Appendix I Tilt table design for rapid and sinusoidal posture change with minimal vestibular stimulation

J. Gisolf, E.M. Akkerman, A.W. Schreurs, J. Strackee, W.J.Stok and J.M. Karemaker, *Aviat Space Environ Med 2004Dec;75:1086-1091*

The following chapter deals with a tilt table method, developed by Akkerman and others, for inducing a rapid, uniform orthostatic challenge. The requirements for such a table are discussed, and calculations of the tilt-induced accelerations are given in the appendix. Twently healthy volunteers were subjected to fast head-up tilt and to sinuisoidal tilts at a set frequency.

Introduction

The use of a tilt table to study the cardiovascular response to a passive posture change in humans is a well-established method first described more than 90 years ago [7]. Such a table is a valuable tool for studying cardiovascular adaptation to orthostatic stress because it does not result in muscle tensing which is associated with 'active' standing up [115]. The tilt table is used mainly to investigate cardiovascular steady states, whereas to study dynamics a lower-body negative pressure (LBNP) tank is commonly used as a model for orthostatic stress [131]. LBNP can induce rapid venous pooling in the lower body, without the technical complications of a fast tilt table. LBNP, however, does not result in gravity-induced hydrostatic pressure changes evoked in a 'real' posture change. To study the dynamics of cardiovascular response to actual posture change, a motorized tilt table can be used. Tilt motion should be fast, without inducing a gravity-exceeding force on the test-subject. To prevent involuntary muscle tensing, tilt motion should be smooth, following a space profile designed to prevent a 'launch sensation'. Vestibular stimulation due to the tilt motion should be limited to prevent nausea and vertigo.

The purpose of this study was to develop a computer-controlled, motorized table to cope with these requirements. We also conducted an exploratory study protocol of fast head-up tilt for a time-domain approach and a series of 'oscillatory tilts', viz., repeated sinusoidal tilt movements, for a frequency-domain approach to the blood pressure and heart rate response to posture change. We hypothesized that undisturbed, reproducible tilt motion can provide a hemodynamic response characterizing an individual. This individual response can be further used as input parameter to model cardiovascular response after volume depletion and space flight [38; 59; 73].

Methods-tilt table

Smooth, fast tilts (time profile)
The tilt table is designed for a posture change between 0 and 70º within one second. The smoothness of tilting was analyzed by computing the time profile of the tilt angle (α) and the angular acceleration (η). A parabolic time profile is used, ensuring a smooth HUT to 70º within one second without abrupt starts and stops of the acceleration. For practical purposes an 'effective angle tilt time' is defined: the time needed to complete 95% of the total angular displacement. The mathematical description of the tilt angle α as a function of time can be found in the Appendix.

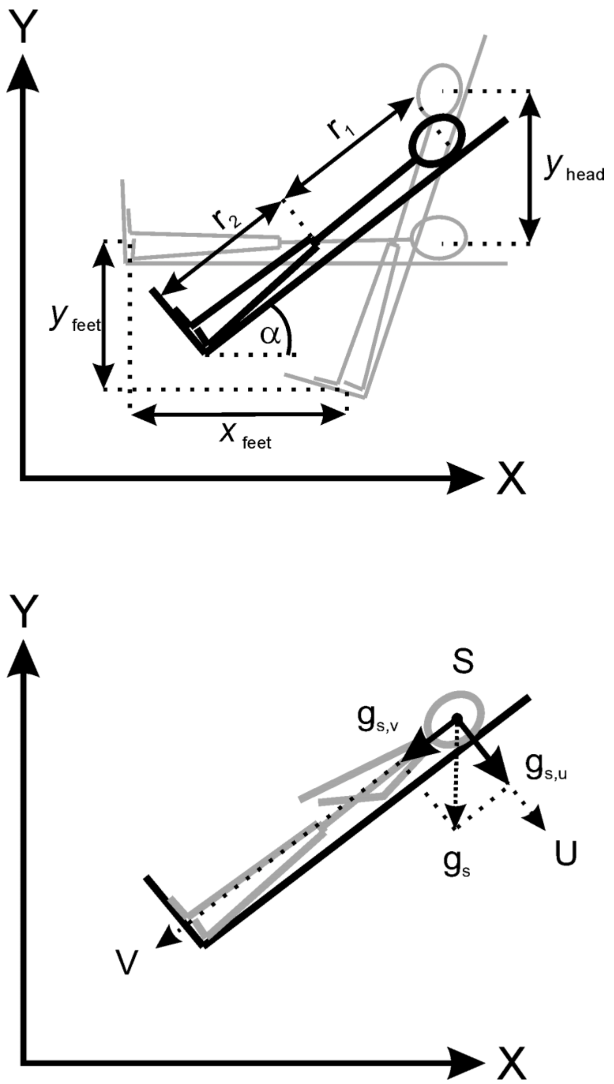

Figure I.1
Top: diagram of tilt motion showing the movement of the head (only in the vertical direction) and that of the hips (only in the horizontal direction). Movement of the head and the feet are indicated in an x,y plane (x_{feet}, y_{feet}, x_{head}, y_{head}). Distance from the vestibulum to hip (r_1) and from hip to toe (r_2) are indicated.
Bottom: diagram of forces acting on a subject at point S during tilt motion. Total force (g_S) is resolved into a head-to-toe directed force, parallel (V) to the subject, $g_{S,V}$, and a force perpendicular (U) to the table surface, $g_{S,U}$.

Limited launch sensation, G-force and vestibular stimulation (space profile)
The major requirements for the space profile of the tilt motion are threefold. Firstly, the motion should not induce a launch sensation: the subjects should not feel propelled from the tilt table. Secondly, acceleration along the body axis should be limited, as extra G-force

results in an exaggerated cardiovascular response to HUT. Thirdly, vestibular stimulation should be limited. To achieve this, the tilt 'space profile' allows the head to move only in the vertical direction, while the hip moves solely in the horizontal direction. The result is a 'sliding tilt'; the location of the vestibulum, 15 cm caudal to the top of the head of the subject on the table, moves in a vertical direction only during tilt. (Fig. I.1, top). The G-force (g_S), the combined effect of tilt movement and gravity acting on a test subject at S, can be resolved into the components V and U (Fig. *Ap.I.*1, bottom). The vector $g_{S,V}$ indicates the size and direction of the force acting parallel to the body axis, (the head-to-toe direction). During tilt-induced acceleration of S, the V-component of the acceleration has effects on the cardiovascular system. The direction of this force is comparable to that of gravitation in standing man and therefore its magnitude should be limited. The vector $g_{S,U}$ indicates the size and direction of a force acting perpendicular to the tilt table surface, i.e., in the front-to-back direction.

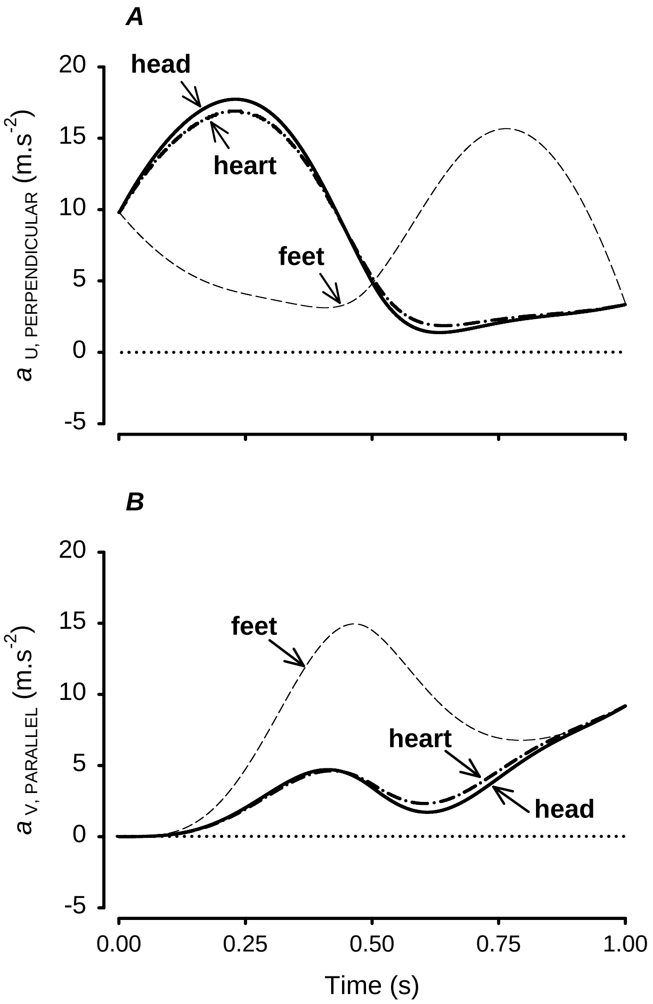

Figure I.2
Computation of forces
perpendicular (in A) and parallel (in B) to the tilt table surface, acting on the subject's head (solid line), heart (solid-dot-solid line) and feet (dashed line) during a head-up tilt completed in one second.

We calculated the forces acting on a subject's head, heart and feet during a fast HUT to 70º using 'sliding tilt' motion with parabolic acceleration (mathematical description can be found in the Appendix). Fig. I.2A shows $g_{S,U}$ versus time during HUT. The forces acting perpendicular to the tilt table do not reach negative values during the tilt movement. A negative value implies a back-to-front directed force in the sagittal plane, which causes a ‘launch’ sensation. The forces acting along the body axis, $g_{S,V}$, are shown in Fig. I.2B. At 70º HUT the $g_{S,V}$ is 9.4 m.s^{-2}, which is the gravitational component (g_0) at 70º. During the tilt movement $g_{S,V}$ at head-level and the one at heart level do not exceed g_0 at 70º, thereby limiting the additional ‘gravitational’ stress induced by the tilt motion itself.

Tilt table construction

The tilt table was designed and constructed by two of us (E.M.A. and A.W.S.); the design is shown in Fig. I.3. To make the table stable and as stiff as possible, square profiled iron bars and massive axles for the rotation points were used for the construction.

The total mass of the table is 360 kg. The tilt table motion is powered by a motor drive consisting of a screw (SKF, SRF 30x20R) driven by an electromotor (Contraves, CMT40ZD4-60), which pushes or pulls the table to a new position. The transmission to the screw consists of two gearing wheels connected by a tooth belt, giving a transmission factor of 25/46 from the motor to the screw.

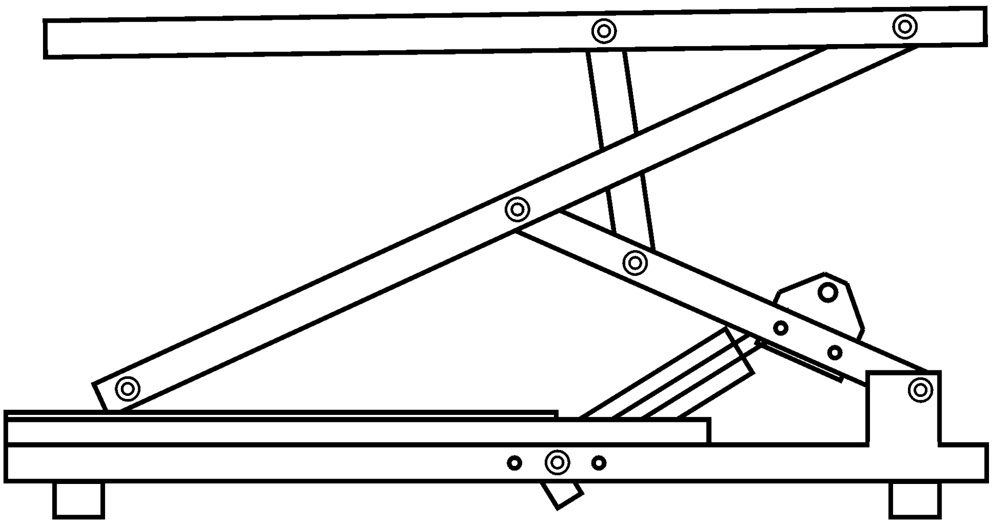

Figure I.3
Diagram of the design of the motorized tilt table
showing rotation points and positioning of the motor beneath the table surface

Control system

The motor is steered by a programmable servo controller and a microcomputer, allowing easy and efficient operation of the table during experiments. The control parameters to the servo system can be adjusted interactively or by dedicated software, running on a PC; the tilt moves are programmed. The servo controller (Galil Motion Control, DMC 210) gives its digital output signal to a current amplifier (Elmo Engineering, ESA 25/200 RC) that feeds the motor.

Safety aspects
The tilt table structure and motor are situated beneath the table surface, which constitutes an important safety aspect (Fig. I.3). An adjustable footboard, shoulder supports and two safety belts ensure that the test subject is secured to the table. An uncontrolled table movement, in the unlikely case of an error in the servo control, is stopped at the extreme tilt angles by hydraulic end-stoppers. In an experiment all table movements are pre-programmed and executable with a few keystrokes on the microcomputer, minimizing the risk for servo errors and uncontrolled movement.

Methods-experiments

Procedure and measurements
Twenty test subjects (age 40±8 years, height 176±9 cm and weight 71±11 kg; 4 female) participated in the study, which was approved by the Medical Ethics Committee of the Academic Medical Center, Univ. of Amsterdam (MEC00/069). Each subject was informed of the experimental procedures and signed an informed consent form in accordance with the Helsinki Declaration. Sessions were conducted in the afternoon, at least 2 hours after a light meal and at least 5 hours after the last caffeinated beverage or alcohol, in a quiet room with an ambient temperature of 22ºC.

Subjects were instrumented on the computer-controlled tilt table in the supine position. After instrumentation a practice tilt was carried out. After at least 15 minutes of supine rest, the subject was rapidly tilted upright (within one second). After 5 minutes head-up tilt the subject was tilted back to supine. The 'sinusoidal tilts' started with a head-up tilt to 30º, followed by 10 minutes of baseline recording in this position. To separate the breathing frequency from the tilting frequency, breathing was paced at 13 breaths/min by an audio-cue on a Walkman. Hyperventilation was prevented by clear instruction and practicing fast, 'shallow' breathing; expiratory CO_2 partial pressure was sampled and visually monitored. Repeated tilts, starting from 30º and ranging from 0 and 60º, were set in. The tilt angle describes a sine with a frequency of 0.042 Hz (2.5 tilts/min), for a total duration of 2 minutes. The acceleration due to tilt motion at this tilt frequency is negligible (sinusoidal tilt up and back again has a total duration of 24 s).

Arterial blood pressure was continuously measured by a servo-controlled photophletysmograph (Finapres, Model 5; Netherlands Organization for Applied Scientific Research, Biomedical Instrumentation, TNO-BMI, Amsterdam, the Netherlands) placed on the midphalanx of the middle finger of the right hand [69], which was positioned at heart level and held in place using an arm-sling. The finger cuff pressure was used to track arterial blood pressure.

Data acquisition and preprocessing
Finger blood pressure and the angle of tilt were analog-to-digital converted at 100 Hz. Mean arterial blood pressure was computed as the integral over one beat. The inverse of inter-beat pressure interval (IBI) is heart rate (HR). Beat-to-beat values of systolic (SAP), diastolic (DAP), mean blood pressure and tilt angle were calculated. To allow averaging of all subjects on a time scale, data were interpolated and re-sampled to obtain 1 second time intervals.

Beat-to-beat SAP and IBI were further analyzed to derive spectral power and the baroreflex sensitivity in the tilting frequency range (0.02 to 0.07 Hz). The beat-to-beat SAP and the IBI of the sinusoidal tilt episode was detrended and Hanning Windowed. Power spectra were computed using a Discrete Fourier Transform as described elsewhere [38]. Spectral smoothing was applied using a triangular window with a 9-points width. Power spectral density was computed, and cross spectra of SAP and IBI were calculated for the 0.02 to 0.07 Hz range for baroreflex sensitivity (BRS) gain analysis.

Statistical Analysis
Results are presented as means ± SE, unless stated otherwise. All data were tested for normality and using the Kolmogorov-Smirnov test. The hemodynamic responses to tilt were normally distributed; differences were tested with Student's paired t-Test. Bivariate correlation was tested using Pearson's regression coefficient. For all tests, the level of significance was set at $P \leq 0.05$.

Results

Fast head-up tilt
The fast head-up tilt movement was experienced by all subjects as smooth. None of the subjects reported lightheadedness during the tilt motion or during the 5 minutes passive standing. Averaged over intervals 60 to 120 seconds prior to and 60 to 120 seconds following HUT, the SAP increased from 113±9 mmHg to 119±11 mmHg ($P<0.05$). IBI decreased from 987±154 ms to 785±124 ms ($P<0.05$), the corresponding rise in HR is 62±11 to 78±13 bpm. The dynamic IBI response to HUT was calculated as the range (difference between maximum and minimum) over the 15 seconds from the start of tilt motion, normalized for the IBI value just prior to the tilt motion, with IBI computed from beat-to-beat data resampled at 1 Hz. The IBI just prior to HUT was 978±145 ms, the IBI range over the 15 seconds was 212±89 ms and the normalized IBI response to HUT was 0.22±0.08. Similarly calculated, the SAP just prior to HUT was 115±10 mmHg, the SAP range over 15 seconds from the start of tilt motion was 16±7mmHg and the normalized SAP response to HUT was 0.14±0.05.

Sinusoidal tilts
All subjects experienced sinusoidal tilts as a smooth motion that did not result in lightheadedness or dizziness. Subjects were able to follow the auditory cue to pace the breathing at 13 breaths/min, separating the breathing from the tilt frequency. Per-second averaged SAP, DAP, IBI and tilt angle, averaged for all subjects, are shown in Fig. I.4. Note the phase lag in the IBI with respect to the tilt angle; the cyclic IBI minimum occurs some 4 to 6 seconds after the peak tilt angle.

Spectral analysis of SAP and IBI of the sinusoidal tilt period and selection of the frequency band of the tilt frequency (0.02 to 0.07 Hz), gave a SAP spectral power of 27±6 $mmHg^2.Hz^{-1}$ (Fig. I.5, top), an IBI spectral power of 4.5±0.6 10^3 $s^2.Hz^{-1}$ (Fig. I.5, bottom) and a cross-spectral gain of 13±5 $ms.mmHg^{-1}$. The cross-spectral coherence ranged from 0.4 to 0.9 with median 0.7. We used SAP as measured at heart level without computing heart-to-carotid sinus hydrostatic height corrections.

Tilt test results as individual parameters
To find individual response parameters to tilt suitable for input to a model using a control-system approach to modeling reflexes, we calculated the correlation (Pearson) between

individual frequency domain results of the repeated sinusoidal tilts and time domain results of the single HUT motion. The per-subject SAP power in the sinusoidal tilt frequency band was mildly correlated to the SAP dynamics during single HUT (R=0.47, P<0.05). The spectral power of IBI during tilt motion was strongly correlated to the IBI dynamics during a single HUT motion (R=0.74, P<0.05).

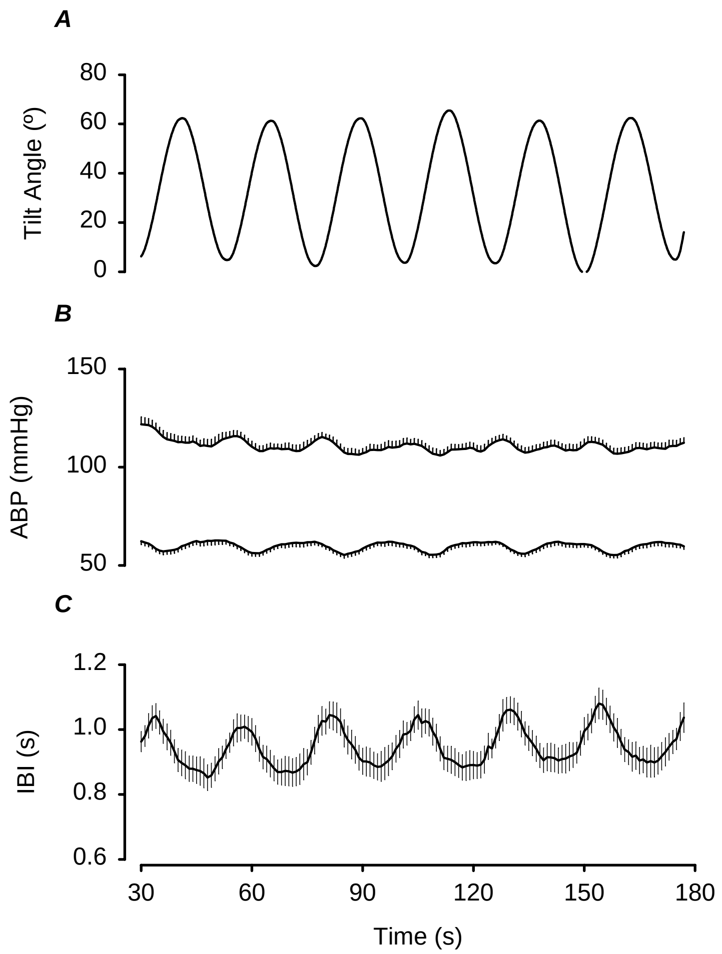

Figure I.4
Sinusoidal tilts at 2.5 /min time response
(**A**) shows the tilt angle in time; (**B**) shows the beat-to-beat arterial systolic & diastolic blood pressure (ABP) and the inter-beat interval (IBI). Beat-to-beat results were resampled at 1 Hz and averaged for 20 subjects; bars indicate S.E.

Discussion

In this study we present a novel, computer controlled tilt table capable of repeated sinusoidal tilts and rapid HUT within one second. The fast tilt motion does not induce cardiovascular stress exceeding 1 G, neither does it result in muscle tensing or nausea. Using the tilt table we conducted experiments including single, fast head-up tilt and sinusoidal tilts; there was a strong correlation between the IBI spectral power at the tilting frequency (2.5 tilts/min) and the dynamic IBI response to rapid HUT. The tilt table therefore rendered cardiovascular response parameters suitable as input for modeling individual response to orthostatic stress under normal circumstances; eventually this approach can be used for modeling orthostatic response under abnormal circumstances such as fluid depletion and after space flight.

The ‘sliding tilt’ differs from a traditional tilt profile; commonly a tilt table has a central axis in the middle of the tilt table and during HUT the table will rotate around this axis (‘rotating tilt’). During the HUT motion, the head will be displaced in the vertical and horizontal direction until both head and feet are lined up with the central axis (mathematical description can be found in the Appendix). The sliding tilt seeks to limit vestibular stimulation (and thereby limit nausea and vertigo) during tilt motion, by displacing the head in the vertical direction only (*Ap.I.*1).

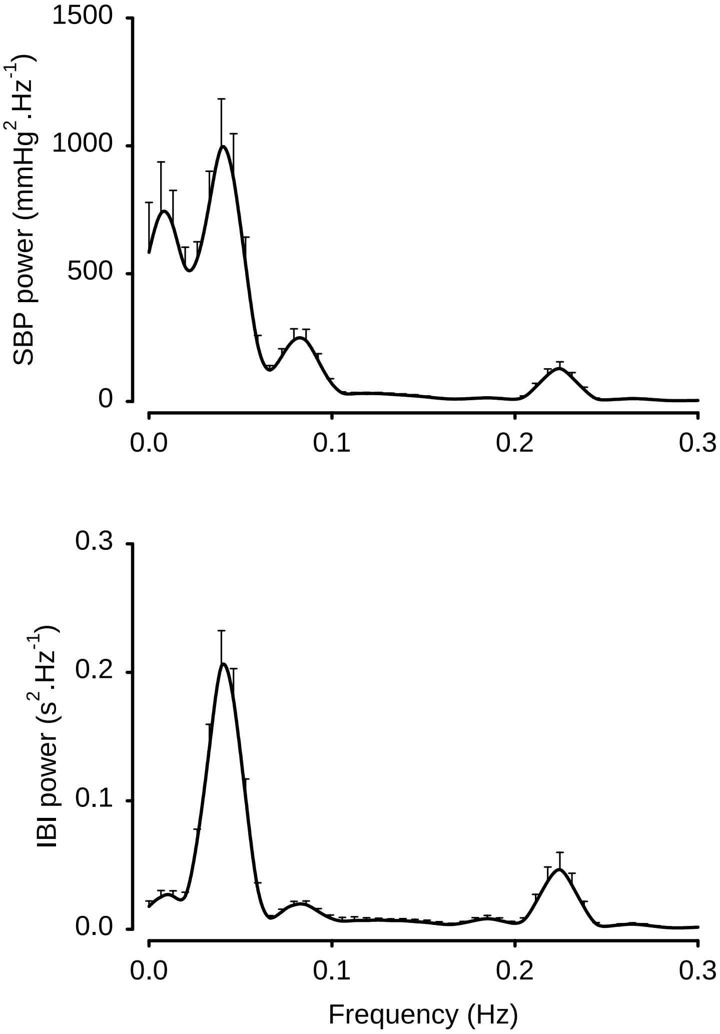

Figure I.5
Blood pressure and inter-beat interval responses to sinusoidal tilts at 0.042 Hz
Top: the systolic blood pressure (SBP) spectral power; bottom: the inter-beat interval (IBI) spectral power during tilting at 0.042 Hz (2.5/min) and respiratory rate of 0.217 Hz (13/min). Spectral results are averaged for 20 subjects; the drawn line is a spline interpolation; bars indicate S.E.

Frequency response characteristics of human cardiovascular regulation during hypotensive stress were studied previously using oscillatory LBNP [83]. For LBNP oscillations below 0.02 Hz the blood pressure control is optimal; with increasing oscillatory frequency peripheral resistance and HR lag the input and become less optimally timed for blood pressure regulation. The results of the present study, 4 to 6 second phase lag of IBI with regard to the tilt angle at 0.042 Hz, confirm the findings in LBNP and extend them for genuine orthostatic stress.

This is an exploratory study to find subject-individual input to a mathematical model for predicting orthostatic response to posture change. Developing specific mathematical models and application of existing models for simulation of the cardiovascular response to orthostatic stress after fluid depletion or space flight, are plans for future use of the tilt table and the sinusoidal tilt protocol.

Concluding, in this study designed to determine individual characteristics of hemodynamic response to orthostatic stress, we introduce a computer controlled tilt table capable of fast HUT and repeated sinusoidal tilt motion. Sinusoidal tilts provide frequency domain IBI power that correlates with the time-domain IBI response to fast HUT.

Appendix

Symbols	*Definition*	*Units*
α	tilt angle	degrees (º)
η	angular acceleration	degrees.s^{-2}
T	tilt duration	s
τ	running time	s
α_{MAX}	maximal tilt angle	degrees (º)
$\{x_{head}, y_{head}\}$	position of the vestibulum	m
$\{x_{heart}, y_{heart}\}$	position of the heart	m
$\{x_{feet}, y_{feet}\}$	position of the feet	m
r_1	distance from the vestibulum to the rotation point	m
r_2	distance from the rotation point to the feet	m
l	distance from the vestibulum to the heart	m
$\{a_{x,i}, a_{y,i}\}$	acceleration of i (i = head, heart, feet)	m .s^{-2}
β_i	angle of the acceleration of i (i = head, heart, feet)	degrees (º)

Time Profile

The tilt angle (α) and the angular acceleration (η) as a function of time, read for $0 < \tau \leq 0.5$ as,

$$\alpha(\tau) = 8\, \alpha_{MAX}\, \tau^3 (1-\tau)$$

$$\eta(\tau) = 48\, (\alpha_{MAX}/T^2)\, \tau\, (1-2\tau)$$

and for $0.5 < \tau \leq 1$ as

$$\alpha(\tau) = \alpha_{MAX} - 8\, \alpha_{MAX}\, \tau\, (1-\tau)^3$$

$$\eta(\tau) = -48\, (\alpha_{MAX}/T^2)\, (1-\tau)\, (2\tau - 1)$$

with T the tilt duration, τ the running time divided by T and α_{MAX} the maximal angle of tilt.

Space profile

The tilt movement takes place in a 2-dimensional plane. We define the horizontal axis as *x* and the vertical one as *y*. The position of the vestibulum $\{x_{head}, y_{head}\}$, defined as a location 15 cm caudal to the top of the head, of the heart $\{x_{heart}, y_{heart}\}$ and of the feet $\{x_{feet}, y_{feet}\}$ are calculated as a function of tilt angle, α. Position is indicated by its $\{x,y\}$ coordinates:

Position		Sliding tilt	Rotating tilt
Head	x_{head} (α)	0	$r_1 \cos \alpha$
	y_{head} (α)	$r_1 \sin \alpha$	$r_1 \sin \alpha$
Heart	x_{heart} (α)	$-l \cos \alpha$	$(r_1\text{-}l) \cos \alpha$
	y_{heart} (α)	$(r_1\text{-}l) \sin \alpha$	$(r_1\text{-}l) \sin \alpha$
Feet	x_{feet} (α)	$-(r_1+r_2) \cos \alpha$	$-r_2 \cos \alpha$
	y_{feet} (α)	$-r_2 \sin \alpha$	$-r_2 \sin \alpha$

with r_1 the distance from the vestibulum to the rotation point, r_2 the distance from the rotation point to the feet (Fig. I.1), and *l* the distance from the vestibulum to the heart, approximated as 35 cm. For our computations we used a virtual test subject height of 2 meter to obtain the results for an extreme situation.

The acceleration of the head, heart and feet i {$a_{x,i}$, $a_{y,i}$; i = head, heart, feet} is calculated as:

$$a_{x,i} = d^2\, x_i / dt^2$$

$$a_{y,i} = d^2\, y_i / dt^2 + g,$$

and the magnitude of acceleration (a_i ; i = head, heart, feet) as:

$$a_i = \sqrt{(a_{x,i}^2 + a_{y,i}^2)}$$

and the angle of acceleration (β) as:

$$\beta_i = \arctan\,(a_{y,i} / a_{y,i})$$

Finally, the acceleration parallel ($a_{i,\ \mathrm{PARALLEL}}$; i = head, feet) and perpendicular ($a_{i,\ \mathrm{PERPENDICULAR}}$; i = head, feet) to the body axis are calculated as:

$$a_{i,\ \mathrm{PARALLEL}} = a_i \cos\,(-\alpha + \beta_i)$$

$$a_{i,\ \mathrm{PERPENDICULAR}} = a_i \sin\,(-\alpha + \beta_i)$$