced sleep efficiency compared to nocturnal sleep [143]. Indeed, in the nap study of Bayer et al. [26] increased sleep latency (first N2 occurrence) and reduced sleep efficiency (sleep latency: 17.6 min; sleep efficiency: 73.1% for baseline sleep) occurred compared to our study involving nocturnal sleep (sleep latency: 8.5 min; sleep efficiency: 96.8% for baseline night). Therefore, in contrast to nap sleep that is usually characterized by lower sleep quality, nocturnal sleep in good sleepers might not benefit additionally from the potential facilitating effects of vestibular stimulation on sleep onset and the transition to deeper sleep stages. Nevertheless, we cannot exclude that vestibular stimulation could have those positive effects also on nocturnal sleep when a population exhibiting prolonged sleep latencies such as for example in the elderly or people suffering from insomnia are considered. Differently from the results regarding sleep onset, the increase in the amount of N2 sleep, which was found for the first 2 hours in the C2 condition, is in line with the findings of the nap study by Bayer et al. [26]. However, this increase occurred only in the C2 condition during which vestibular stimulation was present for the entire duration of the analyzed time window. Therefore, it might be possible that vestibular stimulation at the beginning of the night increases the amount of N2 sleep due to the additional stimuli, which are introduced to the vulnerable progression of sleep. However, as neither SWS or REM latency nor time spent in SWS or REM sleep differed among the conditions, sleep architecture and SWS appear not to be affected by the stimulation. It might be that sleep architecture is only affected when vestibular stimulation is present without influencing sleep beyond the duration of the stimulation.

Nevertheless, when considering sleep architecture of the entire night, the reduction in N2 sleep found in the study of Woodward et al. [27], was not present in our data. However, Woodward et al. [27], applied vestibular stimulation throughout the entire night, which makes a comparison difficult. These findings might indicate that vestibular stimulation also influences later sleep, however, only if stimulation is still present.

**Sleep spindles and slow oscillations**

The total number of sleep spindles (mean (SD), p-value) was significantly increased for the C2 (195.61 (66.56)) condition compared to B (170.00 (44.39), 0.047) and C1 (166.28 (55.03), 0.024). However, this increase was only visible in data from the first 2 hours after lights out. The total number of sleep spindles did not differ between conditions when considering the entire night. However, spindle density was not influenced by the different experimental conditions either during the entire night, or during the first 2 hours. The number of SO did not differ between the experimental conditions for the first 2 hours as well as for the entire night. The same was observed for the density of SO.

An increase in number of spindles was also present in the study of Bayer et al. [26], however this increase was accompanied by a rise in spindle density, which was not observed in our study. Spindle number was only increased for C2 during the time the stimulation was applied. As it is suggested that spindles might have sleep protecting functions due to their role in sensory input gating [144, 145, 146], spindles could be increased to ensure maintenance of sleep during vestibular stimulation.

Although a change in spindle number was found for C2 condition, spectral analysis did not reveal any differences between the conditions. In contrast to the study of Bayer et al. [26] a boost in SWA was not observed. A possible explanation could be that SWA in nocturnal sleep might be already
too high to be influenced by vestibular stimulation (saturation effect), whereas during an afternoon nap with lower sleep pressure there might be a greater potential for slow wave enhancement. The lack of SWA boosting could also be due to the different movement direction and simulation frequencies used in our study compared to [26]. Another explanation for the lack of SWA increase in our study could be that the proposed stimulation intensity was insufficient to trigger slow wave enhancing mechanisms. In the case of auditory stimulation it was hypothesised that the mechanism by which slow waves can be induced is likely to be the same ones used to arouse the organism when changes in the environment are detected [131]. Therefore, it was proposed that the intensity of stimulation has to be strong enough to trigger the ascending pathways but not too strong to lead to an awakening [131]. Although this mechanism has not yet been investigated for vestibular stimuli a similar connection might exist for the relationship between vestibular stimulation and slow waves. Further knowledge about such thresholds might be a key to effective stimulation paradigms and crucial for future applications.

**Cardio-respiratory activity**

Respiration and ECG recordings were of good signal quality and normal sleep stage dependent characteristics of respiration frequency, heart rate and HRV were observed. However, conditions with vestibular stimulation showed no difference in heart rate, HRV or respiration frequency compared to condition without stimulation.

Heart rate was significantly lower in NREM sleep compared to REM sleep. Heart rate (mean (SD), p-value) was significantly lower in NREM sleep (B: 0.834 (0.089) Hz, 0.022; C1: 0.861 (0.100), 0.001; C1: 0.859 (0.085) Hz, 0.000) compared to REM sleep (B: 0.869 (0.118) Hz; C1: 0.916 (0.126) Hz; C2: 0.907 (0.94) Hz). Lower heart rate values were found in condition B compared to C1 (NREM p=0.008, REM p= 0.005) and C2 (NREM p=0.013, REM p= 0.020) for both NREM and REM sleep. Heart rate variability calculated as the HF/LF ratio did not differ among different conditions. HF/LF ratio was significantly lower for NREM sleep (B: 1.350 (0.700), 0.02; C1: 1.370 (0.776), 0.006; C2: 1.435 (0.765), 0.004) as for REM sleep (B: 1.925 (0.990); C1: 2.215 (1.301); C2: 2.008 (1.109)). However, conditions did not differ.

**B.2.2 Memory performance**

The results of the declarative memory task showed a significantly higher number of correct recalled word pairs for the delayed recall compared to the immediate recall (Overnight memory improvement (mean (SD), z-value, p-value) = C1: 6.31 (2.75), 9.18, < 0.001; C2: 6.69 (3.43), 7.79, < 0.001; B: 6.72 (3.76), 7.14, < 0.001). In line with results of previous studies [119, 120, 121, 122] overnight performance in declarative memory was found to be improved after sleep. However, overnight memory improvement exhibited similar gains in all three conditions, leading to the conclusion that vestibular stimulation did not have additional beneficial consequences on memory.
## Appendix chapter 4

### C.1 Snoring detector: Features

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Table C.1: Features. Full list of features.
C.2 Snoring detector: Detailed algorithms descriptions

Learning and removal of background noise (spectral subtraction)

1. Buffering: The signal is divided in frames \( y_k = [y_1, ..., y_N] \) of 30 ms \((N = 330\) samples), with 50\% overlap;

2. Windowing: Hanning window \( W_H \) is applied to each frame \( y_k \);

\[
\tilde{y}_k = W_H y_k \tag{C.1}
\]

3. Discrete Fourier Transform: The spectrum \( Y_k \) is calculated for each frame \( \tilde{y}_k \) \((N_{FFT} = 512)\) by applying FFT;

\[
Y_{k,j} = \sum_{n=0}^{N_{FFT}-1} \tilde{y}_{k,n} e^{-i2\pi nj/N_{FFT}} j = 0, ..., N_{FFT} - 1 \tag{C.2}
\]

\( Y_k = [Y_{k,0}, ..., Y_{k,M}] \) with \( M = N_{FFT}/2 + 1 \) \(\tag{C.3}\)

Total energy \( e_k \) of the signal:

\[
e_k = \frac{1}{M} \sum_{i=1}^{M} |Y_{k,i}| \tag{C.4}
\]

4. Voice activity detection (VAD): A linear energy-based detector is applied to distinguish background noise events \((VAD = 0)\) from events with acoustic activity above a defined threshold \((VAD = 1)\); Initialization \((0.3\) s):

\[
\text{if } k \leq 20
\]

\[
Er_k = \frac{1}{m} ((m-1)Er_{k-1} + e_k) \tag{C.5}
\]

Double threshold strategy:

\[
TH_k = \begin{cases} 
    k_{down} Er_k & \text{if } VAD_{k-1} > 0 \\
    k_{up} Er_k & \text{if } VAD_{k-1} = 0 
\end{cases} \tag{C.6}
\]

\[
VAD_k = \begin{cases} 
    1 & e_k > TH_k \\
    0 & e_k \leq TH_k 
\end{cases} \tag{C.7}
\]

5. Background noise estimation: The background noise spectrum \( \hat{N}_k \) is estimated from the frame when no “acoustic activity” is detected \((VAD_k = 0)\);

\[
\text{if } VAD_k = 0
\]

\[
\hat{N}_k = \frac{1}{m} ((m-1)\hat{N}_{k-1} + |Y_k|) \tag{C.8}
\]

\[
Er_k = \lambda Er_{k-1} + (1 - \lambda)e_k \tag{C.9}
\]
\[ \hat{N}_{max,k} = \max \left( |Y_k|, 0.999 \hat{N}_{max,k-1} \right) \]  
(C.10)

elseif \( \text{VAD}_k = 1 \)

\[ \hat{N}_k = \hat{N}_{k-1} \]  
(C.11)

\[ E_{r_k} = E_{r_{k-1}} \]  
(C.12)

\[ \hat{N}_{max,k} = \hat{N}_{max,k-1} \]  
(C.13)

6. Background noise removal: The estimated spectrum of the background noise is removed from the spectrum of the actual frame \( Y_k \);

\[ m_{Y,k} = \frac{1}{M} \sum_i |Y_{k,i}| \]  
(C.14)

\[ m_{\hat{N},k} = \frac{1}{M} \sum_i |\hat{N}_{k,i}| \]  
(C.15)

\[ VAR_{Y,k} = \frac{1}{M} \sum_i (|Y_{k,i}| - m_Y)^2 \]  
(C.16)

\[ VAR_{\hat{N},k} = \frac{1}{M} \sum_i (|\hat{N}_{k,i}| - m_{\hat{N},k})^2 \]  
(C.17)

\[ COV_{Y,\hat{N},k} = \frac{1}{M} \sum_i (|Y_{k,i}| - m_Y)(|\hat{N}_{k,i}| - m_{\hat{N},k}) \]  
(C.18)

\[ g_k = \frac{COV_{Y,\hat{N},k}}{\sqrt{VAR_{Y,k} VAR_{\hat{N},k}}} \]  
(C.19)

\[ K_{k,j} = g_k |Y_{k,j}| |\hat{N}_{k,j}| \quad j = 1, ..., M \]  
(C.20)

\[ \hat{S}_k = |Y_k|^{\alpha} - \beta |\hat{N}_k|^{\alpha} - K_k \]  
(C.21)

\[ \hat{S}_k = \text{sign}(\hat{S}_k) |\hat{S}_k|^{\frac{1}{\alpha}} \]  
(C.22)

7. Half-wave rectification: Eventual negative magnitudes introduced by step 6 are removed by applying half-wave rectification;

\[ \hat{S}_k = \max \left( \frac{|\hat{S}_k| + \hat{S}_k}{2}, 0.02 \hat{N}_k \right) \]  
(C.23)
8. Residual noise reduction: The noise residual is removed by replacing the spectrum magnitudes \( \hat{S}_{k,j} \) with the minimum values taken from the adjacent frames \( k, k-1, \) and \( k-2; \)
\[
\hat{S}_{k,j} = \begin{cases} 
\hat{S}_{k,j} & \hat{S}_{k,j} \geq \hat{N}_{\text{max},j} \\
\min(\hat{S}_{k-2,j}, \hat{S}_{k-1,j}, \hat{S}_{k,j}) & \hat{S}_{k,j} < \hat{N}_{\text{max},j}
\end{cases} \quad j = 1, \ldots, M \quad (C.24)
\]

9. Add phase: The phase \( \phi_{Y,k} \) of current frame \( Y_k \) is added to the filtered spectrum magnitude \( |\hat{S}_k|; \)
\[
\hat{S}_k = |\hat{S}_k|e^{i\phi_{Y,k}} \quad (C.25)
\]

10. Inverse Discrete Fourier Transform: The time waveform of the filtered signal is reconstructed by applying Inverse Fast Fourier Transform;
\[
\hat{s}_{k,n} = \frac{1}{M} \sum_{j=0}^{M-1} \hat{S}_{k,j} e^{i2\pi jn/M} \quad n = 0, \ldots, N - 1 \quad (C.26)
\]
\[
\hat{s}_k = [(\hat{s}_{k,0}), \ldots, (\hat{s}_{k,N-1})] \quad (C.27)
\]

11. Add and overlap: the effect introduced by the initial overlap (step 1) is finally compensated by adding the first half of the output frame \( \hat{s}_k \) to the second half of the previous frame \( \hat{s}_{k-1}; \)
\[
y_{filt,k} = \Re\{[(\hat{s}_{k,1:N/2} + \hat{s}_{k-1,N/2+1:N})]\} \quad (C.28)
\]

**Event detection algorithm**

1. Buffering: The signal is divided in frames \( y_k = [y_1, \ldots, y_N] \) of 60 ms (\( N = 660 \) samples), with 75% overlap;
2. Windowing: Hanning window \( W_H \) is applied to each frame \( y_k; \)
\[
\tilde{y}_k = W_H y_k \quad (C.29)
\]
3. Discrete Fourier Transform: The spectrum \( Y_k \) is calculated for each frame \( \tilde{y}_k \) (\( N_{FFT} = 1024 \)) by applying Fast Fourier Transform (FFT);
\[
Y_{k,j} = \sum_{n=0}^{N_{FFT}-1} \tilde{y}_{k,n} e^{-i2\pi jn/N_{FFT}} \quad j = 0, \ldots, N_{FFT} - 1 \quad (C.30)
\]

The spectral energy \( e_k \) of the signal frame is calculated as a weighted sum of the squared amplitudes of the spectrum \( Y_k; \)
\[
e_k = \sum_{i=1}^{M} w_i |Y_{k,i}|^2 \quad \text{with} \quad M = N_{FFT}/2 + 1 \quad (C.31)
\]
\[
w_j = \begin{cases} 
0 & \text{if } f_j < f_{m \text{ in}} \\
\frac{1}{|m|} & \text{if } f_j \geq f_{m \text{ in}} \text{ with } j = 1, \ldots, M
\end{cases} \quad (C.32)
\]

where \( f_j \) is the \( j^{th} \) spectrum’s frequency and \( w \) is the weighting vector.
4. Adaptive threshold: The signal frames with total energy \( e_k \) above a defined threshold \( TH_k \) are labeled as acoustic events. The threshold \( TH_k \) is calculated online on 30 s frames with 83.3\% (25 s) overlap. The approach is based on the assumption that the signal is mainly composed of background noise characterized by low energy.

\[
\mathbf{e}_{TH,k} = [\tilde{e}_{k-M+1}, ..., \tilde{e}_k]
\]
with \( M = 2004 \) (30 s frame) (C.33)

Outlier removal: Robustness of the approach is improved by removal outliers deviating from the mean energy \( \mu_{e_k} \) for more than \( \varepsilon \) times the standard deviation \( \sigma_{e_k} \) (\( \delta = 10 \))

\[
\tilde{e}_k = \begin{cases} 
    e_k & \text{if } e_k \leq \mu_{e_k} - \varepsilon \sigma_{e_k} \\
    \text{NaN} & \text{if } e_k > \mu_{e_k} + \varepsilon \sigma_{e_k} 
\end{cases}
\]
with \( \varepsilon = 10 \) (C.34)

Histogram:

\[
[c_{hist}, n_{hist}] = \text{histogram}(e_k, N_{hist})
\]
with \( N_{hist} \) (C.35)

\[
TH_k = \min \{c_{hist,i} | n_{hist,i} < \delta \max \{n_{hist}\}, i > \argmax \{n_{hist}\}\}
\]
with \( \delta = 10 \) (C.36)

Moving average:

\[
TH_{filt,k} = \frac{1}{5} \sum_{j=1}^{5} TH_j
\]
with \( 5 \) (C.37)

5. Buffering and thresholding: The signal energy \( e \) is stored and analyzed in 4 s frames \( N = 267 \) with overlap of \( N-1 \) samples. Label \( l_{k,j} = 1 \) is assigned when the energy \( e_{ED,k,j} \) is higher than the threshold \( TH_k \):

\[
e_{ED,k} = [e_{k-N+1}, ..., e_k]
\]
with \( N = 267 \) (C.38)

\[
l_{k,j} = \begin{cases} 
    1 & \text{if } e_{ED,k,j} > TH_k \\
    0 & \text{if } e_{ED,k,j} \leq TH_k 
\end{cases}
\]
with \( 0 \leq l_{k,j} \leq 1 \) (C.39)

6. Boundary adjustment: After thresholding, the frame \( e_{ED,k} \) is reprocessed a first time in order to adjust the event boundaries. Starting with the initial values obtained after thresholding, the event boundaries are expanded outside the event until the fitted slope sign changes. The fitted slope is obtained from ordinary least-squares linear regression applied on \( N \) energy samples outside the current boundary \( e_{SF} \). The process is repeated progressively proceeding by one sample outside the vent until the fitted slope sign changes with respect to its previous value. Linear regression line:

\[
r_j = \beta_1 + \beta_2 e_{SF,j}
\]
with \( \beta_2 \) corresponding to the fitted slope. The parameter \( \beta = [\beta_1, \beta_2] \) is calculated through ordinary least square:

\[
\beta = (X^T X)^{-1} X^T e_{SF}
\]
with \( X^T = \begin{bmatrix} 1 & 2 & ... & N \end{bmatrix} \) (C.40)

7. Fragmentation adjustment: The frame \( e_{ED,k} \) is processed a second time to merge the events which are separated by less than \( D_{event} = 0.2 \) s (C.41).

8. Duration adjustment: In the last step the frame \( e_{ED,k} \) is processed again to eliminate events which are too long or to short to be associated to snoring \( (0.5 \text{ s} < L_{event} < 2.2 \text{ s}) \) (C.42).

9. Event time: The event detection algorithm output for each event \( d \) the time indexes \( k_{d,s} \) and \( k_{d,e} \) corresponding the start and the end of the event. The event time index \( k_d \) is calculated as \( k_d = \text{round}((k_{d,e} - k_{d,s})/2) \).
Source localization

1. Event spectral energy: The spectral energy $e_d$ of each noisy event is calculated summing the frame spectral energy $e_k$ (see event detection algorithm) of all the frames associated to the event. Same procedure is applied for both left and right microphone. Higher spectral energy is assumed to be associated to the microphone that is closer to the source.

$$e_d = \sum_k e_k \text{ with } k \in \text{event}_d$$  \hspace{1cm} (C.42)

"source location" $\text{loc}_d = \begin{cases} \text{"left"} & \text{if } e_{d,\text{left}} > e_{d,\text{right}} \\ \text{"right"} & \text{if } e_{d,\text{left}} \leq e_{d,\text{right}} \end{cases}$  \hspace{1cm} (C.43)

C.3 Classifiers training

Feature ranking

1. Feature matrix: The feature matrix $\tilde{X}$ is composed by all data points $\tilde{x}_{m,n}$, measured for feature $m$ at the time $t_n$.

2. Normalization: Quartile based normalization and outlier removal are applied to improve reliability and robustness of the feature selection. The normalization parameter are obtained from the empirical probability distribution of the normalized features $X$.

$$q_{1}^{(m)} = \text{"25% quantile of } x_{(m),n}$$  \hspace{1cm} (C.44)

$$q_{3}^{(m)} = \text{"75% quantile of } x_{(m),n}$$  \hspace{1cm} (C.45)

$$\text{med}^{(m)} = \text{"median of } x_{(m),n}$$  \hspace{1cm} (C.46)

$$iqr^{(m)} = q_{3}^{(m)} - q_{1}^{(m)}$$  \hspace{1cm} (C.47)

$$lb^{(m)} = \text{"5% quantile of } x_{(m),n}$$  \hspace{1cm} (C.48)

$$ub^{(m)} = \text{"95% quantile of } x_{(m),n}$$  \hspace{1cm} (C.49)

where $x_{(m),n} = [x_{m,1}, ..., x_{m,N_s}]$ is the $m^{th}$ row of matrix $X$. The data points below the lower bound $lb$ or above the upper bound $ub$ are classified as outliers and not considered in the F-score calculation. The rows of the normalized feature matrix $X$ are calculated as:

$$x_{(m)} = \frac{|x_{(m)} - \text{med}^{(m)}|}{iqr^{(m)}/2}$$  \hspace{1cm} (C.50)
3. Features ranking: The normalized features are ranked based on ANOVA F-test.

\[ VAR_{inter-class}^{(m)} = N_s (\bar{x}_s^{(m)} - \bar{x}_s^{(m)})^2 \] (C.51)

\[ VAR_{intra-class}^{(m)} = \frac{1}{N_s - 1} \sum_{j=1}^{N_s} (x_{s,j}^{(m)} - \bar{x}_s^{(m)})^2 \] (C.52)

\[ f^{(m)} = \frac{VAR_{inter-class}^{(m)}}{VAR_{intra-class}^{(m)}} \] (C.53)

\[ f = [f^{(1)}, ..., f^{M}] \] (C.54)

Where \( N_s \) is the number of data points of class “snoring”, \( M \) is the total number of features, \( \bar{x}_s^{(m)} \) is the mean value of feature \( m \) calculated from all data points, \( \bar{x}_s^{(m)} \) is the mean value of feature \( m \) calculated from “snoring” data points, and \( f \) is the F-scores vector. The features are finally sorted from highest to lowest F-score \( f^{(m)} \).
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Curriculum vitae

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