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Somnomat: A Novel Device to Investigate the Influence of Vestibular Stimulation on Sleep

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***Abstract*— Sleep disorders affect about one third of the general population. Rocking movements may help to shorten sleep onset latency and enhance sleep quality. However, from a scientific point of view, the relation between vestibular stimulation and sleep remains unclear. This paper presents a novel device to investigate the influence of vestibular stimulation on sleeping human subjects. The developed device includes two actuated bed platforms allowing to provide adjustable rocking motion along five different movement axes: three translations along the longitudinal, lateral, and vertical body axes, and two swing-like rotations along longitudinal and lateral direction. The robotic platforms have been designed in order to fulfil the special requirements of sleep research. Rocking trajectories with linear velocity below 15 cm/s ensure smooth, confortable, and quiet conditions ($L_{eq} < 40\ dBA$) for all the five axes. The presented approach will allow to systematically investigate the influence of different kinds of rocking movement on human sleep.**

I. INTRODUCTION

About 33% of the general population presents insomnia symptoms [1]. Sleep disturbances as insomnia increase risk of cardiovascular diseases and obesity [2], [3], have a negative impact on mood, cognitive performance and motor function [4] and has an important economic cost (92.5-107.5 billion dollars annually in the USA [5]).

Despite the potentially serious consequences that sleep disorders can have on health, many learn to live with their sleep problems or are not even aware of them. Then, when the consequences of a disturbed sleep become too important to be neglected, a common choice is to resort to pharmaceutical helps. Sleep inducing drugs are not for long term use and may have side effects, such as changes in sleep architecture and dependency [6].

A promising non-pharmaceutical approach to improve sleep quality is vestibular stimulation. Many examples in daily life suggest a relation between vestibular stimulation and facilitation in falling asleep. People tend to fall asleep easily while travelling by train or by car. Parents help babies to fall asleep by rocking them in their arms or in a cradle. Moreover, many people like to relax or fall asleep in a hammock or in a rocking chair.

In spite of the fact that many popular examples and applications suggest evidence about a relation between vestibular stimulation and sleep, from a scientific point of view this phenomenon remains unclear. Only two studies were conducted, where the effect of the provided vestibular stimulation on sleep was analyzed based on physiological measurements including brain activity (Electroencephalogram, EEG). Both studies suggest a facilitated transition between wakefulness and sleep and to deeper sleep stages [7], [8]. However, in both studies the characteristics and the direction of the chosen movements were not particularly motivated. Bayer [7] used a bed rocking along the lateral axis (amplitude = 7.5 cm, frequency = 0.25 Hz), while Woodward [8] applied a longitudinal oscillation (amplitude = 3 cm, frequency = 0.42 Hz). Thus, despite the promising results of these studies, the relation between vestibular stimulation and sleep remains unclear. Especially, there is no information concerning how the effect differs between diverse kind of movements (e.g. various directions, amplitudes, and frequencies).

The goal of our project is to fill this lack of knowledge, by conducting a systematic evaluation of the influence of different movements, characterized by diverse directions, amplitudes and frequencies on sleep onset and on the process of sleep. The aim of such investigation is to analyze which effects these different stimulations have on sleep and to identify which kind of movement is best to promote relaxation and sleep. This may lead to the identification of a novel approach, based on scientific evidence that exploits rocking movements to improve sleep quality.

In order to enable the desired investigation, an actuated bed is needed to move a sleeping subject along various, adjustable trajectories.

The available systems that could be used to perform the desired task can be divided into two groups. The first group includes some commercial moving beds such as simple passive hanging or rocking beds and hammocks, vibrating beds or chairs, and few actuated rocking beds. The second group includes some complex robots such as Stewart platforms, commonly used in flight or drive simulators or positioning systems (antenna, military applications, etc.), enabling six degree-of-freedom (DOF) trajectories, fast dynamics, and high payloads. On the one hand, the beds belonging to the first group provide only passive motion or one actuated axis, limiting the range of movement that can be tested. On the other hand, the second group is comprised by bulky, highly complex, noisy, and commonly expensive systems that hardly satisfy the requirements of a sleep study. Thus it was decided to develop a novel actuated platform, dedicated to the investigation of the effect of different rocking movements on sleep. Such device had to be designed to be applied in sleep studies involving human subjects, conducted in

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standard apartments or sleep laboratories. The design and a first evaluation of the developed approach are presented in this paper.

II. TECHNICAL SETUP

A. First Investigation and the M^3 Setup

A preliminary investigation has been performed using the M^3 lab [9], [10], a robotic system developed in our laboratory. A tendon based parallel robot was used to move a platform, carrying standard single size (90 x 200 cm) slatted frame and mattress, along different 6-DOF trajectories (Fig. 1).

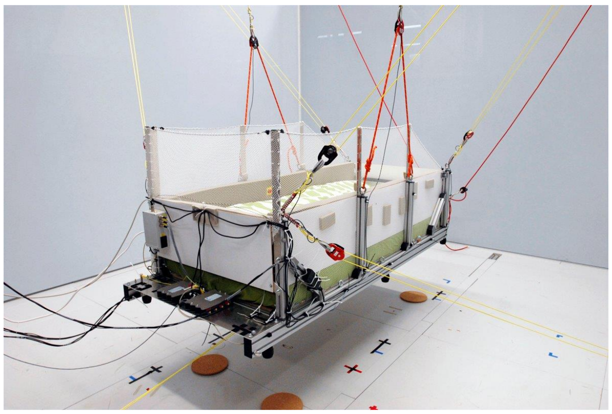

Fig. 1. Somnomat M^3 setup. The photo shows the setup used for the first investigation. Seven ropes of a tendon-based parallel robot were used to move the bed platform along any 6-DOF trajectory within the workspace of the M^3 lab.

In a first phase of the investigation a wide set of different movements was tested and evaluated by the subjects lying in the platform. This allowed to reduce the range of movements. Simple 1-DOF trajectories resulted as the most promising in promoting relaxation without inducing motion sickness or dizziness.

Six movements were chosen in the identified set to be further investigated in a study with 25 healthy human subjects. Aim of this first study was to investigate the effect of these movements on relaxation and their potential to promote sleep. The chosen trajectories were: translations along x-, y-, and z-axis (sinusoidal trajectoies with amplitude of 15 cm and frequency of 0.3 Hz), lateral and longitudinal swing-like rotations, and rotation around the vertcal axis (sinusoidal trajectoies with amplitude of 6° and frequency of 0.3 Hz). The body coordinate frame is shown in Fig 2.

Each movement and the three baselines without motion were presented for 5 min to each subject in randomized order. The effects of the provided stimulation were evaluated based on physiological recordings (EEG, ECG, and respiration), describing the state of the subject; and on questionnaires rating how pleasant and relaxing the condition were perceived by the subjects.

No significant differences between the conditions resulted from the analysis of the EEG and the ECG. The questionnaires suggested the vertical translation as the most promising in promoting relaxation, but no significant differences support this tendency and the variability of the ratings was very high between the subjects.

B. From Relaxation to Sleep

Based on this first investigation, it was not possible to identify one particular motion as the most promising to promote relaxation. However, the M^3 setup allowed to reduce the range of motion to a limited set of movements with the potential to improve relaxation and promote sleep, to be further investigated in a sleep study. Thus, the experience gained with the first setup was implemented in the design of the new Somnomat platforms, to be applied with sleeping subjects.

C. Requirements and Design of the Somnomat Platforms.

Five trajectories were implemented in the new device. This choice was made by combining the results of the first investigation phase with spatial, practical, and technical requirements. The chosen trajectories are three translations along the three body axes (longitudinal X, lateral Y, and vertical Z) and two swing-like rotations (lateral Roll and longitudinal Pitch) (Fig. 1). The design was then based on following requirements. The robotic device had to include a platform with the size of a standard single bed (90 x 200 cm) allowing the subject to lie comfortably in a supine position. An actuation system was needed to move the platform along the five different trajectories described above. The whole device had to be transportable, easy to install, and to be placed in a normal private bed room or in the room of a standard sleep laboratory. The device had to include a stable moving structure, sustaining a standard slatted frame, a mattress, and an adult human subject up to 100 kg, resulting in a total moving mass up to 200 kg.

To allow noise-free relaxation and sleep, the system had to satisfy requirements concerning acoustic noise level and comfort. For a healthy sleep environment, Griefahn [11] and the World Health Organization (WHO) [12], [13] recommend a threshold of a continuous background noise level between 30 and 40 dBA.

Another important requirement was the quality and the smoothness of the trajectories. Parsons [14] showed a median sensitivity threshold of approximately 1 cm/s^2 r.m.s. amplitude for whole-body vibration with frequencies between 2 Hz and 100 Hz. Because of this high sensitivity, trajectory disturbances due to mechanical or control reasons had to be minimized in order to guarantee a comfortable stimulation.

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

Finally, safety of subject, research staff, and hardware had to be guaranteed in order to apply the device in a study involving healthy human subjects.

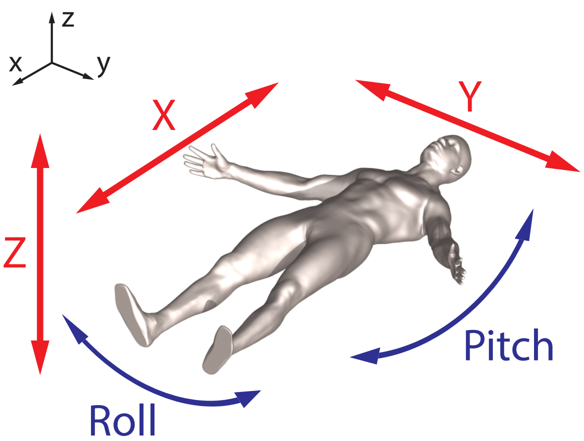

Fig. 2. Body coordinate frame. *Red:* longitudinal (X), lateral (Y), and vertical (Z) translations. *Blue:* Lateral (Roll) and longitudinal (Pitch) swing-like rotations.

D. Function and Technical Description of the Somnomat Platforms.

In order to optimize the movement performance as well as to minimize design complexity, it has been decided to develop two different platforms: One for the three linear translations (*Somnomat Platform A*, Fig. 3, A) and one for the rotations (*Somnomat Platform B*, Fig. 3, B). The detailed description of the devices is presented in the following sections.

1) Platform A: Platform A (Fig. 3, A) is a serial kinematic system that can be divided into four stages.

Starting from the bottom, the first stage is the basis frame. Four wheels mounted on the basis allow the whole platform to be easily moved and positioned when unblocked; and provide a stable stand when blocked.

The second stage is mounted on a set of linear guides (Haudenschild AG, Altendorf, Switzerland) allowing vertical translation with respect to the basis. The actuation is provided using a brushless 3-phase synchronous AC servomotor (TPM010 dynamic, Wittenstein AG, Igersheim, Germany) including a low-backlash planetary gearhead ($i = 31$) mounted on the basis driving a high quality tooth-belt system (Poly Chain GT Carbon Belt, Gates, Denver, USA). Four gas springs (preloaded with a force of 425 N, Bansbach easylift GmbH, Lorch, Germany) are used to compensate the static load of the moving platform (stages 2-4) and part of the payload.

The third stage is mounted on two linear guides (Flexi-Line, Nadella GmbH, Nufringen, Germany) placed atop the second stage. The two guides allow the third stage to translate horizontally with respect to the second stage. The horizontal motion is actuated by an electro-magnetic direct linear actuator (PS01-48x360F-C, LinMot, Spreitenbach, Switzerland) mounted between stage 2 and 3.

The fourth stage, the bed frame, is coupled with the third stage via a passive rotary joint. This joint allows a rotation of the bed frame with respect to stages 1-3. During the motion, the bed frame is fixed to stage 3 with a constant angle equal to 0° or 90°. Such rotation allows the orientation of the subject to be changed with respect to the translation axis. Hence, the subject can be moved along both longitudinal and lateral body axis using the same actuator (Fig. 4). The bed frame includes support frame, slatted frame, and a viscous-elastic mattress (Viscopedic, Elite SA, Aubonne, Switzerland), which reduces eventual vibrations and disturbances perceived by the subject lying on it.

All frames are mainly constructed using aluminum profiles (Assembly Technology, Bosch Rexroth, Lohr am Main, Germany) providing high mechanical performance and modularity.

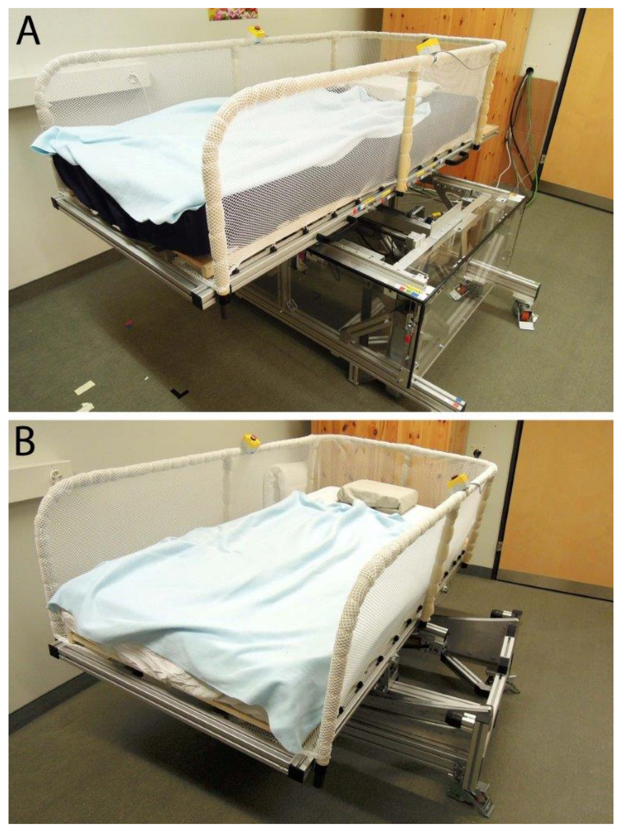

Fig. 3. The Somnomat platforms set up in the sleep laboratory. *A:* Somnomat Platform A, configured for Y trajectory. *B:* Somnomat Platform B, configured for Roll trajectory.

2) Platform B: The second platform (Fig. 3, B) is similar to the Platform A presented in the previous section. It has one DOF and can be divided into three stages: basis, stage 2, and stage 3 (including bed frame, slatted frame, and mattress).

The basis and bed frame are analogous to Platform A (see previous section). In Platform B the second stage is mounted on two curved guides (Curviline, Haudenschild AG, Altendorf, Switzerland) allowing a swing-like rotation with respect to the basis. Two different guides are used, allowing movement along an arc trajectory with a radius of either 200 cm or 400 cm. Actuation is provided by the same brushless 3-phase synchronous AC servomotor (TPM010 dynamic, Wittenstein AG, Igersheim, Germany) used in Platform A, including a low-backlash planetary gearhead ($i = 31$) mounted on the basis driving a high quality tooth-belt system (PowerGrip HTD, Gates, Denver, USA).

A system equivalent to the approach described in the previous section is used to change the orientation of the subject with respect to the actuated axis (Fig. 4).

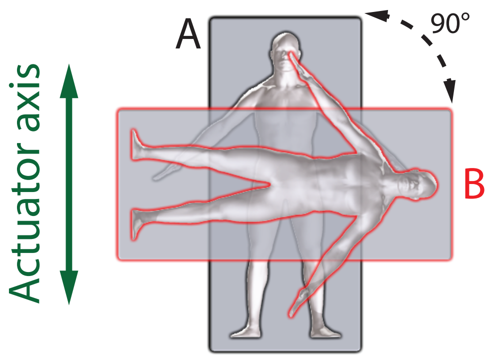

Fig. 4. The bed frame of the two Somnomat platforms can be turned 90° from position *A* to position *B*. This allows to move the subject along different directions using only one actuator.

3) Control: Each platform is controlled using a control program implemented in MATLAB/Simulink (Matlab 2013b, MathWorks, Natick, USA), running on a real-time xPC Target PC.

For each actuated axis a similar control strategy is applied including a linear proportional-integral (PI) velocity controller combined with a model based feedforward (FF) term to compensate friction, inertia, and static load.

An automatic monitoring system is implemented in the control program in order to guarantee the safety of the subject, the staff, and the hardware components in case of failures. Redundancy is provided by additional monitoring of I/O motor signals performed on the motor drives. Finally, an independent loop includes a watchdog checking the communication with the xPC target and a set of emergency stop buttons placed on the bed platforms and at the control station; any detected failure triggers an emergency stop by switching off the motor power supply.

4) Sensing: The position feedback used to control the motions is provided by resolvers integrated in the motors. Additional inertial measurement units (IMU, YEI Technology, Portsmouth, USA) are mounted on the bed frame of the two platforms to measure accelerations and angular velocities independently from the motor and closer to the subject.

5) Communication and Electronics: The communication between the xPC Target and other components (motor drives, sensors, etc.) is based on the EtherCAT communication protocol (EtherCAT Technology Group, Nuremberg, Germany). Inputs and outputs are managed using I/O Beckhoff EtherCAT Terminals (Beckhoff, Verl, Germany).

For each platform other than the actuators all electronic components that contribute to the overall acoustic noise level are placed inside an electric cabinet located departed from the platform in another room.

6) Shielding: In order to avoid electromagnetic interferences in the recorded physiological signals, an aluminium plate has been mounted below the mattress, in the zone corresponding to the upper half body of a lying subject. This shield is electrically isolated from the rest of the platform and connected to the ground of the amplifier used to acquire the physiological signals.

III. EVALUATION

A. General Requirements and Sleep Study Setup

The devices have been set up in two rooms of a sleep laboratory at the University of Zurich. Control PC, xPC target, and the electronic cabinet are placed in the corridor and wired to the platform inside the acoustically isolated experiment room. The platforms are presently applied in a study involving healthy human subjects. The objective of the ongoing study is to analyze the influence of the movements provided with the developed Somnomat platforms on the sleep onset and on the process of sleep. The technical characteristics of the two platforms are summarized in table I.

TABLE I

PLATFORM CHARACTERISTICS

Characteristics	Platform A X / Y	Platform A Z	Platform B Roll / Pitch
Length [cm]	227	227	227
Width [cm]	100 / 176	100	126 / 100
Height [cm]	126	156	108
Tot. mass (no payload) [kg]	200	200	145
Moving mass [kg]	67	121	75
Max payload (static) [kg]	253	199	505
Max force [kN]	1.02	3.33	3.33
Max lin. velocity [cm/s]	210	60	60

B. Motion Quality

The performance of the platforms was evaluated by analyzing the measured linear velocity profile for a set of different rocking motions, chosen within the range of movements identified as the most promising in promoting relaxation. The analysis was repeated for each movement axis with a payload of 90 kg. The tested movements were sinusoidal trajectories with fixed linear amplitude of 15 cm and maximal linear velocity varying from 5 cm/s to 20 cm/s (concerning Roll and Pitch, the linear velocity indicates the magnitude of the platform's velocity tangential to the curved trajectory, while the linear amplitude corresponds to the arc length of the curved trajectory). The absolute errors between reference trajectory and the values measured by the motor resolver ($v_{err} = |v_{ref} - v_{meas}|$) are summarized in Fig. 5.

C. Acoustic Noise

The acoustic impact of the platforms was evaluated by measuring the A-weighted equivalent continuous sound level L_{eq} at the subject head position using a Sound Level Meter (Real Time Octave Band Analyser type 114, Norsonic,

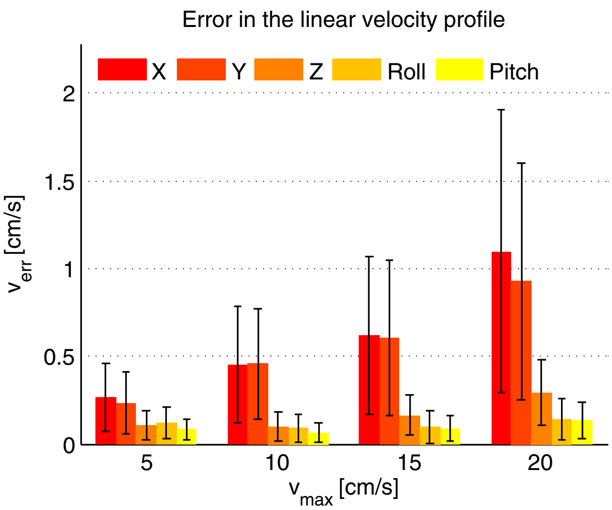

Fig. 5. Linear velocity error $v_{err} = |v_{ref} - v_{meas}|$ calculated for four representative trajectories (linear amplitude $a = 15\ cm$, max linear velocity $v_{max} = \{5, 10, 15, 20\}\ cm/s$) and for all movement axes X, Y, Z, Roll, and Pitch. The plot visualizes the mean error and the standard deviation (SD).

Lierskogen, Norway). Analogously to the analysis of the motion quality, the acoustic measurements were performed for each motion axis for a set of sinusoidal trajectories with a payload of 90 kg on the platform. The tested movements were sinusoidal trajectories with a fixed linear amplitude of 15 cm and maximal linear velocity varying form 0 cm/s (baseline with no motion) to 20 cm/s. For each trajectory the sound level was averaged over 10 s and each measurement was repeated three times. The results are summarized in Fig. 6.

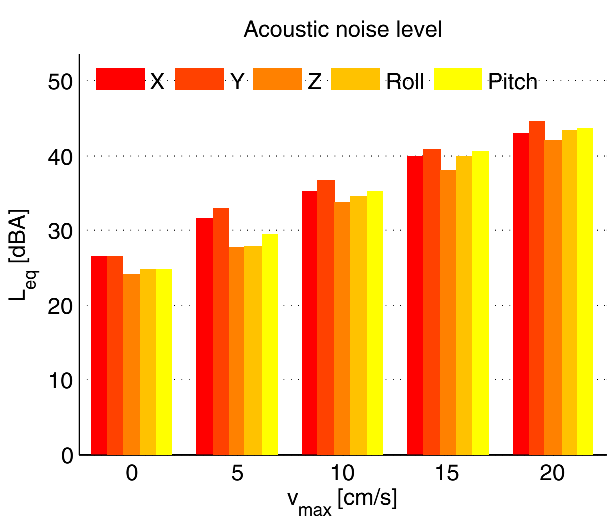

Fig. 6. A-weighted equivalent continuous sound level L_{eq} measured without motion (device on) and during four representative trajectories (linear amplitude $a = 15\ cm$, max linear velocity $v_{max} = \{5, 10, 15, 20\}\ cm/s$), for all movement axes X, Y, Z, Roll, and Pitch.

D. *Interferences with Physiological Recordings*

To identify potential interferences in the recorded physiological signals, the following test was performed. Grass electrodes were placed on the skin of a ready to cook chicken analogously how they are usually applied on the head of the human subject to record EEG. The electrical characteristics of the chicken skin are similar to the characteristics of the human subject. This, combined with the absence of any electrical activity, provides a clean reference signal. On such a low noise reference signal, occurring artifacts and disturbances can be easily identified. The conducted test showed that no interferences are present for axes Z, Roll, and Pitch. Small disturbances (1-2 μV) were noticed for X and Y axes.

IV. DISCUSSION

A. *General Requirements and Sleep Study Setup*

The fulfillment of the requirements concerning size and transportability has been proven by setting up the devices in a sleep laboratory, where the room size and the infrastructural characteristics are similar to the bedroom of a standard apartment. The safety of the platforms has been evaluated and approved by the ETH Ethical Committee (Ethical Committee of the Swiss Institute of Technology) for application in a sleep study involving healthy human subjects. The study is presently in progress and the devices were successfully applied with 15 subjects for a total of 30 measurement nights. Furthermore, the qualitative feedback of the participants confirms that the platforms provide a comfortable and natural sleep environment.

B. *Motion Quality*

For the tested trajectories, the analytical evaluation of the motion quality shows errors in the linear velocity profile below 0.91 cm/s for Pitch and Roll (Roll: mean: = 0.14 cm/s, standard deviation (SD) = 0.1 cm/s; Pitch: mean = 0.13 cm/s, SD = 0.1 cm/s), below 1.24 cm/s for Z (mean = 0.29 cm/s, SD = 0.18 cm/s), and below 3.56 cm/s for X and Y (X: mean = 1.10 cm/s, SD = 0.80 cm/s; Y: mean = 0.93 cm/s, SD = 0.67 cm/s).

Small ripples during the motion and little jerk in the conversion points were noticed as perturbations of smoothness of the trajectory. The controllers were tuned trying to minimize the impact of these disturbances. This tuning process was performed manually, starting from control parameters guarantying stability and the desired bandwidth, based on a dynamic model of the system. A first tuning was performed to improve the ability of the platform to track desired position and velocity trajectories. Then, the controllers where further adjusted based on the feedback of a test subject, in order to improve the perceived smoothness when lying on the mattress.

Best performance has been observed for Roll and Pitch axes, where the motion appears smooth and almost ripple-free. The vertical motion presents higher jerk in the conversion points, probably caused by the damping added to the system by the four gas springs. Highest perturbations were observed for the horizontal translations X and Y. This is due to the difficulty to drive the linear motor along a smooth trajectory at slow speed. Even though the errors were consistently high compared with the other axes, when lying in the platform the perception of the motion remains pleasant.

Overall the motion performance reached with both devices is suitable for a first sleep study. Especially for the motion axes X and Y, adaptions of the control strategies are currently investigated in order to increase perceived smoothness by minimizing disturbances such as ripples and jerk. These adaptations include the identification of a better friction model to be used in the feedforward term of the controller as well as adaptive algorithms able to learn and compensate unmodelled disturbances in periodical trajectories.

C. Acoustic Noise

The acoustic noise level highly depends on the maximal velocity reached during the sinusoidal motion (Fig. 6). Main sources of such noise are the carriages moving on the rails and the gear box of the rotary motors. In trajectories with a maximal linear velocity below 15 cm/s the limit of a continuous acoustic noise below 40 dBA is fulfilled.

A qualitative evaluation suggests that in a very quiet environment such as the sleep lab (L_{eq} with no motion ca. 25 dBA), acoustic noise above 30-35 dBA can already be perceived as disturbing. This threshold reduces the application workspace to trajectories with maximal velocities below 10 cm/s. This limitation matches with the range of motions, which was identified as interesting to be investigated.

D. Interferences with Physiological Recordings

The aluminium shielding plate mounted under the mattress resulted effective in avoiding electrical interferences in the EEG signal generated by the powerful AC servomotor used for Z, Roll, and Pitch axes. For the horizontal axes X and Y, small perturbations were observed. The cause is probably that the cables of the electrodes are moving in the permanent magnetic field of the linear motor used for the actuation. These disturbances are much lower than the usual range of a human EEG signal and they can be considered as negligible when brain activity is present.

V. CONCLUSIONS

This paper presents a novel device composed by two actuated bed platforms. The two platforms have been designed and developed to be applied in sleep research to provide adjustable rocking motions along five different movement axes (three translations and two rotations) to sleeping human subjects.

The challenge and the novelty proposed by this project were to conciliate the characteristics of actuators as well as mechanical and electronic components, which are usually developed to be applied in automation and robotics, with the critical requirements of sleep research. Especially two aspects were carefully considered: acoustic noise and motion smoothness. The developed platforms fulfilled the requirements in a satisfactory way and are presently applied in a sleep study. The aim of the current study is to analyze how a rocking movement, selected by the subject and identified as pleasant, influences sleep onset and sleep.

The result is a novel robotic device, where design and characteristics have been shaped and adapted to be applied with sleeping human subjects. This allows to study systematically the influence of different movements on human sleep. Such investigation could finally extend the knowledge about the link between vestibular stimulations and sleep.

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