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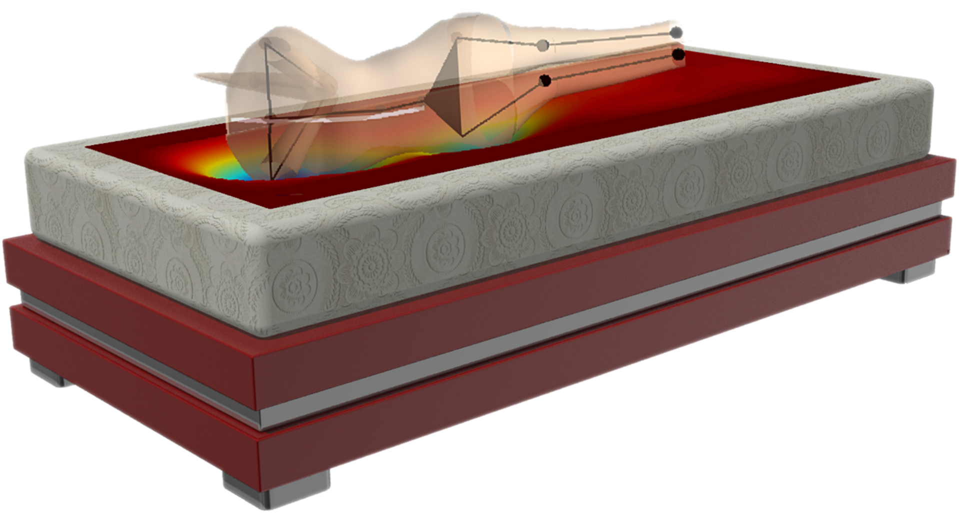
Ergonomic analysis of integrated bed measurements: towards smart sleep systems

Vincent VERHAERT



Dissertation presented in partial fulfillment of the requirements for the degree of Doctor in Engineering

December 2011

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D/2011/7515/151
ISBN 978-94-6018-450-5

If sleep doesn't serve an absolutely vital function, then it is the greatest mistake the evolutionary process ever made.

Prof. Dr. Allen Rechtschaffen, University of Chicago

Dankwoord

Met de eindmeet in zicht wil ik graag enkele mensen bedanken die hebben bijgedragen tot de realisatie van dit doctoraat. Ik wil hierbij in de eerste plaats mijn promoter, Prof. Jos Vander Sloten en co-promoter, Dr. Bart Haex, bedanken. Beiden hebben, elk op hun eigen manier, mij ertoe aangezet om dit werk met succes te kunnen afronden.
Jos, bedankt voor het vertrouwen, de steun en de vrijheid die ik heb gekregen tijdens de invulling van dit doctoraat. Het aangename werkklimaat op de Afdeling Biomechanica is voor een groot stuk uw verdienste. Bart, bedankt om me te introduceren in de wereld van ergonomie en slaap. Het pionierswerk dat je verricht hebt rond dit thema was een belangrijke inspiratiebron. Bedankt ook voor de begeleiding, ideeën, kritische blik en het nalezen van dit werk en de artikels.

Hartelijk dank aan Prof. Dirk Vandermeulen, Prof. Sabine Van Huffel, Prof. Daniel Berckmans, Prof. Arthur Spaepen, Prof. Raymond Cluydts en Prof. Richard Goossens om deel uit te maken van mijn examencommissie. Jullie kritische, maar constructieve opmerkingen waren onontbeerlijk voor de kwaliteit van dit werk. Prof. Goossens, bedankt om — tot twee maal toe — naar Leuven te komen voor de beoordeling van mijn werk.

Het onderzoek dat verricht is in dit doctoraat was nooit mogelijk geweest zonder de multidisciplinaire omkadering van het EASI-project en alle mensen die aan dit project hebben meegewerkt. Ik wil Guido, Arnoud, Johan, Sandra, Tim en Dorien bedanken voor de noeste arbeid in het experimenteel slaaplabo in Brussel. Slaaponderzoek is ontzettend arbeidsintensief en zonder een coherente groep die onder elkaar de taken kan verdelen, is dit soort werk niet realiseerbaar. Bedankt ook aan Elke, Marie, Vasilis, Stijn, Bart en Johan voor de begeleiding en de strategische invulling van dit toch wel unieke onderzoeksproject. In het bijzonder wil ik Raymond bedanken, de “sjamaan” van de bende, voor zijn enthousiasme, paraatheid, betrokkenheid en gidsing gedurende de ganse looptijd van het project. Daarnaast verdienen alle testpersonen die hebben deelgenomen aan de experimenten ook een vermelding in dit dankwoord. Ten slotte was dit project ook enkel mogelijk dankzij de financiële steun van het IWT-Vlaanderen, waarvoor dank.

Voor de technische aspecten van de slaapsystemen ben ik veel dank verschuldigd aan de mensen van Custom8 NV. Tom, bedankt voor alle hulp bij de implementatie van de software. Ik had nooit gedacht dat punten en komma's zoveel miserie met zich konden meebrengen. Hans en Karel, bedankt voor het vele werk en het snelle depaneren in geval van nood.

Uiteraard wil ik ook mijn collega's op de Afdeling Biomechanica bedanken voor hun bijdrage. Eerst en vooral mijn bureaugenoten, Koen, Dorien, Tim en Bart; bedankt dat ik jullie ten allen tijde mocht storen met om het even wat (zin en onzin). Daarnaast wil ik Stefan en Ivo bedanken voor hun technische hulp. Eén van de spilfiguren van de afdeling is Rita. Als ik op korte termijn iets gedaan moest krijgen, dan wist ik bij wie ik kon aankloppen. Bedankt voor het snel regelen van heel wat administratieve taken, de boekingen voor de congressen, het beheer van de kosten, de vastberadenheid bij het contacteren van drukbezette professoren en het luisterend oor. Ook de rest van de collega's wil ik bedanken voor de ontspannen sfeer en de leuke middagpauzes. Ten slotte wil ik ook Bert, Nele en Joris bedanken. Vanaf de laatste studentenjaren tot nu liepen onze wegen aan de K.U.Leuven nagenoeg parallel, het zal wennen worden wanneer dit verandert.

Naast al deze wetenschappelijke bijdragen hebben ook verschillende mensen op andere manieren bijgedragen tot dit doctoraat. In de eerste plaats mijn ouders, bedankt voor alle begrip, motivatie en steun. Jullie hebben je nooit echt gemoeid in de keuzes die ik doorheen mijn leven heb gemaakt, maar hebben ze wel steeds ten volle gesteund. Ik word mij hoe langer hoe meer bewust van het feit dat dit niet altijd even vanzelfsprekend is. Daarnaast hebben ook alle vrienden en familie ervoor gezorgd dat ik een uitlaatklep buiten het academisch milieu had, hetgeen me toeliet om het juiste perspectief te behouden. Mijn zussen, Caroline en Isabelle, wil ik bedanken om ervoor te zorgen dat hun "broertje" met zijn voeten op de grond bleef lopen.

Tot slot rest mij nog twee heel bijzondere mensen te bedanken. Annelore, jij hebt — zeker het voorbije jaar — het begrip multitasken tot op het bot doorgrond. Zonder jouw flexibiliteit was er van dit werk geen sprake geweest. Ook als het minder vlot ging en ik minder aangenaam gezelschap was, kon ik altijd rekenen op jouw liefde en steun. Anton, mijn flinke zoon, jij hebt mijn leven het laatste jaar des te interessanter gemaakt. Alhoewel ik niet mag klagen, herinner je mij er van tijd tot tijd toch aan wat de gevolgen van slaapdeprivatie zoal inhouden. Je guitige glimlach is de grootste motivator om nieuwe uitdagingen het hoofd te bieden.

Vincent
November 2011

Abstract

Ergonomic aspects of sleep are gaining importance in order to develop individually optimized sleep environments promoting sleep initiation and maintenance. The research domain of sleep ergonomics is relatively young and requires bridging the expertise of sleep physiologists, psychologists, ergonomists and engineers; a challenge in itself. This PhD dissertation focuses on one of the main environmental components the sleeping body interacts with, namely the sleep system (i.e. the combination of mattress, bed base and pillow). The presented work contributes to the state-of-the-art in bed design by integrating control algorithms that allow bed properties to be actively changed during sleep in order to continuously optimize body support. Furthermore, the developed tools were validated during overnight experiments in a dedicated sleep laboratory.

First, the effect of spinal alignment on objective and subjective sleep parameters was studied. Sleep systems with adjustable comfort zones were used in order to alter spinal alignment independently from other confounding variables. During overnight studies two well-defined experimental conditions were compared: a sagging support and a personalized support. Since spinal alignment is dependent on the adopted posture, the amount of time spent in each sleep posture was considered as an influencing factor during the results analysis.
Secondly, an unobtrusive technique was introduced for the assessment of motor patterns during sleep. An algorithm was developed to automatically detect body movements and sleep postures based on integrated mattress indentation measurements. Validation was performed during an overnight study by means of combined polysomnographic and video recordings.
Thirdly, the problem of evaluating spine shape without disturbing sleep was dealt with. Therefore, a generic surface model representing human body shape was developed. Based on specific anthropometric information (derived from measured body contours), personalized human models could be generated. The combination of these surface models with an inner skeleton model allowed simulating distinct sleep postures. Furthermore, an algorithm was implemented to automatically fit the person-specific model in the measured mattress indentation in order to estimate spine shape. Validation of the estimated

spine shapes was performed by means of simultaneous 3-D scans of the back surface in lateral positions.
Fourthly, the previous two developments were integrated in a feedback control system aimed at optimizing spinal alignment by means of controlling the mechanical properties of eight comfort zones continuously throughout the night. The performance of the developed control system was tested both in laboratory conditions and during overnight sleep experiments.
Finally, the effect of such an actively controlled sleep system on sleep was studied. Therefore, the actively controlled sleep system was compared to a standard (static) sleep system. Polysomnographic measurements were performed and questionnaires were completed to derive both objective and subjective outcome measures.

The results presented in this work indicated that spinal alignment indeed affects sleep. Primarily, it was shown that habitual sleep postures determine to what extent subjects experience a negative effect while sleeping on a sagging sleep system. More specifically, subjects preferring prone and lateral sleep postures demonstrated impaired sleep on a sagging support whereas no such effect was noted for supine sleepers.
Furthermore, the results proved the feasibility of integrated mattress indentation measurements to detect body movements and adopted sleep postures unobtrusively. Movement detection based on mattress indentation measurements showed to be more sensitive than movement detection based on standard actigraphic recordings. In addition, a high accuracy was achieved for the automatic classification of indentation images into supine, left lateral, right lateral and prone positions based on five image features.
In order to evaluate spinal alignment, knowledge of mattress indentation alone was not sufficient. However, combined with personalized body shape models, proper spine shape estimation was shown to be feasible.
The actively controlled sleep system resulted in significant improvements in terms of spinal alignment compared to a static sleep system. In addition, the ability to change mattress characteristics dynamically was successfully used to detect intermediate postures (between lateral and prone), providing a proof of concept for the added value of dynamic classification algorithms. Results of overnight experiments demonstrated the stability of the control when subjects were not bound to prescribed postures and showed a positive effect on subjectively perceived sleep.

The multidisciplinary work presented in this thesis, was merely a first step towards creating a smart sleep environment. Several tools were developed and validated for ergonomic evaluation and control during sleep. Although a clear focus was put on the sleep system, a similar approach can be followed for other components of the sleep environment.

Beknopte samenvatting

Ergonomie wordt steeds belangrijker in de slaapsector omwille van de groeiende bewustwording van het belang van een individueel aangepaste slaapomgeving ter bevordering van het inslapen en doorslapen. Ergonomisch ontwerp van de slaapomgeving is echter een relatief jong onderzoeksdomein en vereist een multidisciplinaire samenwerking tussen slaapfysiologen, psychologen, ergonomen en ingenieurs; een uitdaging op zich. Deze doctoraatsthesis focust op één van de belangrijkste componenten van de slaapomgeving, met name het slaapsysteem (i.e. de combinatie van matras, bedbodem en hoofdkussen). Het werk draagt bij tot de huidige stand van de techniek door de implementatie van controle-algoritmes die toelaten de bedeigenschappen actief te wijzigen tijdens de slaap met als doel een continu geoptimaliseerde lichaamsondersteuning te garanderen. Bovendien werden alle ontwikkelde methodes gevalideerd tijdens overnachtingen in een daartoe bestemd slaaplaboratorium.

In eerste instantie werd het effect van de uitlijning van de ruggengraat op objectieve en subjectieve slaapparameters bestudeerd. Hiertoe werden slaapsystemen gebruikt met aanpasbare comfortzones om de uitlijning van de ruggengraat te wijzigen zonder andere variabelen te beïnvloeden. Twee goed gedefinieerde experimentele condities werden tijdens slaapstudies met elkaar vergeleken: een doorhangende ondersteuning en een gepersonaliseerde ondersteuning. Omdat de uitlijning van de rug afhankelijk is van de aangenomen slaaphouding, werd de hoeveelheid tijd in elke houding beschouwd als een beïnvloedende factor in de analyse van de resultaten.
Daarnaast werd een methode geïntroduceerd om bewegingspatronen onmerkbaar te registreren tijdens de slaap. Een algoritme werd ontwikkeld om automatisch bewegingen en slaaphoudingen te detecteren op basis van geïntegreerde indrukkingsmetingen in de matras. Deze methode werd in slaapstudies gevalideerd aan de hand van polysomnografie en video-opnames.
Vervolgens werd een methode uitgedacht om de vorm van de rug te beoordelen zonder de slaap te verstoren. Om dit te verwezenlijken werd een oppervlaktemodel ontwikkeld dat de vorm van het menselijk lichaam voorstelt

en dat kan gepersonaliseerd worden op basis van specifieke anthropometrische informatie (afgeleid uit de gemeten lichaamscontouren). Een intern skeletmodel liet toe om afzonderlijke slaaphoudingen te simuleren. Verder werd een algoritme geïmplementeerd om het gepersonaliseerde model automatisch in te passen in de gemeten matrasindrukking met als doel de vorm van de rug te voorspellen. Validatie gebeurde aan de hand van simultane 3-D scans van het rugoppervlak in zijlig.

De integratie van de voorgaande algoritmes in de terugkoppeling van een controlesysteem maakte het mogelijk om de uitlijning van de ruggengraat te optimaliseren door de mechanische eigenschappen van acht comfortzones continu te controleren tijdens de nacht. De performantie van dit controlesysteem werd niet alleen bepaald tijdens ligtesten, waarbij verschillende voorgedefinieerde houdingen werden doorlopen, maar ook tijdens overnachtingen in het slaaplaboratorium.

Ten slotte werd ook het effect bestudeerd van zo'n dynamische controle van het slaapsysteem op slaap. Hiertoe werd het dynamische slaapsysteem vergeleken met een standaard (statisch) slaapsysteem. Polysomnografie en afname van vragenlijsten zorgden voor zowel objectieve als subjectieve uitkomstmaten. De resultaten die voortvloeien uit dit werk tonen aan dat de uitlijning van de ruggengraat wel degelijk de slaap kan beïnvloeden. In de eerste plaats blijkt dat persoonlijke voorkeuren inzake slaaphouding bepalend zijn voor de mate waarin men een negatief effect ondervindt van een doorhangende ondersteuning. Meer specifiek vertoonden personen met een voorkeur voor buik- en zijlig een verslechterde slaap op een doorhangende ondersteuning, terwijl dit niet het geval was voor rugslapers.

De resultaten van een tweede studie geven aan dat het mogelijk is om op basis van een continue meting van de matrasindrukking lichaamsbeweginen en slaaphoudingen te detecteren. Bewegingsdetectie op basis van matrasindrukking was gevoeliger dan op basis van actigrafie. Daarnaast werd ook een hoge nauwkeurigheid bereikt voor de automatische classificatie van indrukkingsbeelden in ruglig, linker zijlig, rechter zijlig en buiklig met behulp van vijf beeldkenmerken.

Om de vorm van de rug te kunnen beoordelen volstond het niet om de vervorming van de matras te meten. Echter, in combinatie met gepersonaliseerde modellen van de lichaamsvorm bleek het mogelijk om een goede inschatting te maken van de lijn doorheen de doornuitsteeksels van de rug.

Ten slotte volgt uit de resultaten dat een actief gecontroleerd slaapsysteem resulteert in een significante verbetering van de uitlijning van de rug in vergelijking met statische slaapsystemen. Daarenboven werd aangetoond dat een actieve sturing van matraseigenschappen toelaat om ook tussenliggende houdingen (tussen zijlig en buiklig) te detecteren. Overnachtingen in een slaaplaboratorium bevestigden de stabiliteit van het controlesysteem en toonden een positief effect op de subjectief waargenomen slaap.

Het multidisciplinair werk in deze thesis was slechts een eerste stap naar de ontwikkeling van een slimme slaapomgeving. Verscheidene methoden werden uitgewerkt en gevalideerd voor ergonomische beoordeling en controle tijdens de slaap. Niettegenstaande de duidelijke focus op het slaapsysteem kan een vergelijkbare aanpak ook gevolgd worden voor andere componenten van de slaapomgeving.

List of Symbols and Abbreviations

ACS	active support
AS	lateral asymmetry matrix
BM	body movements
BMI	body mass index
C7	seventh cervical vertebra
CAP	cyclic alternating pattern
CI	consolidation index
COI	center of indentation
DC	direct current
DHM	digital human modeling
dm	midpoint between the dimples of the posterior superior iliac spine
DOF	degree of freedom
EEG	electroencephalogram
EMG	electromyogram
EOG	electrooculogram
EPS	Epworth sleepiness scale
FE	finite element
HR	high resilient
in	induction
k	spring stiffness coefficient
KSS	Karolinska sleepiness scale
L1	first lumbar vertebra
L5	fifth lumbar vertebra
LAI	lateral asymmetry index
N1	stage 1 NREM sleep
N2	stage 2 NREM sleep
N3	stage 3 NREM sleep

NLR	negative likelihood ratio
NPV	negative predictive value
NREM	non-rapid eye movement
OSAS	obstructive sleep apnea syndrome
PC	posture changes
PI	period of immobility
Pi	spine shape parameter, i= 1-7
POMS	profile of mood states
PPI	period of postural immobility
PPV	positive predictive value
PSG	polysomnography
PSL	persistent sleep latency
PSQI	Pittsburgh sleep quality index
PU	polyurethane
re	reference
REF	reference
REM	rapid eye movement
RMSE	root mean square error
SACL	stress arousal adjective check list
SEI	sleep efficiency index
SEMG	surface electromyography
SOL	sleep onset latency
SSS	Stanford sleepiness scale
SST	sleep stage transitions
SVM	support vector machine
SWS	slow wave sleep
TIB	time in bed
TST	total sleep time
UCL	upper critical limit
VAS	visual analogue scale
vp	vertebra prominens
W	wakefulness

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Among the various factors that influence sleep, external factors are probably the easiest to control. Therefore, it is surprising to find out that little scientific research is available on the influence of external factors on sleep and how sleep quality can be improved by managing the external environment. An important component of the sleep environment is the sleep system (i.e. mattress, bed base and pillow) that supports the human body at night. Ergonomic design of sleep systems aims at optimizing bed properties to achieve maximal recovery during sleep and therefore requires a multidisciplinary approach bridging the expertise of sleep physiologists, psychologists, ergonomists and engineers. By adopting such a multidisciplinary approach, this thesis aims at developing a dynamically controlled sleep system that continuously optimizes body support during sleep.

This chapter introduces the basic concepts of sleep and provides an overview of various kinds of sleep system technologies. Moreover, a literature review is given on the effect of sleep system properties on sleep and on the available assessment tools regarding ergonomic design of sleep systems.

Synopsis

Ergonomic aspects of sleep are gaining importance in order to develop individually optimized sleep environments promoting sleep initiation and maintenance. This PhD dissertation focuses on one of the main environmental components the sleeping body interacts with, namely the sleep system (i.e. the combination of mattress, bed base and pillow). The presented work contributes to the state-of-the-art in bed design by integrating control algorithms that allow changing bed properties actively during sleep in order to continuously optimize body support. Furthermore, the developed tools are validated during overnight experiments in a dedicated sleep laboratory. First, the effect of spinal alignment on sleep is experimentally verified. Secondly, the ergonomic assessment tools are described that — when combined — allow for continuous optimization of spinal alignment during sleep. A final step closes the loop by verifying the effect of such actively controlled sleep systems on sleep.

This introductory chapter starts with providing background information which is necessary to fully apprehend the used methodologies of the following chapters. The first section elucidates the most important aspects of modern sleep research, including the sleep assessment techniques that are used throughout this work. Next, an overview is given of the various kinds of sleep system technologies that are currently available on the consumer market.
After providing the necessary background, the chapter continues by reviewing scientific literature with respect to ergonomic design of sleep systems. Several studies have been performed investigating the effect of mechanical sleep system properties on quality of body support. Other studies focus on the effect of various sleep system technologies on sleep quality. Both approaches are discussed and the main methodological issues are pointed out. Finally, a review is given on the main methods for assessing bed properties, including unobtrusive alternatives that might be suited for long-term home monitoring.
The introduction concludes by listing the main voids in literature and clarifies how this dissertation aims at filling some of these voids. The general research hypothesis is provided along with the scientific objectives that need to be accomplished in order to confirm or reject the stated hypotheses.

1.1 The sleep process

1.1.1 Sleep and society

During the last century two phenomena can be observed in human sleep-wake behavior: an increase in self-induced sleep shortage and an increase in sleep loss. The former reflects the fact that we sleep less due to a changed socio-economic life style, the latter indicates the non-voluntary reduced amount of sleep that is experienced by poor sleepers [20].

Compared to one century ago we sleep about 1.5 hours less per night. For middle age American individuals the average amount of self-reported sleep decreased by one hour per night between 1959 and 1992 [104, 18]. In 2008, a national survey of adult Americans who work at least 30 hours per week reported average sleep duration of 6 hrs 40 min on workdays and 7 hrs 25 min on non-workdays [140]. A similar trend, though less explicit, is observed in European populations [105]. Most of this reduction in sleep time has been attributed to voluntary sleep restriction due to clear changes in our socio-economic lifestyle, e.g. more and more activities are planned in the evening while increased commuting time forces people to leave for their job earlier in the morning. Many even work in shifts divided over the 24 hour period. This evolution towards a 24 hour society imposes a lot of challenges, not only in terms of its effect on sleep and general health, but also in terms of decreased efficiency and productivity. The cost of sleepiness-related accidents can be serious, the estimated total cost of such accidents per year being US$80 billion worldwide [132]. Sleepiness at the wheel, sleep restriction and nocturnal driving have been incriminated in 20% of all types of motor vehicle accidents [147, 61]. Tragedies such as Chernobyl, Three Mile Island and Bhopal have been linked to sleep loss [150] and the consequent failures in executive functions such as judgment, logic, complex decision-making, memory, vigilance, information management and communication. These processes are most affected by fatigue and sleepiness resulting from sleep shortage [159, 56].

Insomnia is commonly defined as an inability to obtain sufficient sleep in the presence of adequate opportunity and willingness to sleep [158]. It is characterized by one of the following features: difficulty getting to sleep (sleep initiation), difficulty staying asleep (sleep maintenance) and waking up too early. These disturbances may cause perceivably minor next-day effects, such as yawning or feeling tired, but often give rise to serious and far-reaching implications concerning one's own health as well as others'. One of the problems in understanding the development of chronic insomnia is that almost all empirical research on insomnia has studied patients with chronic psychophysiologic insomnia. In truth, a much larger segment of the population suffers from occasional or situational insomnia, defined as poor sleep related to specific stressful circumstances, such as a new sleep environment (first-night effect), situational stress, circadian shifts, or intake of stimulants [21]. When the situation passes, sleep returns to normal. It is believed that poor sleep in these unusual circumstances may depend on individual sensitivity to the situational stress and that responding individuals may be at risk for developing chronic insomnia and other associated disorders [21]. Epidemiological studies from all over the world have reported a lifetime prevalence rate ranging from 36% to 40% for occasional insomnia and 9% to 17% for chronic insomnia [12, 141]. Health risks that have been reported in relation to sleep restriction are increased heart rate and blood pressure [183], increased inflammation [130], impaired glucose tolerance [175], increased hunger/appetite [177], and decreased immune function [176]. Recently, and very significantly, it was shown that untreated insomniacs have a 2 to 3 times higher risk to develop major depression [161, 174, 54]. Consequently, insomnia accounts for increased healthcare costs and services, patients with moderate to severe insomnia see their physicians 2.5 times more often and are admitted to the hospital nearly twice as much as those without insomnia [115]. Up to now, the treatment of insomnia consists in most cases only of the use of hypnotics and anxiolytics, the use of which remains a source of controversy amongst prescribers [53].

In conclusion it is clear that sleep loss, whether from disorder or lifestyle, whether acute or chronic, has a substantial impact on social welfare and poses a significant cost to society, which is often underestimated [160].

1.1.2 Sleep stages and sleep regulation

The idea of sleep being a passive state has evolved substantially since the first description of the repeating stages of the human sleep cycle [119, 49]. Human sleep is characterized by the cyclic recurrence of non-rapid eye movement (NREM) sleep and rapid eye movement (REM) sleep. NREM sleep can be further divided into stages 1, 2, 3, 4. According to the new regulations of the American Academy of Sleep Medicine (AASM), stages 3 and 4 should be considered as one sleep stage resulting in 3 NREM phases (N1, N2, and N3) [88]. During a sleep cycle the stages progress from stage N1 to REM sleep. Overall we spend approximately 50 % of our sleep time in stage N2, about 20 % in REM sleep and the remaining 30 % in stage N1 (5-10%) and N3 (20-25%). However, the different sleep stages are not evenly distributed over time, the earlier sleep cycles showing more N3 sleep and the later cycles showing longer periods of REM sleep. N3 is often referred to as deep sleep or slow wave sleep (SWS) because of the difficulty of waking from N3 and the low frequency/high amplitude brain waves that characterize this particular sleep phase. During REM sleep, synchronous rapid eye movements are seen and heightened cerebral activity occurs simultaneously with atonia in the major voluntary muscle groups. Clearly sleep is an active and dynamic state indicated by variable and complex brain activity.

The main determinants of sleep-wake regulation have been described in the two-process model of Borbély and Acherman: a sleep/wake dependent homeostatic Process S (the longer we are awake, the higher the probability to fall asleep) and a circadian Process C (we normally sleep in a specific time frame within the 24 hour day) [23, 170]. Both processes interact via a key switch in the hypothalamus (the flip-flop switch model) to allow consolidated sleep [164].

1.1.3 Assessment of sleep

Polysomnography

Polysomnography (PSG) is the most commonly used diagnostic tool in the study of sleep disorders. A standard PSG consists of the simultaneous recording of four electrophysiological signals, namely 1) cerebral activity recorded via the electroencephalogram (EEG), 2) ocular movement via the electrooculogram (EOG), 3) muscular tone via the sub chin electromyogram (EMG), and 4) cardiac activity via the electrocardiogram (ECG). EEG electrodes are attached according to the standardized 10-20 system of electrode placement [92] at the F3, C3, O1, F4, C4, and O2 positions. Left EEG channels (F3, C3, O1) are recorded against the right mastoid (A2) and right EEG channels are recorded against the left mastoid (A1). EOG electrodes are positioned bilaterally 1 cm below the left outer canthus and 1 cm above the right outer canthus. EMG surface electrodes are positioned submentally. ECG is recorded with two precordial electrodes.

The combination of these signals allows differentiating between sleep stages at 30 sec intervals according to the internationally adopted guidelines formulated by Rechtschaffen and Kales [152] and the recent revision brought by the AASM [88]:

- Stage W (wakefulness): epochs containing more than 50% of alpha activity (8-12 Hz) in the occipital region or either eye blinks, reading eye movements or rapid eye movements associated with normal or high chin muscle tone.

- Stage N1: epochs containing more than 50% of low amplitude, mixed alpha and theta activity (4-7 Hz) with concomitant slowing of W background frequencies or slow, rolling eye movements.

- Stage N2: epochs containing sleep spindles (sudden burst of increased frequency, 12-14 Hz) and/or K-complexes (brief negative, high amplitude peak followed by a slower positive complex and a final negative peak) on a background of low amplitude, mixed frequency EEG activity (mostly theta).
- Stage N3: epochs containing at least 20% of high amplitude delta activity (0.5-2 Hz).
- Stage REM: epochs containing low amplitude, mixed alpha and beta (12-30 Hz) activity associated with a low chin EMG muscle tone and rapid eye movements.

Sleep scoring is generally performed visually by sleep technicians having regular training to ensure an inter-rater agreement of more than 90%. The description of sleep stages in fixed 30 sec time intervals is represented in the hypnogram and is often referred to as the macrostructure of sleep. Figure 1.1 shows an example of a hypnogram of normal sleep with stage N3 predominating in the early sleep cycles and REM sleep in the later cycles. Figure 1.2 illustrates some sample brain waves for each sleep stage. A variety of sleep parameters can be derived from the hypnogram and compared in a between or within subject experimental design. Table 1.1 gives an overview of some commonly used parameters related to sleep continuity (sleep initiation and maintenance) and sleep architecture (distribution of sleep stages).

Studying sleep by means of macrostructure analysis implies some important limitations. Due to the analysis of epochs with a fixed time duration, the method is not flexible enough to recognize short-lasting events or to analyze the temporal relationship between such events in different channels. To overcome these limitations several descriptors of sleep microstructure have been proposed, such as sleep spindles, K-complexes, arousals and cyclic alternating patterns (CAP) [121, 133]. Furthermore, all-night spectral analysis by means of a Fast-Fourier transform routine, typically on one of the central channels, reveals additional information on the power density in different frequency bands (e.g. slow wave activity, slow delta, fast delta, theta, alpha, spindle frequency activity, beta and gamma). Power density data are expressed in each frequency band as percentage of the corresponding baseline values [7, 111].

Although PSG recordings are considered the gold standard for the assessment of sleep, its main drawback is that it needs to be done in a formal sleep laboratory under the supervision of a technician, which involves high costs. Secondly, since the particular measurement conditions do not reflect regular sleep conditions, it has been suggested that PSG is not an appropriate tool to diagnose extrinsic sleep disorders such as those related to environmental

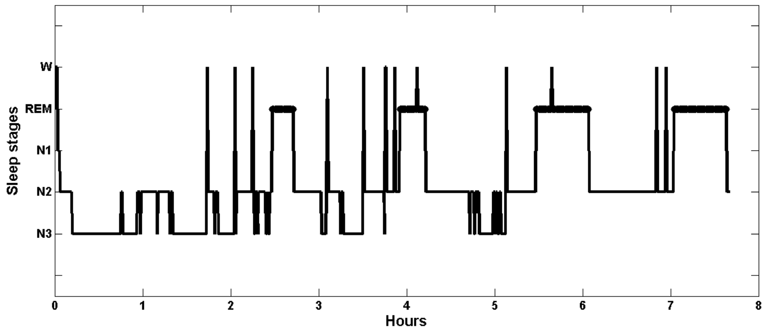

Figure 1.1: Hypnogram representing normal sleep

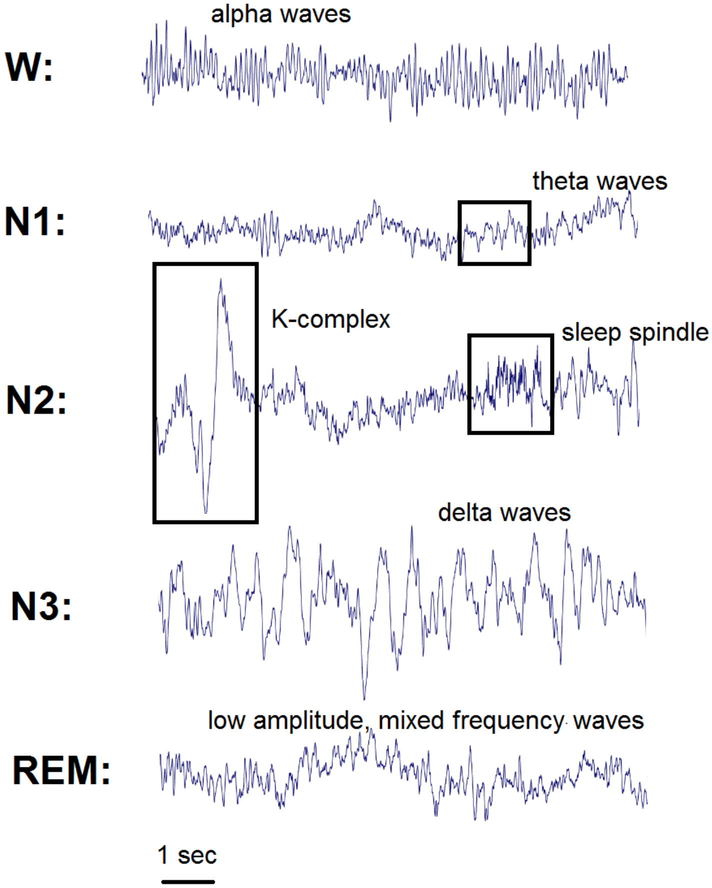

Figure 1.2: Sample brain waves for the different sleep stages

Table 1.1: Non-exhaustive list of commonly used parameters derived from the sleep hypnogram related to sleep continuity (initiation and maintenance) and sleep architecture (distribution of sleep stages)

Variable	**Abbreviation**	**Definition**	**Unit**
Sleep initiation			
Sleep onset latency	SOL	Time from lights out to first sleep epoch (N1, N2, N3 or REM)	min
Persistent sleep latency	PSL	Time from lights out to first 10 minutes of consecutive sleep (N1, N2, N3 or REM)	min
Sleep maintenance			
Time in bed	TIB	Total time spent in bed	min
Total sleep time	TST	Duration of all sleep stages (N1, N2, N3 and REM)	min
Sleep efficiency index	SEI	100∗TST/TIB	%
Total intrasleep wake time	ISW_T	Duration of all W episodes during sleep period time (SPT)	min
Number of intrasleep wake episodes	ISW_N	Total number of W episodes during SPT	N
Mean duration of intrasleep wake episodes	ISW_M	Mean duration of all W episodes during SPT	min
Number of sleep stage transitions	SST	Number of transitions between sleep stages	N
Sleep fragmentation index	FI_TST	Number of transitions from [N2/N3/REM] to [W/N1] during TIB divided by TST	N/h
Distribution of sleep stages			
Time spent in stage N1	ST1	Duration of all N1 episodes during TIB	min
% time in stage N1	ST1_TST	100∗ST1/TST	%
Time spent in stage N2	ST2	Duration of all N2 episodes during TIB	min
% time in stage N2	ST2_TST	100∗ST2/TST	%
Time spent in stage N3	SWS	Duration of all N3 episodes during TIB	min
% time in stage N3	SWS_TST	100∗SWS/TST	%
Time spent in stage REM	REM	Duration of all REM episodes during TIB	min
% time in stage REM	REM_TST	100∗REM/TST	%
REM activity	REMA	Number of REM during REM episodes	N
REM density	REMD	REMA/REM	N/h
REM latency	REM_L	Time from sleep onset to first REM epoch	min
SWS latency	SWS_L	Time from sleep onset to first N3 epoch	min

disturbance [19]. Finally, visual scoring of PSG recordings is tedious, time consuming and subject to observer bias. Consequently, software for automated staging of sleep and cardiorespiratory events is continuously being developed. This makes validation difficult, and currently there is no widely accepted fully automated polysomnographic analysis [32].

Actigraphy

Actigraphy is an increasingly popular tool to study sleep because it is cost-effective, easy to use and less invasive than PSG [182]. Actigraphs are small, usually wrist-worn, devices that detect body movements through accelerometry. The raw activity scores are translated to sleep-wake scores based on computerized scoring algorithms. In response to the growing number of research articles utilizing actigraphy, its use for sleep-wake identification has been subject to debate [149, 186]. In general, most studies validating actigraphic sleep-wake detection with PSG report high sensitivity values (90% or more) for the detection of sleep, but low to very low specificity (ranging from 20% to 60%) [143, 182], indicating a low ability of actigraphy to detect wakefulness. The issue of high sensitivity and low specificity is further addressed by Gale et al. who argued that some of the observed associations between sleep-wake estimates of PSG and actigraphy are due to statistical artifact [60]. This study raises the example that if both PSG and actigraphy indicate that sleep efficiency is 90%, the agreement rate will be at least 80%, even if every possible disagreement occurs. The art of developing algorithms for sleep-wake detection relies on maximizing both specificity and sensitivity or maximizing the area under the Receiver Operating Characteristic (ROC) curve. A recent review on the role of actigraphy in sleep medicine [163] concludes that the inability to properly detect quiet wakefulness makes it unsuited to analyze sleep in populations with poor sleep quality, even in healthy subjects submitted to sleep challenges. On the other hand, it is stated that actigraphy has reasonable validity and reliability in assessing sleep-wake patterns in normal individuals with average or good sleep quality. More specifically, the ability to easily collect data over long periods makes it a useful tool to study circadian rhythm cycles or to perform long term field studies [11, 190]. In conclusion, although actigraphy is useful in specific situations where PSG is difficult to record, it is always crucial to keep in mind that it only measures movements and not sleep per se. With this in mind, other measures have been suggested in addition to movement to increase the wake detection capacity of actigraphs. Most promising results were obtained with skin temperature [191] and hearth rate [29, 145], yet further validation needs to be done on the synergistic effect when combining such measures with standard actigraphic recordings.

Subjective assessment of sleep

Next to the objective assessment of sleep by measuring physiological parameters, another way of assessing sleep is by querying the individual's perception of sleep. Numerous self-rated questionnaires have been proposed, the most widely used being the Stanford Sleepiness Scale (SSS) [82], the Karolinska Sleepiness Scale (KSS) [8], the Epworth Sleepiness Scale (EPS) [93] and the Pittsburgh Sleep Quality Index (PSQI) [31]. The SSS and the KSS access the momentary degree of sleepiness and are useful in tracking symptoms during a given time epoch. The EPS offers a more appropriate method for assessing overall sleepiness [68]. The PSQI differs from the other scales in that it aims at providing a measure of global sleep quality instead of measuring sleepiness. It is based on a respondent's retrospective appraisal (of the past month) of a variety of factors related to sleep quality, including sleep latency, sleep duration, habitual sleep efficiency and daytime functioning. Other common approaches to assess subjective sleep parameters are the use of sleep diaries and visual analogue scales (VAS).

Sleep quality

Although the term "sleep quality" is often referred to in various studies, no established definition for the term has been generally accepted [106]. Sleep quality is sometimes inferred from a collection of parameters derived from the sleep hypnogram (table 1.1). However, it has been noted that some individuals have sleep complaints while having sleep onset latencies, sleep efficiencies, wake after sleep onset and awakenings that are comparable to those seen in normal, non-complaining individuals [35]. Therefore, "sleep quality" is sometimes used to imply an aspect of sleep that is orthogonal to sleep quantity, representing a complex phenomenon that is difficult to define and measure objectively [31]. In this sense, the term "sleep quality" can not yet be used as a comprehensive sleep parameter directly related to other (objective) sleep measures, but should be considered as an additional (subjective) outcome that describes variations in the experience of sleep itself.

1.1.4 The sleep environment

The environment plays a vital role in providing adequate conditions to initiate and maintain sleep. For instance, in the case of sleep disturbances it is observed that external factors are almost always involved in the perpetuating aspect of the condition. This section provides an overview of the most relevant environmental

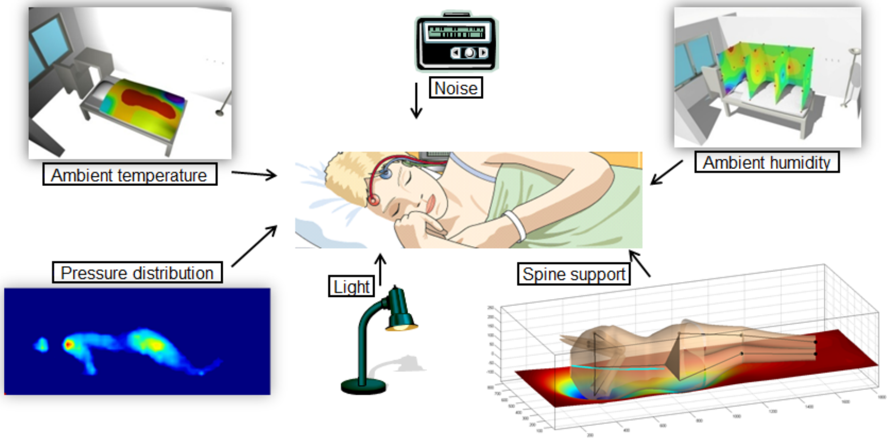

Figure 1.3: Environmental factors influencing sleep

factors related to sleep (figure 1.3). In-depth information on the separate factors can be found in the referred studies.

Noise

Worldwide, more individuals are exposed to environmental noise than ever before due to increased urbanization and industrialization. In their Guidelines for Community Noise, the World Health Organization (WHO) [17] recommended a maximum equivalent sound level of 30 dB(A) for continuous background noise and 45 dB(A) for individual noise events between 22h-06h, both measured indoors. Noise-induced sleep disturbances comprise primary effects such as awakenings, sleep stage changes, body movements, but also secondary effects such as excessive daytime sleepiness, impairment of mood and performance [67]. The strength of these reactions depends on a number of variables, for example acoustical variables, information content [139], individual sensitivity [43] and other situational conditions. Intermittent noise is found to be particularly disturbing [67]. Although habituation over successive noise-exposed nights exists in terms of nighttime awakenings, autonomic responses, such as heart rate changes and vasoconstriction, have been found not to habituate over time [135].

Light

Exposure to light influences the circadian rhythm, one of the two key determinants of sleep-wake regulation (see 1.1.2), characterized by the distinct rise and fall of body temperature, plasma levels of certain hormones (e.g. melatonin, cortisol) and other biological conditions at 24 hour intervals [51]. The action spectrum for melatonin suppression is situated between 440-480 nm, indicating that the circadian pacemaker is specifically sensitive to bright light [24]. Bright light administration is mainly studied to improve nocturnal alertness and daytime sleep of shift workers (e.g. by nocturnal bright light administration and attenuating morning light) [198] and as a treatment to improve rest-activity disruption in patients suffering from dementia or depression [118].

Thermal environment

One of the manifestations of the circadian rhythm is through the time course of core body temperature, which is linked with subjective sleepiness and the ability to initiate sleep [34, 63]. Sleep initiation typically occurs when the circadian core body temperature rhythm is declining and sleep onset latency is shortest around the circadian core body temperature minimum [40]. One of the key mechanisms behind the cyclic variations of core body temperature is peripheral heath loss [103]. At the beginning of the night, increasing skin blood flow in the body's extremities, due to vasodilatation, induces a greater heat dissipation leading to a decrease in body temperature. These thermoregulatory mechanisms are largely dependent on ambient temperature and humidity [134]. Warm and humid conditions reduce the amount of N3 and REM sleep and increase the amount and duration of awakenings [187]. In cold environments more wake time is observed and less REM sleep [28]. Most sleep studies have looked at the effect of rather extreme thermal conditions, far outside the thermal neutral zone (TNZ). Small deviations from the TNZ might lead to different findings.

Body support

Since the human body is incapable to control/stabilize the vertebral column actively during sleep, this function has to be taken over by the sleep system we lye on [71]. Body support during sleep is the result of the mechanical interaction between the sleep system and the human body and encompasses two main aspects: musculoskeletal support and pressure relief of soft tissues. Both aspects are related to physical (dis)comfort and may interfere with sleep [91]. A survey conducted in the United States estimated that 7% of sleep problems were related to an uncomfortable mattress [6]. However, the available scientific studies remain inconclusive on the effect of body support on sleep [90, 165, 14], partially due to many methodological issues (addressed in 1.3.3). A detailed literature review on this topic is provided in section 1.2.

1.1.5 Conclusion

This section introduced the basic concepts of sleep and the sleep environment. The main sleep assessment techniques were presented along with their advantages and disadvantages. Although no general definition of the term “sleep quality” has been generally accepted, throughout this thesis “sleep quality” will be considered as an additional (subjective) outcome that describes variations in the experience of sleep itself. As such it is not necessarily related to a collection of parameters derived from the sleep hypnogram.

1.2 Sleep system technologies

The sleep system is defined as the set of components that support the human body during sleep. It generally consists of a mattress (whether or not with separate topper), a bed base and a pillow. The combination of these components determines the overall behavior of the sleep system in terms of body support and thermal regulation, both of which should be adapted as much as possible to personal needs, preferably in an objective way. This section provides an overview of the most common types of sleep systems along with their main properties.

1.2.1 Mattresses

Most mattresses consist of three integrated components: the mattress core, the top layer and the mattress ticking. Figure 1.4 illustrates these three main components on a pocket spring mattress. In general, the mattress core determines the stiffness distribution whereas the top layer and mattress ticking comprise the comfort layer and mainly determine pressure distribution characteristics. However, it is important to note that, to a lesser extent, a bad choice of top layer might also inversely affect stiffness distribution and vice versa. Although a variety of materials have been developed for use in mattresses, the most common technologies remain foam- or spring based.

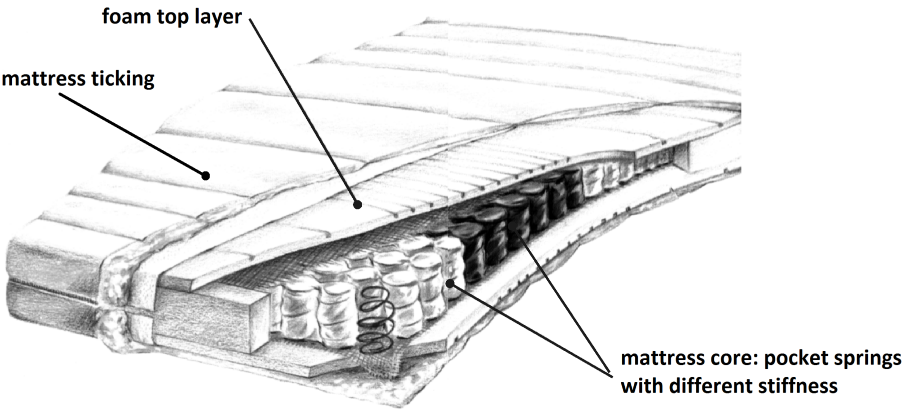

Figure 1.4: The three main components of a pocket spring mattress: mattress core, top layer and mattress ticking. Adapted from Haex 2005 [71].

Mattress cores

The most commonly used foam material is polyurethane (PU); a synthetic, petroleum based material that consists of a cellular network with a specific density, elasticity and permeability. With respect to bedding applications, standard polyurethane cells are characterized by an open cell structure which can be adjusted to achieve a wide variety of material properties. A distinction can be made between polyether foam, high resilient foam and viscoelastic foam. Polyether (PE) is the most basic type of polyurethane foam and can be produced in a variety of densities. It is commonly used in mattresses in the medium/low quality range. High resilient (HR) foam — also called cold foam — achieves good elastic properties and a good resistance to fatigue at relatively low densities. It has an irregular, open cell structure, which is beneficial for breathability and moisture regulation. HR foam is often used in mattresses of the medium/high quality range. Visco-elastic foam — also called slow foam or memory foam — is made from PU with additional chemicals that increase the foam's hysteresis and density, making it slower to recover. Moreover, high density memory foams have temperature dependent elastic properties. Body heat softens the material, allowing it to mold to the body and distribute pressure over a large contact area. This behavior is especially favorable in clinical settings in order to prevent decubitus ulcers. Polyurethane mattress core properties may vary along the length of the mattress to create different comfort zones, such as a softer shoulder zone and a firmer waist zone [71]. Next to their use in mattress cores, low density PU foams are commonly used in mattress top layers as well.

Latex foam mattresses consist of foamed rubber particles gained either naturally from the sap of the Hevea brasiliensis tree or synthetically derived. The addition of vulcanizing agents, such as sulfur, converts natural latex into a stable, durable substance. Furthermore, compressed air is added to create a foam, making it suitable for use in mattresses. Since World War II, initially due to lack of availability of natural rubber, the petrochemical industry has developed a variety of synthetic substitutes for natural latex. Nowadays synthetic latex is increasingly being used in the mattress industry — mostly in combination with natural latex — due to its cost-effectiveness and stability in delivery. Today, two methods are used to synthesize latex foam for use in mattresses: the Dunlop method (1931) and the Talalay method (1965). The Talalay method is considered the premium process as it results in more evenly distributed cells and a more consistent cell structure. Thanks to adequate mold design different patterns of material cut-away can be achieved to create heterogeneous mattress cores with distinct elastic behavior along the length of the mattress [71]. Analogous to PU foams, lower density latex foams are commonly used in mattress top layers whereas the higher density foams are used in mattress cores.

Inner spring mattresses are very popular around the world because they are generally considered reliable, well-experienced products. They exist in all kinds of shapes and dimensions. Elastic behavior of individual springs can be easily adapted by varying wire thickness. Considering spring shape, three main types can be distinguished: bi-conical, cylindrical and barrel-shaped springs. Bi-conical springs — also called "Bonnell springs" — are hour-glass shaped compression springs, mounted independently next to each other, linked by spiral wires on both sides. Unlike cylindrical springs, Bonnell springs have no constant spring rate but offer an enlarged resistance against increased loading [71], as shown in figure 1.5. Pocket springs are mostly cylindrical or barrel-shaped and are individually wrapped in a fabric encasement, assuring a very good point-elasticity (individual springs are able to deform almost independently from each other). Furthermore, the encasement allows pre-compression of the spring coil, which in turn affects elastic behavior by increasing the initial load needed to deflect the spring. Next to standard metal springs, more and more synthetic springs are being used as well. All inner spring mattress cores require a top and bottom foam layer to assure adequate sleep comfort.

Top layers

Whereas mattress core properties mainly determine the global deformation characteristics of the mattress, top layer properties play a role in how the support provided by the mattress core is translated into local loads acting on the skin. The top layer is defined as the collection of material layers between the

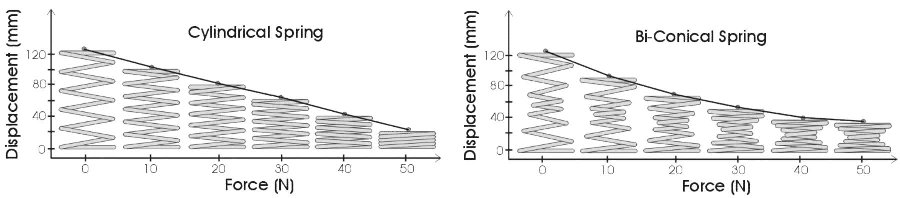

Figure 1.5: Force displacement curves of cylindrical (left) and bi-conical (right) springs. Adapted from Haex 2005. [71].

mattress core and the quilt. Next to latex foams and PU foams, other commonly used top layer materials include silk, wool, cashmere, goose down, cotton fibers and coconut fibers. Recently, structured polymer gels are increasingly being used in mattress top layers as well.

Mattress tickings

Mattress tickings, i.e. the protective fabric cover encasing the mattress, have long been considered as mattress components that were merely necessary for holding the other components together. Fortunately, nowadays mattress tickings have gained merit because of the various requirements they have to meet. The ticking acts as the interface between the sleep system and the human body and therefore plays a role in body support (e.g. a softer shoulder zone requires a stretchable ticking in order to properly contour the body), humidity regulation and bed hygiene (e.g. reducing allergens such as house dust mites). A variety of fabrics have been used, including natural (wool, silk, cotton and linen) and synthetic materials (acrylic, polyester, rayon and nylon) [71]. Apart from intrinsic material properties of the fabric fibers, ticking materials also differ in the manner of construction. In general, knitted textiles are much more elastic than woven textiles, which is why they are increasingly being used in mattress tickings, especially for medium/high quality mattresses. A few layers of padding are sometimes stitched to the bottom of the ticking fabric, the so called quilt. Apart from its decorative effect, the density and pattern of the quilt also affect the elastic behavior of the ticking, a tightly quilted ticking being more firm than a ticking with a widely spaced quilting pattern. Recently, numerous innovations have been made in the field of mattress tickings; including 3D knitted fabrics to improve moisture regulation and pressure distribution, incorporation of phase changing materials to balance temperature swings, triggered release of fragrances, etc.

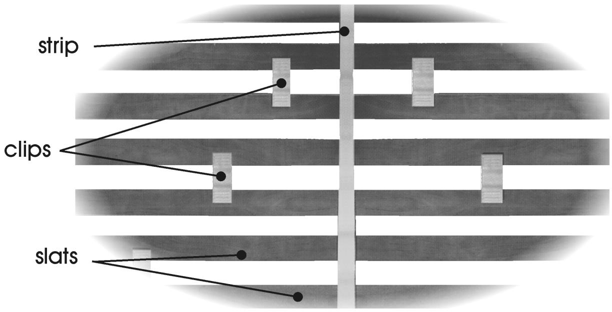

Figure 1.6: Sliding clips between slats allow adjustment of bending properties. Adapted from Haex 2005. [71].

1.2.2 Bed bases

Different kinds of bed bases have been developed to support mattresses. In the Western world the most commonly used bed bases are rigid bases, slatted bases, spiral bases and box springs [71].

In general, rigid bases, such as wooden platforms, have poor support and ventilation properties. Rigid bases are very firm, offering inferior support properties, especially in combination with homogeneous mattresses. The addition of perforations improves ventilation characteristics slightly, yet frequent aeration remains important to avoid mildew formation at the bottom of the mattress [71].

A slatted base consists of a frame on which slats are fixed perpendicular to the cranio-caudal direction. Slats are traditionally fabricated in wood and are attached to the frame separately by means of synthetic slat suspensions. Some suspensions allow the slats to cant or bend in various directions, improving general support quality. Alternatives to wooden slats are fiber glass profiles. Their high mechanical stiffness assures equal elastic behavior over the entire width, yet requires flexible slat suspensions to conform to the mattress. Comfort zones with different stiffness properties can be created by varying the bending stiffness of the slats, or by varying the stiffness of the suspensions. More advanced systems allow a manual adjustment of the stiffness properties of the comfort zones, for example by mechanically linking two slats with sliding clips (figure 1.6) or by adjusting the height of the slat suspensions.

Mesh bases consist of double-twisted steel wire that is woven into a network and spanned across the width of a metal frame. They are known to have premium ventilation characteristics due to their open structure. Different comfort zones can be created by applying variable tensions across the wires along the length of the bed system. Adjustable comfort zones can be provided by means of cuts across the width of the mesh that can be controlled in length by means of sliding clips (similarly as with slatted bases, figure 1.6).

Box springs generally consist of the same components as spring mattresses, yet feature heavy-duty springs that offer a firm mattress support. Some box springs have a “coil upon coil” design in which the springs of the box spring match those of the mattress. Box springs provide extra shock absorption across the entire mattress surface. Together with the absence of hard edges this additional shock absorption gives rise to a softer feel compared to other bed bases. Comfort zones are easily integrated by using different coil thickness along the length of the mattress. Some high end systems also allow adjusting stiffness properties manually by means of preloading the spring units or by means of interchangeable, modular comfort zones.

1.2.3 Fluid-based systems

Other common technologies include so-called fluid-based beds: waterbeds and air beds. It is a common misconception that standard (free flow) waterbeds provide optimal body support because of their conformance to the human body. In fact, this is only partially true. In terms of pressure relief, the distribution of pressure over a larger contact area avoids concentrated pressure points. However, the conformation of waterbeds to the body does not necessarily provide proper musculoskeletal support. Because of the incompressibility of water the water volume that is pushed away by heavy body parts flows to other mattress zones, effectively lifting light-weight body parts. Consequently, the heavy pelvic zone will cause the shoulder region — which is relatively light due to the presence of the air-filled lungs — to rise. This phenomenon often results in improper spinal alignment, particularly in lateral sleep postures. Therefore, modern systems consist of several independent fluid chambers and are often combined with foams or coils to provide structural support and minimize wave motion. Furthermore, most types of waterbeds are able to individually adjust temperature. Today’s air beds are designed to resemble traditional mattress/bed base combinations. Distinct air chambers are completely enclosed with foam and controlled electronically to pump and release air in and out of the mattress in order to adjust stiffness distribution at will.

1.2.4 Pillows

The main function of the pillow is to provide cervical support in order to bring the cervical spine in alignment with the other parts of the vertebral column. In general, pillows can be classified according to their height (high or low) or according to their degree of deformability. A variety of materials are used, including feathers, foams (various kinds of PU and latex) and springs. From an ergonomic point of view, the selection of a suitable pillow should be performed considering the other components of the sleep system as well. For instance, for lateral sleepers the amount of shoulder indentation allowed by mattress and bed base partially defines optimal pillow height (together with anthropometric features). Therefore, a lot of people are accustomed sleeping on high pillows that compensate for the rather small amount of shoulder indentation provided by traditional, homogeneous sleep systems. In any case, pillow selection should also take into account personal pillow use (e.g. preferred sleep posture; embracing, folding or crumpling the pillow; etc.).

1.2.5 Conclusion

Over the last decades, the bedding industry has known a proliferation of new technologies and materials being deployed in all components of the sleep system. The majority of these innovations claim to provide significant improvements in terms of body support, thermal regulation or sleep quality in general. However, it should be noted that rather few of these claims are supported by scientific evidence.

1.3 Ergonomics and sleep: a literature review

1.3.1 The effect of sleep systems on body support

Body support during sleep is the result of the mechanical interaction between the sleep system and the human body and encompasses two main aspects: musculoskeletal support and pressure relief of soft tissues.

Musculoskeletal support

The main function of a sleep system is to provide body support during sleep in a way that allows the musculoskeletal system to recover from daily activities

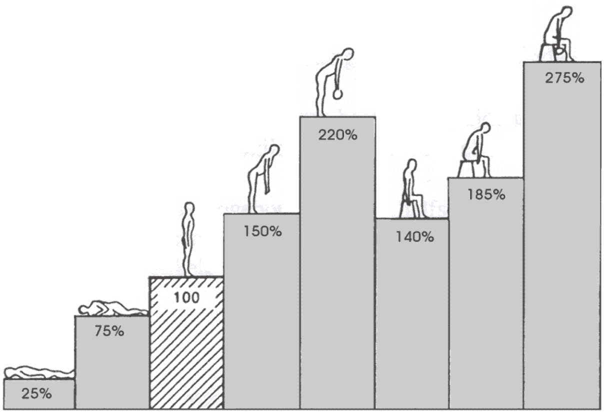

Figure 1.7: Relative change in intradiscal pressure in the third lumbar disc in various postures. Adapted from Nachemson 1976 [138].

[66]. In upright postures the vertebral column is continuously loaded along the spine, resulting in a total height loss of 15 to 20 mm or approximately 1% of total body height [153, 188]. A similar height gain appears in recumbent postures. The intervertebral discs appear to be the only reasonably likely tissues to be undergoing sufficient height change to produce such body height changes. Whether this is occurring by means of annular fiber strain or by means of fluid loss remains unclear [102]. Since the intervertebral disc is an avascular structure it depends for its nutrient supply on two processes: diffusion and fluid flow. Diffusion occurs as a result of a chemical concentration gradient, whereas fluid flow is caused by pressure changes on the disc. High pressure causes fluid to be expelled from the disc, while low pressure allows fluid to be sucked in from surrounding tissue [5]. Intravital pressure measurements in both lumbar and thoracic discs have shown that intradiscal pressures are minimal when lying down [136, 137, 148], indicating that during bed rest the intervertebral discs are rehydrated. This statement is supported by Wilcke et al. [197] who found that intradiscal pressure substantially increased during sleep, presumably because of disc rehydration. Pressure increased after 7 hours in a recumbent posture up to 240% of the pressure at the time of going to bed. No consensus has been reached on the effect of different lying postures on intradiscal pressures. Whereas Nachemson [136] found a threefold lumbar pressure increase from lying supine to lying lateral (figure 1.7), Wilke et al. [197] found no differences between supine, lateral and prone postures. Thoracic pressure was found to be 1.5 times higher in lateral postures compared to prone [148]. At present, no information is available on the effect of sleep system properties on intradiscal pressures.

During sleep, the muscles are relaxed and therefore generate a minimal amount of active force. Stabilization of the vertebral column is therefore the result of the force equilibrium between the gravitational forces acting on the human body, the reaction forces provided by the sleep system and the inner forces acting on the intervertebral joints. This force equilibrium determines the deformation of the soft tissues of the musculoskeletal system (e.g. the intervertebral discs and ligaments) and the resulting shape of the spine. Optimal spinal recovery takes place when the spine is in its natural physiological shape, yet with slightly flattened lumbar lordosis due to the changed orientation of the working axis of gravity with respect to the craniocaudal direction [52]. In other words, the spine should adopt its unloaded shape, as experienced by astronauts during weightlessness [112]. It is hypothesized that this theoretical optimum can be represented by a smoothing spline through the spine shape, as measured during stance. In order to approximate this optimal shape, the mechanical characteristics of the sleep system should account for two anthropometrical aspects: body contours and weight distribution [146]. For this reason, current sleep systems consist of separate comfort zones with different stiffness for shoulder, waist and pelvis [72]. Since body contours and weight distribution are highly individual features, a personalized approach is of primary importance when assigning a sleep system to a specific person [71]. Furthermore, the body contour that interfaces with the mattress surface depends on the adopted sleep posture. For instance, in most Caucasian people lateral contours are far more pronounced than sagittal contours. Therefore, changing sleep posture would require the sleep system to change accordingly. At present, such so-called “smart sleep systems” are not yet discussed in literature.

Surprisingly little research is available that quantifies the influence of sleep system characteristics on spinal alignment. Ray tested more than 40 subjects on 9 different mattresses in a supine posture [151]. Support quality of the mattresses was evaluated by calculating the average deviation between the (estimated) supine spine shapes and the spine shape during stance. Results show large interpersonal differences depending on the subjects’ main physical characteristics (age, weight, sex, body contours). Haex et al. developed a simplified 2-D finite element model of the combination human-mattress to predict the curvature of an individual’s vertebral column when lying on a specific sleep system [72]. Although they found low correlation between the predicted and measured spinous processes, the large differences between the three different mattresses allowed identifying the best one for each individual. Lahm and Iaizzo studied the physiological response of 22 back pain free participants during a 30 min trial on a sleep system at three levels of firmness [108]. They reported no difference in EMG activity, heart rate, blood pressure and subjective comfort. In contrast, spinal alignment was significantly improved at mid-range and higher firmness levels. Finally, De Vocht et al. evaluated spinal alignment in lateral postures on four ‘top of the line’ mattresses in a male population [50]. Significant differences were found at the T1/T3 and the T6/T8 spinal segments. Interestingly, measurement of contact pressure revealed inconsistent results; the mattress with the lowest spinal distortions tended to have the highest maximal contact pressure.

Considering the high societal costs of low-back pain due to its increasing prevalence rate in the working population [171, 122], it is not surprising that various studies have looked into the role of sleep systems in the development and maintenance of low-back pain. In healthy people, sleep system characteristics may trigger pain in the morning [100] whereas chronic sufferers of low-back pain are known to be extra sensitive to mattress quality in relation to their sleep [57]. In a survey of orthopaedic surgeons conducted in 1996, 95% believed that mattresses played a part in the management of low-back pain, with 76% recommending a firm mattress [117]. The belief in the orthopaedic community of firmer mattresses offering better support is supported by an earlier study concluding that hard beds should be recommended to patients with chronic low-back pain [62]. In 2003, Kovacs et al. challenged the conception that firmer is better in a randomized, double-blind, controlled multicenter trial on a total of 313 adults suffering from chronic non-specific low-back pain [101]. Patients were randomly assigned a firm or medium-firm mattress. Pain when lying in bed, pain on rising and the degree of disability after a period of 90 days were assessed and compared to baseline. They concluded that, although results showed improvements for both mattresses, the use of mattresses with medium firmness improved the clinical course of low-back pain in a higher proportion of patients than the use of a firm mattress. After the study by Kovacs and colleagues, clinicians were suggested to recommend medium-firm mattresses for patients with chronic non-specific low-back pain [127]. Although Kovacs’ results were supported by other studies [131, 90, 89, 16], the recommendation of specific mattress types to patients with low-back pain remains subject of discussion [70], which is not surprising since the exact etiology of low-back pain is currently unknown [138, 38].

Pressure relief

Whereas musculoskeletal support is defined by the global deformation of the human body when lying on a sleep system, pressure relief is related to the local stresses on the skin. More specifically, the global forces providing musculoskeletal support are transferred from the sleep system to the human body by means of local pressure and shear loads acting on the skin. These local mechanical loads on the body surface lead to stresses and strains in the underlying soft tissues. When maintained for too long, blood flow and tissue oxygenation might be affected. In healthy subjects, local tissue ischemia (i.e. restriction in blood supply) generates metabolic substances that stimulate the nerve extremities, causing the person to change posture [71]. However, if the subject is not able to move, the combined effect of loading time and intensity may result in the development of decubitus (i.e. pressure ulcers). Therefore, pressure relieving qualities of sleep systems are considered of primary importance and should gain priority over musculoskeletal support when considering bedridden patients.

It has been known for quite a while that both the intensity and the duration of pressure loads play a role in the development of pressure ulcers [99, 155]. Many authors have been looking for a critical pressure limit below which no tissue damage would occur. The value of 32 mmHg is often used to judge whether or not pressure ulcer prevention devices are considered effective. However, the scientific evidence for using this 32 mmHg boundary is not very strong. It is taken from early work by Landis [110], who measured the pressure in an open arterial capillary of the human finger. However, capillary blood pressure in intact arterial capillaries has shown to be higher (on average 47 mmHg) and increasing when pressure is exerted on the surrounding tissue [46]. Other studies have shown that critical pressures (in terms of blood supply) are lower when a combination of pressure and shear was applied, compared to a situation in which only pressure was applied [15, 64]. Next to pressure and shear, other risk factors — such as tissue tolerances for pressure and for oxygen need/supply — have been introduced in an attempt to explain the individual nature of pressure ulcer development [46]. Recently, Goossens provided an excellent overview of the history on the research in pressure ulcers [65]. He stated that the main challenge for future research in this topic lies in the combination of research on mechanical load, tissue deformation and cell death.

A huge variety of pressure relieving surfaces have been described in literature (e.g. visco-elastic foam mattresses; gel-, fiber-, air-, water-filled mattresses; alternating pressure mattresses; air-fluidized beds; low-air-loss beds; . . .) [193, 192, 178, 39, 58, 10]. A recent, extensive review [129] compared the results of 53 studies on different support surfaces. They concluded that both high-specification foam mattresses (e.g. visco-elastic) and alternating pressure mattresses reduced the incidence of pressure ulcers in high-risk individuals. No consistent differences were found between constant low-pressure devices or alternating pressure supports. However one particular study reported a decrease in heel pressure ulcers on an alternating pressure mattress compared to a vico-elastic foam mattress [193]. The few studies on air-fluidized (warmed air circulates through fine ceramic beads covered by a permeable sheet) and low-air-loss beds (series of air sacs through which warmed air passes) reported inconsistent results. The authors state that the most important limitation when comparing the results of the different trials was the lack of a clearly defined “standard” mattress/condition. After all a “standard” hospital mattress varies by hospital, country and with time. In addition, it makes sense to incorporate patient turning schemes as an independent factor when evaluating the effectiveness of pressure relieving surfaces [48].

1.3.2 The effect of sleep systems on sleep parameters

Next to offering proper body support in order to allow musculoskeletal recovery, the sleep system should also provide adequate conditions to initiate and maintain sleep. Little is known about the exact mechanisms through which sleep systems affect sleep. As mentioned before, posture changes and body movements are necessary to prevent overloading of soft tissue. Consequently, normal sleep is characterized by the presence of 20 - 40 posture changes per night [44, 37]. Although necessary, too much movement during sleep may reduce sleep quality, since it is associated with arousals and sleep fragmentation [3]. In NREM sleep, motor activity progressively decreases from stage N1 to stage N3 [81], indicating that high activity levels are related to intermittent wakefulness and fragmented sleep. Hence, on the one hand proper sleep system design should allow the person to change postures easily. On the other hand, too much movement should be avoided by means of providing adequate body support (i.e. preventing overloading of intervertebral discs and preventing local pressure peaks). Both factors seem to be important to provide appropriate sleep conditions. In addition, an improperly designed sleep system may cause physical discomfort and trigger low-back pain [100]. Physical discomfort during sleep onset may lead to cognitive arousal, which is known to prolong sleep onset latency [73, 173]. More severe (low-back) pain has a two-way relationship with sleep: pain causes sleep disturbances, which in turn increase pain [33, 125]. Sleep disturbances associated with pain include difficulty falling asleep, difficulty staying asleep, early awakening and interrupted sleep [78]. Although the through relationships between these disturbances and pain remain unknown [172], pain may be thought of as a stressor that activates and maintains areas within the central nervous system responsible for the wake state [33]. Consequently, it is not surprising that multiple surveys have confirmed impaired sleep in patients with low-back pain [124, 125, 173].

The available literature on sleep systems that include sleep parameters as outcome variables yielded quite contradictory findings. An early study performed in 1957 by Suckling and colleagues, compared objective and subjective sleep parameters on hard, medium and soft beds [180]. The terms hard, medium and soft were quantified by providing the load-deflection curves of all three supporting surfaces. Four male subjects slept under observation for five nights a week during a period of three or six weeks, rotating through three rooms that differed only in the nature of the sleep surface. Results showed that the hard surface tended to increase motility and decrease sleep depth and subjective sleep quality. Bader and Engdal investigated nine men, sleeping in their homes for at least five consecutive nights on a soft and a firm mattress [14]. They experienced no global preference for any of the test beds. Jacobson et al. studied subjective sleep ratings of 62 persons at home for 28 nights in their own beds (pre) and for 28 nights on a new "medium-firm" bedding system (post) [91]. Unfortunately, order effects were not controlled by way of counterbalancing the two mattress conditions. They found immediate and significant improvements in all areas of physical pain, sleep comfort and sleep quality on the new bedding systems. Enck et al. evaluated questionnaires of 265 hotel guests in a double-blind study comparing three new mattresses of different price and quality with respect to the eight year old mattresses of the hotel [57]. They reported a positive correlation of mattress quality and subjective sleep quality, particularly in subjects suffering from chronic low-back pain. Monsein et al. compared an adjustable airbed with the participants' own beds in an A-B-A design on 30 subjects suffering from chronic low-back pain [131]. One night on their own bed (baseline data) were followed by 28 nights on the adjustable airbed and 14 nights on their own bed. No information was retrieved on the firmness levels of the subjects' own mattresses. Participants were allowed to determine the firmness level of the airbed themselves on a scale of 0-100. Pressure preference did not correlate with weight, body mass index, or pain improvement. VAS assessments of pain and sleep showed a 32% pain decrease and 73% increase in sleep quality. However, conclusions drawn from these results should be tempered by the absence of standardization and the fact that subjects where not blinded from experimental conditions. Scharf et al. performed full polysomnographic recordings in 10 normal subjects in a laboratory setting on both a high-quality innerspring mattress and a unique foam support mattress [165]. The order of mattress conditions was counterbalanced. No significant changes in sleep architecture were reported, but cyclic alternating pattern rate was significantly reduced on the foam support mattress, suggesting better recuperation during sleep on this type of mattress. Lee and Park, however, did find differences in sleep architecture, with significantly more slow wave sleep and a higher sleep efficiency index on "comfortable" than on "uncomfortable" mattresses [113]. However, no quantitative characteristics were provided that describe the difference between "comfortable" and "uncomfortable". Recently, two actigraphic studies were performed by Tonetti et al. to verify the effect of new mattresses on sleep in a home setting [185, 184]. A first study compared introducing a new latex mattress in one subgroup and a new innerspring mattress in another subgroup with the subjects' own mattresses [185]. Results showed improvements in actigraphic parameters for both mattresses, but no differences in subjectively perceived sleep. A second study compared the subjects' own mattresses with both an innerspring mattress and a visco-elastic PU mattress in a within subject design [184]. Again, subjective data revealed no differences whereas actigraphic outcome favored the visco-elastic mattress. However, both studies suffer from the fact that most reported differences cover wake-related parameters, whereas the wake-detection capability of actigraphy is generally considered extremely poor (see 1.1.3). The same limitation applies to another recent study that compared home recorded actigraphic readings in a randomized cross-over design on a conventional and a pressure-relief mattress [126]. The authors used pressure mapping systems to assess interface pressure between the sleeper and both sleep surfaces. Although no systematic difference was found in actigraphic nor self-reported sleep parameters, their findings provided some support for the idea that baseline characteristics of home mattresses might explain performance of newly introduced mattresses. Table 1.2 summarizes the main outcomes and methodological remarks of the studies that look into the effect of sleep systems on sleep parameters.

1.3.3 Methodological issues

A substantial number of the aforementioned studies suffer from poor methodological design, which hampers the interpretation and comparison of results. The most important limitation is the lack of quantification and standardization of the applied intervention. Sleep system specifications are typically limited to vague descriptions such as "soft", "firm", "medium firm", "conventional", "comfortable", "standard", "high-quality", etc. [14, 113, 165, 129, 69]. Often, no further quantification is provided to specify these descriptive terms. In addition, only few studies include anthropometric information of the tested population in their methodological design. This is remarkable, since from an ergonomic point of view, the interaction between a human body and a sleep system is not only determined by the properties of the sleep system, but also by the anthropometric features of the sleeper. The main anthropometric features that need to be accounted for, include

- stature & body weight
- shoulder height & width
- waist height & width
- hip height & width
- angle of thoracic kyphosis
- angle of lumbar lordosis

Stature and body weight determine the overall stiffness of the sleep system; shoulder, waist and hip measures determine the stiffness distribution in lateral

Table 1.2: Summary of studies looking into the effect of sleep system properties on sleep parameters

Author	**Population**	**Follow-up**	**Intervention**	**Outcome measure**	**Main results**	**Main methodological remarks**	**Ref.**
Suckling et al.	4 healthy male subjects	3 x 10 nights or 3 x 5 nights	Hard, medium, soft	PSG macrostructure, Body movement, VAS sleep quality	All measures favored medium and soft surfaces	Outdated/intrusive PSG & movement analysis	[180]
Scharf et al.	10 healthy subjects	2 x 3 nights	Experimental foam surface, innerspring mattress	PSG macrostructure, CAP rate	Decreased CAP rate on foam surface	No quantified SSC, no anthropometric data	[165]
Enck et al.	265 hotel guests	Length of stay	8 yr old hotel mattress, 3 new mattresses	Subjective quality of sleep and mattress	Sleep quality increased with price mattress	No standardized experimental conditions	[57]
Bader & Engdal	9 healthy male subjects	1 x 3 nights & 2 x 5 nights	Own mattresses, medium-firm and soft spring mattress	SCSB macrostructure, body movements	No global preference		[14]
Monsein et al.	90 CLBP patients	1 x 28 nights & 1 x 14 nights	Own bed, adjustable airbed	Pain VAS, Sleep VAS, EPS	Pain decrease and SQ increase on airbed	No standardized conditions, no blinding	[131]
Lee and Park	16 healthy subjects	2 x 1 night	Comfortable mattress, uncomfortable mattress	PSG macrostructure, Subjective scales, skin temperature	Subj. & obj. sleep improved on comfortable mattress	No quantified SSC	[113]
Jacobson et al.	59 healthy subjects	2 x 28 nights	Own bed, new medium-firm bed	Pain VAS, Sleep VAS	improved sleep and decreased pain on new beds	No counterbalancing, no blinding	[91]
Tonetti et al.	28 healthy subjects	2 x 1 week	Own bed, latex mattress, innerspring mattress	Actigraphic sleep parameters, MSQ, POMS	Improved sleep on new beds, no subj. difference	Actigraphy not reliable to detect wake time	[185]
Tonetti et al.	28 healthy subjects	3 x 1 week	Own bed, viso-elastic PU mattress, innerspring mattress	Actigraphic sleep parameters, MSQ, POMS	Improved sleep on visco-PU, no subj. difference	Actigraphy not reliable to detect wake time	[184]
McCall et al.	6 married couples	3 x 2 weeks	Own mattress, pressure relief mattress, conventional mattress	Actigraphic sleep parameters, sleep diary, VAS, pressure mapping	No significant differences, base-line characteris-tics predict WASO	Actigraphy not reliable to detect wake time	[126]

PSG: polysomnography; VAS: visual analogue scale; CAP: cyclic alternating pattern; SSC: sleep system characteristics; SCSB: Static Charge Sensitive Bed; CLBP: chronic low-back pain; EPS: Epworth sleepiness scale; SQ: Sleep quality; PU: Polyurethane; MSQ: Mini sleep questionnaire; POMS: Profile of mood states.

positions; and sagittal curvatures (kyphosis and lordosis) define the stiffness distribution in supine positions. Neglecting these individual features when comparing two or more sleep systems actually corresponds to applying a different experimental condition for each participant.
Next to the lack of quantification and standardization, other methodological concerns include blinding of participants/scorers and exclusion of order effects. Although complete blinding is practically impossible when comparing sleep systems because participants may correctly perceive differences between conditions [70], subjects should at least be blinded from the study hypothesis (e.g. mattress A is better than mattress B). Order effects can be easily accounted for by means of counterbalancing experimental conditions using well-designed schemes. Finally, it is suggested to include baseline characteristics of sleep systems used at home as well as information on preferred sleep postures. The former has shown to be a predicting factor of sleep on a newly introduced sleep system [126]; subjects sleeping on an old mattress are more likely to benefit from a new mattress. Information on preferred sleep postures should be incorporated in the comparison of results because it is known that supine sleepers have different mattress requirements than lateral or prone sleepers [71].

1.3.4 Conclusion

A review on the available literature demonstrates a strong demand for fundamental research regarding the effect of sleep systems on body support and sleep parameters. This implies not just comparing two or more types of sleep systems on a certain population, but also incorporating knowledge on biomechanics and ergonomics to assess the individual interaction between the subject and the sleep system.

1.4 Ergonomic assessment of sleep systems

1.4.1 Basic mechanical characteristics of sleep systems

Basic mechanical properties of sleep systems are generally determined by means of standardized load-deflection characteristics. Displacement-controlled benches measure force at fixed intervals, resulting in a force-displacement curve consisting of a loading and a relaxation phase. Since several boundary conditions (e.g. velocity of deformation, indentor shape, ...) have a significant influence on the resulting load-deflection characteristics, a number of international standards are currently in use.

The international ISO 2439:2008(E) [2] standard describes the determination of hardness as a measure of the load-bearing properties of flexible cellular polymeric materials (latex foam, urethane foam and PVC foam). Four methods are presented for determining the indentation hardness (HA, HB, HC, HD) and one method for determination of the compressive deflection coefficient (S_f) and hysteresis loss rate (A_f). The five methods are not applicable to sleep systems or mattresses as a whole, but may be used to characterize the intrinsic properties of foamed mattress cores. Measurements are performed with a test bench capable of indenting samples between a supporting surface and an indentor with a uniform relative motion of (100 ± 20) mm/min. The indentor should be mounted by a ball joint free from vertical movement and should be flat and circular (diameter 200_0^{+3} mm). The supporting surface is a smooth, flat, horizontal and rigid surface larger than the test sample and foreseen of holes with 6 mm diameter at a distance of 20 mm (to prevent airflow occlusion). Force should be measured with a precision of ± 1 N and displacement with a precision of ± 0,25 mm. The following measures can be derived using this standard:

- Indentation hardness index ($\mathrm{HA}_{(40\%/30\mathrm{s})}$) [N]: The sample is indented by (40 ± 1) % of its thickness, after maintaining this deformation for (30 ± 1) s, the force is measured.
- Product indentation hardness characteristics ($\mathrm{HB}_{(25\%/30\mathrm{s})}$, $\mathrm{HB}_{(40\%/30\mathrm{s})}$, $\mathrm{HB}_{(65\%/30\mathrm{s})}$) [N]: The sample is indented by (25 ± 1) %, (40 ± 1) % and (65 ± 1) % of its thickness. After maintaining each deformation for (30 ± 1) s, the force is measured and the indentation increased.
- Indentation hardness check ($\mathrm{HC}_{(40\%/0\mathrm{s})}$) [N]: The sample is indented to (40 ± 1) % of its thickness after which the instantaneous maximum force is recorded.
- Low indentation hardness index ($\mathrm{HD}_{(25\%/20\mathrm{s})}$) [N]: After preloading to an indentation of (75 ± 1) % of its thickness, the sample is immediately indented to (25 ± 1) % of its thickness, which is maintained for (20 ± 1) s after which the force is measured.
- Compressive deflection characteristic ($S_f = \frac{F_{65}}{F_{25}}$) [-]: The sample is indented to (75 ± 1) % of its thickness and released. S_f is the ratio of the force at 65% indentation to the force at 25% indentation.
- Hysteresis loss rate ($A_f = \frac{\mathrm{Area}_{\mathrm{within}}}{\mathrm{Area}_{\mathrm{below}}} \times 100$) [%]: A_f is the ratio of the area contained within the hysteresis curve to the area under the loading curve.

Figure 1.8 clarifies the determination of the most important outcome parameters of ISO2439:2008.

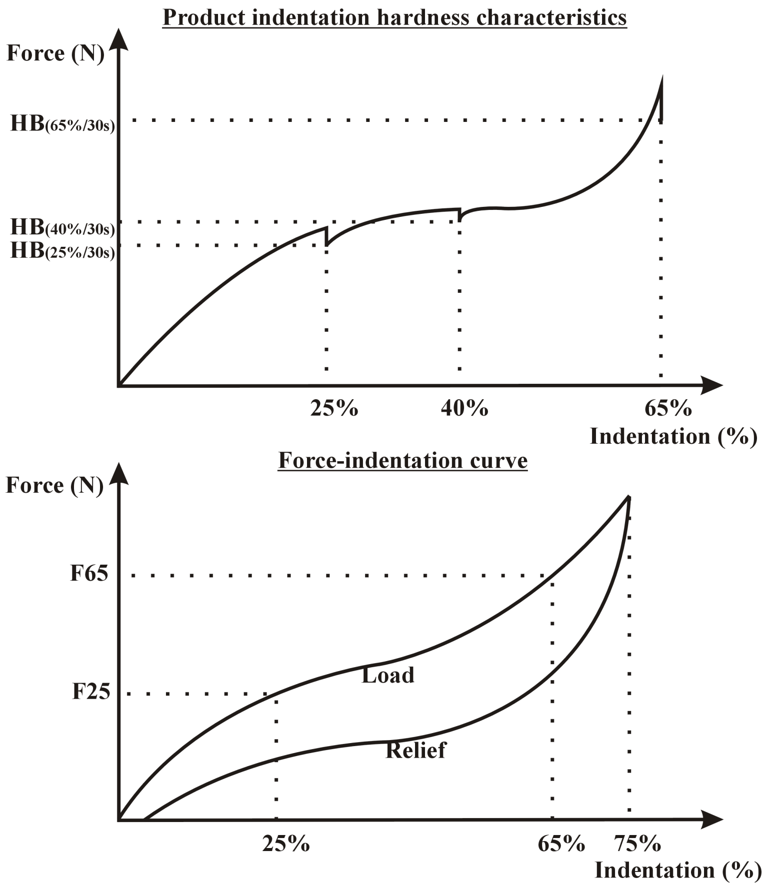

Figure 1.8: Product hardness characteristics (upper) and force-displacement curve for determining the compressive deflection characteristic and the hysteresis loss rate according to ISO 2439:2008. [2].

Whereas ISO2439 applies to mattress components (foam materials), the European standard EN 1957:2000 [1] describes a standardized method to determine the functional characteristics of both mattresses and sleep systems as a whole. The standard specifies a test for determining the durability and hardness of mattresses — with or without bed base — of all types other than water beds, air beds and children cots. The following sequence of testing should be carried out:

- Conditioning: $(23 \pm 2)°C/(50 \pm 5)\%$ RH, at least one week

- Measurement of unit height (i.e. height when the force equals 50 N)
- Durability test: 100 cycles
- Conditioning, at least 5 hours
- Measurement of unit height, and hardness measurement
- Durability test: 29 900 cycles
- Conditioning
- Determination of hardness and height loss between 100 cycles and after the test
- Determination of hardness and height loss between 100 cycles and after the test

The durability test is performed with a barrel-shaped roller (rotation moment of inertia 0.5 $\frac{kg}{m^2}$± 10%) and a mechanism capable of relative horizontal movement of the roller on the mattress surface. The total rolling system applies a load of (1400 ± 7) N in the static condition, is free to pivot along its longitudinal and lateral axis and is free to move up and down to follow the mattress surface. The applied horizontal motion should approximate sinusoidal motion with a frequency of (16 ± 2) cycles per minute. Hardness is derived from the load-deflection characteristic recorded with a test bench capable of applying a vertical downward load up to 1000 N at a travelling speed of (90 ± 5)mm/min. Force should be measured with an accuracy of ± 10 N and height measuring accuracy should be ± 0.5 mm. The indentor is a rigid circular object (diameter 350 mm) with a convex spherical curvature of 800 mm radius, mounted to the loading system of the test bench by a ball joint. The hardness value is defined as:

$$H = \frac{(C_1 + C_2 + C_3)}{3} N/mm \tag{1.1}$$

with C_i the average of the slopes of the load deflection curves at 210 N, 275 N and 340 N. The firmness rating is a number on a scale of 1 (very firm) to 10 (very soft) defined by the following equation:

$$H_s = 10 \left(1 - e^{-(Ka+b)}\right)^2 \tag{1.2}$$

where a = 5.92 10-4, b = 0.148, and K is calculated from the load-deflection curve as follows:

$$K = \frac{A}{H} \tag{1.3}$$

with A the area under the load curve between 0 and 450 N, and H the hardness value 1.1.

Although these standards provide interesting information to compare material properties and functional characteristics of sleep systems, their use to categorize whole sleep systems as soft, medium-firm or firm based on one single value (e.g. H_s) is somewhat blunt. Therefore — especially in the case of multi-zone systems — measurements should be performed on different locations of the sleep system, results of which can be summarized in charts illustrating variations in characteristics across the mattress surface.

1.4.2 Assessment of body support

The assessment of body support, which is the result of the mechanical interaction between the sleep system and the human body, requires not only information on the mechanical characteristics of the sleep system, but also on the characteristics of the sleeper. Several measures have been proposed to evaluate body support, such as spinal alignment, pressure distribution and muscle fatigue.

Spine shape

Rather few studies have studied techniques to measure spinal alignment during rest on a sleep system. Ray [151] assessed spine shape indirectly using a sonic echoing device. First anterior and posterior contours were registered during stance in order to determine the distance from the anterior contour to the spine. Second, the anterior body contour was registered in a relaxed supine position on each of the mattresses. Subtraction of the erect data from the supine data resulted in the indirect assessment of spine shape when lying supine. Average deviations with the spine shape during stance were used to assess mattress support quality. Although questions can be raised regarding the accuracy of the indirect spine assessment method, its primary importance lies in the fact that it was the first attempt to objectively quantify the effect of various sleep surfaces on spine shape. Other techniques that have been described in literature include marker based anatomical landmark detection [108, 50, 72], the use of geometrical instruments [128, 22], or spine modeling from back shape data [55, 87]. Marker based methods require the palpation and indication of the spinous processes, which is time consuming and error prone. Furthermore, markers might shift when the person moves. Nevertheless, it is relatively cheap and when multiple cameras are used to digitize the marker position, a 3-D curve can be reconstructed from the images. Geometrical instruments are placed against the subject's back surface, which requires palpation as well. Because these instruments are in contact with the person, they often cause discomfort, which as such might influence spinal alignment. The development of 3D surface scanning technology has allowed capturing the 3-D shape of the back surface [59] without making contact with the body. Starting from the measured 3-D point cloud of the back surface, several algorithms have been proposed to automatically localize landmarks, such as the vertebra prominens, the dimples of the posterior superior iliac spines, and the sacrum point [55, 87]. In addition, Huysmans showed [87] that the line through the spinous processes can be accurately reconstructed based on analysis of back surface data. Results indicated that the use of an active contour model iterating on a weighted combination of surface curvature information and lateral asymmetry information, as defined by Hierholzer [80], allows spine shape reconstruction in lateral sleep postures with an RMSE of 2.6 mm with respect to full spine CT measurements. Figure 1.9 illustrates the process of spine modeling from back shape data.

Contact pressure

The contact interaction between the human body and the sleep surface can be partially characterized by means of contact pressure measurements. Contact pressure is a scalar quantity, representing a measure of forces acting normal to the skin surface over a certain area. It is commonly measured by means of pressure mapping, in which data from a large array consisting of hundreds of sensors are processed and displayed numerically as color images [179]. Most thin, flexible pressure mapping systems either use capacitive or resistive sensor technologies. Capacitive mapping systems consist of a raster of overlapping electrodes separated by an air gap, effectively forming capacitances at each overlap. When loaded, the air gap changes, and therefore so does the capacitance. Resistive sensors are composed of two pieces of conductive material separated by a material whose resistance changes as force is applied. Although the technology of pressure mapping is continuously improving, several issues regarding the reliability of pressure readings remain present. First, most systems suffer from sensor hysteresis (higher reading during loading than during unloading) and sensor creep (pressure readings drift over time). Second, cross talk might occur between neighboring sensors. Third, the measurement itself might influence interface pressure. For instance, systems that are only capable of deforming in one direction sometimes introduce errors because their inability to stretch hinders compliance with the mattress surface (i.e. hammocking). Finally, both mat placement and subject positioning should be standardized as much as possible and hot spots should always be checked for folds and creases.

Most studies that make use of pressure mapping systems are related to the prevention of pressure ulcers in clinical settings [47, 74, 156, 168]. In this context

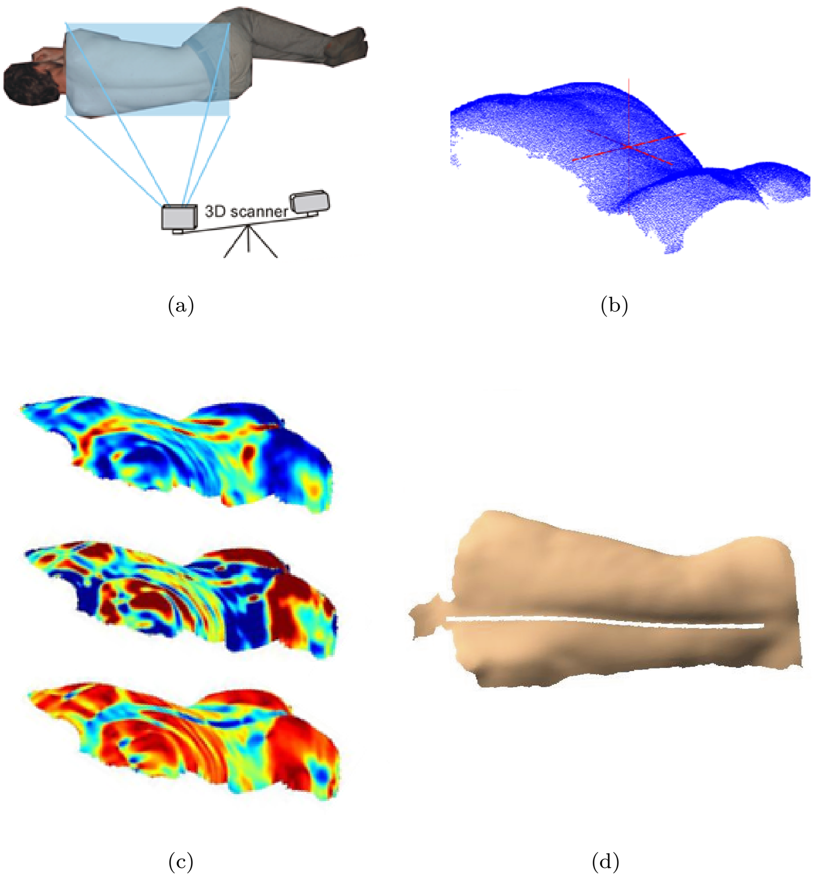

Figure 1.9: (a) A 3-D scan of the back surface is taken while lying in a lateral position on a sleep system. (b) The point cloud that represents the back surface. (c) Surface curvatures and asymmetry functions are calculated. (d) Based on curvature and asymmetry information, an active contour or active shape model iterates to the correct spine shape.

a variety of outcome measures have been proposed to evaluate support surfaces:

- Maximum pressure (global, local in high-risk areas) [mmHg].
- Average pressure (global, local in high-risk areas) [mmHg].
- Pressure area index (PAI) [-]: the area for which contact pressure is greater than a chosen threshold, related to the whole contact area [156, 116, 126].
- Pressure relief index (PRI) [-]: proportion of time that the contact pressure at a particular location is below a specific threshold [157].
- Pressure index (PI):$P_{index} = [(\text{Mean}_{10} - 10)^2 + (\text{Stdev}_{10})^2]^{\frac{1}{2}}$ with Mean_{10} and Stdev_{10} the mean and standard deviation of all active cells measuring greater than or equal 10 mmHg. [168].

Although these measures might be suited for evaluating sleep systems in specific clinical settings, it has to be stressed that no evidence is present that the same measures are applicable to evaluate quality of sleep systems for people that are not at risk of developing pressure ulcers [126]. In addition, it is important to stress that pressure distribution provides no information on the global deformation of the human body and therefore cannot be used to asses spinal alignment.

Electromyography

Surface electromyography (SEMG) is often used to assess spine muscle activity and fatigue during voluntary muscle contractions (e.g. lifting a weight) [107] or in relation to low-back pain [162, 123]. However, its validity for the assessment of body support during sleep is poorly documented. Lahm and Iaizzo recorded SEMG of the major back muscles during 30-min trials on a sleep system at varied degrees of firmness [108]. While spinal alignment did fluctuate significantly between mattress inflation pressures, EMG activity did not follow accordingly. Consequently, the hypothesis, that improper spinal alignment while lying on a mattress causes increased activity of the back musculature, could not be confirmed. Nevertheless, several commercial systems based on the use of SEMG are currently on the market that give advice on body support properties of sleep systems [96]. Therefore, additional research is urgently needed to confirm or reject the preliminary findings of Lahm and Iaizzo. In this regard it might be interesting to look at bilateral (a)symmetry of muscle activity during rest in lateral sleep postures. Second, analogous to studies on seating comfort [114, 166], longer SEMG recordings (1-2 hrs) are required to identify time effects of muscle activity and muscle fatigue (i.e. simultaneous increase in EMG amplitude and shift to lower frequencies).

1.4.3 Subjective comfort

Although the term “comfort” is often used in literature, its meaning is very broad and no single definition has been generally acknowledged so far. Whereas some authors define comfort as the absence of discomfort [169] or that comfort and discomfort concern two sides of one multi-level scale [144], others state that comfort and discomfort may be associated with different factors and should be expressed on different scales [199, 45]. Several studies have investigated the possibility to predict the level of comfort based on a set of objective measures, both in (car) seat and in sleep applications. According to a review on the relationship of seating comfort with objective measures, pressure distribution shows the clearest association with subjective ratings [45]. However, this statement is tempered by other studies that found no association between subjective discomfort and pressure distribution [114, 26, 194]. Moreover, the few studies on sleep comfort, reported no significant associations between contact pressure and subjective ratings of mattress comfort [27, 108], indicating that mattress comfort is dependent on a wider set of factors than contact pressure alone. Therefore, analogous to the term “sleep quality” (see 1.1.3 and 1.1.5), the term “comfort” can not yet be used as a comprehensive parameter directly related to objective measures, but should be considered as an additional subjective parameter influenced by psychological, physiological and physical impressions of the personal environment.

1.4.4 Conclusion

Throughout this section several techniques have been elucidated to assess sleep system properties (see table 1.3). Standardized load deflection characteristics provide a framework to compare functional characteristics of sleep systems, but are incapable of describing the complex interaction between the human body and the sleep system. Other measures are more suited to evaluate this interaction, such as spinal alignment, pressure distribution or muscle fatigue. Throughout this thesis, spinal alignment will be considered as the main criterion in terms of body support for the following reasons. First, spinal alignment provides a direct measure of the global deformation of the human body when lying on a sleep system. Second, although pressure distribution is of primary concern for the prevention of pressure ulcers, it is sufficient to avoid concentrated pressure peaks when considering a general (healthy) population. Most modern sleep systems meet this requirement. Third, at present the validity of SEMG for the assessment of body support on sleep system is too poorly documented.

Table 1.3: Summary of assessment techniques for sleep systems

Technique	**Outcome measure**	**Main assets**	**Main shortcomings**	**Ref.**
Load-deflection characteristics	Hardness, Firmness, Hysteresis loss rate	Standardized procedure	General outcome, Only sleep system (no interaction)	[2, 1]
Geometrical instruments (e.g. lordosimeter)	Kyphosis, Lordosis	Dynamic measurement	Palpation required, Contact during measurement	[128, 22]
Marker based anatomical landmark detection	Location of spinous processes	Low-cost, Fast acquisition	Palpation required, Skin shifts during motion	[108, 50, 72]
Spine modeling from back shape data	Line through spinous processes	Accurate, No contact, Fast acquisition	Expensive scanning equipment, Extensive post-processing	[55, 87]
Pressure mapping	Distribution of contact pressure	Easy to use, Unobtrusive	No clear interpretation, Sensor hysteresis, -creep	[156], ...
Electromyography	Muscle activity, Muscle fatigue	Physiological measure	Poorly documented w. r. t. sleep system applications	[108]
Questionnaires	Subjective comfort	Easy to use, Reflects perception	No clear definition	[108, 27]

1.5 Unobtrusive assessment tools during sleep

The previous section introduced the most important techniques for the assessment of sleep system properties (see 1.4). Most of these techniques however, are not suited to be used in a bedroom environment because of their interference with the actual sleep process (e.g. wearing a device on the back, lighting conditions for scanning, . . .). An important implication of the restriction to laboratory settings is that most studies involve short trials on sleep systems in predefined postures, which do not reflect habitual sleep conditions. This section provides an overview of integrated bed measurements and introduces digital human modeling as a valuable tool for the ergonomic analysis of anthropometric design. Finally, the necessary requirements are listed for continuous monitoring of body support without disturbing sleep.

1.5.1 Integrated bed measurements

Recently, interest in instrumenting the bed itself has grown to provide an off-body alternative to study body movements during sleep. The main advantage of this approach is that no equipment has to be mounted on the sleeper, thus avoiding disturbance of habitual sleep conditions due to the measurement itself.

Lu et al. [120] and Tamura et al. [181] assessed changes in bed temperature as an index of body movement and validated their setup with simultaneous video image and actigraphic recordings. Results showed that leg movements were detected more accurately than torso movements. Moreover, the inherently long reaction time of temperature sensors determines a detection interval of at least 15-30 s, making it impossible to discriminate between short movements such as sleep twitches. Van der Loos [189] tried to overcome this by combining an array of 54 resistive temperature devices with an array of 54 force sensitive resistors to monitor breathing rate and temperature overnight. Unfortunately, results were only reported for one subject that slept in a supine posture during the entire night and no validation of the outcome was accounted for. Several authors installed load cells at the corners of a bed to determine body movements during sleep [3, 4, 25]. Next to body movements, the high accuracy of such load cells allowed Brink et al. [25] to determine heart rate and breathing activity as well. However, no detailed information on sleep posture could be derived. Other authors assessed the problem of posture recognition by means of pressure distribution images [75, 76, 77, 167, 84, 85]. The developed methods provided interesting results but were only tested on a set of predefined sleep postures of a very limited subject population. Furthermore, no overnight experiments were performed to validate performance when subjects were not bound to these predefined postures. Finally, recent work [83] incorporated accelerometers in a mattress topping to evaluate body movements and sleep postures. Unfortunately, the algorithm had to be trained for each subject separately before it could be used to asses body movements and sleep postures, narrowing its general applicability. In addition, full night validation of the algorithm was restricted to only one subject and only ten discrete time stamps per night.

The majority of the aforementioned studies aim at providing an off-body alternative for actigraphy and PSG to record objective sleep measures in home settings [95, 98]. As a consequence, these technologies focus on the detection of body movements and other physiological signals (e.g. heart and breathing rate). However, few studies on integrated bed measurements provide tools to detect ergonomic parameters (e.g. information on adopted sleep postures and quality of body support).

1.5.2 Digital human modeling

Digital human models (DHMs) are increasingly being used in a wide spectrum of applications, e.g. in animation development [13, 79, 154], markerless human motion capture [36, 30], garment design [97, 195] and the ergonomic evaluation of early stage product design [109, 94]. Depending on the intended application, distinct specifications become more or less important. For example, in animation development the primary focus is on the realistic visualization of human characters whereas from an ergonomic point of view the interaction between the model and its environment is more important.

Several ergonomic software packages are commercially available that allow three dimensional modeling of humans (e.g. RAMSIS, Jack, Delmia Safework). Most of these modeling tools are developed to visualize the interaction of a human and a system — for instance reach and visibility in a car interior — by integrating the generated models in a computer aided design (CAD) environment. They provide either percentile model generation for different genders and age groups or model generation based on user specified anthropometric dimensions. The development of 3-D whole body scanning technologies [41] has enabled accurate and fast acquisition of human body shapes. Several authors use whole body scans or derived measures to morph a template model to the scanned subject, resulting in highly realistic body shape models [9, 142]. However, 3-D scanning based methods require either expensive scanning equipment or paid access to 3-D anthropometric databases (e.g. through web portals such as WEAR [42] or iSize [86]). In addition, extensive post-processing of the scanned point clouds [196] and standardized data acquisition procedures are required to obtain reliable results.

Although the use of DHMs to evaluate automotive seating comfort has been thoroughly studied [194], little research applies DHMs to evaluate sleep comfort. Haex [72, 71] developed a 2-D finite element (FE) model of the combination human-mattress to predict the curvature of the vertebral column when lying on a sleep system. Such models have the advantage that they can handle nonlinear mechanical behavior (e.g. deformation of soft tissue), yet require a lot of input parameters that are currently impossible to determine on an individual level (e.g. modulus of elasticity of soft tissues). Harada and co-workers [75, 76] combined a full body human model (surface model and skeleton) with pressure distribution images in order to track human motion in bed and automatically detect adopted sleep postures. The model was manually scaled based on the subject's body height to account for anthropometric differences. No further personalization was considered. Joint rotation and translation parameters were optimized to minimize the difference between the model based pressure distribution and the measured pressure distribution. However, the study primarily focused on simulation of body movements but did not incorporate the evaluation of personalized comfort parameters related to bed design (such as spinal alignment, maximal contact pressure,...).

1.5.3 Unobtrusive assessment of body support during sleep

Continuous and unobtrusive assessment of body support during sleep might be achieved by combining integrated bed measurements with digital human models. Depending on the desired outcome measure, distinct measurement technologies and models are appropriate. For instance, in order to assess the risk of pressure ulcer development in a clinical environment the combination of pressure mapping systems with full body FE models might be preferable. On the other hand, the assessment of spinal alignment requires the combination of global mattress deformation and human models with highly individualized body contours. In both applications the adopted posture needs to be a priori known before a meaningful simulation can be performed, which can be accounted for by means of posture recognition algorithms based on the output of the integrated bed sensors.

1.5.4 Conclusion

This section provides an overview of integrated bed measurements and how they are currently used to assess body movements during sleep as an off-body alternative for actigraphy and PSG. Although the combination of such measurements with digital human models provides promising perspectives in terms of unobtrusive assessment of body support during sleep, this approach has not yet been explored in the existing literature. Moreover, such assessment techniques might provide the necessary feedback for controlling bed properties actively (e.g. by means of integrated actuators) during sleep.

1.6 Conclusion

In this chapter the basic concepts of sleep were introduced and the various components of the sleep system were presented. Moreover, the available scientific literature regarding the effect of the sleep system on both body support and sleep parameters was reviewed. Finally, the main methods for the assessment of bed properties were summarized, including unobtrusive alternatives that might be suited for long-term home monitoring.

Ergonomic design of sleep systems aims at optimizing bed properties to achieve maximal recovery during sleep and therefore requires a multidisciplinary approach bridging the expertise of sleep physiologists, ergonomists and engineers. However, based on a review of literature it can be concluded that most studies on the ergonomics of sleep have a rather unilateral approach, resulting in the following bridges to be built:

- Very few ergonomists perform actual sleep registrations to test whether their findings have an effect on how people sleep.
- Although a diversity of distinct sleep systems have been compared, hardly any objective specifications are provided on bed properties.
- Anthropometric features of the population are often neglected. Since quality of body support is dependent on both the properties of the sleep system and its user, neglecting sleeper anthropometrics in fact corresponds to applying a different experimental condition for each participant.

Validation by means of overnight experiments involves accounting for behavioral aspects during sleep. Therefore, the following voids remain to be filled:

- Although quality of body support is influenced by the adopted sleep postures at night, few studies incorporate information on sleep postures in the analysis of their results.

Finally, ergonomic assessment tools are required that do not interfere with normal sleep. In this regard, it can be inferred from literature that:

- Integrated bed measurements have been explored in literature, yet not with respect to the unobtrusive monitoring of body support during sleep.
- Although the use of digital human models (DHMs) to evaluate automotive seating comfort has been thoroughly studied, little research applies DHMs to evaluate sleep comfort.
- Since healthy sleep requires various posture shifts per night, the sleep system should be able to change its characteristics according to the adopted sleep posture. At present, such so-called "smart sleep systems" have not yet been discussed in literature.

The final section of this chapter clarifies how this dissertation aims at filling some of the aforementioned voids in literature. The different objectives are stated that form the base for the underlying research hypothesis and the general outline of the thesis is provided.

1.7 General research hypothesis and objectives

1.7.1 General hypothesis

The ultimate goal of bed design is providing optimal conditions to promote sleep initiation and sleep maintenance while allowing physical and mental recovery from daily activities. Although pressure peaks should be avoided, scientific consensus has been achieved on the fact that musculoskeletal support should gain priority over pressure distribution when considering a general (healthy) population. Therefore, this dissertation focuses on ameliorating spinal alignment during sleep. A first underlying hypothesis is that spinal alignment affects sleep. In this regard an important contribution to the available literature is that individual differences — concerning not only anthropometric features but also posture preferences — are accounted for. A second hypothesis is that it is feasible to continuously assess and optimize spinal alignment throughout the night by means of a smart bedding system.

1.7.2 Objectives

In order to confirm these hypotheses the following objectives are proposed:

- The **first objective** is to study the fundamental effect of spinal alignment on sleep parameters. In this context, it is of primary importance to define experimental conditions that only differ in terms of spinal alignment. This implies that — although the market is characterized by various types of sleep systems (see 1.2.1) — a mere comparison of two technologies is not relevant since they presumably differ among various properties (e.g. spinal alignment, pressure distribution, thermal insulation, vapor permeability, ...). Therefore, one distinct technology should be chosen. Furthermore, an adjustable stiffness distribution allows determining individual mattress configurations — based on a priori measured anthropometrics — independent from other confounding variables. Finally, data on the adopted sleep postures should be registered during the night to account for between-subject differences in posture preference.

- A first step towards the unobtrusive assessment of spinal alignment during sleep is the automatic recognition of sleep postures based on integrated bed measurements, which constitutes the **second objective** of this thesis. Mattress indentation measurements are used as primary input because they provide an easy to interpret measure of the deformation of the mattress surface.

- Since spinal alignment is also affected by the anthropometric characteristics of the sleeper, the **third objective** consists of developing a generic human body model that can be personalized based on a set of anthropometric parameters derived from silhouette extraction. The focus lies on the accurate representation of body contours and the realistic simulation of different sleep postures for a variety of body types.

- The **fourth objective** is to estimate spinal alignment during sleep by fitting the developed human model in the measured mattress indentation according to the detected sleep posture. This problem can be formulated as an optimization problem in which the appropriate values of a set of degrees of freedom (DOFs) need to be determined. The DOFs correspond to the global positioning of the model with respect to the mattress as well as the deformation of the model according to the adopted sleep posture.

- The implementation of a feedback control loop to continuously optimize spinal alignment throughout the night constitutes the **fifth objective**. If the fourth objective is met, the comparison of the estimated spine shape with the desired (reference) shape provides the necessary feedback for a controller to determine new mattress settings based on the measured mattress indentation and the modeled body shape of the sleeping subject.

- Finally, the **sixth objective** is to verify the effect of controlling spinal alignment in overnight sleep experiments. Although a dynamic sleep

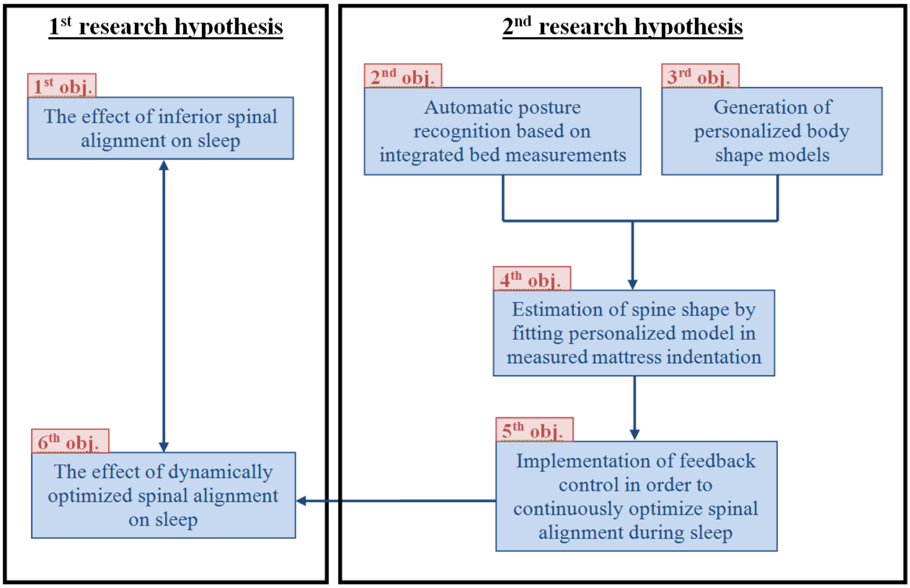

Figure 1.10: Schematic overview of the research hypotheses and objectives

environment (in this case a dynamic sleep system) might be preferable from an ergonomic point of view, it should be implemented in a way that normal sleep is preserved. In this context, gentle transitions between mattress configurations without any noise disturbance are presupposed to assure sleep continuity.

Figure 1.10 provides an overview of the aforementioned objectives and how they are related to the two main hypotheses of this thesis.

1.7.3 Thesis outline

In chapter 2 the effect of spinal alignment on objective (PSG-derived) and subjective sleep parameters is studied during overnight experiments in a sleep laboratory. Sleep systems with adjustable comfort zones are used to make sure no other variables are altered between conditions (first objective). In a within-subject design two experimental conditions are compared. A personalized mattress configuration — which serves as reference — is determined a priori based on measured anthropometric features and validated in terms of spinal alignment. During the induction night a sagging sleep system is simulated by means of lowering the stiffness of the waist and hip zones. Chapter 3 addresses the problem of sleep posture recognition based on integrated mattress indentation measurements (second objective). The performance of the developed classification scheme is validated with simultaneous PSG and video recordings during overnight experiments. Chapter 4 focuses on the unobtrusive assessment of spinal alignment during sleep. A generic human model is developed (third objective) that can be personalized based on anthropometric information derived from silhouette extraction. The model consists of a surface mesh (representing body shape) and a simplified skeleton that allows the model to adopt various sleep postures. The optimization of a set of DOFs is implemented to fit the model in the measured mattress indentation after which spine shape can estimated (fourth objective). In chapter 5 the developments of chapter 3 and 4 are integrated in a feedback control loop that optimizes spinal alignment by means of controlling the actuators of eight comfort zones (fifth objective). The developed control system is validated both in laboratory conditions and in overnight sleep experiments to verify its performance. The final chapter provides a detailed analysis of sleep structure during nights with active control of spinal alignment (sixth objective). General sleep macrostructure is compared with a reference night in which the sleep system remains in its standard configuration.

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Chapter 2

Ergonomics in bed design: the effect of spinal alignment on sleep parameters

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Adapted from a manuscript published in Ergonomics, 54(2), 169-178, Feb. 2011

Abstract

This study combines concepts of bed design and sleep registrations to investigate how quality of spine support affects the manifestation of sleep in healthy subjects. Altogether, 17 normal sleepers (nine males, eight females; age 24.3±7.1 years) participated in an anthropometric screening, prior to the actual sleep experiments, during which personalized sleep system settings were determined according to individual body measures. Sleep systems (i.e. mattress and supporting structure) with an adjustable stiffness distribution were used. Subjects spent three nights of 8 h in bed in the sleep laboratory in a counterbalanced order (adaptation, personalized support and sagging support). During these nights, polysomnography was performed. Subjective sleep data were gathered by means of questionnaires. Results show that individual posture preferences are a determinant factor in the extent that subjects experience a negative effect while sleeping on a sagging sleep system.

Statement of Relevance

This study investigated how spine support affects sleep in healthy subjects, finding that the relationship between bedding and sleep quality is affected by individual anthropometry and sleep posture. In particular, results indicate that a sagging sleep system negatively affects sleep quality for people sleeping in a prone or lateral posture.

Keywords

bed design, sleep posture, sleep quality, sleep system, spinal alignment

2.1 Introduction

Although the domains of both sleep research and ergonomics are rapidly expanding, it is surprising to learn how little research is at hand that combines the knowledge of both disciplines. A key issue in the design of current, state of the art sleep systems (i.e. mattress and supporting structure) is how the optimization of bed design affects the manifestation of sleep in healthy human beings. Whereas some research is available on the influence of the mechanical characteristics of mattresses and supporting structures on spinal alignment [21, 9], very few ergonomists perform actual sleep registrations to test whether their findings have an effect on how people sleep. Additionally, the available research that looks at sleep quality on different bedding systems remains very vague on the actual bed properties, using terms such as soft, firm, medium-firm, (un)comfortable, etc. without further specification [2, 22, 18, 17]. This lack of quantification makes it difficult to compare and interpret results.

The main function of sleep systems is to support the human body in a way that allows the muscles and intervertebral discs to recover from nearly continuous loading by day [26]. This recovery can be achieved when the shape of the spine is in its natural physiological shape, yet with a slightly flattened lumbar lordosis due to the changed orientation of the working axis of gravity with respect to the craniocaudal direction [10]. In general, the mechanical characteristics of a sleep system should account for two anthropometrical aspects: body contours and weight distribution. Since both of these factors are highly individual, the allocation of an appropriate sleep system to a specific person should be done on a personalized basis [14]. Furthermore, the body contours that are in contact with the mattress surface are dependent on the adopted sleep posture. Because healthy sleep requires the presence of several major posture changes throughout the night [7, 6], the ideal sleep system should be able to cope with these variable loading conditions; for instance, by changing its characteristics according to the adopted posture at any moment during the night [32].

The objective assessment of a sleep system's support qualities is generally done by evaluating either contact pressure or spinal alignment. Although the objective of bed design is to meet both criteria (a properly aligned spine while avoiding pressure peaks), it has been suggested in literature that they might be at cross purposes: design features that minimize pressure might maximize spinal distortion [9]. A lot of research has already been done in the field of pressure distribution because of its clinical relevance in the prevention of pressure ulcers [8, 28, 31]. Little research however focuses on the influence of spinal alignment on normal sleep quality and quantity. Lahm and Iaizzo [21] studied the physiological response of 22 'back pain-free' participants during a 30 min trial on a sleep system at three levels of firmness. They reported no difference in electromyographic activity, heart rate, blood pressure and subjective comfort. In contrast, spinal alignment was significantly improved at mid-range and higher firmness levels. DeVocht et al. [9] measured both contact pressure and spinal alignment to evaluate four 'top of the line' mattresses in a male population. They reported significant differences between mattresses, but the pattern of results was not consistent; the mattress with the highest maximal contact pressure tended to have the lowest spinal distortions. Again, the impact on sleep was not incorporated in the study.

The few scientific reports of sleep quality on different mattress types yielded quite contradictory findings. Bader and Engdal [2] investigated nine men, sleeping in their homes for at least five consecutive nights on a soft and a more firm mattress. They experienced no global preference for any of the test beds. Jacobson et al. [18] studied subjective sleep ratings of 62 persons at home for 28 nights in their own beds (pre) and for 28 nights on a new ‘medium-firm’ bedding system (post). Unfortunately, order effects were not controlled by way of counterbalancing the two mattress conditions. They found immediate and significant improvements in all areas of physical pain, sleep comfort and sleep quality on the new bedding systems. Kovacs et al. [20] looked at 313 adults with chronic non-specific low back pain and randomly assigned them a firm or medium-firm mattress. Pain when lying in bed, pain on rising and the degree of disability after a period of 90 d were assessed and compared to baseline. Results showed improvements in all variables for both mattresses. Scharf et al. [30] performed full polysomnographic recordings in 10 normal subjects in a laboratory setting on both a high-quality innerspring mattress and a unique foam support mattress. The order of mattress conditions was counterbalanced. No significant changes in sleep architecture were reported, but cyclic alternating pattern rate was significantly reduced on the foam support mattress, suggesting better recuperation during sleep on this type of mattress. Lee and Park [22], however, did find differences in sleep architecture, with significantly more slow wave sleep (SWS) and a higher sleep efficiency on ‘comfortable’ than on ‘uncomfortable’ mattresses. However, no quantitative characteristics are provided that describe the difference between ‘comfortable’ and ‘uncomfortable’.

The lack of consistency in the above findings might be due to the diversity of sleep systems that were used in the different studies, with no specifications on the actual bed properties. Another possible explanation is the lack of individualization of the experimental conditions. The interaction between a bed and its user is not only dependent on the properties of the bed, but also on the anthropometric features of the sleeper. Neglecting such individual properties corresponds to applying a different experimental condition for each participant. This paper will assess sleep system quality by measuring the spinal alignment of the sleeper, rather than by the characteristics of the sleep system itself. This approach accounts intrinsically for anthropometric differences as well, because the resulting interaction between both sleep system and human body is measured. Since spinal alignment is influenced by the adopted sleep postures during the night, the amount of time spent in each posture is considered as an independent factor in the analysis of the results.

2.2 Methods

2.2.1 Subjects

Altogether, 17 subjects (nine males, eight females; age 24.3±7.1 years) were recruited through advertisement. Inclusion criteria were a regular sleep-wake schedule and a good general health condition. According to the Pittsburgh Sleep Quality Index [4] and a sleep diary, all subjects were normal sleepers and did not suffer from insomnia. At home, they were used sleeping on mid-range sleep systems (€300 - €1000), which had been in use for 2-7 years. Exclusion criteria were medical problems that can interfere with normal sleep, e.g. intake of sleep medication, antidepressants, any form of back pain. All subjects signed an informed consent. The study was approved by the Ethics Committee of the Vrije Universiteit Brussel.

2.2.2 Experimental design

After a baseline night, each subject underwent two experimental conditions: (1) a reference condition with a personalized stiffness distribution; (2) an induction with a stiffness distribution that simulates a sagging mattress. Counterbalancing was applied to avoid carry-over effects between both conditions.

2.2.3 Procedure

Prior to the actual sleep experiments, the subjects underwent an anthropometric screening. The purpose of this screening was to determine the sleep system configuration for each of the subjects that best matched their individual body dimensions and to objectively validate the effect of both experimental conditions on spinal alignment (see 2.2.4). In order to provide both a personalized and a sagging support for a variety of people, sleep systems with an adjustable stiffness distribution were used (DynaSleep; Custom8, Leuven, Belgium). The mattress core of these systems consists of pocket springs and comprises 10 comfort zones. Eight of these comfort zones can be separately adjusted in stiffness by applying a vertical displacement of the zones' spring bases, effectively creating positive or negative preloads.

The reference condition consists of an individualized sleep system configuration that minimizes spinal deformation in a lateral sleep posture (i.e. when the spine approximates a straight line in the frontal plane). A lateral posture was considered because it is the most commonly adopted sleep posture in the

Western world (approximately 60% of time in bed is spent in a lateral sleep posture) [14]. Furthermore, this corresponds to how most modern sleep systems with comfort zones are designed at present [6]. However, it should be noted that the individual aspect of habitual sleep postures poses an important limitation on this working method. To account for this limitation, the amount of time spent in each posture is registered and considered as an independent factor in all further analyses (see 2.2.5).
The induction consists of a configuration with a relatively high stiffness of the shoulder zone and a relatively low stiffness of the waist and hip zones compared to the reference condition. This simulates a homogeneous sleep system that is worn down and suffers from sagging of the most load-bearing zones. Subjects were blinded from the experimental conditions to eliminate expectation effects.

A night in the sleep laboratory consists of approximately 8 h in bed: subjects entered the sleep laboratory at 19.00; bedtime was between 22.30 and 23.30; subjects were awakened at 07.00 hours. In the evening, they were allowed to engage in recreational activities, such as watching television, reading and conversation. No caffeinated drinks or heavy meals were allowed. Subjects completed the sleepiness, state of arousal and mood scales at 22.15 and 07.20 hours. Subjective sleep quality was assessed at 07.20 hours.

2.2.4 Measurements and analysis

Anthropometric screening

During anthropometric screening, the following series of measurements was conducted. First, a set of 29 x 1-D body measurements was collected by means of a calliper and a tape measure. Height, width and circumference were measured on the following anatomical sites: acromion; shoulder; breast; waist; pelvis; hip; crotch. An additional depth measure was taken on the acromion, shoulder, breast, waist and pelvis sites. Finally, body weight, total body length and neck base height were also determined. Second, 2-D body contours in both the sagittal and frontal planes were automatically registered (Ikélo; Custom8). Finally, back surface measurements were done by means of rasterstereography for a lateral sleep posture on both the personalized and the sagging sleep system (3D Vario; Vialux, Chemnitz, Germany). These measurements were used to validate spinal alignment in both conditions [11, 15].

The measurements of body dimensions and body contours serve as a basis to estimate the personalized stiffness distribution for each of the participants. First, the location and size of three comfort zones (shoulder zone, waist zone and hip zone) are individually determined with regard to the eight adjustable

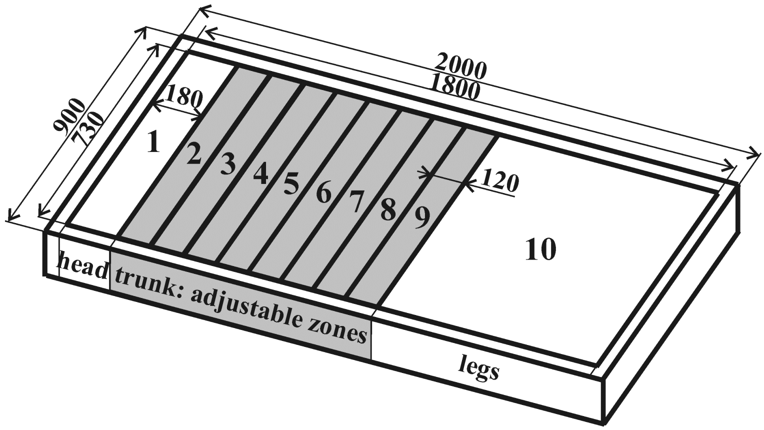


Figure 2.1: Dimensions (mm) and locations of the sleep system's stiffness zones

Table 2.1: Possible settings for the sleep system's stiffness zones in both experimental conditions

		Zone 1	Zones 2-4	Zones 5-6	Zones 7-9	Zone 10
Intrinsic spring stiffness coefficient (N/mm)		0.20	0.076	0.20	0.20	0.20
Spring preload (N)	Personalized stiffness distribution	0	-0.76 0 +0.76 +1.52 +2.28 +3.04	-2.00 0 +2.00 +4.00	-2.00 0 +2.00 +4.00 +6.00	0
	Sagging stiffness distribution	0	-1.52	+4.00	+4.00	+4.00

stiffness zones. This first step allows the adaptation of the sleep system to longitudinal body measurements, such as shoulder height, waist height and hip height. Second, the estimation of the actual stiffness settings per comfort zone is done based on BMI, shoulder width/waist width ratio (SW) and hip width/waist width ratio (HW). The values of SW and HW are compared to the percentiles (25th, 50th and 75th) of a dataset of 64 subjects. This results in four different stiffness settings per comfort zone. Finally, for people with a BMI of ≥ 25 kg/m^2, the general stiffness of the sleep system across the eight adjustable zones is increased. Figure 2.1 illustrates the dimensions of the different stiffness zones and their locations with regard to the sleep system. Table 2.1 lists the intrinsic stiffness coefficients for each mattress zone, together with the possible preload values. Both stiffness and preload values refer to the properties of the individual springs, rather than the entire zones. Positive and negative preload values correspond to tensile and compressive preload respectively. The sagging stiffness distribution is the same for all subjects, regardless of their anthropometric features.

In order to objectively quantify the effect of both conditions on spinal alignment, an algorithm is used that detects the line through the spinous processes, based on back shape data, with a mean accuracy of 2.6 mm [15]. Four shape parameters are calculated that objectively quantify spinal alignment in the frontal plane [14]. Figure 2.2 clarifies the definition of the four shape parameters. The first parameter is defined as the angle between the horizontal axis and the straight line that connects the vertebra prominens with the midpoint of the dimples of the posterior superior iliac spine. Second, the mean distance is determined from the measured line to the least squares line through the points representing the line through the spinous processes (parameter 2). The third parameter is the angle between the horizontal axis and the least squares line through the spinous processes. Finally, the angle between the least squares lines through the lumbar and the thoracic part of the line through the spinous processes (parameter 4) completes the quantification of spine shape. Parameters 1 and 3 describe the global orientation of the spine with respect to a horizontal plane, whereas parameters 2 and 4 describe the deviation from a straight line.

Objective and subjective sleep measures

The subjects underwent three full night polysomnographic recordings (DREAM; Medatec, Brussels, Belgium). Electrodes were attached according to the standardized 10-20 system of electrode placement [19] at the F3, C3, O1, F4, C4 and O2 positions, together with electrooculography, submental electromyography and electrocardiography. Furthermore, video frames and chest orientation were recorded in order to determine the adopted sleep postures during the night. The nights were blinded and scored according to the Rechtschaffen and Kales criteria and the modifications of the American Academy of Sleep Medicine [27, 16].

Further to this objective evaluation of sleep, several subjective measures were also determined. Subjective sleep quality was evaluated on a visual analogue scale of zero (extremely poor) to 20 (extremely good) in the morning following the test night. Furthermore, the restorative effect of sleep was determined by three different scales, comparing the subjective level of functioning the evening before and the morning after the test night. The first scale was the Karolinska Sleepiness Scale, which has been widely used in literature to evaluate subjective sleepiness [1]. Second, state of arousal was determined by the arousal scale of Cox's Stress/Arousal Adjective Check List [24]. Third, the fatigue scale of the

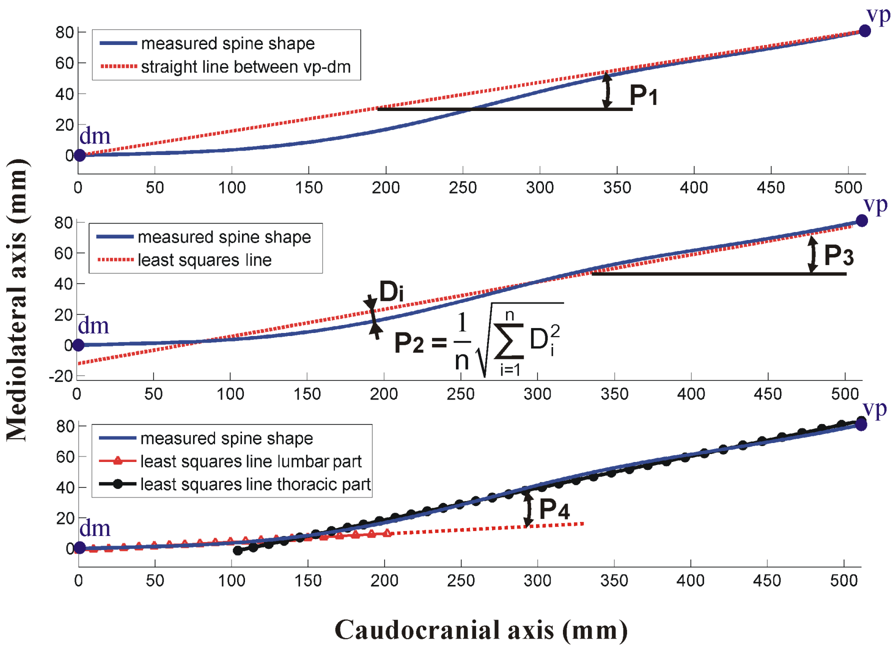


Figure 2.2: Objective quantification of spinal alignment during lateral recumbency by four shape parameters. vp = vertebra prominens; dm = midpoint between the dimples of the posterior superior iliac spine. For details of parameters, see section 2.2.4

Profile of Mood States was used to evaluate subjective fatigue [5]. All three scores were scaled to five and sleepiness and fatigue were inversed to make sure that a positive difference between morning and evening scores reflects a more restorative night.

2.2.5 Statistical analysis

First, all grouped data were tested for normality using Lilliefors' adaptation of the Kolmogorov-Smirnov test [23]. Normal distributions were analyzed using parametric repeated measures ANOVA. For non-normal distributions, non-parametric Friedman ANOVA were performed. Subjective data were analyzed using non-parametric Friedman ANOVA because of the ordinal nature of the subjective scales. Unsupervised cluster analysis based on the k-means algorithm [25] was performed to partition the data on sleep postures into different categories. The amount of clusters was determined by means of cluster silhouettes [29]. Using this approach, each cluster could be represented by its average silhouette width, which is based on the comparison of its tightness and separation from other clusters. The silhouette value for each sample is defined as follows:

$$s(i) = \frac{(b(i) - a(i))}{\max(a(i), b(i))} \tag{2.1}$$

where $a(i)$ is the average distance from the i$^{\text{th}}$ point to the other points in its cluster, and $b(i)$ is the average distance from the i$^{\text{th}}$ point to points in the closest cluster. The silhouette value ranges from -1 (the sample is misclassified) to +1 (the sample is appropriately clustered). Averaging over the entire cluster provides a measure of how tightly grouped all data samples in the cluster are. Averaging over the entire dataset provides a measure of how appropriate the data has been clustered; hence, providing a method to determine the optimal number of clusters. The squared Euclidean distance was used as distance measure to perform the k-means clustering and to calculate silhouette values. Both experimental condition (personalized vs. sagging support) and the amount of time spent in each posture (cluster A vs. cluster B) were considered as independent factors in the statistical analysis of the results of the sleep experiments.

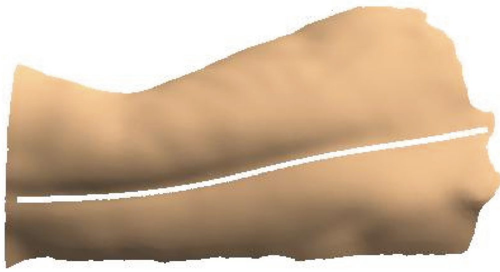
2.3 Results

2.3.1 Anthropometric screening

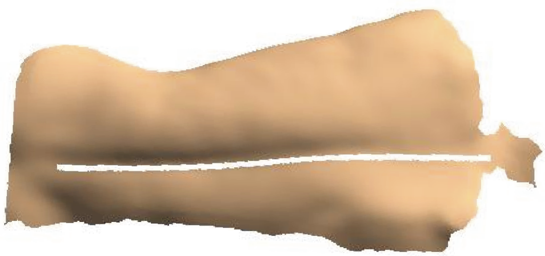
The calculated spine shape parameters for the reference and induction nights are listed in Table 2.2. All parameters are significantly higher in the sagging condition. This means that the change in stiffness distribution results in a changed spine shape and that the applied sagging induction corresponds to an impaired spinal alignment, both in terms of orientation (P1, P3) and distortion (P2, P4) of the spine. In addition, the effect of experimental condition on spine shape parameters was independent of posture cluster (see 2.3.2), indicating that experimental conditions were similar for both subgroups. Figure 2.3 visualizes the effect of both support conditions on the shape of the spine during lateral recumbency for one of the subjects.

Table 2.2: Spine shape parameters

	P1 (°)	P2 (mm)	P3 (°)	P4 (°)
Reference condition (personalized support)	3.31 ± 1.49	4.81 ± 2.31	2.92 ± 1.93	6.31 ± 4.52
Induction (sagging support)	7.77 ± 2.68	6.10 ± 2.56	7.69 ± 3.25	8.53 ± 5.61
Significance	$< 10^{-5}$	0.01	$< 10^{-5}$	0.046



(a)



(b)

Figure 2.3: (a) Effect of sagging induction on spine shape as determined from back shape measurements. (b) Effect of personalized condition on spine shape as determined from back shape measurements.

2.3.2 Sleep experiments

Sleep postures and cluster analysis

Three main sleep postures were considered: supine; lateral (left and right aggregate); prone. Most time is spent in a lateral posture (55.4 ± 17.3%), followed by a supine posture (32.2 ± 19.2%) and the least time is spent in a prone posture (12.4 ± 13.7%). However, these mean values go along with a lot of variation and most of this variation has to do with interpersonal rather than night-to-night differences [32]. Cluster analysis is performed considering two and three clusters. The two-cluster solution reveals the highest average silhouette width (0.66) and is therefore chosen to reorganize the dataset. Figure 2.4 shows the obtained clusters together with the corresponding silhouette values. Cluster A consists of eight subjects who spent most time in a lateral and prone posture (61.0 ± 16.9% and 23.4 ± 9.1%, respectively) and a relatively small amount of time in a supine posture (15.0 ± 9.9%). Cluster B comprises nine subjects who spent most time in a lateral and supine posture (51.9 ± 14.7% and 44.1 ± 12.8%, respectively) and almost no time in a prone posture (4.0 ± 5.5%). Comparing the amount of time spent in each posture within subjects reveals no significant differences between conditions (supine: p = 0.92, lateral: p = 0.88, prone: p = 0.91), indicating that subjects did not alter their postural habits during the course of the experiment.

Subjective assessment

In general, subjective sleep quality is lower in the sagging induction condition compared to the reference condition (12.1 ± 3.8 vs. 14.4 ± 1.8; $\chi^2(1) = 4.57$, $p < 0.05$). However, it can be inferred from Figure 2.5 (a) that a large variation exists in the subjective sleep quality scores after the induction condition. Taking into account the amount of time spent in each posture as an independent factor in the analysis of the results reveals some new insights. In cluster A, subjective sleep quality is significantly lower during the sagging condition compared to

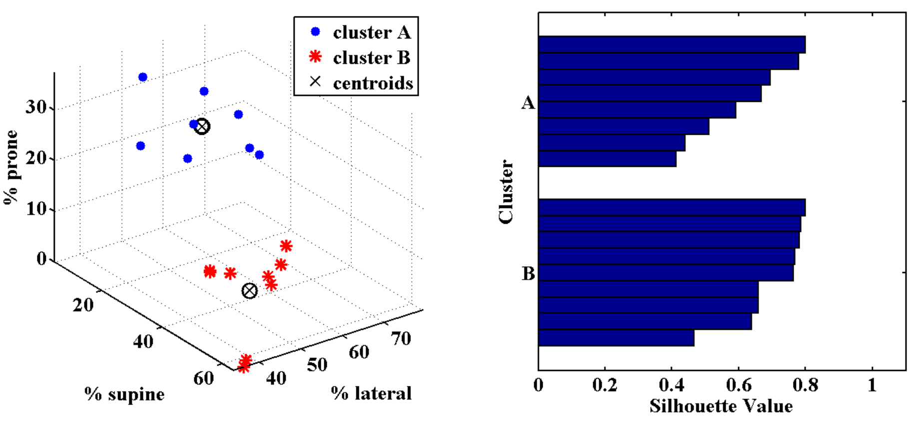


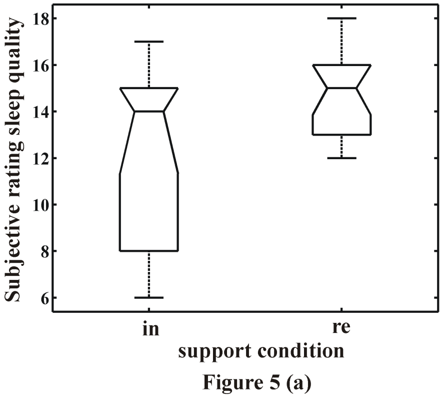
Figure 2.4: Two-cluster solution and silhouette plot of sleep posture preference

reference (9.0 ± 3.1 vs. 13.4 ± 1.8; $\chi^2(1) = 7$, $p < 0.01$). No such difference between conditions is present in cluster B (14.9 ± 1.4 vs. 15.2 ± 1.4; $\chi^2(1) = 0.14$, $p = 0.71$), indicating that subjects of cluster B did not report a lower sleep quality score on a sagging than on a personalized sleep system. Figure 2.5 (b) shows the reported scores of subjective sleep quality for both conditions in both posture groups.

The restorative effect of sleep is determined by the difference in mood, sleepiness and arousal between the morning after and the evening before the test night. Figure 2.6 illustrates the interaction effects between condition and posture preference for these three scales. Statistically significant differences were only present in the arousal scale. Subjects in cluster A were less recuperated in terms of their state of arousal after the night on the sagging sleep system compared to the personalized sleep system (morning-evening difference: -0.6 ± 0.9 vs. 1.0 ± 0.7; $\chi^2(1) = 7$, $p < 0.01$). Cluster B showed no difference between both conditions (morning-evening difference: 0.6 ± 1.1 vs. 0.8 ± 0.8; $\chi^2(1) = 0$, $p = 0.99$). Neither the sleepiness scale nor the fatigue scale revealed a statistically significant interaction effect.

Sleep architecture

No general effects of condition on the parameters derived from the sleep hypnogram have been found. Analogous to the results of the subjective assessment, the amount of time spent in each posture has been considered as an independent factor influencing sleep on different sleep systems. Tables 2.3 and 2.4



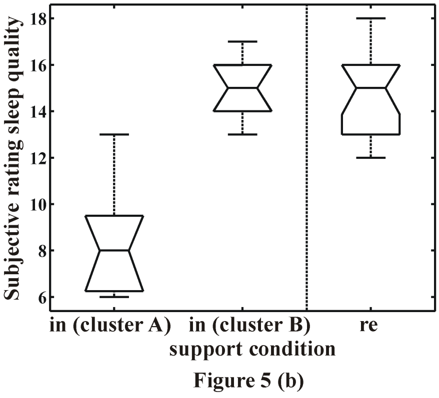


Figure 2.5: Subjective ratings of sleep quality in general (a) and considering the two clusters (b) in the induction (in) and reference condition (re)

Table 2.3: Objective sleep data for cluster A

	Induction	Reference condition	Significance
TIB (min)	454.92 ± 20.13	470.08 ± 15.21	0.65
SOL (min)	24.75 ± 11.39	20.08 ± 9.40	0.99
PSL (min)	28.50 ± 16.43	21.67 ± 8.37	0.99
TST (min)	374.33 ± 18.39	408.50 ± 25.57	0.10
Awake (min)	55.83 ± 25.44	41.50 ± 28.34	0.01
Awake (%TIB)	12.13 ± 5.08	8.79 ± 5.81	0.01
REM sleep (%TIB)	11.53 ± 6.24	17.09 ± 6.36	0.01
SWS (%TIB)	28.22 ± 4.33	28.00 ± 5.00	0.41
SST (n)	144.17 ± 30.49	138.17 ± 16.99	0.41
Awakenings (n)	21.17 ± 7.52	25.50 ± 4.85	0.10
Awakening duration (min)	4.00 ± 1.33	2.40 ± 1.10	0.01
REM latency (min)	150.83 ± 62.11	101.42 ± 34.49	0.01
SWS latency (min)	12.17 ± 10.75	13.83 ± 4.25	0.41
SEI (%)	84.20 ± 5.50	86.97 ± 5.95	0.10

TIB = time in bed; SOL = sleep onset latency; PSL = persistent sleep latency; TST = total sleep time; REM = rapid eye movement; SWS = slow wave sleep; SST = sleep stage transitions; SEI = Sleep Efficiency Index (TST/TIB)

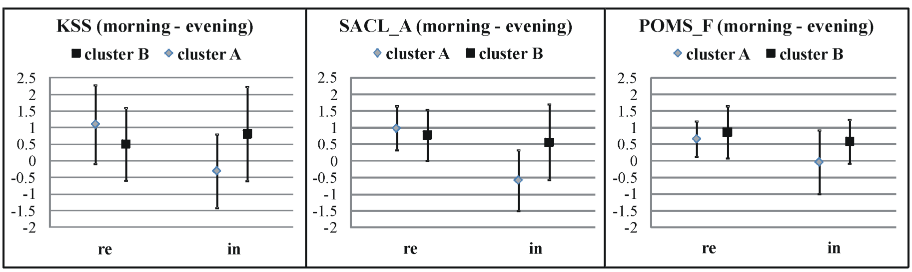


Figure 2.6: Estimated marginal means and standard deviations for morning-evening difference of sleepiness (Karolinska Sleepiness Scale [KSS]), state of arousal (Cox's Stress Arousal Adjective Check List [SACL_A]) and fatigue (Profile of Mood States [POMS_F]) with the independent variables condition (induction [in] vs. reference [re]) and posture preference (cluster A vs. cluster B)

list the characterizing parameters of the scored nights for both conditions in clusters A and B respectively. Similar to subjective findings, differences between conditions were dependent on the posture group. First, a significant difference in wake time is present between conditions in cluster A. Subjects spent more time awake (as a percentage of time in bed) during the night on the sagging

Table 2.4: Objective sleep data for cluster B

	Induction	Reference condition	Significance
TIB (min)	479.37 ± 26.96	464.87 ± 21.99	0.16
SOL (min)	12.56 ± 9.95	11.37 ± 7.38	0.48
PSL (min)	23.75 ± 19.88	16.44 ± 14.67	0.99
TST (min)	443.12 ± 34.42	430.56 ± 33.97	0.16
Awake (min)	23.69 ± 15.48	19.69 ± 13.29	0.99
Awake (%TIB)	4.98 ± 3.39	4.30 ± 3.01	0.99
REM sleep (%TIB)	17.63 ± 5.29	18.16 ± 5.11	0.48
SWS (%TIB)	26.73 ± 8.93	26.30 ± 9.28	0.99
SST (n)	132.37 ± 32.21	121.25 ± 25.05	0.16
Awakenings (n)	20.25 ± 6.76	21.62 ± 6.84	0.26
Awakening duration (min)	1.96 ± 0.86	1.84 ± 1.20	0.48
REM latency (min)	96.75 ± 59.43	101.00 ± 52.48	0.48
SWS latency (min)	18.81 ± 17.41	24.19 ± 24.40	0.48
SEI (%)	92.42 ± 4.94	93.21 ± 4.33	0.48

TIB = time in bed; SOL = sleep onset latency; PSL = persistent sleep latency; TST = total sleep time; REM = rapid eye movement; SWS = slow wave sleep; SST = sleep stage transitions; SEI = Sleep Efficiency Index (TST/TIB)

system compared to the reference condition (12.1 ± 5.1% vs. 8.8 ± 5.8; $\chi^2(1) = 6$, $p < 0.05$). For subjects of cluster B, no difference in wake time is present between conditions (5.0 ± 3.4% vs. 4.3 ± 3.0%; $\chi^2(1) = 0$, $p = 0.99$). The increase in wake time for subjects of cluster A in the induction condition goes along with an increase in awakening duration (4.0 ± 1.3 min vs. 2.4 ± 1.1 min; $\chi^2(1) = 6$, $p < 0.05$) rather than an increase in the amount of awakenings (21.2 ± 7.5 vs. 25.5 ± 5.8; $\chi^2(1) = 2.67$, $p = 0.10$). Again, no increase in awakening duration is present in cluster B (2.0 ± 0.9 min vs. 1.8 ± 1.2 min; $\chi^2(1) = 0.5$, $p = 0.48$).

Second, subjects of cluster A spent significantly less time in rapid eye movement (REM) sleep during the induction night compared to the reference condition (11.5 ± 6.2% vs. 17.1 ± 6.4%; $\chi^2(1) = 6$, $p < 0.05$). This decrease in REM sleep during the induction night entails a significant increase in REM latency (150.8 ± 62.1 min vs. 101.4 ± 34.5 min; $\chi^2(1) = 6$, $p < 0.05$). None of these differences between conditions in REM sleep characteristics is apparent in cluster B.

Table 2.5 presents awakening duration and the occurrence of SWS by thirds of the night for subjects of cluster A. Apparently, the increase in awakening duration in the induction condition is particularly tangible during the first third of the night. Additionally, the amount of SWS during the last third of the night is significantly higher in the induction condition compared to reference.

Table 2.5: Occurrence of slow wave sleep and awakening duration in cluster A presented by thirds of the night

		Induction	Reference condition	Significance
SWS(%)	1st	31.8 ± 12.3	35.2 ± 5.5	0.69
	2nd	30.0 ± 11.4	29.0 ± 13.3	0.99
	3rd	17.2 ± 8.6	11.2 ± 6.8	0.01
Awakening duration (min)	1st	5.0 ± 3.2	2.8 ± 2.2	0.01
	2nd	2.6 ± 1.1	1.9 ± 1.0	0.41
	3rd	4.1 ± 3.2	2.5 ± 1.1	0.99

SWS = slow wave sleep

2.4 Discussion

This study emphasizes the importance of a personal approach when studying the effects of sleep system properties on sleep. On the one hand, an anthropometric screening was conducted to account for anthropometric differences between subjects so that similar conditions could be imposed for each distinct test person. Results indicate that spinal alignment was significantly worse on the configuration that was used in the induction night , with average spine angles twice as high compared to the reference condition. This confirmed the hypothesis that a sagging sleep system actually results in an impaired spinal alignment for lateral postures. On the other hand, since spinal alignment is highly dependent on the adopted sleep posture, the amount of time spent in each posture was considered as an independent factor in the statistical analysis of the results.

Cluster analysis revealed the existence of two distinct subgroups in terms of preferred sleep postures. Cluster A consisted of eight subjects who spent most time in a lateral and a prone posture and relatively little time in a supine posture. The remaining nine subjects constituted cluster B and spent most time in a lateral and a supine posture and almost no time in a prone posture. Interestingly, the difference between both subgroups was found in the amount of time spent in a prone/supine posture. Both subgroups spent the majority of time in a lateral posture.

Results of subjective sleep quality indicate a significant interaction effect between posture preference (cluster A vs. cluster B) and experimental condition (personalized vs. sagging support). Subjects of cluster A experienced their sleep quality on the sagging bed setting as inferior compared to the reference condition. No difference in sleep quality was reported in cluster B between both support conditions. These results were also reflected in the outcome of the Stress/Arousal Adjective Check List, administered in the evening before and the morning following the test night. Whereas the evening scores did not differ significantly between both conditions, subjects of cluster A reported being in a lower state of arousal the morning following the induction night compared to the reference night. This suggests that subjects who spend relatively little time in a supine posture show less recovery in terms of arousal after a nights' sleep on a sagging mattress in comparison with a non-sagging mattress.

Objective sleep data showed an interaction between posture preference and mattress type for parameters related to wake time and REM sleep. First, subjects who preferred a prone and lateral posture spent more time awake during the sagging induction than during the reference condition. The increased wake time was due to longer awakenings, rather than more awakenings. No differences in wake time were present in the group that preferred a supine and lateral posture. Prior research regarding the effects of aircraft noise on sleep [3] suggests that the risk of recalled awakenings increases with the duration of the awakening and that recalled awakenings are correlated with the subjective evaluation of sleep quality and sleep quantity. Consequently, a higher amount of recalled awakenings could be an explanation for the low sleep quality rating that prone/lateral sleepers reported after the night on the sagging sleep system. Second, these subjects spent less time in REM sleep during induction compared to reference. In addition to this decrease in REM sleep, a higher REM latency was also observed. Analysis by thirds of the night revealed two additional findings for prone/lateral sleepers. On the one hand, the increase in awakening duration during the induction night was mainly present during the first third of the night. On the other hand, the amount of SWS in the third part of the night was significantly higher during the induction night compared to reference. The persistence of SWS in the later parts of the night in combination with suppression of REM sleep and increased REM latency might indicate a recovery from disturbed SWS episodes due to the prolonged awakenings in the first part of the night.

One of the underlying causes for the distinct reaction of both posture groups could be related to the nature of the induction. Depending on the adopted sleep posture, the sagging mattress setting will result in a different loading of the human spine and therefore a different spinal alignment. The induction is chosen so as to deteriorate spinal alignment in a lateral sleep posture, because this is the most commonly adopted posture during sleep in the Western world. However, the effect of the sagging configuration on both a supine and a prone posture should also be taken into account. The range of motion of the spine in the sagittal plane is quite large for frontal bending, yet quite small for backward bending. Therefore, lying in a supine posture on the sagging bed will cause little discomfort. A prone posture on the other hand will result in hyperlordosis of the lumbar spine. This hyperlordosis will become more explicit in the condition that simulates a sagging mattress. One can look at it in a similar way as lying in a hammock; in this case, it is not hard to see that a supine posture will cause less discomfort than a lateral and especially a prone posture.

A first limitation of the present study is that it involves short-term changes of body support. These data suggest that people do not change their adopted postures during the course of one night; within subjects, the adopted postures were not different for both conditions. On the one hand, it is possible that if subjects slept on the sagging sleep system during a prolonged period, they would alter their habits and adopt a supine posture more often. Another possibility is the existence of an adaptation effect to the deteriorated conditions. On the other hand, prolonged sagging support could also result in back and/or sleep complaints. Further research is necessary to test these hypotheses. Second, the current study deals with young healthy sleepers with no back or sleep problems. A population with pre-existing back/sleep problems might be more affected by a sagging sleep system [13, 17]. In this context, Enck et al. [12] showed in a field study with 265 hotel guests that for those with chronic back pain the influence of mattress quality was more pronounced compared to subjects without chronic back pain.

In conclusion, the effect of bed design on sleep cannot be fully assessed by a mere comparison of two different sleep systems in a population of normal sleepers without taking into account interpersonal variability. This interpersonal variability does not only concern anthropometric differences, but individual posture preferences as well. The results of this study indicate that a sagging sleep system has a negative effect on sleep quality for people who spend most time in a lateral and prone posture. People who spend more time in a supine posture do not experience this negative effect. Consequently, future research should consider the amount of time spent in each posture as a determining factor when studying the effect of bed properties on sleep.

Currently, most sleep systems in the Western world are designed to optimize spinal alignment in a lateral posture because it is the most commonly adopted sleep posture in these regions. Some of the high-end sleep systems have the option of individually adjusting mechanical characteristics to the customer's anthropometric features, which is already an important step forward regarding personalization. However, this approach does not account for the amount of time that is spent in each posture. For instance, a high-end sleep system that is personalized based on a sleeper's lateral body contours does not result in an optimal spinal alignment if this person sleeps most of the time in a prone and/or supine posture. Therefore, one could think of a future sleep system being able to detect posture changes [32] and, in a second step, actively change its mechanical properties to optimize spine support for the recognized posture during the night: a so-called 'active' sleep system. In fact, since sleep is commonly referred to as an active process, the concept of an active sleep system does not seem that far-fetched.

2.5 Acknowledgements

This study was carried out thanks to the financial support of the Flemish agency for innovation by science and technology.

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Chapter 3

Unobtrusive assessment of motor patterns during sleep based on mattress indentation measurements

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Adapted from a manuscript published in IEEE Transactions on Information Technology in Biomedicine, 15(5), 787-794, Sep. 2011

Abstract

This study investigates how integrated bed measurements can be used to assess motor patterns (movements and postures) during sleep. An algorithm has been developed that detects movements based on the time derivative of mattress surface indentation. After each movement, the algorithm recognizes the adopted sleep posture based on an image feature vector and an optimal separating hyperplane constructed with the theory of support vector machines. The developed algorithm has been tested on a dataset of 30 fully recorded nights in a sleep laboratory. Movement detection has been compared to actigraphy, whereas posture recognition has been validated with a manual posture scoring based on video frames and chest orientation. Results show a high sensitivity for movement detection (91.2%) and posture recognition (between 83.6% and 95.9%), indicating that mattress indentation provides an accurate and unobtrusive measure to assess motor patterns during sleep.

Index Terms

Body movement detection, mattress indentation measurements, sleep posture recognition.

3.1 Introduction

Inadequate sleep is generally considered as one of the most compelling problems in the industrialized world because of its adverse effects on performance, health, and quality of life [31, 34]. Various factors have been known to influence sleep quality, but most people with minor sleep disturbance associate cognitive and emotional stress [40] or physical discomfort [27] with poor sleep. During sleep, the human body is in sustained contact with the sleep system (i.e., mattress and supporting structure). Therefore, the sleep system is often considered the most important environmental component that affects physical comfort [16]. However, it is surprising how little interactive technology is integrated in current, state-of-the-art sleep systems.

The main function of sleep systems is to support the human body in a way that allows the muscles and intervertebral discs to recover from nearly continuous loading by day [32, 29]. This is achieved when the shape of the spine is in its natural physiological shape, yet with a slightly flattened lumbar lordosis due to the changed working axis of gravity [12, 28]. In order to realize this, the mechanical characteristics of a sleep system should be optimized concerning both body contours and weight distribution of the sleeping person. For this reason, current state-of-the-art sleep systems consist of separate zones with different stiffness for shoulders,waist, and pelvis. However, the body contours that are interfacing with the mattress surface are posture dependent. For instance, in most Caucasian people lateral contours are far more pronounced than sagittal contours. Therefore, changing sleep posture would require the mattress or supporting structure to change accordingly. The first step toward such “intelligent sleep systems” is to correctly determine the adopted sleep posture during the night.

Several authors agree that healthy sleep requires the presence of various posture shifts per night [1, 11]. Posture changes and body movements are necessary to prevent overloading of soft tissue, especially around bony prominences [16]. Although necessary, too much movement during sleep may reduce sleep quality, since it is associated with arousals and sleep fragmentation [2]. In non-rapid eye movement sleep, motor activity progressively decreases from Stage I to Stage IV [21]. High activity levels are related to intermittent wakefulness and fragmented sleep. Moreover, several sleep disorders are characterized by specific movement, such as restless legs syndrome and periodic limb movements during sleep. Other sleep abnormalities, such as obstructive sleep apnea syndrome (OSAS), have a higher prevalence in specific postures (supine for OSAS) [33]. In such cases, accurate follow-up of adopted sleep postures can serve as a useful tool in challenging these disorders.

The assessment of body movements and posture shifts during the night is traditionally performed using polysomnography (PSG), actigraphy, or video analysis. PSG provides detailed information on sleep architecture and a quantification of sleep quality, but can only be performed in a laboratory setting. Actigraphy, although suitable for field research, can only detect movements of the specific limb on which the system is worn. In order to get a complete picture of body movement, devices must be worn on multiple limbs, which increases the burden on the subject. Privacy issues remain a major concern for movement detection based on video analysis.

Recently, interest in instrumenting the bed itself has grown to study body movements and monitor sleep. The main advantage of this approach is that no equipment has to be mounted on the subjects themselves, thus avoiding influence on normal motor patterns during sleep. Lu et al. [30] and Tamura et al. [36] assessed changes in bed temperature as an index of body movement and validated their setup with simultaneous video image and actigraphic recordings. Results showed that leg movements were detected more accurately than torso movements. Moreover, the inherently long reaction time of temperature sensors determines a detection interval of at least 15-30 s, making it impossible to distinguish short movements such as sleep twitches. Van der Loos [38] tried to overcome this by combining an array of 54 resistive temperature devices with an array of 54 force sensitive resistors to monitor breathing rate and temperature overnight. Unfortunately, results were only reported for one subject that slept in a supine posture during the entire night and no validation of the outcome was accounted for. Chan and coworkers [8, 7] developed a system composed of infrared motion sensors to assess mobility of patients in a hospital room. Although their system was capable of monitoring activity in bed and out of bed, it could not discriminate between a person in bed and a person near the bed. Heinrich and Van Vugt [20] proposed near-infrared video actigraphy as an off-body alternative for standard actigraphy. Five subjects were tested in their home environment and movement detection was compared with traditional actigraphy. Although processing was done in real time with volatile memory, privacy issues remain a major concern for this type of systems. Several authors installed load cells at the corners of a bed to determine body movements during sleep [2, 3, 6]. Next to body movement, the high accuracy of such load cells allowed Brink et al. [6] to determine heart rate and breathing activity as well. However, no detailed information on sleep posture could be derived. Other authors assessed the problem of posture recognition by means of pressure distribution images [17, 18, 19, 35, 24, 25]. The developed methods provided interesting results but were only tested on a set of predefined sleep postures of a very limited subject population. Furthermore, no overnight experiments were performed to validate performance when subjects were not bound to these predefined postures. Finally, recent work [23] incorporated accelerometers in a mattress topping to evaluate body movements and sleep postures. Unfortunately, the algorithm had to be trained for each subject separately before it could be used to asses body movements and sleep postures, narrowing its general applicability. In addition, full night validation of the algorithm was restricted to only one subject and only ten discrete time stamps per night.

This paper focuses on mattress indentation measurements for the unobtrusive assessment of both body movements and adopted sleep postures during the night. The developed algorithm has been validated on different healthy subjects during full night experiments in our sleep laboratory. The proposed algorithm can be used not only to assess motor patterns during sleep, but also as part of a so-called intelligent sleep system that adopts its mechanical characteristics according to the adopted sleep posture.

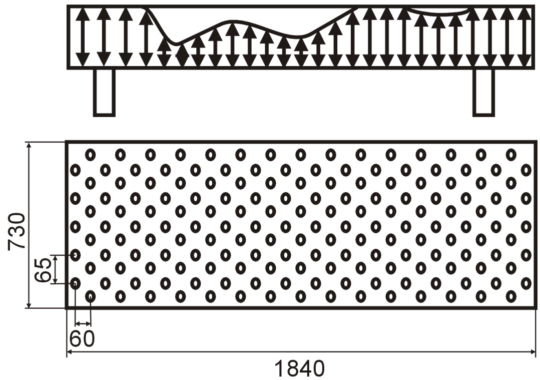

Figure 3.1: Location of integrated indentation sensors in the sleep system in relation to the mattress core dimensions (mm).

3.2 Materials and methods

3.2.1 Data collection

Sleep systems were used that measure the perpendicular indentation of the mattress surface in a 2-D grid of 170 points at a sampling rate of 0.5 Hz (DynaSleep, Custom8, Leuven, Belgium). The mattress core of these systems consists of pocket springs and comprises ten comfort zones. Spring indentation is measured by logarithmic potentiometers that are positioned in such a way that they are most sensitive in the region of small indentations. The total range of the potentiometers (100 mm) consists of three linear regions in which sensitivity is, respectively, 0.05 mm (0–10 mm), 0.15 mm (10–40 mm), and 4 mm (40–100 mm). Figure 3.1 shows the sensor positions in relation to the dimensions of the mattress core. Fifteen subjects (nine males, six females; age 25.8 $\pm$ 8.6 years) were recruited through advertisement. Calculated body mass indices (BMI) varied between 18.4 and 29.4 kg/m^2, with an average of 22.0 $\pm$ 2.5 kg/m^2. Inclusion criteria were a regular sleep-wake schedule and a good general health condition. Exclusion criteria were medical problems that could interfere with normal sleep, e.g., intake of sleep medication, antidepressants, and any form of back pain. The subjects spent on average four nights in the sleep laboratory. During the night, the following data were gathered. First, continuous mattress indentation measurements were registered by the sleep systems. Second, actigraphic recordings (SenseWear, BodyMedia, Pittsburgh, PA) were performed at a sampling rate of 32 Hz. Third, the subjects were asked in the morning what sleep posture they perceived as dominant during the

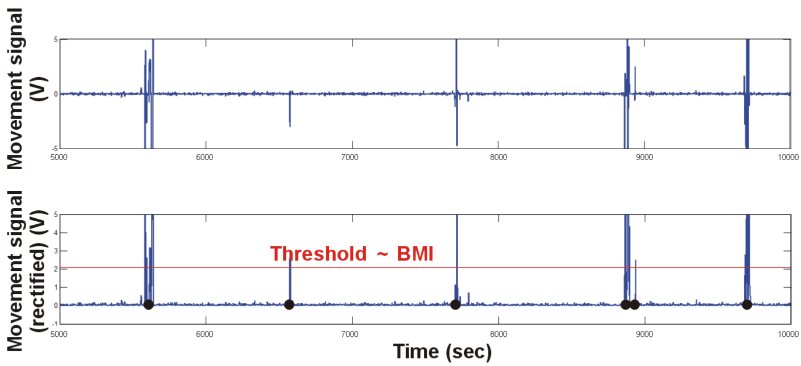

Figure 3.2: Movement detection by thresholding the rectified movement signal demonstrated on a 5000-s time interval

previous night. And finally, simultaneous polysomnographic (Dream, Medatec, Brussels, Belgium) and video recordings served as a gold standard.

3.2.2 Analysis of Bed Measurements

The first step in the analysis of the indentation data is the accurate detection of body movements. After each movement, when a stable situation is achieved, a posture recognition algorithm determines the adopted sleep posture. Four basic postures are considered: supine, left lateral, right lateral, and prone. In reality, intermediate postures occur as well. First of all some persons tend to turn their shoulders toward prone, whereas the pelvic girdle remains lateral. These cases will be considered lateral as spinal deformation is closest toward the case of lateral bending. Another commonly adopted intermediate posture is when the pelvis is canted toward prone, whereas the shoulders remain lateral. In this posture, similar to what happens in the prone posture, lumbar lordosis is exaggerated compared to the desired spinal shape. Consequently, these postures will be considered prone.

Detection of body movements

The detection of body movements throughout the night is quite straightforward. Even small body movements coincide with shifts of mass above the mattress surface, thus resulting in an altered indentation of the inner springs. Consequently, summation of the derivative over time of each potentiometer output z_i across the entire mattress surface provides a signal with negative or positive peaks during movements (i.e., the movement signal in Figure 3.2). This signal is rectified

$$\text{movement signal} = \sum_{i=1}^{170} \left| \frac{dz_i}{dt} \right| \tag{3.1}$$

after which a threshold determines when movements occur. The threshold is constant over time, yet individually different for each test person since it is related to BMI. Subsequent peaks are considered as being the result of one major movement to assure that movements with a duration of 4 s or more are detected only once for each occurrence.

Classification of sleep posture

The classification of the indentation measurements into four distinct classes is performed using a supervised learning method based on the theory of support vector machines (SVMs) [42]. Supervised learning methods construct classification rules based on a finite set of training data. In order to perform well, learning machines should not only be optimized to minimize the empirical risk (the number of errors in the training data), but they should possess good generalization abilities as well (a small confidence interval). This concept is outlined in the principle of structural risk minimization that states that for any set of functions f_α:

$$R(\alpha) \leq R_{emp}(\alpha) + \Phi\left(\frac{h}{l}\right) \tag{3.2}$$

with R being the risk, R_{emp} the empirical risk, α the function index, Φ the confidence interval, l the number of training examples, and h the Vapnik-Chervonenkis dimension [42]. The first approach in minimizing the right-hand side of the aforementioned equation is by keeping the confidence interval fixed and minimizing the empirical risk (the working principle of artificial neural networks). The main drawback of this type of learning machines is that there are many local minima solutions. Furthermore, *a priori* knowledge about the problem is required to find a suitable architecture of the machine. The second approach keeps the value of the empirical risk factor fixed and minimizes the confidence interval. SVM classifiers apply this second approach by constructing the optimal hyperplane [41] that separates the vectors x_i of the training set $(y_1, x_1), \ldots, (y_i, x_i)$ belonging to two different classes $y \in \{-1, 1\}$. Assume that the points in the training set are not linearly separable (the soft margin separating hyperplane) [9]

$$\begin{cases} \omega \cdot x_i - b \geq & +1 - \xi_i, \text{ if } y_i = +1 \\ \omega \cdot x_i - b \leq & -1 - \xi_i, \text{ if } y_i = -1 \end{cases} \qquad (\xi_i \geq 0) \tag{3.3}$$

with ω being the normal vector of the hyperplane, b a constant, and ξ_i the slack variables. For the purpose of calculating the soft margin separating hyperplane, one has to solve the following optimization problem:

$$\begin{gathered} \min_{\omega,\xi} \frac{1}{2}(\omega \cdot \omega) + c\sum_{i=1}^{l} \xi_i \\ \text{s.t.} \begin{cases} y_i[(x_i \cdot \omega) - b] \geq 1 - \xi_i, & i = 1, 2, \cdots, l \\ \xi_i \geq 0, & i = 1, 2, \cdots, l \end{cases} \end{gathered} \tag{3.4}$$

with c being a constant.

The theory of linear SVM classifiers is further expanded to nonlinear SVM classifiers by mapping the input vectors into a high-dimensional space through nonlinear mapping, and then constructing the soft margin separating hyperplane in this space. The Mercer condition avoids the need for an explicit knowledge of the nonlinear mapping by the application of a kernel, the so-called kernel trick [42].
Although SVMs were originally designed for binary classification, several methods have been proposed for solving multiclass problems. A commonly used approach is to decompose a multiclass problem into multiple binary problems distinguishing between one class and all others (one-against-all method) or between every pair of classes (one-against-one method). More recently, approaches for multiclass problems by solving one single optimization problem were proposed (all-together) and compared with the aforementioned methods based on binary classification [26]. However, at present the extension of SVMs to multiclass classification is still an ongoing research issue and the preferred method for solving multiclass problems seems to be dependent on the classification problem.

For the purpose of classifying a mattress indentation measurement into one out of four sleep postures, the decision rules are constructed by means of an SVM classifier that is developed using a radial basis function kernel. Three methods were considered to solve the multiclass problem: one-against-all [5], one-against-one [13], and all-together [43]. The input space consists of a limited set of features that is representative for each indentation measurement. The most reliable features are the following: shoulder-hip ratio, knee-hip ratio, total indentation, lateral asymmetry index (LAI), and lower leg indentation. The shoulder-hip ratio is defined as the total amount of indentation in the shoulder zone relative to that in the pelvic zone. Analogously, the knee-hip ratio is defined as the total amount of indentation in the knee zone relative to that in the pelvic zone. The third feature is defined as the total indentation measured across the entire mattress surface, adjusted with a factor that is inversely related to BMI. The LAI is determined as the mean signed distance from the line of minimal lateral asymmetry in shoulder, waist, and hip zone to the straight line connecting its starting point and end point. Lateral asymmetry in a point (i, j) of the mattress is defined as follows:

$$\mathrm{AS}(i,j) = \left(\sum_{k=1}^{j-1} Z(i,k) - sum_{k=j+1}^{w} Z(i,k) \right)^2 \quad \text{with} \begin{cases} i = 1, \cdots, l \text{ the longitudinal index} \\ i = 1, \cdots, w \text{ the lateral index} \end{cases} \tag{3.5}$$

AS being the lateral asymmetry matrix, and Z the indentation matrix. Finally, the amount of indentation in the area of the lower legs, again with BMI correction, completes the set of features. The location and size of the mattress zones were fixed and identical for each test person. Figure 3.3 clarifies the previously described features on indentation samples of a supine, lateral, and prone posture adopted by one of the participating subjects.

Validation

First, movement detection based on mattress indentation measurements is compared to movement detection based on actigraphic recordings. The acceleration record of the actigraph is synchronized with the movement signal derived from the bed measurements. The signals are normalized and the same threshold criterion is used on both signals to determine body movements

$$\mathrm{UCL} = \mathrm{mean(signal)} + 0.75 \times \mathrm{st\ dev(signal)} \tag{3.6}$$

with UCL being the upper critical limit. Video recordings are used as a gold standard to verify the detected movements. Second, a graphical user interface has been developed that allows performing an independent posture scoring based on the combination of video analysis and spatial orientation of the chest, both provided by the polysomnographic measurement equipment (see Figure 3.4). This manual scoring of sleep posture is performed completely blinded from the indentation measurements and from the output of the automatic posture recognition. Afterward, both scorings are compared.

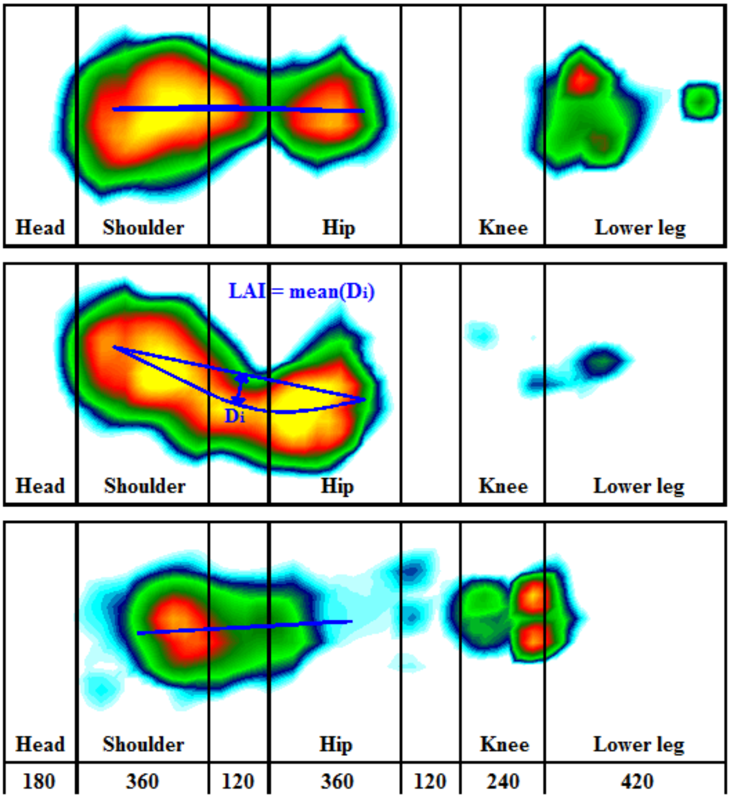

Figure 3.3: Indentation samples of a supine (upper), left lateral (middle), and prone (lower) posture for one of the test persons. LAI and the location of the mattress zones are indicated to clarify the feature set.

3.2.3 Analysis of motor patterns

All recorded nights are analyzed for motor patterns based on the following parameters. First, the amount of body movements (BM) is determined as the amount of movements in bed without posture change. Variability of BM's and posture changes (PC) is analyzed within and between subjects. Second, postural immobility is quantified. Hobson and coworkers [22] introduced postural immobility as episodes of immobility punctuated by major postural shifts and showed the organization of these periods to be periodic and related to the sleep cycle phase. They computed the “consolidation index” as the ratio of immobile epochs to the total numbers of epochs asleep. In this study, the same definition

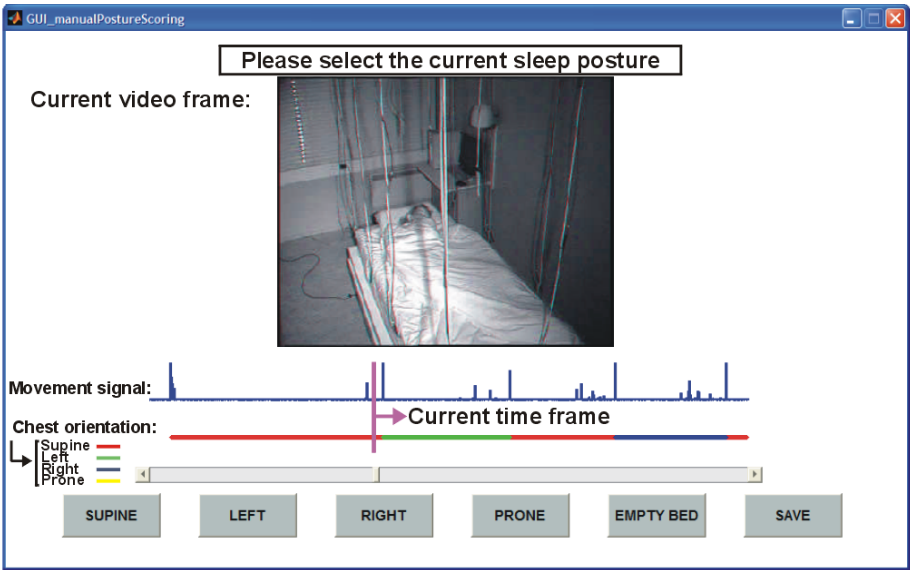

Figure 3.4: Graphical user interface for manual scoring of sleep posture

is used for the consolidation index. In addition, periods of immobility (PI) are defined as episodes of 30 min or more without any occurrence of movement. Analogously, periods of postural immobility are periods of 30 min or more without any posture changes.

3.3 Results

3.3.1 Performance

Movement detection

Sensitivity analysis showed a higher sensitivity for movement detection based on bed measurements compared to movement detection based on actigraphy and a similar specificity (see Table 3.1). Video analysis showed that the higher sensitivity could be explained by the capability of detecting small leg movements (e.g., sleep twitches) that were not recorded by the actigraph. The high specificity values were mainly due to the high amount of true negatives. During the night, PI were far more common than periods with movements. In this regard, values of negative likelihood ratio are shown in Table 3.1 as an additional measure that

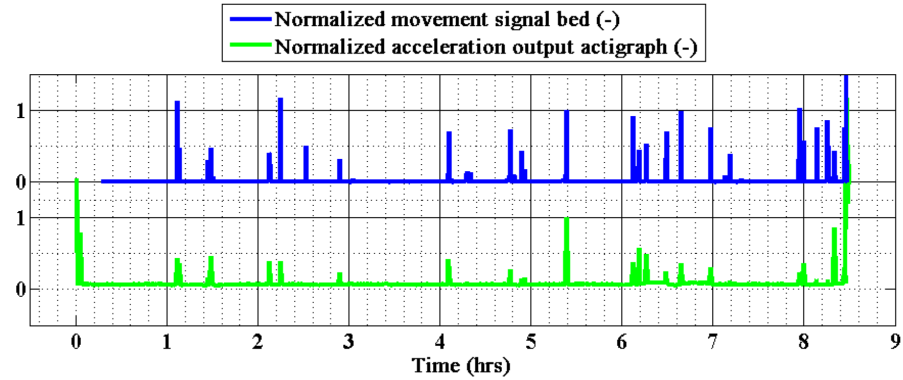

Figure 3.5: Movement signal derived from bed measurements (upper) and acceleration output of actigraph (lower) after synchronization and normalization

Table 3.1: Sensitivity analysis for movement detection based on bed measurement and actigraphy. Video analysis served as reference.

	Movement signal bed	Acceleration output actigraphy
Sensitivity	91.2%	72.2%
Specificity	99.9%	99.9%
PPV	98.7%	94.9%
NPV	99.9%	99.7%
NLR	0.09	0.28

PPV = positive predictive value, NPV = negative predictive value, NLR = negative likelihood ratio.

is less likely to depend on the prevalence of the detectable event. Figure 3.5 clarifies the correspondence between the actigraphic output and the movement signal derived from the bed measurements.

Posture recognition

A training set consisting of 139 indentation samples from five subjects (16 prone, 36 back, 44 left lateral, and 43 right lateral) was used to construct the classification rules based on the three multiclass SVM approaches (one-against-all, one-against-one, all-together). Although training results were similar, the one-against-one method yielded the highest training rate (99.3) and was further

Table 3.2: Sensitivity analysis for posture detection

	supine	left lateral	right lateral	prone
Sensitivity	90.0%	95.9%	92.8%	83.6%
Specificity	97.8%	94.1%	98.5%	98.2%
PPV	95.3%	87.2%	94.8%	89.2%
NPV	95.2%	98.2%	97.9%	97.1%

PPV = positive predictive value, NPV = negative predictive value.

Table 3.3: Results of posture and movement analysis during sleep

	mean	s.d.
Time in Bed (min)	465.0	22.9
Body Movements per minute	0.162	0.071
Posture Changes per minute	0.034	0.019
% supine per night	30.2	20.5
% left lateral per night	30.2	16.8
% right lateral per night	26.0	17.2
% prone per night	13.6	16.4
% moving per night	2.8	1.2
% Movement Time (min)	13.3	6.4

used for testing. Prone postures were generally characterized by a higher knee-hip ratio, a higher shoulder-hip ratio, and a lower total mattress indentation compared to nonprone postures. This can be inferred from Figure 3.6, which depicts an optimal separating hyperplane (one-against-all) between prone and nonprone postures based on the features knee/hip, shoulder/hip, and total indentation. A hypothesis that explains the higher indentation in the area of the knees in prone postures is that the limited range of motion of the hip joint in extension forces the knees to indent the mattress surface. The lower total indentation and the lower indentation in the pelvic area during prone are mainly due to the less pronounced anterior body contour as compared to lateral and posterior contours. Supine sleep postures were characterized by a low LAI (near zero) and significant indentation in the area of the calves. Left lateral postures showed a negative asymmetry index, and right lateral postures showed a positive asymmetry index. Figure 3.7 shows that lateral asymmetry and lower leg indentation mainly account for the classification of supine, lateral left, and lateral right, whereas no clear separation of prone postures is accomplished by these two features.

The test set consisted of 30 fully recorded nights (mattress indentation, video

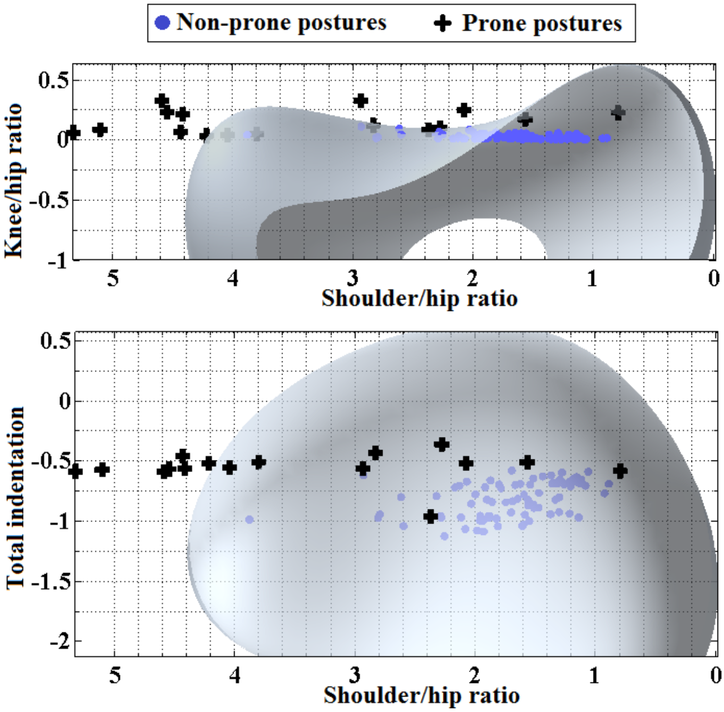

Figure 3.6: Front view (upper) and top view (lower) of an optimal separating hyperplane between prone and nonprone sleep postures of the training set based on the features knee/hip ratio, shoulder/hip ratio, and total indentation

recording, and PSG recording) of 10 different persons (six males and four females). These 30 nights resulted in a total number of 1910 indentation samples to be scored. The correspondence between the automatically recognized postures and the scoring based on video recording and orientation of the chest over the complete test set was 0.91. The mean episode-to-episode correspondence per night was 0.92 ± 0.10. A sensitivity analysis was performed for posture detection, as shown in Table 3.2. Overall, the classification algorithm showed a high sensitivity and specificity for the considered sleep postures. Sensitivity was highest for the detection of lateral sleep postures and lowest for prone postures, indicating that prone postures were most difficult to detect with the described algorithm. This is mainly due to the difficulty of classifying intermediate postures with canted pelvis. These are considered prone, but sometimes detected lateral due to the image characteristics that often resemble lateral postures.

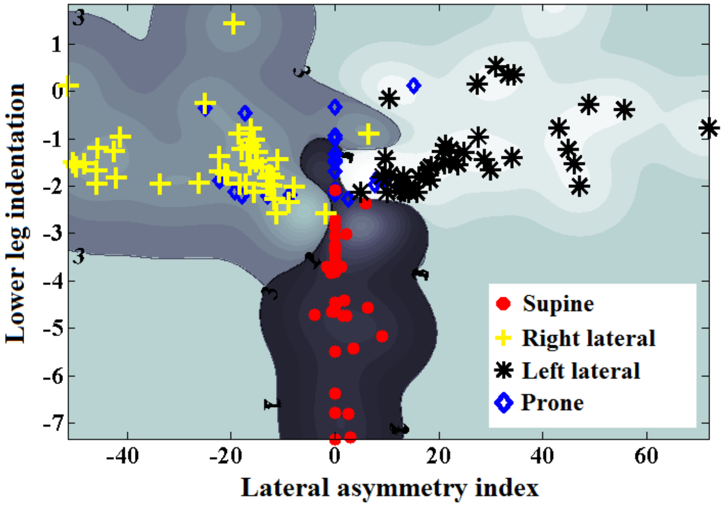

Figure 3.7: LAI and lower leg indentation for all postures of the training set

Analysis of motor patterns

A total of 60 nights (15 persons: 9 males and 6 females, aged 26.1 ± 8.8 years) were recorded and analyzed for body movements and sleep postures. The main results are listed in Table 3.3. Overall, the average amount of body movements per night was 75.0 ± 33.3, whereas the average amount of posture changes was 15.7 ± 8.7. Possible explanations for the relatively high standard deviations for both measures are either large interpersonal differences or intrapersonal night-to-night variability. Interpersonal differences can be characterized by the standard deviation of the intrapersonal averages for all test nights. Intrapersonal variability can be characterized by computing the average of the intrapersonal standard deviations. Our results showed large interpersonal differences for both body movements and posture changes compared to intrapersonal night-to-night variability (BM: 28.3 versus 17.7, PC: 7.8 versus 3.5).

Friedman analysis of variance was performed on the prevalence per night of the four basic sleep postures, showing significant differences ($p < 10^{-3}$). Post hoc analysis (with Bonferroni correction) showed that whereas the prevalence of supine, left, and right lateral postures did not differ significantly, prone sleep postures were adopted signifcantly less. On the other hand, if left and right lateral were to be considered the same lateral sleep posture, then post hoc analysis suggested a significant difference between all three groups ($p < 10^{-10}$).

Table 3.4: Additional parameters describing motor patterns during sleep

	mean	s.d.
# Periods of Immobility per night (PI)	2.9	1.9
# Periods of Postural Immobility per night (PPI)	5.4	1.5
Maximal PI (min)	48.0	14.8
Maximal PPI (min)	108.5	46.4
Average PI per night (min)	7.0	2.8
Average PPI per night (min)	37.1	25.8
Consolidation Index (CI)	73.1	18.8

The lateral posture was most commonly adopted (56.2 ± 16.2%), followed by the supine posture (30.2 ± 20.5%), and finally the prone posture (13.6 ± 16.4%). These values are in line with what can be found in literature [16]. A comparison between actual preferred sleep postures and subjectively perceived dominant sleep postures revealed that 67% of the tested population correctly judged their dominant sleep posture. Additionally, it was found that the large majority of test persons (93.7%) spent more than 50% of time in bed in their dominant sleep posture. On the other hand, only 43.7% (mainly lateral sleepers) of the tested population spent more than 60% of time in bed in their dominant sleep posture.

Table 3.4 shows the consolidation index and summarizes some additional parameters that quantify (postural) immobility. Values for the consolidation index are somewhat higher (73.1 ± 18.8) compared to Hobson's results (55 for good sleepers versus 34 for bad sleepers) [22].

3.4 Discussion

This study shows that mattress indentation measurements are useful for the unobtrusive assessment of motor patterns during sleep. Since BMI is the only required a priori information, the proposed algorithm is generally applicable, without the need for person-specific training. The advantages compared to more traditional techniques are plural. First of all, it does not place any burden on the sleeping subject (as does PSG). Second, it captures movements of the entire body, rather than focussing on one specific body part (actigraphy). Third, not only movement is detected, but a complete set of motion related parameters is provided, including detailed information on sleep postures. It is important to note that, in the current study, integrated bed measurements are not proposed to replace PSG, nor actigraphy. Both have specific advantages over integrated bed measurements when it comes to detailed sleep stage analysis (PSG), or to the analysis of day-night patterns (actigraphic recorders can be worn during the entire 24-h cycle). However, it is proposed as a valuable tool, providing information on sleep that is complementary to other techniques.

Results show a high correspondence between detected postures and validated postures. Furthermore, sensitivity values for the detection of supine and lateral postures are above 90%, indicating that the proposed classification algorithm has a good detection capability for the most commonly adopted postures. Sensitivity of prone detection was somewhat lower (83.6%). The main reason for this can be found in the occurrence of intermediate postures (between lateral and prone), which are sometimes misclassified. Regarding the classification of such intermediate postures, this study discriminates between prone and lateral based on the orientation of the pelvis. An intermediate posture is considered prone if the pelvis is canted toward prone, if not it is considered lateral. The developed posture recognition algorithm has difficulties to classify intermediate postures when the pelvis is only partially canted toward prone.

Values for the amount of body movements and posture changes per night are within the range of what can be found in literature [11, 10, 14]. Results show large interpersonal differences for both body movements and posture changes. Consequently, it will be very difficult to determine a correlation between the mere amount of body movements during sleep and sleep quality. In general, one could state that although movement is necessary, too much movement is detrimental for sleep quality [2]. On the other hand, the large interpersonal variability in our results indicate that this tradeoff between too little and too much movement is subject specific; and therefore, often heard statements such as “good sleep requires 15 posture changes per night” are oversimplifying the complex relation between movement and sleep. More specific, the reference to decide what is too little and too much should be determined individually. Regarding the general prevalence of sleep postures during the nights, most time was spent in lateral sleep postures, followed by supine postures and least time was spent in prone postures. Furthermore, the majority of subjects (67%) correctly judged their dominant sleep posture. On the other hand, it should be noted that only 43.7% of subjects spent more than 60% of time in their dominant posture, indicating that for most subjects a significant amount of time was spent in non-dominant postures as well. This finding suggests that the optimization of the sleep system’s mechanical properties based on the subject’s dominant sleep posture intrinsically suffers from limitations in terms of providing proper body support during the night. Finally, values describing postural immobility have been determined and compared with literature [22]. Higher values for the consolidation index compared to Hobson can be explained by an underestimation of immobility due to his 15-min-interval technique as compared to our 2-s-interval technique.

A first limitation of the developed algorithm involves that the location of the mattress zones — defined to calculate the image features — was not adapted to the subject's position on the mattress. Our results indicated that this limitation had no considerable effect on the performance of the algorithm. However, it should be noted that subjects slept in single beds, effectively limiting their freedom of movement compared to double beds. Therefore, a suggestion for future work is to automatically adapt the location of these mattress zones to the position of the sleeper. A second limitation is that currently only four basic sleep postures can be detected. As described earlier, apart from these basic postures, some intermediate postures are adopted as well. With the current approach, namely a static recognition based on SVM theory, it is very difficult to find image features that discriminate between intermediate postures. Therefore, future work should concentrate on dynamic estimation methods to classify such intermediate postures [18, 4]. An additional advantage of such dynamic estimators is that in combination with a model of human motion more detailed information can be derived about the type of movements (e.g., protraction or retraction of shoulder girdle, crossing of legs, etc.) that occur during sleep.

3.5 Conclusion

The integration of sensors in sleep systems offers the possibility to provide accurate feedback on motor patterns during sleep in an unobtrusive way. First of all, the knowledge on adopted sleep postures is important since the main function of sleep systems, to provide proper body support, is dependent on the adopted sleep posture. In this context, the developed algorithm might be used to advise people on how to change their sleep system settings if their sleep habits change. A more advanced application involves so-called intelligent bedding systems. Such bedding systems are capable of actively changing their mechanical characteristics during the night. The proposed algorithm can be integrated in such systems to provide feedback to the actuators on the adopted sleep postures. This allows for an automatic adjustment of bed system properties when a person changes posture, and therefore overcomes one of the most important limitations of current (static) sleep systems. Finally, the suggested relation between motor patterns during sleep and sleep cycle patterns [21, 22, 10, 15] offers the possibility of providing feedback on actual sleep quality based on bed measurements. In this regard, similar algorithms can be used as for sleep-wake detection based on actigraphic measurements [37, 39].

3.6 Acknowledgements

This study was carried out thanks to the financial support of the Flemish agency for innovation by science and technology.

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Chapter 4

Estimating spine shape during sleep using silhouette-derived body shape models

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Adapted from a manuscript submitted to International Journal of Industrial Ergonomics

Abstract

This study aims at evaluating spinal alignment during sleep by combining personalized human models with mattress indentation measurements. A generic surface model has been developed that can be personalized based on anthropometric parameters derived from silhouette extraction. Shape assessment of the personalized surface models, performed by comparison with 3-D surface scans of the trunk, showed a mean unsigned distance of 9.77 mm between modeled and scanned surface meshes. The surface model is combined with an inner skeleton model, allowing the model to simulate distinct sleep postures. An automatic fitting algorithm sets the appropriate degrees of freedom to position the model on the measured indentation according to the adopted sleep posture. Validation showed a root mean square deviation of 9.1 mm between estimated and measured spine shapes, indicating that silhouette-derived body shape models provide a valuable tool for the unobtrusive assessment of spinal alignment during sleep.

Keywords

Spinal alignment, sleep comfort, human body shape model, silhouette extraction.

4.1 Introduction

Multiple factors have ensured an increased interest to promote sleep and sleep awareness in the industrialized world. First of all, prolonged work days and increased commuting time force us to go to bed later and get up earlier [32]. When maintained, this increase in self-induced sleep shortage eventually may lead to partial but chronic sleep restriction [5]. In addition, inadequate sleep is known to have severe, adverse effects on daytime performance, health and quality of life [29, 34]. As a consequence, interest in optimizing sleep efficiency, given the shorter period of time in bed, is growing rapidly. One way to achieve this is by optimizing the bedroom environment (e.g. reduced noise, dimmed lights, increased physical and thermal comfort) to promote the sleep process. Since the bedding system (i.e. mattress and supporting structure) is considered as one of the most important environmental components that affect physical comfort during sleep [12], research increasingly focuses on the effect of bed design on the sleep process [36]. In addition to its effect on sleep, bed comfort is often linked to low back pain, a leading cause of temporary disability and sick leave [8]. Although the causes of non-specific back complaints are not well understood, it has been shown that low quality bed systems may contribute significantly to the onset or persistence of low back pain [22]. Consequently, it comes to no surprise that ergonomic aspects of bed design have evolved substantially during the last decade. However, only little research is at hand that explores the use of human body models to simulate human-bed interaction and reduce development time and cost in the early phases of bed design.

The main function of bedding systems is to provide body support during sleep while allowing muscles and intervertebral discs to recover from nearly continuous loading by day [26, 31]. Optimal recovery is achieved when the spine is in its natural shape, yet with a slightly flattened lumbar lordosis due to the changed orientation of the working axis of gravity with respect to the craniocaudal direction [7, 23]. Several techniques have been described to determine spine shape during sleep, such as marker based anatomical landmark detection (with markers on the spinous processes) [24], the use of geometrical instruments (e.g. thoracic and pelvic inclinometers) [28], or markerless 3-D scanning of the back surface [17]. The use of markers and geometrical instruments requires palpation of bony structures, which is time consuming and requires operator experience, whereas markerless back surface scanning does not require contact with the subject's body [18]. However, a common drawback of the aforementioned techniques is that they are not suited to be used in a bedroom environment because of their interference with the actual sleep process (e.g. wearing a device on the back, back surface needs to be visible for scanning,...). The current study tries to overcome this limitation by combining unobtrusive mattress indentation measurements, integrated in the bedding system, with a model of the sleeper that contains relevant anthropometric information.

Digital human models (DHMs) are increasingly being used in a wide spectrum of applications, e.g. in animation development [2, 15, 35], garment design [20, 39] and the ergonomic evaluation of early stage product design [25, 19]. Several ergonomic software packages are commercially available that allow three dimensional modeling of humans (e.g. RAMSIS, Jack, Delmia Safework). Most of these simulation systems are developed to assess the interaction of a human and a system, for instance reach and visibility in a car interior. Some DHMs provide percentile model generation for different genders and age groups, others provide model generation based on user specified anthropometric dimensions. The development of 3-D whole body scanning technologies [6] has enabled accurate and fast acquisition of human body shapes. Several authors use whole body scans or derived measures to morph a template model to the scanned subject, resulting in highly realistic body shape models [1, 33]. However, 3-D scanning based methods require expensive scanning equipment and extensive post-processing of the scanned point clouds [40].

Although the use of DHMs to evaluate automotive seating comfort has been thoroughly studied [38], few research groups apply DHMs to evaluate sleep comfort. Harada et al. [13, 14] combined a full body human model (surface model and skeleton) with pressure distribution data in order to track human motion in bed and automatically detect adopted sleep postures. The model was manually scaled based on the subject's stature to account for anthropometric differences. No further personalization was considered. Joint rotation and translation parameters were optimized to minimize the difference between the model based pressure distribution and the measured pressure distribution. However, the study did not incorporate the evaluation of individual parameters related to bed comfort (such as spinal alignment, maximal contact pressure,...).

The current study aims at evaluating spinal alignment without interfering with sleep by combining body shape models with unobtrusive mattress indentation measurements. The models can be personalized based on anthropometric information derived from silhouette extraction. In order to accomplish this objective, three research questions are to be answered: 1) Which body measures can be determined based on silhouette extraction and what is the accuracy with respect to manual measurements?; 2) Is it feasible to generate personalized human body shape models based on information derived from silhouette extraction?; and 3) Does mattress indentation — in combination with personalized body shape models — provide a measure to estimate spine shape during sleep?

4.2 Materials and methods

4.2.1 Body dimensions based on silhouette extraction

Data collection

A total of 65 subjects (32 male, 33 female, age: 27.3 ± 11.5 y, BMI: 22.2 ± 5.0) participated in the study. First, two-dimensional body contours in both the sagittal and coronal plane were automatically registered using an optical measurement system (Ikélo, Custom8, Leuven, Belgium). Subjects were asked to wear a tight fitting shirt. Medio-lateral contours were determined in a standing posture with the back surface oriented towards the camera-pair and with the arms in front of the body and bent in such way that the angles between upper and lower arm and between upper arm and chest approximated 90° (figure 4.1). This posture was chosen because it resembles the situation during lateral recumbency. Antero-posterior contours were determined in a standing posture with the arms next to the body and the camera-pair at the right hand side. Secondly, a set of 26 one dimensional body dimensions was collected by means

Table 4.1: Manually determined body dimensions

Anatomical site	Height	Breadth	Depth	Circumference
neck base	x			x
acromion	x	x		
shoulder (deltoid)	x	x	x	x
breast	x	x	x	x
waist	x	x	x	x
pelvis (spina iliaca anterior superior)	x	x	x	x
hip (trochanter major)	x	x		x
crotch/thigh	x	x		x

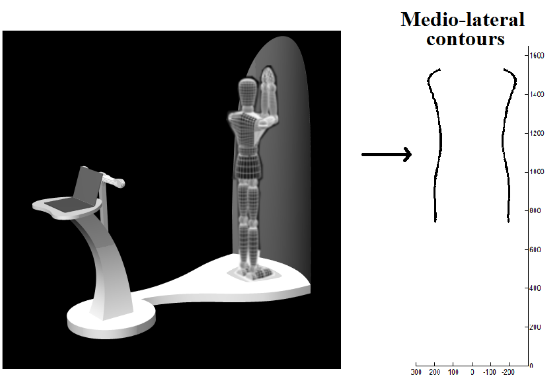

Figure 4.1: Silhouette extraction of medio-lateral body contours using the Ikélo system

of caliper and tape measure at various anatomical sites (table 4.1). Furthermore, stature and body weight were determined as well.

Data processing

Based on the measured body contours, the following body measures are determined: 1) height, breadth and depth at shoulder, breast, waist, pelvis and hip, 2) neck base height, acromion height, crotch height and stature. The medio-lateral and antero-posterior body contours in itself provide no information on body circumferences. Therefore, the manually measured circumferences are used in a multiple linear stepwise regression to estimate body circumferences based on the anthropometric information available from silhouette extraction.

Validation

The linear measures derived from 2-D medio-lateral and antero-posterior body contours were validated by calculating the root mean square error (RMSE) with the manual measurements. The regression equations that estimate body circumferences based on these linear measures were evaluated by a leave one out RMSE cross validation.

4.2.2 Modeling human body shape

Surface model

A generic model has been developed that is constituted of five major body parts: an upper body, two arms and two legs. Each part consists of consecutive superellipses that represent the transverse cross sections of the human body. Superellipses are geometrical shapes that are defined as the sets of points (x, y) that satisfy the equation

$$\left|\frac{x}{a}\right|^n + \left|\frac{y}{b}\right|^n = 1 \tag{4.1}$$

with a and b the semi-diameters, and n the ellipse order [11]. The semi-diameters allow accommodating to different breadths and depths, whereas the ellipse order determines the extent to which the shape is more star-like ($0 < n < 1$), ellipsoidal ($n = 2$) or rectangular ($n > 2$) (Figure 4.2). In general, four input values are necessary to model a transverse cross section: height, breadth, depth and circumference. The height measure is used for caudocranial positioning of the superellipse, breadth and depth determine the semi-diameters, and the ellipse order is determined in such way that the ellipse circumference optimally corresponds to the measured circumference by means of a least square optimization. A triangular mesh is created by interconnecting neighboring points of subsequent superellipses.

The generic model is personalized based on the anthropometric information derived from silhouette extraction (see section 4.2.1) Alignment with the measured posterior contour assures personalized back curvatures. Intermediate superellipses (between the measured anatomical sites) are calculated by means of shape-preserving piecewise cubic Hermite interpolation [10]. Estimates for measures on knees, ankles and neck base were made based on lookup tables that were obtained from the Belgian garment industry [9]. Arm and forearm measures were derived from regression equations and lookup tables available in literature [3, 27]. Hand measures were determined according to the mean values of the DINBelg 2005 database, adjusted according to height percentiles [30].

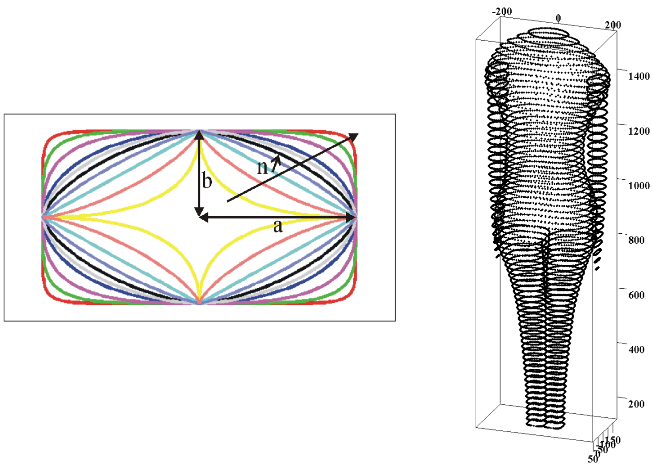

Figure 4.2: Effect of ellipse order on the shape of a superellipse (left) and modeled body shape by consecutive superellipses (right)

Inner skeleton and model deformation

For the purpose of modeling sleep postures a simplified skeleton has been integrated in the human body model. The skeleton consists of the following joints: two knee joints, two hip joints, three spinal vertebrae (representing L5, L1, and C7 approximately), two shoulder joints and two elbow joints. The shoulder is modeled as a rod between the humeral head and C7. The pelvis is modeled as a triangular plate connecting both hip joints and the lower spinal vertebra. The other joints are interconnected by rods. The skeleton is scaled in order to properly fit the surface model based on the body dimensions that were used to personalize the surface model.

Altogether 28 degrees of freedom (DOFs) allow the model to adopt a variety of different poses. Two types of articular motion are modeled in the shoulder joint: 1) three DOFs allow the three rotations (flexion-extension, abduction-adduction and inward-outward rotation) of the glenohumeral joint and 2) two DOFs allow two rotations (protraction-retraction and elevation-depression) of the sternoclavicular joint. Two DOFs allow rotation in the elbow joint (flexion-extension and pronation-supination). Spinal deformation is allowed by six DOFs allowing three rotations in both lumbar vertebrae L1 and L5 (flexion-extension, lateral bending and inward-outward rotation). Hip motion (flexion-extension, abduction-adduction and inward-outward rotation) is guaranteed by three DOFs and one DOF in the knee joint allows knee flexion and extension. Table 4.2

Table 4.2: Range of motion for the different types of articular motion that are implemented to model sleep postures

Joint	Motion	Range [°]	
Glenohumeral joint	flexion-extension	180	-45
	abduction-adduction	180	-50
	inward-outward rotation	90	-70
Sternoclavicular joint	protraction-retraction	20	-20
	elevation-depression	45	-10
Elbow joint	flexion-extension	145	-3
	pronation-supination	90	-90
Vertebral column L1	flexion-extension	35	-15
	abduction-adduction	15	-15
	inward-outward rotation	20	-20
Vertebral column L5	flexion-extension	35	-10
	abduction-adduction	15	-15
	inward-outward rotation	20	-20
Hip	flexion-extension	110	-20
	abduction-adduction	50	-20
	inward-outward rotation	35	-35
Knee	flexion-extension	160	0

illustrates the implemented range of motion for the above described types of articular motion.

Validation

Validation of the personalized surface models was performed on a (randomly chosen) subgroup of 20 subjects (12 male, 8 female, age: 22.9 ± 3.8, BMI: 22.3 ± 2.9) by means of three dimensional surface scans of the upper body (zSnapper multiple, Vialux, Chemnitz, Germany). 3-D shape assessment was performed by means of distance maps between the models and the surface scans of the upper body. Rigid registration of modeled and scanned meshes was performed in 3-Matic (Materialise, Leuven, Belgium), which makes use of an iterative closest point (ICP) approach.

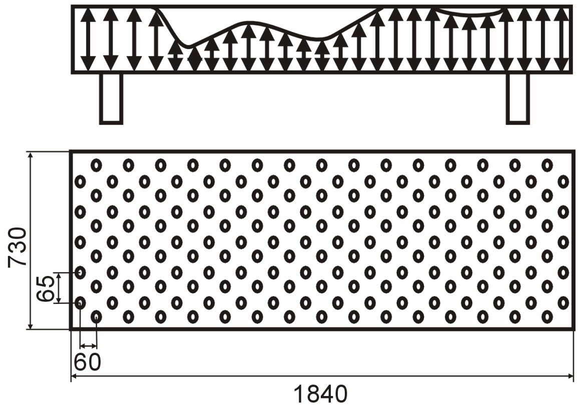

Figure 4.3: Position of integrated indentation sensors with respect to mattress core dimensions

4.2.3 Spine shape estimation

Mattress indentation measurements

Evaluation of spinal alignment requires not only information on the sleeper's anthropometrics, but also information on the deformation of the sleep system due to the sleeper's body weight. Therefore, a sleep system equipped with integrated indentation sensors was used (DynaSleep, Custom8, Leuven, Belgium). Perpendicular mattress indentation was measured in a two-dimensional grid of 170 points at a sampling rate of 1 Hz. The mattress core of this sleep system consists of pocket springs and comprises ten comfort zones. Eight of these comfort zones can be separately adjusted by applying a vertical displacement of the zones' spring bases. Spring indentation is measured by linear potentiometers with a total range of 100 mm and a measurement sensitivity of 0.1 mm. Figure 4.3 shows the sensor positions in relation to the dimensions of the mattress core. On top of the mattress core the combination of a thin felt layer (5 mm) and a latex top layer (30 mm) distribute the load over the inner springs.

Fitting procedure

Spine shape is estimated by combining the measured mattress indentation and the anthropometric information incorporated in the modeled body shape. More specifically, the model is fitted into the indentation measurement by varying a set of DOFs that is confined according to the adopted sleep posture. The fitting procedure is automated as follows.

The following pre-processing algorithms are applied on the raw data of the bedding system. First, bicubic interpolation is performed on the measured mattress indentation in a [0,200] $\times$ [0,600] regular grid. In addition, a 2-D convolution of the interpolated indentation matrix with an 80 $\times$ 80 Gaussian low pass filter (with standard deviation 30) is performed to simulate the effect of the felt and latex top layers. The result of this pre-processing step represents the deformation of the actual mattress surface, rather than the measured deformation of the mattress core.

Fitting the modeled body shape in the mattress indentation comes down to identifying appropriate values to a set of DOFs. According to the adopted sleep posture different DOFs need to be optimized. In case of a supine or prone posture the body shape is not deformed before it is fitted to the indentation data. Consequently, only three positioning DOFs of the model need to be determined: rotation in the plane of the mattress surface (θ), longitudinal (x) and lateral translation (y). The values of these parameters are set based on the location of two specific points on the mattress surface: the point of maximal indentation in the breast/shoulder zone (O_1) and the point of maximal indentation in the hip zone (O_2). The location of these zones with respect to the mattress is determined adaptively according to the center of indentation (COI), which is defined as:

$$COI = \frac{\sum z_i \cdot (x_i, y_i)}{\sum z_i} \tag{4.2}$$

with (x_i, y_i) the longitudinal and lateral coordinates and z_i the indentation. The angle between the longitudinal axis and the connection line of O_1 and O_2 ($\overline{O_1O_2}$) determines the value of θ. Values of x and y are determined based on the alignment of the model's buttocks with O_2 for supine postures and based on the alignment of the model's breast with O_1 for prone postures. In case of lateral sleep postures the fitting procedure is more complicated. Next to three positioning DOFs, four additional DOFs (joint angles) have to be determined: flexion of the knees, hips, lumbar spine and thoracic spine. Similar to the procedure for supine/prone postures, two points of maximal indentation (O_1 and O_2) are determined with respect to the COI. In addition, the saddle point (O_3) between O_1 and O_2 is determined as well. The three positioning DOFs (x, y and θ) are determined by the location of O_3 (x and y) and by the angle between the longitudinal axis and $\overline{O_1O_2}$ (θ). The angle between $\overline{O_1O_3}$ and the connection line of shoulder and L1 determines thoracic flexion. The angle between $\overline{O_3O_2}$ and the connection line of L5 and hip determines lumbar flexion. Starting from O_2, a 90° circle sector (with radius the length of the femur) is

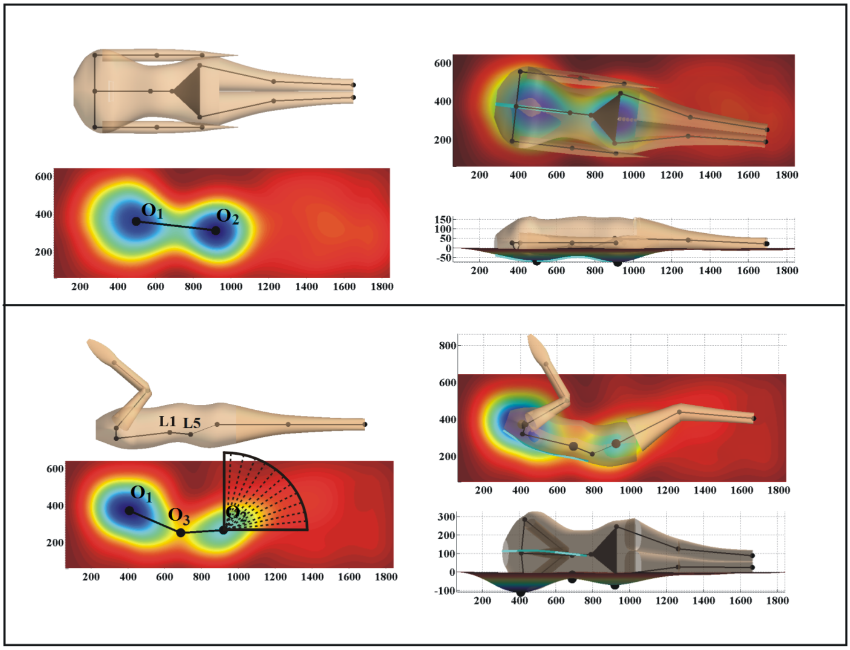

Figure 4.4: Fitting procedure and spine shape assessment for a supine (upper) and a lateral (lower) sleep posture

scanned to find the line of maximal indentation. This line determines hip flexion and the position of the knee (O_4). Knee flexion is determined analogously by scanning a 120° circle sector (with radius the length of the tibia) starting from O_4.

Once the appropriate DOFs are determined, the model is lowered into the mattress indentation by calculating the vertical distances of consecutive model segments to corresponding indentation values. In a final step a cubic smoothing spline is fitted through the model points on the back surface that represent the spinous processes to estimate spine shape. Figure 4.4 illustrates the fitting procedure and spine shape estimation for a lateral and supine posture.

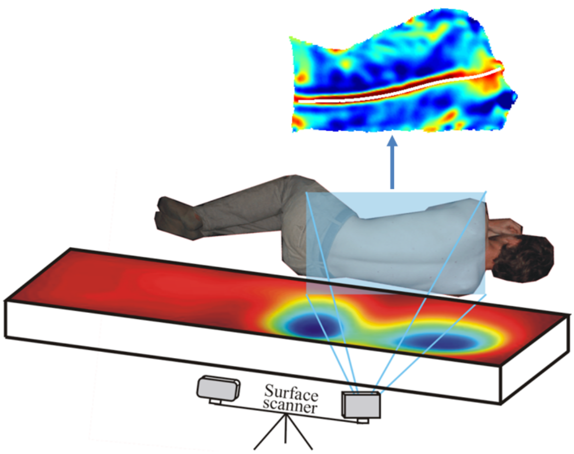

Figure 4.5: Simultaneous mattress indentation recordings and back surface scanning. An active contour model iterating on surface curvatures and lateral asymmetry information serves as gold standard for spine shape assessment.

Validation

Validation of spinal alignment is performed by means of a 3-D scan of the back surface (zSnapper, Vialux, Chemnitz, Germany). Prior research [18] has shown that the line through the spinous processes can be accurately reconstructed based on analysis of back surface data. Results indicated that the use of an active contour model iterating on a weighted combination of surface curvature information and lateral asymmetry information, as defined by Hierholzer [16], allows spine shape reconstruction in lateral postures with a root mean square deviation of 2.6 mm with respect to full spine CT measurements [17]. The current study uses the same active contour approach to provide validation data for the simulated spine shapes. 3-D scanning of the back surface was performed simultaneously with mattress indentation measurements (as shown in Figure 4.5) to assure synchronization between simulation and validation data.
The adjustable comfort zones allowed simulation of different types of sleep systems. Hence, validation was performed on two distinct types of mattress configurations. A first configuration (configuration A) was characterized by a heterogeneous stiffness distribution that was individually optimized according to shoulder breadth/waist breadth ratio, waist breadth/hip breadth ratio, shoulder/waist/hip height and BMI (analogous to 2.2.4). A second configuration (configuration B) represented a sagging sleep system (cf. table 2.1), which has shown to result in impaired spinal alignment for lateral postures (see chapter

Table 4.3: Mean values and standard deviations of manual measurements and root mean square errors (RMSE) between silhouette-derived and manual measurements

Variable	mean [mm]	std [mm]	RMSE [mm]	RMSE [%]
Stature	1720	89	18	1.07
Neck base height	1466	80	16	1.08
Acromion height	1420	75	17	1.21
Shoulder height	1347	72	21	1.53
Breast height	1248	78	24	1.95
Waist height	1087	58	24	2.25
Pelvis height	982	60	22	2.20
Hip height	882	56	21	2.35
Thigh height	787	49	20	2.59
Shoulder breadth	408	29	11	2.85
Breast breadth	287	24	15	3.82
Waist breadth	262	29	14	5.54
Pelvis breadth	306	24	9	4.45
Hip breadth	343	19	9	2.63
Thigh breadth	338	17	12	2.79
Shoulder depth	182	22	14	6.57
Breast depth	221	28	23	6.41
Waist depth	190	31	20	12.10
Pelvis depth	217	28	12	9.23

2). By performing the validation on these two configurations, it was possible to verify whether the accuracy of spine shape assessment was dependent on the configuration of the bedding system.

4.3 Results

The comparison of the automatically determined body measures based on silhouette extraction (i.e. the output of the Ikélo system) with the manual measurements is shown in Table 4.3. Overall, RMSE between silhouette-derived and manual measures was 17 ± 5 mm. More specifically, it can be inferred from Table 4.3 that, in terms of percentage error, heights were estimated most accurately (1.80 ± 0.59 %), followed by breadths (3.7 ± 1.15 %) and depths were estimated least accurately (8.60 ± 2.68 %). Since silhouette extraction provides no information on body circumferences, the manually measured circumferences were used in a multiple linear stepwise regression to estimate body circumferences based on the available linear measures from silhouette extraction. The mean adjusted R^2 value of the regression equations was 0.84 ± 0.08 and a leave one

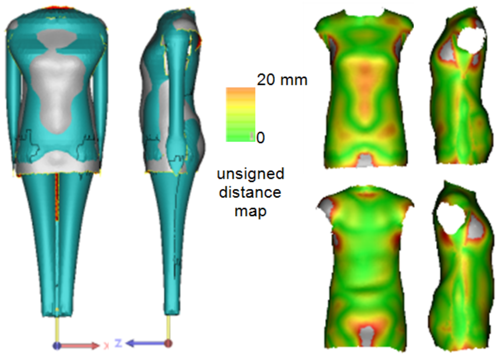

Figure 4.6: Shape assessment by 3-D distance map between a personalized surface model and a surface scan of the trunk after registration of both meshes

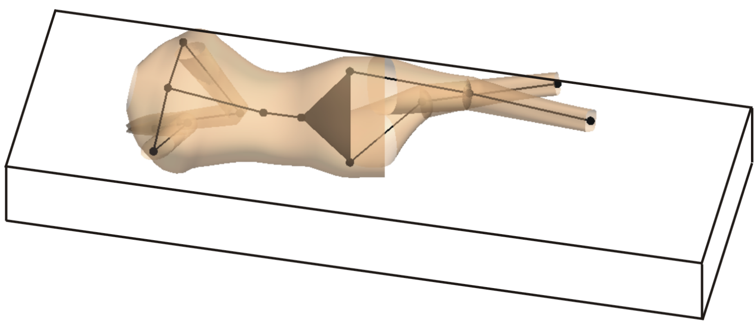

Figure 4.7: Modeled intermediate sleep posture with the shoulder girdle turned towards the mattress surface, resulting in spine torsion.

out cross validation revealed a percentage RMSE of 3.27 ± 0.50 % between estimated and manually measured circumferences.

Shape assessment of the modeled body shape surfaces was performed by 3-D distance maps between personalized models and surface scans of the upper body after registration of both surface meshes. Figure 4.6 illustrates the results of such a distance map on one of the subjects. Mean unsigned distance was 9.77 ± 9.31 mm, with the surface scan forming the source and the modeled mesh forming the target mesh. The majority of the scanned points (86.9 %) were within a range of [0, 20] mm distance of the modeled mesh points. In addition,

Table 4.4: Deviation between estimated and measured spine shapes

	RMS deviation [mm]	Maximal deviation [mm]
Configuration A (n=14)	9.26 ± 4.38	17.43 ± 6.78
Configuration B (n=9)	8.86 ± 4.72	16.80 ± 7.36
Total (n=23)	9.10 ± 4.41	17.18 ± 6.85

Table 4.5: Model based and measured spine shape parameters on both mattress configurations

		Configuration A (n=14)	Configuration B (n=9)	Sign.
Model based	P1[°]	4.48 ± 1.86	9.24 ± 1.50	*
	P2[°]	4.87 ± 2.11	10.13 ± 1.84	*
Validation	P1[°]	3.68 ± 1.43	8.36 ± 2.14	*
	P2[°]	3.00 ± 1.64	8.32 ± 2.60	*

* $p < 10^{-5}$

most points outside this range were located at body sites where the tight fitting shirt was not in contact with the subject's body.

Simultaneous back surface measurements were performed along with the unobtrusive mattress indentation measurements, assuring a synchronized, objective validation for spinal alignment in a lateral sleep posture. Table 4.4 summarizes the comparison between estimated and measured spine shapes for both mattress configurations. Overall, root mean square deviation was 9.1 ± 4.4 mm. No difference was noted considering results on both mattress configurations separately. Quantification of spinal alignment is generally performed by shape descriptive parameters [12, 36]. Table 4.5 compares two such parameters calculated from the estimated and measured spine shapes respectively: 1) the angle between the horizontal axis and the straight line between starting point and end point (P_1) and 2) the angle between the horizontal axis and the least squares line through the data points representing the spine (P_2). Pearson's correlation coefficient between model based and measured shape parameters was 0.91 ($p< 10^{-8}$) and 0.84 ($p< 10^{-6}$) for P_1 and P_2 respectively. In addition, as could be expected, both parameters were significantly higher on a sagging mattress configuration, indicating an impaired spinal alignment, in comparison to an individually optimized configuration.

At present the amount of DOFs that need to be optimized in the fitting procedure is limited because only the basic sleep postures are considered (3 position DOFs for supine and prone postures, 3 position DOFs and 4 joint angles for lateral postures). However, quite often intermediate postures are adopted as well. For instance, some people tend to turn their shoulders or pelvis towards the mattress surface for more stability in a lateral posture. For the purpose of modeling such intermediate postures a total of 28 joint DOFs are currently implemented (ranges of motion are shown in Table 4.2). Figure 4.7 shows an example of such an intermediate sleep posture that affects loading of the spine because of torsion between the vertebrae.

4.4 Discussion

This study describes how body shape models can be used to assess spine support on bedding systems without interfering with sleep. A generic surface model has been developed that consists of consecutive superelliptic cross sections. Personalization of the models is achieved by a set of anthropometric input parameters derived from silhouette extraction. Fitting the personalized models in the measured mattress indentation allows estimating spine shape.

Results showed that body measures derived from silhouette extraction, provided reliable anthropometric information. Percentage errors for heights and breadths were within the range of inter-viewer variability in traditional anthropometrics [21]. Percentage errors for depths were somewhat higher, which can be explained by the silhouette extraction technique. The projected back contour does not capture the concave region of the back surface around the spinous processes, resulting in an overestimation of depth measures. However, for the purpose of modeling transverse cross sections by means of superellipses (which can never account for local concavities) one can argue that these overestimated depths result in more realistic approximations of the actual cross sections. Furthermore, alignment with the posterior contour assures that kyphotic and lordotic spine curvatures are correctly modeled. Body circumferences were estimated through multiple stepwise regression models based on the detected body measures. Leave one out cross validation revealed that circumference deviations were within range of inter- and intra-rater variability in traditional anthropometric measurements [21]. Finally, shape assessment of the modeled body shapes by means of 3-D distance maps with surface scans of the upper body revealed a mean unsigned distance below 10 mm.

Spinal alignment was evaluated by combining the personalized models with mattress indentation measurements. An indentation based fitting algorithm has been developed that automatically determines the appropriate values of the model DOFs in order to correctly position the model on the measured indentation according to the adopted posture. Validation of the estimated spine shapes was performed by means of spine shape reconstruction from back surface data [17]. Comparison of estimated and measured spine shapes revealed an average root mean square deviation of 9.1 mm. In addition, results on different mattress configurations indicate that accuracy of spine shape estimation does not depend on the type of bedding system. Finally, the high correlations between parameters calculated from the simulated spine shapes and those calculated from the measured shapes suggest the ability of the developed technique to objectively assess/evaluate support quality of different bed systems for a particular person in different postures. Furthermore, since prior research showed the feasibility of automatic posture recognition based on mattress indentation measurements [37], the combination of such techniques with the described spine shape evaluation allows a completely automatic, continuous assessment of back support during the night. Such overnight evaluation of bed support incorporates not only anthropometric, but also behavioral features (e.g. preferred sleep postures) that are often overlooked in the assessment of support quality.

Of course, some limitations remain present. First, the evaluation of spinal alignment was only performed in a lateral sleep posture. The main reason is that the validation method itself, spine modeling from back shape data, has only been validated in lateral sleep postures. Furthermore, it goes without saying that no back surface scans can be recorded in supine sleep postures. However, since in a supine posture the back surface is in direct contact with the mattress surface, there is no reason to believe that the described evaluation of spinal alignment for supine postures is less accurate than for lateral postures. For prone postures, further validation might be required. A second limitation involves that only basic sleep postures were considered, namely supine, lateral and prone. Often people adopt postures that cannot be considered as one of these basic sleep postures. For instance, some people prefer to cross their legs and cant their pelvis towards the mattress while lying in a lateral posture. Such a posture, although providing extra stability, results in torsion of the spine that is not accounted for in the current assessment of spine shape. A final limitation involves that anthropometric input remains necessary, whereas this is not the case for other techniques.

Future work should therefore focus on how to overcome these limitations. Currently, the implemented DOFs allow the model to adopt intermediate sleep postures (Figure 4.7). The challenge remains how to optimize these additional DOFs based on the mattress indentation solely. One approach, similar to Harada [13], might be to simulate mattress indentation for a given set of DOFs. Joint rotation DOFs could further be fine-tuned by minimizing the difference between simulated and measured mattress indentation. In addition, reduction of necessary anthropometric input might be possible if part of this information could be derived from the indentation measurement itself. Finally, the possibility of combining more complex DHMs (such as the open source MakeHuman meshes [4]) with mattress indentation measurements should be explored in terms of accuracy of spine shape assessment and reduction of necessary anthropometric input.

4.5 Conclusion

The present study provides a novel method to evaluate spinal alignment during sleep in an unobtrusive way. A generic human body model has been developed that can be personalized based on silhouette-derived anthropometric information. A variety of sleep postures can be adopted by changing different joint rotation DOFs. The combination of the personalized model with mattress indentation measurements allows the evaluation of spinal alignment by means of an automatic fitting algorithm. The main advantage of the developed technique is that it does not interfere with sleep. Therefore, its use is not limited to snapshots of predefined postures in a pre-sleep testing environment, such as most other techniques [17, 24, 28]. On the contrary, the technique allows overnight continuous measurements of spinal alignment in the actual bedroom environment without compromising the sleep process.

4.6 Acknowledgements

This study was carried out thanks to the financial support of the Flemish agency for innovation by science and technology.

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Chapter 5

Smart control of spinal alignment by adapting mechanical bed properties during sleep

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Adapted from a manuscript submitted to Journal of Ambient Intelligence and Smart Environments

Abstract

This study implements an algorithm for the autonomous control of spinal alignment during sleep by the dynamic adjustment of mechanical bed characteristics according to the adopted sleep posture. Bed systems were used that allow active control of stiffness distribution by means of linear actuators working in eight adjustable comfort zones. Mattress indentation measurements provide the input to detect body movement, recognize sleep posture, and — by combination with a subject specific human model — estimate spine shape. Comparison between the estimated spine shape and the desired shape results in new target values for the actuators. The control loop is repeated until the desired spine shape is reached. Results of overnight experiments revealed a significant improvement of spinal alignment during nights with active control of bed properties compared to a reference night without control. In addition, a significant improvement on subjectively perceived sleep quality was demonstrated after sleeping on the actively controlled systems.

Keywords

Autonomous control, smart bed systems, spinal alignment, sleep posture, spine shape.

5.1 Introduction

Ergonomic aspects are gaining importance in the design of state-of-the-art bed systems (i.e. mattress and supporting structure) as to provide optimal comfort and body support during sleep. The increased interest in bed comfort is justified by its presumed influence on the development and maintenance of low back pain and sleep problems, two public health issues with a substantial economic impact on Western society. Epidemiological studies from all over the world have reported a lifetime prevalence rate ranging from 49% to 80% for low back pain [27, 8, 18] and 36% to 40% for occasional insomnia [3, 22]. Both conditions are related to a greater social and occupational functional impairment, reduced quality of life and a higher health care utilization and institutionalization rate [19, 24, 29, 17]. The epidemiological and economic impact on society is expected to increase further due to prolonged work days, increased commuting time and changing attitudes and expectations [18, 21]. It goes without saying that the improved design of bed systems alone will not expel back and sleep problems from society. However, taking into account that we are physically interacting with bed systems throughout one third of our lives, ergonomic aspects of bed design should be considered as an important factor in the prevention of these disorders.

During daily activities the spine is continuously loaded, resulting in fluid loss in the intervertebral discs. At night, optimal recovery is achieved when the spine is in its unloaded, natural shape, allowing muscle relaxation and rehydration of the intervertebral discs [16, 20]. The unloaded shape resembles the spine during stance, yet with a slightly flattened lumbar lordosis due to the changed orientation of the working axis of gravity with respect to the craniocaudal direction [9]. Since the human body is incapable of controlling the spine actively while sleeping, mechanical bed properties should account for body dimensions and weight distribution in order to provide proper body support. Since both of these factors are highly individual, a personalized approach is of primary importance when assigning a bed system to a specific person [11]. Furthermore, bed properties need to be adapted according to different body dimensions depending on the adopted sleep posture. For instance, when lying in a lateral position, body breadths (mainly shoulder, waist and hip breadth) are decisive whereas in a supine position, back curvatures (such as thoracic kyphosis and lumbar lordosis) need to be accounted for by the bed system. Since in Western society most people prefer a lateral sleep position (60%), the design of bed systems in these regions is focused on providing optimal support in lateral positions. On the contrary, most Asian people prefer sleeping supine, resulting in a design focus of Asian bed producers on supine positions [11]. However, two major limitations are inherent to this focus on dominant postures. First of all, a significant minority of people (40% in Western countries) prefer different postures than their bed is designed for. Therefore, personalization based on anthropometric properties is only relevant if it incorporates information on preferred sleep postures [31]. Second, healthy sleep requires the presence of multiple major posture changes per night to prevent pressure overloading of soft tissue in the contact area with the mattress surface [1, 7]. Recent research showed that only 43.7% of the tested subjects spent more than 60% of time in their dominant sleep posture, indicating that a significant amount of time is spent in non-dominant postures as well [32]. Consequently, future bed systems should be able to cope with these variable loading conditions (due to posture changes) by adapting different mechanical properties according to the adopted sleep posture.

A first step towards such “smart bed systems” is the automatic detection of sleep postures during the night, preferably by sensors integrated in the bed itself. Several authors have studied a variety of technologies to monitor sleep posture in bed. The existing technologies can be categorized according to their location in the bed system: (1) under the bed base, (2) inside the mattress, or (3) on top of the mattress. Adami [2] and Brink et al. [6] installed load cells in the corners of the bed frame to assess body movements during sleep. The advantage of this type of measurements is that sensors are relatively easy to install on existing bed systems. Furthermore, detailed information on physiological signals, such as breathing patterns and heart rate, can be derived [6]. Although both studies were limited to the validation of the detected physiological signals, future applications in terms of home monitoring, apnea detection, sleep monitoring, etc. provide interesting prospects. Adami [2] succeeded in classifying body movements into posture shifts, medium amplitude movements and isolated leg movements. However, no information on adopted sleep postures could be derived from the four measurement signals due to the nonlinear deformation behavior of both human and sleep system. Verhaert et al. [32] measured the vertical deformation of the mattress core in a 2-D grid of 170 indentation sensors, allowing unobtrusive movement detection and posture recognition. Harada et al. [12] and Hsia et al. [14] assessed the problem of posture recognition during sleep by measuring contact pressure between the human body and the mattress surface. By combining the measurements with a kinematic human model, Harada et al. [12] could not only detect, but also simulate movements in bed. Finally, Hoque et al. [13] incorporated accelerometers in a mattress topping. Unfortunately, the algorithm had to be trained for each subject separately before it could be used to recognize sleep postures.

A second step is the automated adaptation of mechanical bed characteristics during sleep according to the adopted posture. Several techniques have been described in literature to adjust bed properties. Finger and Asada [10] designed an active mattress for moving bedridden patients. Actuators embedded into the mattress were capable of generating periodic surface movements to transfer the bedridden in an arbitrary direction. Van der Loos et al. [28] developed an adjustable bed frame that, in case the supine sleeper is sensed to be snoring or having an apnea event, gently encouraged the person to turn to a lateral position. To realize this, the bed frame was divided into four tilting segments actuated with three electric motors. Seo et al. [26] developed a bed system with two external robot arms to provide motion assistance to bedridden patients. The position of the robot manipulator was controlled by the patient's position in bed. Next to active bed systems that manipulate or facilitate posture changes, other authors have looked at the influence of changing bed properties on comfort parameters. Lahm and Iaizzo [15] used an air-inflatable mattress in a laboratory experiment to adjust mattress firmness and determine the effect on the physiological responses and spinal alignment of 22 back-pain free subjects. Data were collected during a 30 min trial at three degrees of firmness. Park et al. [23] adjusted the height of separate bed sectors and evaluated the effect of different configurations on subjective comfort and pressure distribution for different postures.

This study presents an autonomous bed system that controls bed properties in order to optimize spinal alignment in different postures during sleep. Continuous mattress indentation measurements are used as input of the control system, because they have the advantage over other posture recognition technologies that, in combination with anthropometric models, they allow predicting spine shape during sleep [30]. The proposed bed control system is validated both in laboratory conditions and in overnight sleep experiments.

5.2 Materials and methods

5.2.1 Bed systems

Bed systems were used that allow continuous measurement of mattress indentation and active control of stiffness distribution (DynaSleep, Custom8, Leuven, Belgium) (figure 5.1). The perpendicular indentation of the mattress surface is measured in a two-dimensional grid of 165 points at a sampling rate of 1 Hz by means of linear potentiometers. The mattress core consists of pocket springs and comprises ten comfort zones, eight of which can be separately adjusted in stiffness by actuators applying a vertical displacement of the zones' spring bases. Two types of pocket springs with different intrinsic stiffness coefficients (k = 0.20 N/mm and k = 0.076 N/mm) are used in the comfort zones. The vertical position of the zones' spring bases is controlled by Linak actuators (type LA27). These are linear 24V DC permanent magnet motors, with maximal thrust of 6000 N and 4000 N in push and pull applications respectively, a stroke length of 225 mm and maximal speed of 13 mm/s. For the purpose of controlling bed properties, two control speeds were implemented: 3.2 mm/s for laboratory tests and 0.67 mm/s for overnight experiments. These low speeds assure a gentle transition between configurations without any noise disturbance to assure sleep continuity. The adjustable zones are located in the mattress region supporting the trunk, i.e. the region that determines spine support during sleep. The total length of the adjustable zones is 960 mm. To allow a meaningful adjustment range for each comfort zone, the spring bases are individually positioned, enabling for instance lower target settings for the shoulder zones than for the waist zones. Lower target values of the actuators correspond to a decreased stiffness of the comfort zones and vice versa. Figure 5.1 illustrates the location of the adjustable zones in the mattress as well as the default motor configuration — resembling a standard bed system — along with the possible deviations from this default configuration.

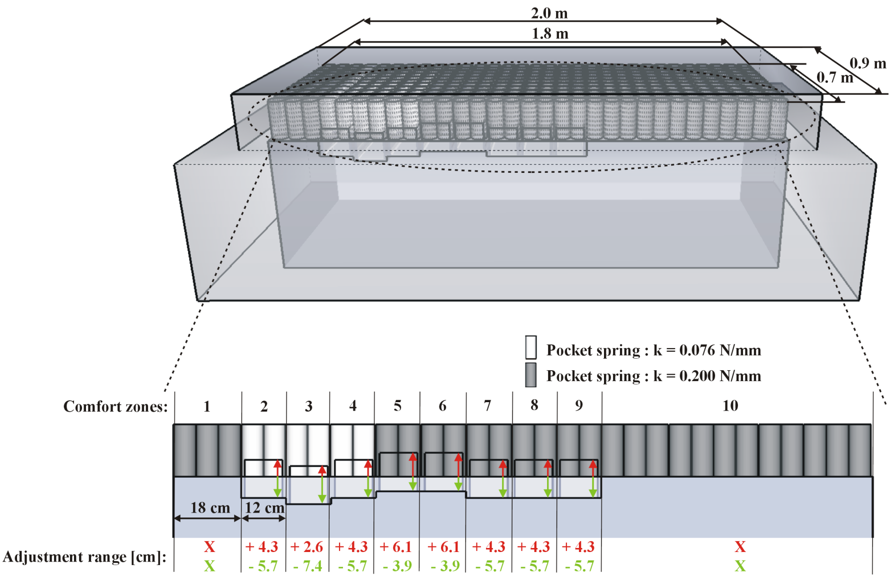


Figure 5.1: Location of adjustable comfort zones in the bed system. The default configuration is shown along with the adjustment range for each comfort zone.

5.2.2 Control system

Figure 5.2 gives an overview of the feedback control that is implemented in the bed system. The central component of this feedback system is the bed system whose characteristics need to be controlled in order to optimize spinal alignment (i.e. the output of the system). Mattress indentation measurements provide the necessary input to estimate spine shape by means of the following procedure. Body movements are detected by thresholding the (unsigned) derivative over time of mattress indentation [32]. After each detected movement, when a stable situation is achieved , the adopted sleep posture is recognized. A delay of 10 sec. is incorporated after the last detected movement to avoid that steering begins while the subject is still moving. According to the detected posture, a human body model — which is personalized based on anthropometric information — is fitted into the measured indentation to estimate spine shape [30]. The comparison of the estimated spine shape with a reference shape provides the input of the controller, which proposes a new bed configuration (i.e. new target values are forwarded to the actuators, as explained in the section on the determination of mattress configurations on page 136). When all targets are reached, steps II and III of the spine shape estimation block are repeated until the estimated shape approximates the reference shape close enough, as

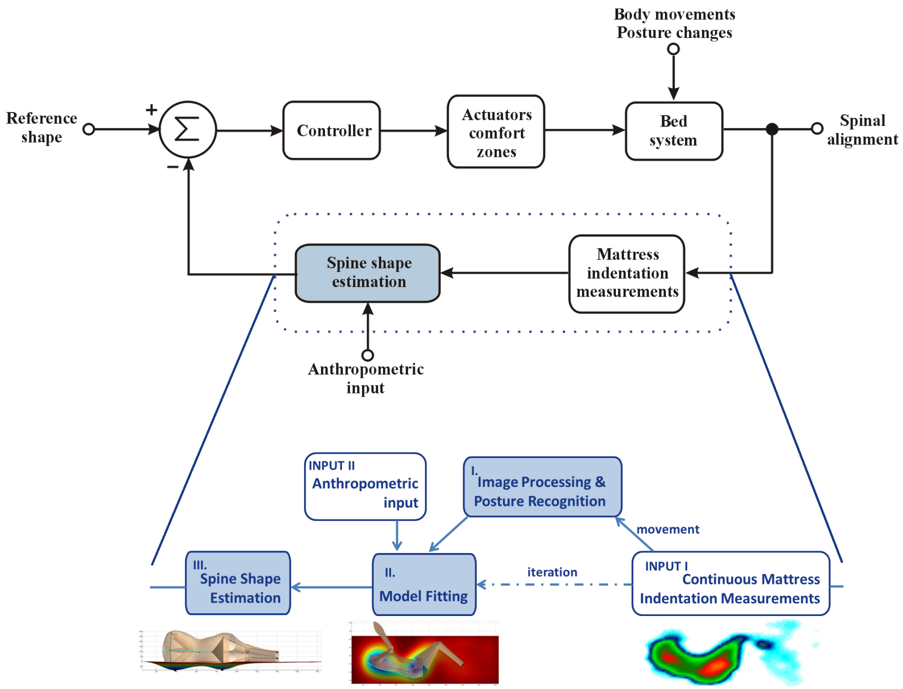


Figure 5.2: Schematic representation of the implemented feedback control for the optimization of spinal alignment during sleep. A detail is given on the followed procedure for spine shape estimation.

determined by means of a priori defined threshold criteria (see page 136). The reference shape is individually determined based on the measured sagittal body contour (see 5.2.3). This shape, registered during stance, is slightly flattened by means of a smoothing spline.

Posture recognition

Previous research has shown the feasibility of classifying mattress indentation images into four main sleep postures: supine, lateral left, lateral right, and prone [32]. Support vector machine theory was applied on five-element feature vectors of a training set (shoulder-hip ratio, knee-hip ratio, total indentation, lateral asymmetry index (LAI), and lower leg indentation) to construct an optimal separating hyperplane. Results showed high sensitivity values (above 90%) for the detection of the four main sleep postures. One of the limitations however, was the inability to detect so-called intermediate postures. For instance, in a lateral sleep posture some people tend to turn their shoulders forward towards the mattress surface. It seemed to be very difficult to detect such intermediate postures based on image features solely. The current study aims at overcoming this limitation by means of an active sensing approach. More specifically, the ability to actively change mattress characteristics is used to detect intermediate postures. In lateral postures, the amount of shoulder indentation is expected to increase when lowering the target values of the shoulder zones. In intermediate postures this effect is far less apparent due to two factors. First, the body contour interfacing the mattress surface is far less pronounced because of the turned shoulders. Second, the contact surface with the mattress is larger, effectively spreading the weight over an increased amount of springs. Therefore, if a lateral posture is initially detected and lowering the target values of the shoulder zones does not result in an increased indentation of the shoulders, the posture will be considered as intermediate and the shoulder targets will be raised to an intermediate configuration (see paragraph on prone and intermediate configurations on page 139).

Spine shape estimation

One of the advantages of measuring mattress indentation is that — by combining the measured deformation of the mattress surface with personalized anthropometric models — it is possible to assess spine shape during sleep unobtrusively [30]. For this purpose, a surface model consisting of consecutive superelliptic transversal cross sections is combined with a simplified skeleton model that allows adopting a variety of sleep postures. The model is fitted into the measured indentation by varying a set of degrees of freedom (DOFs). The fitting procedure can be performed automatically provided that anthropometric information on the sleeper (body contours, sex, age, weight) is available so that the generic model can be personalized based on this information. Further, the adopted sleep posture needs to be known before fitting, because it defines which DOFs need to be optimized and determines the initial model orientation with respect to the mattress. Since sleep posture can be automatically determined (cf. supra), the only a priori knowledge that is necessary to assess spine shape involves the sleeper's anthropometric features.

Determination of mattress configurations

Based on the fitted model and the estimated spine shape, the controller proposes a new mattress configuration by comparing the spine shape with a reference condition. This reference shape corresponds to the measured back contour during stance, yet with a slightly flattened lumbar lordosis [9]. For lateral postures the coronal projection of the estimated spine is compared to a horizontal line, whereas for supine postures the sagittal projection of the spine is compared to the reference shape.

Supine configurations Alignment of reference shape and estimated shape is achieved by calculating and aligning the bending points of both shapes. The sagittal root mean square deviation (RMSD) between both curves serves as a decision criterion to determine whether the configuration should be altered or not

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(z_i - z_i')^2}{n-1}} \tag{5.1}$$

where z_i are the sagittal coordinates of the estimated spine shape, z_i' are the sagittal coordinates of the reference shape, and n is the number of points. Setting the exact threshold value corresponds to finding a trade-off between 'needlessly attempting to correct small differences' and 'not correcting large differences'. This was achieved by means of trial and error on multiple test runs (RMSD = 7 mm). If the threshold criterion is met, the difference between reference and estimated shape along the longitudinal axis is determined. The mean of this so-called difference line (Figure 5.3) in each of the eight adjustable comfort zones determines the new target settings for the actuators. When these new actuator targets are reached, the process is repeated until the RMSD is below the threshold value. To avoid an infinite loop, the evolution of the RMSD during the control is verified after each mattress adjustment. Whenever it remains constant or increases, no further adjustments are proposed and the control system awaits newly detected body movement.

Lateral configurations Lateral configurations are determined in a similar way as supine configurations. Two decision criteria determine whether adjustments to the current configuration should be proposed: 1) the angle between the horizontal axis and the least squares line approximating the set of points that constitute the estimated spine (Figure 5.4), and 2) the lateral RMSD between the estimated spine and the reference shape. The least squares line in the lateral plane ($y = a + bx$) is determined by minimizing the function

$$Q(a,b) = \sum_{i=1}^{n}[y_i - (a + bx_i)]^2 \tag{5.2}$$

where x_i and y_i are the lateral and longitudinal coordinates of the estimated spine shape, a and b are the intercept and slope of the least squares line, and n

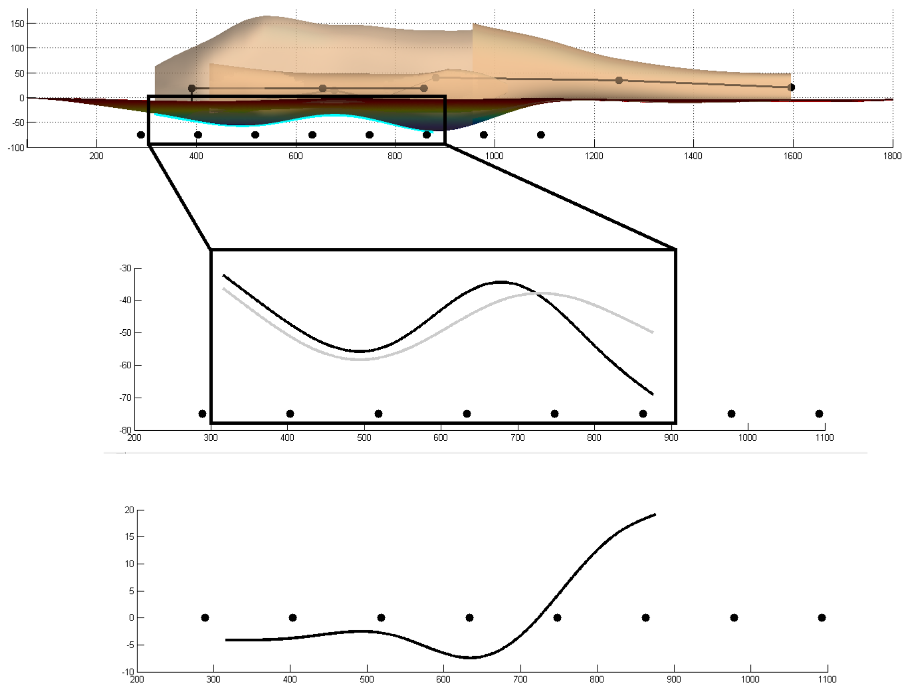


Figure 5.3: Determination of supine configurations. After the fitting procedure (upper) the difference line (lower) between estimated spine shape (middle-black) and reference shape (middle-grey) determines new target settings for the eight zones. Black dots correspond to the centers of the comfort zones.

is the number of points. Analogous to the sagittal RMSD (eq. 5.1), the lateral RMSD is defined as:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_i')^2}{n-1}} \tag{5.3}$$

where x_i are the lateral coordinates of the estimated spine shape, x_i' are the lateral coordinates of the reference shape, and n is the number of points. The first threshold value (2.1 °) is set based on the results of chapter 4, table 4.4, which shows the maximum deviation of the estimated spine shape with respect to validation to be less than 18 mm. Considering a (horizontal) trunk length of 500 mm, a vertical deviation of 18 mm corresponds to an angle of 2.1 °. The second threshold value (RMSD = 4 mm) was determined by means of trial and error during test runs. If one of these limits is exceeded, new actuator targets

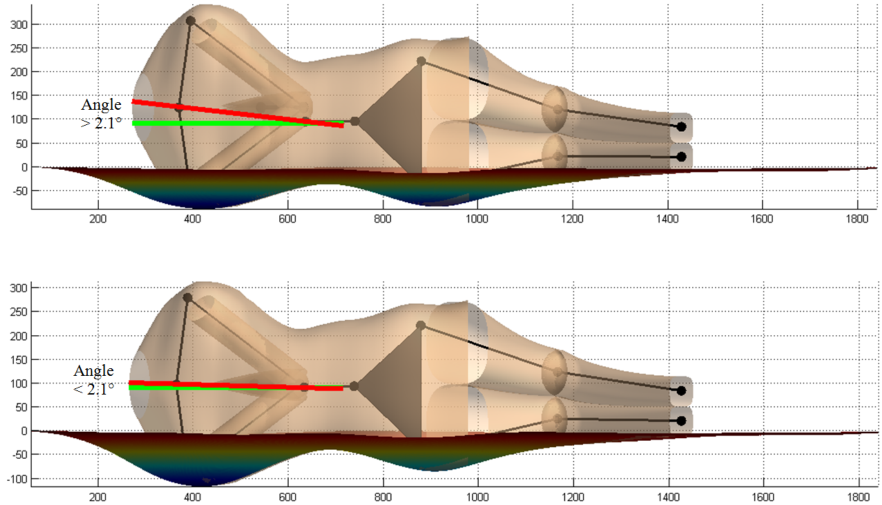


Figure 5.4: Spine shape before (upper) and after steering (lower). The red line represents the least squares line through the spine and the green line is the reference shape. If the angle between these lines or the RMSD between spine shape and reference shape exceeds a certain threshold, mattress settings are adjusted.

will be determined based on the mean difference between the estimated and the reference shape in each of the adjustable comfort zones.

Prone and intermediate configurations No control is implemented for prone and intermediate postures. A standard mattress configuration is applied when these postures are detected. The standard configuration for prone postures provides extra support at the abdomen in order to flatten lumbar lordosis. For intermediate postures, the standard configuration assures sufficient support in the breast region by increasing stiffness of the shoulder zones slightly compared to lateral configurations. The actuator settings for prone and intermediate configurations can be inferred from figure 5.6(a). No personalized adaptation or fine-tuning occurs for these postures.

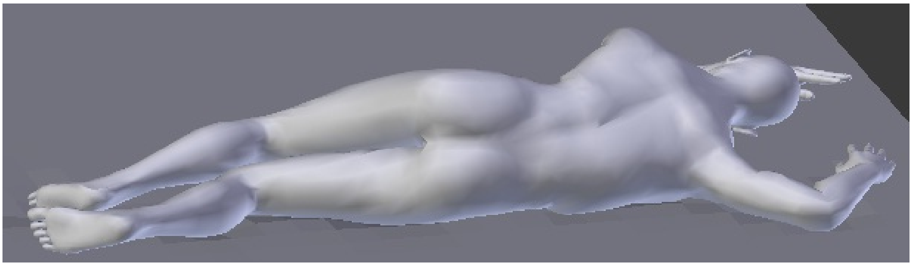


Figure 5.5: Right intermediate sleep posture, prescribed as right lateral with the shoulder girdle turned towards the mattress. Simulated using MakeHuman & Blender [5, 25].

5.2.3 Experimental design

Laboratory experiments

Eighteen subjects (ten males, eight females; aged 31.3 $\pm$ 14.3 years, BMI 23.59 $\pm$ 2.21 kg/m^2) participated in the following series of measurements. First, anthropometric information was gathered by means of silhouette extraction (Ikélo, Custom8, Leuven, Belgium). Next to lateral and sagittal contours, this system determines the following body measures: 1) height, breadth and depth at shoulder, breast, waist, pelvis and hip, 2) acromion height, total body length, body weight, kyphosis and lordosis. This anthropometric information is used to personalize a human surface and skeleton model according to [30]. Second, subjects were asked to lie on the bed system adopting the following sleep postures in a counterbalanced order according to a 6 $\times$ 6 Balanced Latin Square Design: supine, left lateral, right lateral, prone, intermediate left, and intermediate right. A Balanced Latin Square Design assures that each posture occurs precisely once on each position and that each posture appears before and after each other posture an equal number of times. It allows identifying possible order effects of adopted sleep posture on the performance of the control system. The intermediate posture (left/right) was prescribed as a lateral posture (left/right), with the shoulders turned forward towards the mattress as depicted in Figure 5.5.

In lateral and supine postures, spinal alignment was evaluated and quantified by the following spine shape parameters. For lateral postures, four parameters were defined in the frontal plane [31, 11]: 1) the angle between the horizontal axis and the straight line connecting starting and end point of the modeled spine (P1), 2) the mean unsigned distance from the modeled spine to its least square line (P2), 3) the angle between the horizontal axis and the least square line through the modeled spine (P3), and 4) the angle between the least square lines through the lumbar and thoracic part of the modeled spine. For supine postures, three parameters were defined in the sagittal plane: 1) RMSD between the modeled spine and the reference shape (see 5.2.2) (P5), 2) the difference between the lordosis angles of the modeled and the reference shape (P6), and 3) the difference between the kyphosis angles of the modeled and the reference shape (P7).

Overnight study

To validate the performance of the developed control in a situation where subjects are not bound to a set of predefined postures, overnight experiments were performed in a sleep laboratory. Twelve subjects (six males, six females; aged 38.7 $\pm$ 23.4 years, BMI 23.35 $\pm$ 2.97 kg/m^2) were recruited through advertisement. Inclusion criteria were a regular sleep-wake schedule and a good general health condition. Exclusion criteria were medical problems that could interfere with normal sleep, e.g. intake of sleep medication, antidepressants, and any form of back pain. All subjects signed an informed consent. Anthropometric information was gathered prior to the sleep experiments by means of silhouette extraction (see 5.2.3). After a baseline night, each subject underwent two experimental conditions: 1) a reference condition with no active control of bed properties, 2) a night with active control of bed properties towards optimal spinal alignment. Counterbalancing was applied to avoid carry-over effects between conditions and subjects were blinded from experimental conditions. The bed control started 30 minutes after lights out to make sure that subjects were not aware of the condition during sleep onset. The morning following each night, subjective sleep quality was assessed by means of a visual analogue scale. The study was approved by the Ethics Committee of the Vrije Universiteit Brussel.

Based on the indentation data, episodes without movement (periods of immobility) and the adopted sleep postures were identified according to Verhaert et al. [32]. For each period of immobility, spinal alignment was evaluated and quantified by the parameters described in 5.2.3.

Table 5.1: Sensitivity analysis of sleep posture recognition in laboratory conditions

	Supine	Lateral	Prone	Intermediate
Sensitivity [%]	100	94.1	82.4	73.5
Specificity [%]	91.8	98.8	95.3	99.4

Table 5.2: Spine shape parameters after bed control (ACS) in laboratory conditions while lying in prescribed sleep postures

Posture	Parameter	ACS-condition
Left lateral	P1 [°]	0.76 ± 1.31
	P2 [mm]	0.62 ± 0.81
	P3 [°]	0.81 ± 1.34
	P4 [°]	-0.13 ± 1.59
Right lateral	P1 [°]	0.80 ± 1.27
	P2 [mm]	0.62 ± 1.69
	P3 [°]	0.84 ± 1.27
	P4 [°]	-0.79 ± 2.02
Supine	P5 [mm]	7.92 ± 2.65
	P6 [°]	5.75 ± 4.56
	P7 [°]	4.06 ± 3.08

5.3 Results

5.3.1 Laboratory experiments

Posture analysis revealed high sensitivity values for the detection of main sleep postures (Table 5.1). Sensitivity for detection of intermediate postures was 73.5%. From the intermediate postures that were not recognized as such, the majority (78%) was due to an initial misclassification rather than due to the active sensing approach, indicating the active sensing technique to be highly effective. Four of the six intermediate postures directly following a prone posture were misclassified. No additional order effects were noted. Specificity was well above 90.0% for all considered postures (Table 5.1). Spine shape parameters for supine and lateral postures, calculated after bed control, are listed in Table 5.2.

Table 5.3: Spine shape parameters during sleep on a bed with (ACS) and without (REF) active bed control

Posture	Parameter	REF	ACS	Sign.
Left lateral	P1 [°]	5.83 ± 0.91	1.07 ± 1.22	$< 10^{-3}$
	P2 [mm]	3.45 ± 1.87	1.10 ± 1.18	$< 10^{-3}$
	P3 [°]	6.74 ± 1.23	1.25 ± 1.25	$< 10^{-3}$
	P4 [°]	6.01 ± 4.00	0.83 ± 2.32	$< 10^{-3}$
Right lateral	P1 [°]	6.52 ± 1.57	1.21 ± 1.63	$< 10^{-3}$
	P2 [mm]	3.82 ± 2.06	0.94 ± 1.10	$< 10^{-3}$
	P3 [°]	7.46 ± 1.82	1.35 ± 1.62	$< 10^{-3}$
	P4 [°]	6.84 ± 3.61	1.29 ± 2.20	$< 10^{-3}$
Supine	P5 [mm]	8.59 ± 3.41	6.54 ± 2.35	0.03
	P6 [°]	6.67 ± 5.87	5.06 ± 4.95	0.41
	P7 [°]	4.45 ± 2.99	2.80 ± 2.01	0.24

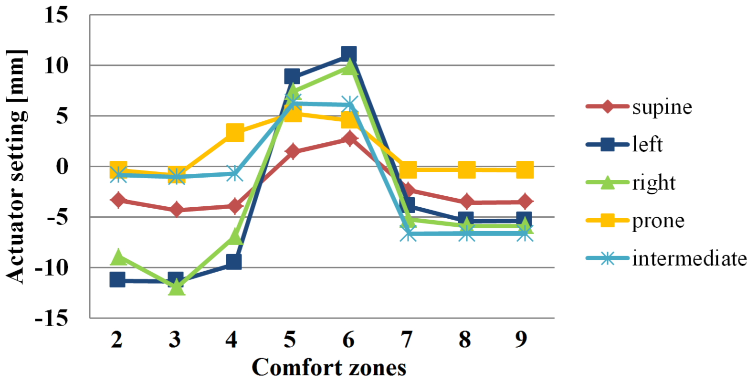
Table 5.4: Adopted sleep postures during overnight experiments in both experimental conditions

	Supine	Lateral	Prone	Intermediate	Moving
REF [%]	42.6 ± 20.1	52.2 ± 18.9	1.2 ± 3.0	–	3.9 ± 3.4
ACS [%]	38.2 ± 19.3	47.0 ± 22.8	0.7 ± 1.8	10.6 ± 14.5	3.1 ± 1.1

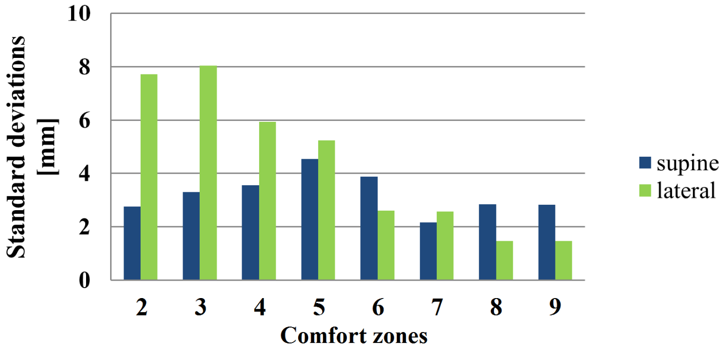
5.3.2 Overnight study

Analysis of the overnight data revealed significant differences between conditions for spinal alignment. In lateral postures, all four spine shape parameters (P1-P4) were significantly lower during the night with active control compared to the reference condition. In supine postures, a significantly lower RMSD between the modeled spine and its reference shape (P5) was noted during nights with active control. In addition, smaller differences in lordosis (P6) and kyphosis (P7) between modeled and reference shape were calculated, although no statistically significant effect could be proven. Table 5.3 summarizes the mean values of the spine shape parameters that quantify spinal alignment for both experimental conditions along with their significance level.

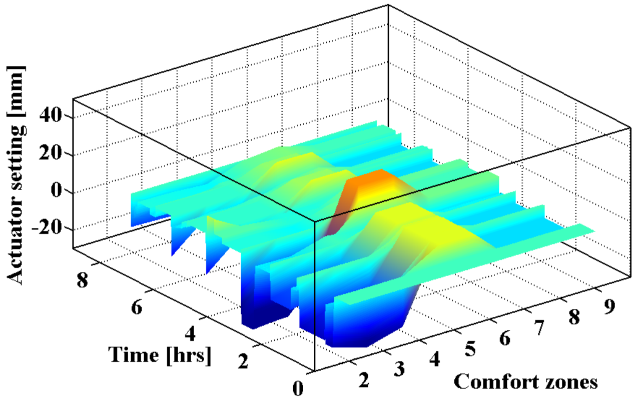
Posture analysis revealed no significant differences between conditions (Table 5.4), indicating that subjects did not alter their postural behavior in the actively controlled bed system. In general, most time was spent in lateral postures, followed by supine postures and least time was spent in prone postures. During the nights with active bed control, intermediate postures were detected as well,



(a)



(b)



(c)

Figure 5.6: (a) Actuator settings per comfort zone for each posture, averaged over the entire subject population. (b) Standard deviations of actuator settings reflect interpersonal variation. (c) Mattress configurations over time during one of the nights.

Table 5.5: Subjective sleep scores after a night on a bed with and without active control of bed properties

	REF	ACS	Sign.
Subjective sleep quality	5.67 ± 1.41	7.00 ± 0.87	0.02
Refreshed feeling	6.11 ± 1.83	7.00 ± 1.41	0.06

accounting for an average occurrence of 10.6 ± 14.5 %. However, significant interpersonal differences were present in terms of adopted postures, which were reflected in relatively high standard deviations (Table 5.4).

Figure 5.6(a) shows an overview of the actuator targets during the nights with active bed control for the considered sleep postures, averaged over the entire subject population. Left and right lateral postures were considered separately to have an idea on the consistency of the proposed mattress configurations. It can be inferred from figure 5.6(a) that lateral postures require the most adjustment with respect to the reference configuration. Furthermore, the proposed actuator settings for left and right lateral postures were almost identical, indicating the consistency of the implemented control. In addition, standard deviations are shown in figure 5.6(b) for lateral and supine postures, reflecting variation in proposed mattress configurations between subjects. For lateral postures most differences were present in the shoulder and waist zones (zones 1 – 4), whereas for supine postures most differences between subjects were present in zones 4 – 5, corresponding to the predominant location of lumbar lordosis. Since no personal steering was applied in prone and intermediate postures (see 5.2.2), they are not incorporated in figure 5.6(b). Figure 5.6(c) shows the variation of the mattress configurations for one specific night by plotting the actuator targets of the adjustable comfort zones over time.

Results of subjectively perceived sleep quality and the evaluation of feeling refreshed showed higher scores after the nights with active control of bed properties, yet statistical significance was only reached for the subjective sleep quality scores (Table 5.5).

5.4 Discussion

This study presents an autonomous bed system that controls mechanical properties of eight comfort zones in order to optimize spinal alignment in different postures during sleep. Continuous mattress indentation measurements provide the input to sequentially detect body movement, recognize adopted sleep posture and estimate spine shape by fitting a personalized human model in the measured indentation. Comparison of the estimated spine shape with the desired shape allows determining whether adjustment is necessary and if so, new target values are forwarded to the actuators of the adjustable comfort zones. The control loop is repeated until no further adjustments are necessary or until spinal alignment worsens after steering.

Results of the laboratory experiments revealed high sensitivity and specificity values for the detection of the main sleep postures (supine, lateral, prone), similar to what is described in prior research [32]. In addition, the ability to change mattress characteristics was used to detect intermediate postures by means of an active sensing approach, resulting in a sensitivity of 73.5%. The majority of the false negatives were due to an initial misclassification of the intermediate postures as prone or supine, rather than due to the active sensing approach itself. Furthermore, the presence of only one false positive resulted in a very high specificity (99.4%). The use of a Balanced Latin Square Design allows looking into how order effects of adopted postures influence the functioning of the control system. Results show that the transition of prone to intermediate (left or right) resulted in most cases in a false negative detection. Presumably, when moving from prone to intermediate, the indentation profile resembles more the profile of a prone posture, resulting in an initial misclassification. No other order effects could be identified. Analysis of spine shape revealed that the implemented bed control results in proper spinal alignment for lateral and supine postures, indicated by low values of the calculated spine shape parameters compared to literature values on static bed systems [31].

Overnight experiments were performed to validate the control system in a situation where subjects were not bound to prescribed sleep postures. Posture analysis revealed similar results as what can be found in literature [11]. Most time was spent in lateral postures, followed by supine postures, intermediate postures and least time was spent in prone postures. Intermediate postures accounted for 10.6% of time in bed, which is probably an underestimation considering the sensitivity (73.5%) and specificity (99.4%) for detection of intermediate postures. No within subject differences were apparent in posture prevalence between both experimental conditions, indicating that subjects did not significantly alter their postural habits as a result of the bed control. Large interpersonal differences were apparent (see high standard deviations in table 5.4) which is consistent with previous literature [7]. These large interpersonal differences point out the limitation of a design focus on one dominant posture based on population statistics.

Comparison of spinal alignment during nights with active support (ACS) and a reference night without control of bed properties (REF) indicates a significant improvement of spinal alignment in the ACS-condition. In lateral postures large and significant improvements were achieved for all spine shape parameters in the ACS-condition with respect to the REF-condition. In supine postures differences were smaller and significant improvement was only reached for the RMSD between the estimated and the reference shape. Lordosis and kyphosis angles in the ACS-condition were also closer to that of the reference shape during the ACS-condition, although no statistical significance could be proven. Looking at the proposed mattress configurations for each sleep posture (Figure 5.6), it can be derived that lateral postures required more adjustment with respect to the reference condition than supine postures, explaining the greater improvement of the implemented control on lateral with respect to supine spine shape parameters. Furthermore, proposed mattress configurations for lateral postures differed between subjects predominantly in the shoulder and the waist region, corresponding to different shoulder/waist width ratios of the participating subjects. For supine postures most between subject differences were apparent in the zones corresponding to the lumbar region of the spine, accounting for differences in lumbar lordosis. Subjectively, the active adjustment of bed properties did not interfere with sleep. Subjects reported a higher subjective sleep quality and evaluation of feeling refreshed after the ACS-condition with respect to reference, yet statistical significance was only reached for subjective sleep quality. Although further research on a larger subject population and more detailed objective sleep data is necessary to investigate the influence on sleep, these results suggest that the active control of bed properties does not interfere with subjective sleep parameters.

In this context, a first limitation of the present study is that no detailed analysis on the influence on sleep was performed. Future research should therefore focus on the effect on the macro- and microstructure of sleep with a clear focus on the periods during and after which the actuators are steering towards a new configuration. In general, during and after posture changes, subjects are in an elevated state of arousal. Since in the implemented control, actuators started working 10 seconds after each posture change, it should be examined whether these arousals were prolonged during the nights with active control compared to similar periods in the reference condition. If this would be the case, a longer period between posture change and active steering should be considered. A second limitation involves that no personalized control was implemented for prone and intermediate postures. This is mainly due to the fact that no validated method has been developed to assess spine shape in these postures [30]. In order to assess spine shape in prone postures, more complex human models are required with integrated soft tissue properties to model soft tissue deformation of the abdomen. Assessment of spine shape in intermediate postures requires the knowledge of additional degrees of freedom to determine the amount of torsion between pelvis and shoulder girdle. Therefore, future research should concentrate on dynamic estimation methods to simulate body movements in bed rather than static posture recognition techniques [12, 4]. A final limitation involves that subjects might shift outside the adjustable comfort zones (towards the foot end of the sleep system). Although this never happened during the performed overnight studies, it is for instance plausible that the lumbar part of the spine is positioned outside the range of the comfort zones. In these cases, although no adaptation for the lumbar spine can be accomplished, the system still allows adaptation in the thoracic region (in a lateral position for instance by lowering the target values of the comfort zones where the shoulders are located).

5.5 Conclusion

This study aims at developing and testing a control algorithm to optimize spinal alignment during sleep by adapting mechanical bed characteristics according to the adopted sleep posture and subject specific anthropometric information. Results show that spinal alignment can be significantly improved resulting in a positive effect on subjectively perceived sleep. Consequently, the concept of an actively controlled bed system, adjusting itself to behavioral aspects of sleep, seems to be a promising aid to promote sleep by dynamically optimizing the sleep environment.

5.6 Acknowledgements

This study was carried out thanks to the financial support of the Flemish agency for innovation by science and technology.

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Chapter 6

Biomechanics-based active control of bedding support properties and its influence on sleep

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Adapted from a manuscript accepted for publication in the Proc. of the 18th World Congress on Ergonomics, Feb. 2012

Abstract

Proper body support plays an import role in the recuperation of our body during sleep. Therefore, this study uses an automatically adapting bedding system that optimizes spinal alignment throughout the night by altering the stiffness of eight comfort zones. The aim is to investigate the influence of such a dynamic sleep environment on objective and subjective sleep parameters. The bedding system contains 165 sensors that measure mattress indentation. It also includes eight actuators that control the comfort zones. Based on the measured mattress indentation, body movements and posture changes are detected. Control of spinal alignment is established by fitting personalized human models in the measured indentation. A total of 11 normal sleepers participated in this study. Sleep experiments were performed in a sleep laboratory where subjects slept three nights: a first night for adaptation, a reference night and an active support night (in counterbalanced order). Polysomnographic measurements were recorded during the nights, combined with questionnaires aiming at assessing subjective information. Subjective information on sleep quality, daytime quality and perceived number of awakenings shows significant improvements during the active support (ACS) night. Objective results showed a trend towards increased slow wave sleep. On the other hand, it was noticed that % N1-sleep was significantly increased during ACS night, while % N2-sleep was significantly decreased. No prolonged N1 periods were found during or immediately after steering.

Keywords

Smart bedding, spine support, sleep quality, spinal alignment, mattress control.

6.1 Introduction

Although our living environment is continuously evolving towards high-tech systems to provide optimal comfort, only little research focuses on the sleep environment. On the other hand, both sleep physiology and ergonomics are continuously growing research fields. Yet, at present there is a lack of knowledge about the impact of the sleep surface on general sleep quality. As a consequence, the question remains whether applying ergonomic design principles affects actual sleep (i.e. sleep quality, sleep architecture, movements, etc.).

According to Webster's dictionary, the primary definition of comfort is "the provision of support and assistance". Applied to the design of bedding systems, improving comfort involves providing optimal body support. Optimal support refers to aligning the spine towards its reference shape, which is comparable to the shape while standing but with a slightly flattened lumbar lordosis due to the changed orientation of the working axis of gravity with respect to the craniocaudal direction [7]. However, bed properties that provide optimal support are posture- and person-dependent. For instance, in most persons coronal and sagittal contours differ, which results in a changed spinal alignment after changing sleep posture [9, 21]. To account for these variable conditions, a new approach in the development of state-of-the-art bedding systems consists of monitoring sleep posture changes based on mattress indentation data. In addition, the combination of mattress indentation with personalized human models allows estimating spinal alignment during sleep in an unobtrusive way [20].

This study makes use of a bedding system that autonomously alters its stiffness distribution according to the estimated spinal alignment. The aim of this study is to investigate the effect of such a "smart" bedding system on sleep in both an objective and a subjective way through polysomnography and questionnaires respectively. Also movement and posture information is gathered using the specified bedding system.

6.2 Methodology

6.2.1 Participants

A total of 11 volunteers (6 males, 5 females) between the age of 20 and 28 years (mean age 21.2 ± 3.2 y) participated in this study. Subjects were recruited through advertisement. All volunteers were healthy sleepers. Exclusion criteria consisted of medical problems that can interfere with normal sleep, e.g. regular smoking, abuse of alcohol, any form of back pain and the intake of sleep medication or antidepressants. Adherence to these standards was ensured using the Pittsburgh Sleep Quality Index [5], the Insomnia Interview Schedule [15], and a general intake interview. All participants signed informed consent forms. The study was approved by the Ethics Committee of the Vrije Universiteit Brussel.

6.2.2 Experimental design

Each subject slept three nights in a sleep laboratory: a first night, considered as habituation night, a reference night (REF) — in which the sleep system was

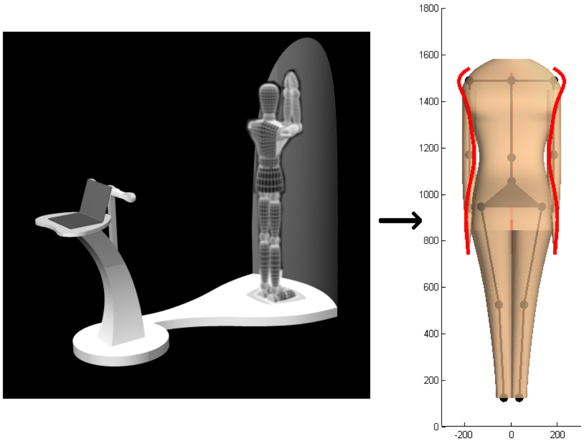

Figure 6.1: Silhouette extraction and personalized human model generated from coronal and sagittal body contours using the Ikélo system. Adapted from Verhaert et al. 2011 [20]

set in its standard configuration — and an "active support" night (ACS) where the sleep system was working automatically towards optimal spine support. Counterbalancing was applied to avoid carry-over effects between conditions. Participants slept one night at home between each night in the laboratory and were blinded from experimental conditions. The experimental nights consisted of approximately eight hours time in bed. The first night in the sleep laboratory was not used for further analysis of the results [1].

6.2.3 Procedure

Two weeks prior to the experiment and during the experimental week, participants had to fill out sleep diaries to check for any abnormalities in their sleep-wake patterns. Two dimensional body contours in both the sagittal and the coronal plane were automatically registered by means of silhouette extraction using an optical measurement system (Ikélo, Custom8, Leuven, Belgium). These body contours provided the necessary anthropometric input to generate a personalized human model (Figure 6.1) [20].

Subjects filled out questionnaires at various moments throughout the course of the experiments. At 19h00 and upon retiring to bed (between 22h30 and 23h30) they completed a Karolinska Sleepiness Scale (KSS) [2], a Profile of Mood State (POMS) [6], a Stress/Arousal Adjective Checklist (SA-CL) [12] and an Activation/Deactivation Adjective Checklist (AD-ACL) [14]. In the morning following the test night (around 07h20) the subjects repeated the above questionnaires. In addition, they completed a sleep diary and were questioned regarding general sleep quality (SQ) and bed comfort. Finally, alertness and sleepiness during the day was questioned in the evening following the test night. The questionnaires were rescaled in such a way that high values implicate positive results (less fatigued, more rested, better sleep quality, . . .). This means that when differences between the evening before and the morning following the test night are reported (see Table 6.2), a negative difference value corresponds to a restorative effect of the night's sleep.

6.2.4 Measurements

Polysomnographic measurements (PSG) were performed during the nights (including EEG, EOG, skin temperature, ECG and EMG measurements). Furthermore, video recording as well as chest orientation were measured. All channels were measured at 200 Hz using a customized Medatec DREAM system (Medatec, Brussels, Belgium). Specifically designed sleep systems were used, equipped with sensors and actuators. A total of 165 linear potentiometers, arranged in a staggered two-dimensional grid of 11 by 30, measured the perpendicular indentation of the mattress core (DynaSleep, Custom8, Leuven, Belgium). Indentation was continuously measured and recorded throughout the nights at a sampling rate of 1 Hz. The main sleep postures (left/right lateral, prone, supine) were estimated from the indentation data using a Support Vector Machine (SVM) classifier, that used five features according to the classification scheme proposed by Verhaert et al. [22]. This algorithm allows posture detection with an overall accuracy of 92%. Based on the detected posture, spinal alignment was estimated by fitting the model in the measured indentation [20].

During the "active support" (ACS) night actuators in the bedding system enabled adaptation of the stiffness in eight zones of the mattress in order to continuously optimize the spine shape. Figure 6.2 presents an overview of the control that is implemented in the bed systems. A more detailed description of the distinct components of the control algorithm is provided in section 5.2.2. The general input of the control algorithm is provided by the mattress indentation measurements, from which posture and spine shape can be calculated using the personalized human models (more detailed information on this procedure can be found in [23]). Based on a comparison of the modeled spine shape with the desired (reference) shape a new bed configuration is proposed (i.e. new target values are forwarded to the actuators). Steps II to IV are repeated until the modeled shape approximates the reference shape close enough.

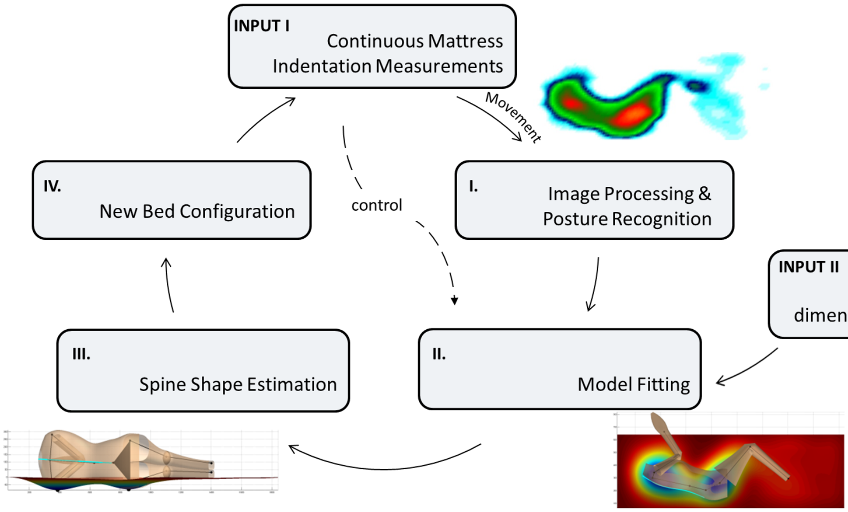

Figure 6.2: Schematic overview of the working principle of the implemented control loop for the alteration of bed properties during sleep. Based on mattress indentation measurements, movements are detected. Postures are estimated when a stable position is achieved for at least 10 seconds. Afterwards, a personalized human model is fitted in the indentation surface in order to estimate spine shape. Based on this estimated shape, the decision is made whether or not to adjust the bedding system. A more detailed description of the control algorithm is provided in section 5.2.2.

The active steering started 30 min after lights out to avoid a prolonged sleep onset due to the steering.

6.2.5 Data analysis

From the recorded mattress indentation a movement signal is derived, which is defined by the summation of the rectified time derivative of each potentiometer output. The signal is then scaled according to the Body Mass Index (BMI) of the sleeper (Eq. 6.1), and used to calculate different movement parameters, such as the number of body movements. Small, medium and large movements were determined by applying a threshold of respectively 2, 10 and 40 times the mean of the signal.

$$\text{movement signal} = \frac{\sum_{i=1}^{165} \left| \frac{d(\text{potentiometer output})}{dt} \right|}{\text{BMI}} \tag{6.1}$$

PSG output was scored according to Rechtschaffen & Kales [16], adopted to the revision of the American Academy of Sleep Medicine [11]. Scoring was performed by a trained professional and the resulting sleep hypnogram was used to calculate objective sleep parameters. Normality was checked with a Lilliefors normality test, while a Bartlett's t-test provided information on whether the variances of both groups were equal. In case of a normal distribution with equal variances, two-sided student's t-tests were used to compare sleep parameters between the active support night (ACS) and the reference night (REF) within subjects. A Wilcoxon signed-rank test was used as a non-parametric alternative. Differences of $p < 0.05$ were considered significant for all statistical analyses.

6.3 Results

6.3.1 Subjective assessment

Sleep quality, derived from a visual analogue scale between zero (extremely bad) and ten (extremely good), showed a significant increase ($p = 0.029$) in the ACS night (Table 6.1). Other subjective results derived from the analysis of the sleep diaries showed that subjects perceived significantly less awakenings ($p = 0.041$) during the ACS night and pointed out that night-time awakenings were shorter ($p = 0.045$). Table 6.2 lists the main results of the questionnaire data. Although all results were in favor of the ACS condition, statistical significance was only reached for daytime quality following the test night.

6.3.2 Objective assessment: sleep architecture

Table 6.3 presents the sleep parameters derived from the hypnogram. The time spent in N1-sleep is significantly ($p = 0.027$) increased with approximately 2 % in the ACS night. Percentage N2, on the other hand, was significantly decreased ($p = 0.014$)), while percentage slow wave sleep (SWS) tended to increase in the ACS night ($p = 0.096$). No other effects were present in terms of sleep macrostructure.

Table 6.1: Subjective results derived from sleep diary

	REF	ACS	p-value
Subjective SOL [15 min]	0.80 ± 0.79	1.10 ± 0.88	0.430[w]
Subjective number of awakenings [−]	1.70 ± 0.95	0.80 ± 0.79	0.041[t]
Subjective mean awakening length [min]	1.25 ± 0.63	0.90 ± 0.88	0.045[t]
Subjective sleep quality [0-10]	6.60 ± 1.63	7.50 ± 1.32	0.029[t]

[t] Two-sided paired t-test; [w] Wilcoxon signed-rank test

Table 6.2: Subjective sleep parameters derived from questionnaire data (morning after, evening before and/or evening after the nights in the lab)

	REF	ACS	p-value
Daytime quality score EA [/ 30]	22.35 ± 4.86	24.36 ± 4.4	0.039[w]
POMS fatigue difference EB-M [-5 – 5]	0.15 ± 0.67	0.00 ± 0.76	0.623[w]
AD-ACL Arousal difference EB-M [-5 – 5]	-0.34 ± 1.04	-0.53 ± 1.08	0.554[t]
KSS Sleepiness difference EB-M [-5 – 5]	-0.72 ± 1.07	-0.95 ± 1.01	0.513[w]
KSS Sleepiness difference EB-EA [-5 – 5]	-0.95 ± 1.09	-1.38 ± 1.03	0.137[t]
Bedding system Quality M [/ 10]	4.53 ± 1.65	4.95 ± 1.68	0.310[w]
Feeling rested score M [0 – 10]	6.71 ± 1.87	7.24 ± 1.92	0.248[t]
Back pain score M [1 (a lot) – 4 (none)]	1.86 ± 1.56	2.39 ± 1.40	0.180[w]

[t] Two-sided paired t-test; [w] Wilcoxon signed-rank test; EB: Evening before; EA: evening after; M: morning

6.3.3 Movement and sleep postures

The number of body movements (small, medium or large BMs, Table 6.3) was not statistically different between conditions. Furthermore no significant changes were present in the amount of time that was spent in each sleep posture (Table 6.4), nor in the number of posture changes (Table 6.3).

Table 6.3: Objective parameters derived from PSG and movement data

	REF	ACS	p-value
SOL [min]	11.78 ± 4.78	13.22 ± 12.67	0.98^{w}
N2-latency [min]	14.17 ± 5.23	16.30 ± 8.22	0.75^{t}
LPS [min]	13.67 ± 5.59	17.14 ± 13.43	0.33^{w}
LDS [min]	26.12 ± 7.60	29.49 ± 8.06	0.31^{t}
TST [min]	423.50 ± 30.90	425.45 ± 28.90	0.68^{w}
Intrasleep wake time [min]	27.30 ± 24.16	22.80 ± 21.33	0.44^{t}
W [% TIB]	8.07 ± 5.22	8.44 ± 5.99	0.56^{w}
N1 [% TIB]	7.91 ± 5.12	9.86 ± 5.77	0.03^{w}
N2 [% TIB]	51.75 ± 8.27	44.85 ± 5.97	0.01^{t}
SWS [% TIB]	24.50 ± 5.89	29.89 ± 6.19	0.10^{w}
NREM [% TIB]	76.25 ± 6.90	74.73 ± 6.34	0.45^{t}
REM [% TIB]	15.78 ± 8.28	15.29 ± 7.20	0.77^{t}
BM small [-]	46.10 ± 32.10	55.00 ± 23.82	0.16^{t}
BM medium [-]	34.30 ± 27.17	32.00 ± 19.56	0.61^{t}
BM large [-]	30.00 ± 9.07	27.50 ± 5.60	0.20^{t}
Number of posture changes [-]	13.00 ± 7.47	12.10 ± 4.07	0.57^{w}

^{t} Two-sided paired t-test; ^{w} Wilcoxon signed-rank test; SOL: Sleep onset latency; LPS: latency to persistent sleep; LDS: latency to deep sleep (SWS); TST: total sleep time; TIB: time in bed; W: wake; N1: stage N1 sleep; N2: stage N2 sleep; SWS: slow wave sleep ; NREM: non rapid eye movement; REM: rapid eye movement; BM: body movement.

Table 6.4: Adopted sleep postures in REF and ACS night

	Supine	Left lateral	Right lateral	Prone
REF [%]	28.20 ± 19.03	26.82 ± 15.87	24.68 ± 19.51	6.30 ± 11.21
ACS [%]	27.19 ± 14.93	25.00 ± 15.23	24.80 ±12.95	5.91 ± 12.77

6.4 Discussion

This study aimed at exploring the influence of an active bedding system — designed to continuously optimize spinal alignment — on objective and subjective sleep parameters. Overnight experiments in a dedicated sleep laboratory were performed in order to look at sleep macrostructure, body movements and subjective parameters.

Subjective results showed an improvement in the feeling that people have about their sleep in the morning following a night on an actively steered bedding system. Moreover, daytime quality after sleeping on the active system, increased significantly.

Movement information showed no significant differences between conditions. No within-subject changes were found in the amount of time spent in each sleep posture. The large standard deviations for the occurrence of sleep postures (Table 6.4) reflect large interpersonal differences in habitual sleep postures. This confirms the need for an individualized (and even actively steered) approach of bedding systems, as presented in this study.

The sleep hypnogram revealed a trend towards more SWS during the ACS night. Since SWS, or deep sleep, is important for physical recuperation [18] these results might indicate a positive restorative effect of the active support. Some studies investigating the effect of bedding systems on sleep failed to find any differences in objective PSG parameters [17]. Others found differences in % SWS during sleep on different bedding systems, but did not incorporate quantified validation of spinal alignment [19, 13]. Tsai and Liu [19] reported differences in SWS in subjects with mild sleep-related respiratory disturbances sleeping on bedding systems that were selected by means of manual muscle testing. Lee and Park [13] found a significant increase in SWS after replacing the mattress with "one that can maintain spinal curvature in a manner more similar to that found while standing". However, they did not provide a quantification of spinal curvature, nor specify how they assessed it.

Furthermore, an increase in percentage N1 sleep was seen during the ACS night. It is known that during and immediately after a posture change subjects are in an elevated state of arousal [10]. Since the current steering control awaited only 10 seconds after the end of each posture change, it is plausible that the subjects were still in an elevated state of arousal when the actuators were working and became aware of the changing bed properties, causing the arousal to prolong. However, no differences in wakefulness, nor in duration of N1 after steering were noted.

Nevertheless, our results should be further analyzed in terms of micro-structural sleep parameters looking into the power density in specific frequency bands of the EEG signal (e.g alpha activity: 8-12 Hz and beta activity: 12-30 Hz).Particularly the periods during and immediately after steering should be inspected in order to check whether steering has an effect on sleep microstructure. If an increase in alpha-activity is apparent in these periods, a possible solution might be to wait until the sleeper has (re)entered a deeper sleep stage before changing bed properties.

One can argue whether objective or subjective results are in favor to draw any conclusions on sleep evaluation. Subjective sleep quality depends a lot on the perceived time awake after sleep onset [6], which is also reflected in the results of this study (Table 6.1). People thus perceive a good sleep quality when sleep continuity is assured [3]. However, this is not always reflected by objective sleep parameters.

Finally, the following recommendations for future research are proposed. First, it should be stressed that this study only investigated a one-night effect. Long term studies are needed to look at long-term effects of optimized support by means of active bedding systems. Second, other factors than spinal alignment have been proposed in relation to sleep comfort, for instance pressure distribution [4, 13]. Therefore, ongoing research is exploring how changing the sleep system's stiffness distribution alters pressure distribution. Finally, specific patient populations should be studied (e.g. low-back pain sufferers), since it has been shown that improved body support is especially beneficial for people with chronic low-back pain or non-specific sleep complaints [8].

6.5 Conclusion

This study aimed at identifying the effects of an actively steered bedding system on objective and subjective sleep parameters. Results showed a positive effect on subjectively perceived sleep and a trend towards more slow wave sleep. On the other hand, a small, yet significant increase in N1 sleep was noted. Since no prolonged N1 periods were found during or immediately after steering, further analysis in terms of micro-structural sleep parameters in these periods is needed to investigate whether subjects became aware of the changing sleep environment during the night.

6.6 Acknowledgements

This study was carried out thanks to the financial support of the Flemish agency for innovation by science and technology.

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Chapter 7

General conclusions and future perspectives

This final chapter starts with a concise summary of the main findings and a recapitulation of the general conclusions that can be drawn from this work. Subsequently, the research outcome is evaluated with respect to the initially stated research hypotheses and finally, recommendations for future work are provided.

7.1 Summary and general conclusions

Ergonomics of sleep is a relatively young research discipline bridging the expertise of sleep physiologists, psychologists, ergonomists and engineers in order to create an individually optimized sleep environment that promotes sleep initiation and maintenance. Ergonomic design of sleep systems (i.e. mattress, bed base and head cushion) aims at optimizing bed properties to achieve maximal recovery during sleep. A new approach in providing optimal body support is to actively change bed properties throughout the night. This approach allows accommodating for individual behavioral factors that affect body support during sleep, e.g. posture changes. However, while optimizing ergonomic aspects of the bedding system, care should be given not to interfere with the actual sleep process. Therefore, this PhD dissertation is not restricted to the development of ergonomic assessment tools and their implementation in so-called "smart" sleep systems, yet covers the effect of these dynamic support conditions on sleep parameters as well.

Chapter 1 introduced the basic concepts of sleep that are referred to throughout the thesis. An overview was given of the most common types of sleep systems and their main properties. In addition, the available literature on the effect of sleep system properties on body support and sleep quality was extensively reviewed. Further, state-of-the-art techniques were described to assess ergonomic aspects of sleep systems. Based on the main voids in the available scientific literature, the different objectives were stated that form the base for the underlying hypothesis of this dissertation.

In chapter 2, the effect of spinal alignment on objective (PSG-derived) and subjective sleep parameters was studied during overnight experiments in a dedicated sleep laboratory. Sleep systems with adjustable comfort zones allowed altering spinal alignment independently from other confounding variables. Results showed that individual posture preferences were a determinant factor in the extent that subjects experienced a negative effect while sleeping on a sagging sleep system. In particular, subjects preferring prone and lateral sleep postures demonstrated impaired sleep on a sagging support.

Since chapter 2 showed that habitual sleep postures played a role in the effect of ergonomic bed design on sleep, an unobtrusive technique for the assessment of motor patterns during sleep was proposed in chapter 3. An algorithm was presented to automatically detect body movements and sleep postures based on integrated mattress indentation measurements. Posture recognition was achieved by means of comparing an image feature vector with an optimal separating hyperplane constructed with the theory of support vector machines. Validation with independent posture scoring based on video frames and chest orientation revealed a high sensitivity for both movement detection and posture recognition. It was concluded that mattress indentation provided an accurate and unobtrusive measure to assess motor patterns during sleep.

Chapter 4 treated the use of human models for the unobtrusive assessment of spinal alignment during sleep. A generic surface model was developed that could be personalized based on anthropometric parameters derived from silhouette extraction. The surface model was combined with an inner skeleton model, allowing the model to simulate distinct sleep postures by means of altering various degrees of freedom (DOFs). In order to estimate spine shape, the personalized human model was fitted in the measured mattress indentation by determining appropriate values of a set of DOFs, corresponding to both the global positioning of the model with respect to the mattress and the deformation of the model according to the adopted sleep posture. Validation by means of spine modeling from 3-D scans of the back surface, indicated a root mean square deviation of 9.1 mm between the estimated and measured spine shape.

In chapter 5, the aforementioned algorithms were implemented in a feedback control system aimed at optimizing spinal alignment by means of controlling the mechanical properties of eight comfort zones throughout the night. Based on the comparison of the estimated spine shape with a reference shape a controller decided whether or not a new bed configuration was forwarded towards the actuators of the comfort zones. The developed control system was validated both in laboratory conditions and in overnight sleep experiments showing a significant improvement of spinal alignment compared to a static sleep system. Furthermore, the adjustment of bed properties during the night resulted in a positive effect on subjectively perceived sleep.

Finally, chapter 6 explored the effect of the actively controlled sleep system on sleep macrostructure. Polysomnographic measurements were performed during overnight experiments and subjective questionnaires were completed at various moments before and after the test nights. Results showed a positive effect on subjective sleep parameters and a trend towards more slow wave sleep. Although a small increase in N1 sleep was noted, it was not clear whether this was due to the active steering.

Throughout this thesis, several tools were developed for the ergonomic assessment of body support during sleep based on unobtrusive measurements. The combination of these tools allowed active control of spinal alignment by continuous adaptation of mechanical bed properties. Furthermore, the developed procedures were validated in overnight experiments to verify their performance in habitual sleep conditions and to study their effect on general sleep structure.

7.2 Confirmation of research hypotheses

Looking back to the first hypothesis of this thesis, which stated that spinal alignment has an effect on sleep, the results presented in this work seem to confirm this statement. With the current state-of-the-art serving as reference condition (namely a static, yet personalized sleep system), both a negative and positive induction were imposed. The negative induction consisted of a static, sagging support whereas the positive induction consisted of a dynamically optimized sleep system. Related to this first hypothesis, the following conclusions can be drawn:

- Spinal alignment is not only influenced by the mechanical characteristics of the sleep system, but also by individual anthropometric characteristics of the sleeper and individual behavioral factors (habitual sleep postures). Particularly prone and lateral sleepers experience a negative effect when sleeping on a sagging sleep system. This effect is reflected both in objective (prolonged awakenings) and subjective outcomes (decreased sleep quality).
- Although impaired spinal alignment negatively affects sleep, it is not yet fully understood whether the continuous optimization of spinal alignment has a positive effect on sleep. Although significant improvements in subjectively perceived sleep were noted, these were not fully reflected by significant improvements of objective sleep macrostructure, showing a trend towards more slow wave sleep, yet slightly increased stage N1 sleep.

To conclude, the presented results confirmed the importance of individual behavioral factors (e.g. preferred sleep postures) when studying the effect of bed properties on sleep. Since individual features are generally not accounted for in state-of-the-art literature, it comes to no surprise that no overall consistent results regarding the effect of bed properties on sleep were reported up to now. On the other hand, more research (long-term studies, specific populations, ...) is needed to confirm to what extent sleep can be further promoted by means of continuously optimizing spinal alignment.

A second hypothesis, more technical in nature, stated that it is feasible to continuously assess and optimize spinal alignment throughout the night by means of a smart bedding system. The developed algorithms and methodologies partially confirm this second research hypothesis. First, mattress indentation measurements provide the necessary information for the unobtrusive assessment of motor patterns during sleep. Body movements are detected straightforwardly by means of the time derivative of mattress indentation whereas the problem of posture recognition is formulated as a classification problem for which a support vector machine classifier is constructed based on limited training data.

Apart from BMI, no other a priori information is needed to classify a particular indentation image into one of four main sleep postures (supine, prone, left or right lateral). Second, the combination of mattress indentation with a model describing human body shape allows the estimation of spine shape in lateral and supine positions, provided that the necessary anthropometric information of the sleeper is available to personalize the model. Third, the aforementioned ergonomic assessment tools are successfully integrated in a feedback control loop that optimizes spinal alignment by means of the active adjustment of mechanical bed properties during sleep. As such, a sleep system has been developed that individually optimizes spinal alignment in lateral and supine sleep positions, while providing a general support in prone and intermediate sleep positions. Although a positive effect on subjective sleep is noted, further research is required to clarify whether subjects become aware of the dynamically changing sleep environment.

7.3 Future perspectives

The work presented in this dissertation is merely a first step towards a smart sleep environment. Additional research is required in two directions. First, the developed methodologies for motor assessment and active control of spine shape should be further investigated. Second, the work should be broadened to other factors of the sleep environment. Regarding this second step a similar multidisciplinary approach is suggested, not only focusing on developing new technologies, but also on early stage validation in overnight experiments.

7.3.1 Further exploration of the developed tools

Effects on sleep microstructure

Although macrostructure analysis provides a global view on sleep structure throughout the night, it implies some important limitations as well. Due to the analysis of epochs with a fixed time duration, the method is not flexible enough to recognize short-lasting events or to analyze the temporal relationship between such events in different channels. With this in mind, a first recommendation for future work is to study the periods during and immediately after steering on the microstructural level. A hypothesis that is insufficiently accounted for in the presented work, is that during these periods subjects become aware of the changing environment, resulting in shifts in EEG spectral power densities. In particular, increased beta activity during wake after posture changes or increased alpha activity might indicate short-lasting disturbance due to the altering support conditions. In this context, it might be advisable to postpone adjustments in mattress configurations until the subject has reentered a deeper sleep stage.

Assessment of motor patterns

The developed algorithms for motor pattern assessment during sleep are characterized by the static recognition of sleep postures based on specific features of one indentation frame. This technique, although suitable for classifying main sleep postures, showed to be insufficient to detect so-called intermediate postures. In chapter 6 an active sensing approach was successfully put forward to detect intermediate postures. However, the result is that six distinct sleep postures can be discriminated instead of four, which is still a significant oversimplification of reality. Therefore, future work should shift its focus from static posture recognition towards dynamic movement simulation. Since the interest in human motion tracking (e.g. by means of kinematic human models) is also present in the research field of human-robot interaction, similar techniques might be applied for simulating human motion in bed. Apart from a more realistic simulation of sleep postures, dynamic motion tracking might also be relevant in terms of detecting specific movement disorders during sleep (e.g. periodic limb movement disorder).

Modeling human body shape

The estimation of spine shape during sleep based on mattress indentation requires a model of the sleeper containing anthropometric information. Therefore, a simplified human model was developed in chapter 4 that was personalized based on a substantial amount of anthropometric input parameters. A recommendation for future work would be to reduce the amount of input parameters that is necessary to personalize the modeled body shape. In the framework of the open source MakeHuman project [1], recent improvements were implemented in terms of scalability and flexibility of the humanoid meshes, allowing realistic modeling of human shapes with a limited amount of anthropometric input. However, since it is not clear to what extend these meshes are data-driven (i.e. based on acknowledged anthropometric databases), they should not be used without thorough validation. A second approach to reduce the necessary input involves deriving anthropometric information from the bed measurement itself (e.g. by adopting a set of prescribed postures before going to sleep). Finally, in the long term, effort should be undertaken to combine anthropometric modeling packages with musculoskeletal, multi-body modeling tools (e.g. Madymo, Anybody, OpenSim). Interfacing these two approaches of human modeling presumably allows individualized estimation of musculoskeletal strain and enhanced comfort assessment for a variety of applications, including bed design [3].

Specific populations and long-term follow-up

Throughout this thesis sleep experiments were performed on a (predominantly) young and healthy subject population. Since prior research has shown that chronic sufferers from low-back pain or non-specific sleep problems are more susceptible to mattress quality [2], it might be useful to repeat the experiments on specific patient populations. However, care should be given to the extremely heterogeneous character of these ailments.

In addition to targeting distinct populations, future work should also look at long-term effects of body support on sleep (e.g. effect of habituation) and general wellbeing. Since the results of this dissertation confirmed the relevance of habitual postures with respect to the effect of body support on sleep, it is of particular interest to study whether people adapt their habitual postures to the support characteristics of the sleep system. In other words, do people alter their sleep habits over time when confronted with a particular sleep system? In order to realize this, the complexity of the current prototypes should be reduced so that home monitoring becomes feasible. Therefore, plausible simplifications (e.g. only one adjustable shoulder zone, reduced amount of sensors) should be verified by means of simulations based on the available data. Furthermore, other (plug & play) techniques to assess mattress indentation should be considered (e.g. textile integrated sensors).

Sleep system quality and expectation effects

Expectations about sleep and comfort have been put forward as important factors contributing to sleep quality. On the one hand, the mere introduction of a new sleep system often coincides with improvements in terms of subjectively perceived sleep (placebo effect). On the other hand, negative expectations with respect to the quality of the sleep system have shown to negatively influence subjects' evaluations of sleep quality (nocebo effect). At present, no attempts have been made to combine variations in sleep system quality and expectations on sleep system quality (for instance, providing an inferior sleep system while communicating it is the best on the market). Therefore, future research should look into such combined effects in order to study whether and how they might be related.

7.3.2 Optimizing other factors of the sleep environment

Although the presented work entirely focused on the optimization of spinal alignment during sleep, other environmental factors have also shown to play an important role in promoting sleep. Next to spinal alignment, another aspect of body support involves the local mechanical loads on the body surface, leading to stresses and strains in the underlying soft tissues. The ability of the sleep system to provide pressure relief of soft tissues has mainly been studied in a clinical context to prevent pressure ulcers in the bedridden. Notwithstanding the fact that in a general (healthy) population pressure relief is considered less critical, an increasing amount of studies uses pressure mapping systems to assess sleep system properties. However, an unambiguous interpretation of pressure mapping images requires the knowledge of the mechanical characteristics of the underlying tissues in order to calculate tissue load and tissue deformation. Future research on dedicated FE-models is therefore essential to translate values of contact pressure into meaningful information on tissue deformation.

Next to body support, other environmental factors affecting sleep include noise, light and the thermal environment. With respect to optimizing sleep conditions the latter two are quite straightforward: noise and light intensity should be kept below certain thresholds during sleep. However, defining the optimal thermal environment to promote sleep seems susceptible to personal and gender-specific preferences. Nevertheless, recent studies have shown interesting perspectives in terms of promoting sleep (sleep onset and sleep depth) by means of optimizing the thermal microclimate between the bed and the sheets [4, 5]. Because thermal properties of the sleep system partially determine the thermal sleep environment, future research should focus on the effect of different material properties on thermal insulation and vapor permeability. In addition, it was suggested by Raymann and coworkers to develop “a system integrated in the bedding that both measures skin temperature and controls the bed microclimate within a feedback control loop” [4].

Keeping in mind the quest for smart environments, a final recommendation for future work is proposed as follows. A truly intelligent sleep environment not only controls spinal alignment or bed microclimate based on integrated measurements, but takes into account the sleep stage of the subject while doing so. From this point of view, the increased effort to achieve (on-line) sleep staging based on unobtrusive (off-body) measurements should be encouraged [6], not to replace PSG in clinical settings but to create a truly personalized sleep environment at home.

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