Acta Polytechnica **54**(5):352–357, 2014
doi:10.14311/AP.2014.54.0352

available online at http://ojs.cvut.cz/ojs/index.php/ap

A COMPARISON OF METHODS USING STRAIN GAUGES TO MONITOR PHYSIOLOGICAL MOVEMENTS ON A HOSPITAL BED

Vladimir Socha[a,*], Patrik Kutilek[a], Pavel Smrcka[a], Lubos Socha[b]

[a] *Czech Technical University in Prague, Faculty of Biomedical Engineering, nam. Sitna 3105, 272 01, Kladno, Czech Republic*

[b] *Technical University of Košice, Faculty of Aeronautics, Rampova 7, 041 21 Kosice, Slovak Republic*

[*] corresponding author: vladimir.socha@fbmi.cvut.cz

Abstract. A comparison is made between two methods for monitoring small movements made by a patient in a horizontal position on a hospital bed. The methods use sensors based on strain gauge bridges configured to measure torsion deformation and sensors based on strain gauge bridges configured to measure the bending deformation of two two-arm brackets. Both methods provide information about the patient's physiological movements. The methods were tested and compared in order to decide which may be most appropriate for use in clinical practice. The two methods have never been compared before, and the results can be used in developing new methods for monitoring patients.

Keywords: strain gauges, hospital bed, torsion deformation, bending deformation, physiological movement, monitoring.

1. Introduction

Monitoring of involuntary movements and other physiological movements made by a patient placed on a hospital bed is required by physicians. There are several widely-used methods for monitoring physiological movements such as breathing and heart beats: seismocardiography [1], phonocardiography [2], ballistocardiography [3], acoustic cardiography [4, 5], and actigraphy [6]. These methods usually require the use of a special medical device [7] equipped with extremely sensitive sensors. The principle known as "ballistocardiography" (BCG) [8], is a promising approach for monitoring the involuntary movements of patient placed on a bed. The sensors are integrated into the bed [5]. Using a range of highly sensitive sensors (e.g., strain gauges [9], accelerometers [10], hydraulic sensors [11], pneumatic sensors [7, 12], and optical devices [13]), BCG systems have been integrated into beds [9] and chairs [14]. However, current sensors have one of two disadvantages: either high cost or low sensitivity, [5, 15, 16]. Currently, the most widely-used sensors are load cells placed in the legs of the bed or directly under the main bed-frame (bearers and/or metal mattress base). Since the most widely-used load cells measure only the normal force (load), i.e., the normal stress, high sensitivity of the sensor is a requirement. However, in some cases these sensors fail to detect any motion. Strain gauge sensors have been used to eliminate this shortcoming. These sensors are configured to measure the torsional deformation in the element when subjected to a torque or shear force, or to measure the bending deformation in the element when subjected to a bending moment [15, 17].

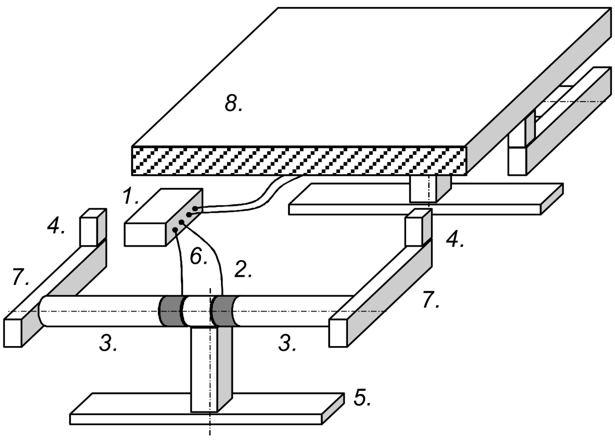

Figure 1. The monitoring system [15]: 1 – data acquisition system, 2 – sensors, 3 – two-arm bracket, 4 – mattress base supports, 5 – stand with a column, 6 – data cables, 7 – beams, 8 – mattress base.

The methods rely on the structure of the bed, which consists of two stands with columns and two-arm brackets and four beams to transfer the gravity forces, see Fig. 1. This paper presents a comparison of two types of strain gauge sensor configurations in order to decide which methods may be most appropriate for use in clinical practice.

2. Methods

Foil strain gauges for measuring normal stress/strain (i.e., axial force or bending moment) and tangential stress/strain (i.e., shear force or torque) were used in the structure of the bed, see Figures 2 and 3. The

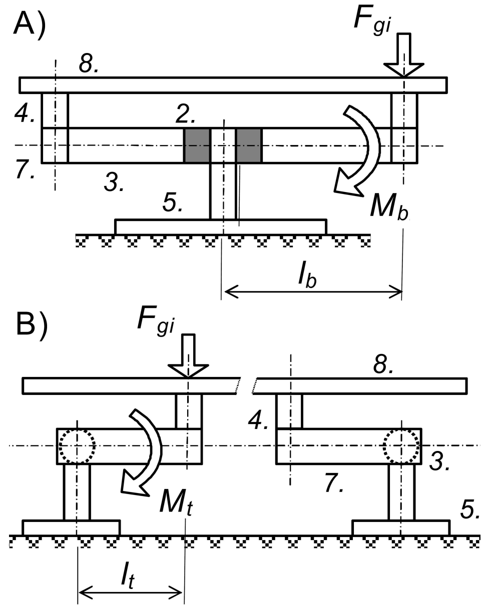

FIGURE 2. Principle of the measurement of bending (A) and torsion (B) [15, 16]: 2 – sensors, 4 – mattress base supports, 5 – stand with a column, 7 – beams to transfer the forces, 8 – mattress base.

following formula can be applied to determine the magnitude of the normal stress due to the bending moment:

$$\sigma_b = \frac{M_b}{W_b} = \frac{F_{gi} l_b}{W_b}, \tag{1}$$

where $M_b = F_{gi} l_b$ is the bending moment by which the beam is loaded, see Fig. 2, and W_b is the section modulus in bending, defined by the dimensional parameters and the shape of the cross section of the profile of the metal frame of the sensor or a structural part (e.g., a bracket). The magnitude of the tangential stress due to the twisting moment is identified by the formula:

$$\tau_t = \frac{M_t}{W_t} = \frac{F_{gi} l_t}{W_t}, \tag{2}$$

where $M_t = F_{gi} l_t$ is the twisting moment, see Fig. 2, and W_t is the section modulus in torsion defined by the dimensional parameters and the shape of the cross section of the profile of the metal frame of the sensor or a structural part. Table 1 shows the calculation of the stress or strain (due to the bending or twisting moment) from the measured change in the output voltage of strain gauges ΔU_o or the measured change in strain ε_m of the full bridge or half bridge strain gauge circuit. The bridge is fed by a constant voltage U_n (i.e., bridge (excitation) voltage), ε_i is the strain of one strain gauge, and k is the gauge factor. Variable G is the shear modulus, and E is the elastic modulus of the material of the metal profile/the frame of the sensor or a bracket [18]. For a circular cross section, or for an annular cross section, it follows that $W_t = 2W_b$. For other cross section shapes, documentation from the manufacturer or from a book on mechanical

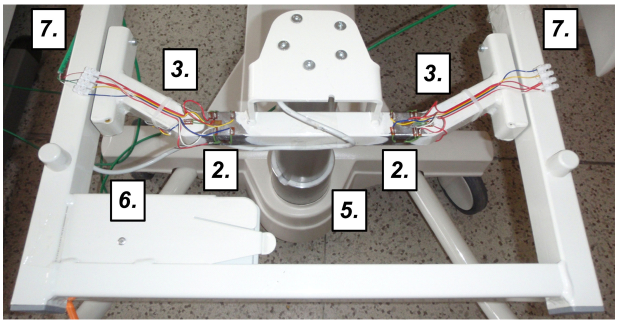

FIGURE 3. Implementation of the strain gauges in the Eleganza bed-frame (LINET Ltd.) [15, 16].: 2 – deformation sensors, 3 – two-arm bracket, 5 – stand with a column, 6 – sensor data cables, 7 – beams.

engineering can be used to determine the dimensions and the cross-sectional properties.

It follows from the above that the measured change in strain due to bending (for a half bridge) equals

$$\varepsilon_{mb} = l_b \frac{2F_{gi}}{EW_b} \tag{3}$$

and the measured change in strain due to torsion equals

$$\varepsilon_{mt} = l_t \frac{2F_{gi}}{GW_t} = l_t \frac{2.6F_{gi}}{EW_b}, \tag{4}$$

provided that the circular cross section or the annular cross section of the frame of the sensor or a bracket is used, and the Poisson ratio of the material (i.e., steel) is 0.3. For the other option, i.e., for the beam with a square hollow section, outside dimensions of 30×30 mm and wall thickness of 2 mm, W_b is $1.81 \cdot 10^3$ mm^3 and W_t is $2.75 \cdot 10^3$ mm^3 (from the Book of Products, Rautaruukki Ltd.). It can be said that:

$$\varepsilon_{mt} = l_t \frac{3.5F_{gi}}{EW_b}. \tag{5}$$

For monitoring the movements of a small patient, the strain gauge sensors should be placed as far as possible (i.e., at a maximum distance l_b or l_t, see Fig. 2) from the line of action of the gravitational force F_{gi}.

The strain gauge sensors are implemented in the commercially mass-produced Eleganza bed (LINET Ltd.). The bed consists of two stands with columns, two-arm brackets, four beams to transfer the gravity forces, etc., see Figures 1 and 3. The two-arm bracket, firmly attached to the column is 460 mm in length with a square hollow cross-section, outside dimensions of 30×30 mm and wall thickness of 2 mm [15]. The mattress base supports transmit the gravitational force from the mattress base to the four beams, and from there to the two-arm brackets. The size of the mattress base used here is 1900×850 mm. The deformation sensors detect the maximum torsional and bending deformation of the bracket in the middle of the length of the two-arm bracket, see Fig. 1. We use XY21-3/120 (HBM GmbH) foil strain gauges in a half-bridge circuit configuration to measure the torsional deformation

Circuit	Strain	Change in output voltage	Stress
Half bridge	$\varepsilon_{mb} = 2\varepsilon_i$	$\Delta U_o = (U_n/2)k\varepsilon_i$	$\sigma_b = E(\varepsilon_{mb}/2)$
Full bridge	$\varepsilon_{mb} = 4\varepsilon_i$	$\Delta U_o = U_n k\varepsilon_i$	$\sigma_b = E(\varepsilon_{mb}/4)$
Full bridge	$\varepsilon_{mt} = 4\varepsilon_i$	$\Delta U_o = U_n k\varepsilon_i$	$\tau_t = G(\varepsilon_{mt}/2)$

Table 1. The calculation of the stress and strain according to the type of bridge [18].

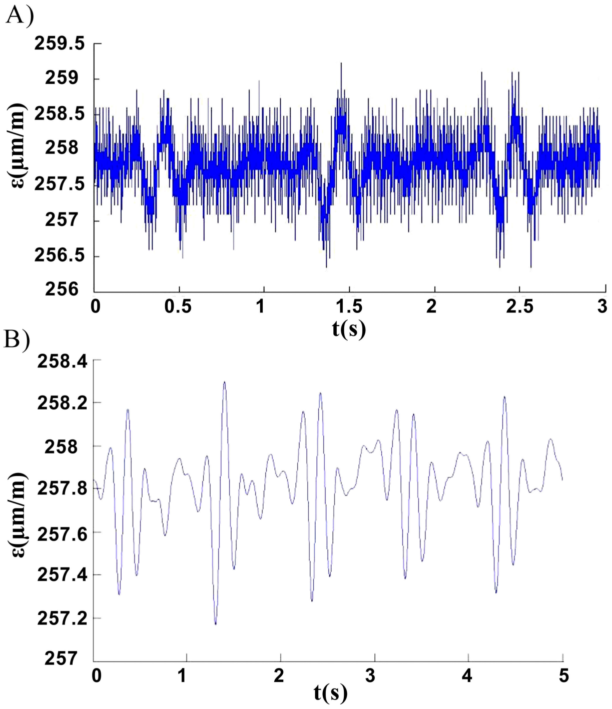

Figure 4. Example of the measured change in the strain due to activity of the heart: A – unfiltered signal, B – low-pass filtered signal.

Body weight of subject [kg]	Magnitude of the change in the strain [μm/m]	
	from torque	from bending
82	1.8	1.6
79	1.5	1.4
75	1.8	1.7
72	1.6	1.5
70	1.5	2.2
65	1.2	1.2
mean	1.6	1.6

Table 2. The measured change in the amplitude of the strain for six measured subjects and movements from the heart [15].

[15, 16] and LY11-6/120 (HBM GmbH) foil strain gauges in a full bridge circuit configuration to measure the bending deformation. The foil strain gauges are connected to the Somat eDAQlite data acquisition system (HBM GmbH), which is then connected to a PC. Together with Catman data acquisition software (Hottinger Baldwin Messtechnik GmbH) information is provided about the measured change in strain ε_m. The deformation is mainly caused by the torque and bending moment from the gravitational forces, which are related to the patient's weight on the mattress base [15–17], see Fig. 2. The distances $l_b = 0.14$ m and $l_t = 0.4$ m are given by the structure of the Eleganza bed. The frame material is steel and $E = 200 \cdot 10^9$ Pa. In these cases, it applies (in SI base units) that $\varepsilon_{mb} = 7.7 \cdot 10^{-7} F_{gi}$ and $\varepsilon_{mt} = 3.9 \cdot 10^{-7} F_{gi}$. It is therefore assumed that $\varepsilon_{mb} \approx 2\varepsilon_{mt}$.

Signal processing toolbox software (The MathWorks, Inc.), a computer program designed in MatLab, was used for signal filtering and signal frequency analysis. Since the removal of all frequencies higher than 4 Hz does not cause loss of the frequencies of heart beats, a low-pass filter type with a cut-off frequency of 4 Hz was used. A band-pass filter with cut-off frequencies of 0.02 Hz and 1 Hz was also used [15].

3. Measurement and testing

To compare the two approaches, the proposed strain gauges are used in the structural design of an Eleganza bed-frame (LINET Ltd.), see Fig. 2. The methods were tested on a set of volunteers (students of the Faculty of Biomedical Engineering, CTU in Prague). Their height ranged from 171 cm to 184 cm (mean 177.5 cm; SD 4.7 cm) and weight ranged from 65 kg to 82 kg (mean 73.8 kg; SD 6.1 kg). The Somat eDAQlite system monitored the deformations of two-arm brackets for 30 s. with a sampling frequency of 500 Hz during each test measurement, with the subject placed on the mattress base of the bed.

For a study of the ballistographic movements from the heart, the subjects were asked to hold their breath. This procedure was followed to eliminate respiratory movements and to ensure clearer identification of ballistographic movements from the heart [15]. The two methods were used simultaneously, since the data were acquired simultaneously from strain gauges configured to measure both the torsional and bending deformation. The signal resulting from the filtration of the measured signal represents the periodic bracket deformation changes, see Fig. 4. Locating the center of mass of the body at the head of the bed and the edge (right or left) of the mattress base provides the best results (i.e., the maximum change in the strain) for both methods (measuring the torsional deformation and the bending deformation). Figure 4 illustrates the change in the amplitude of the deformation repeated

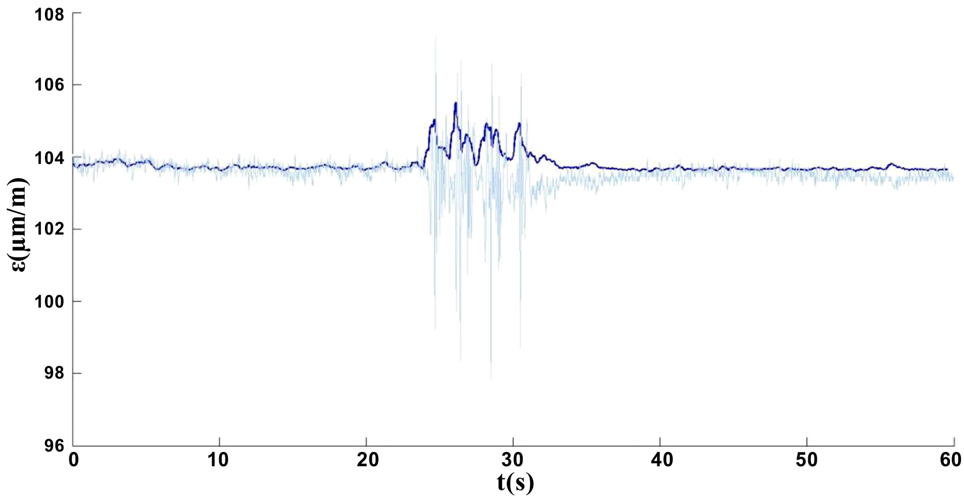

Figure 5. Example of the processed signal of the measured change in strain (from bending) due to coughing.

Body weight of subject [kg]	Magnitude of the change in the strain [µm/m]	
	from torque	from bending
82	5.1	2.5
79	5.0	4.2
75	4.6	3.8
72	4.5	3.0
70	4.8	3.8
65	4.2	3.2
mean	4.7	3.4

Table 3. The measured maximum change in the amplitude of the strain for six measured subjects and movements from breathing [15].

Body weight of subject [kg]	Magnitude of the change in the strain [µm/m]	
	from torque	from bending
82	43	260
79	44	262
75	43	255
72	40	248
70	38	240
65	40	235
mean	41	250

Table 4. The measured maximum change in the amplitude of the strain for six measured subjects and movements from rolling.

with frequency of about $f = 1.0\,\mathrm{Hz}$. The measured frequencies of the changes in the strains correspond to the expected frequency of the heart rate in both cases, see Table 1.

The method for detecting and analyzing the changes in strains caused by breathing is similar to the method for studying the changes in the strains caused by heart activity. In this procedure, each subject was placed on the bed and was asked to breath calmly and regularly. The processed data showed large and periodic changes in the magnitude of the strain, corresponding to the frequency of the physiological breathing, see Table 3. Again, for both variants (i.e., measurement of the torsional deformation and the bending deformation), the frequencies of the changes in the strain detected by the eDAQlite data acquisition system correspond to the expected frequency of breathing.

To monitor rolling of the body, the subjects were placed on the bed and were located at the edge of the mattress base for each measurement. In order to the measure the positions of the subjects, a procedure for moving from the left edge to the rightmost position of the bed was chosen. A similar method for detecting and analysing the changes in strains caused by rolling was used as for studies of the changes in strains caused by the activity of the heart and breathing muscles [15]. The change in the strain from torque caused by movements of the rolling body is shown in the graph, see Fig. 5. Since the changes in the signal amplitude are caused by changes in the positions of the subjects on the bed, we were able to determine the approximate position of the measured subject. Table 4 shows the measured maximum change in the amplitude of the strain for six measured subjects and movements from rolling.

The proposed methods were also used for identifying the intensity of a subject's coughing. Figure 5 shows the measured signal after it was filtered and the computed signal envelope. It can be assumed that a twitchy movement such as coughing will be reflected in the magnitude of the strain in the brackets. Before coughing, the deformation (strain) of the brackets is more or less constant. In the initial phase of the cough (Fig. 5), the strain magnitude shows a remarkable and sudden increase, and then declines to the initial input. These diversions accompany the subject's movements on the bed triggered by the muscles that are involved. Since the changes in the magnitude of the strain vary

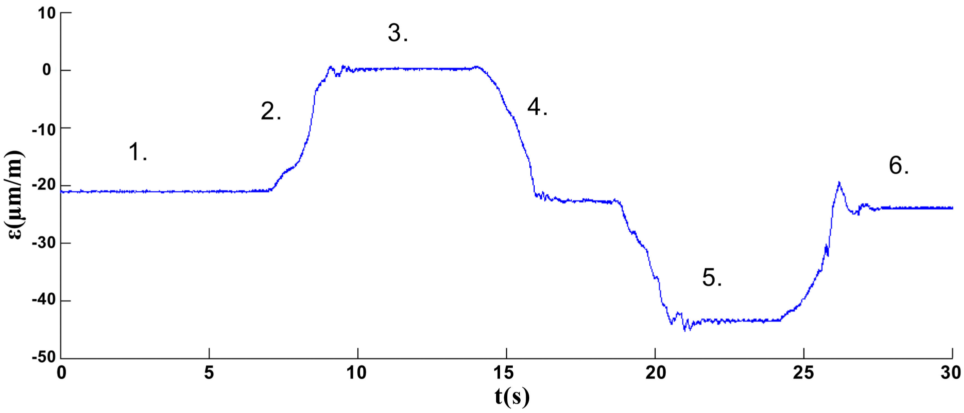

Figure 6. Example of the measured change in the strain due to rolling of the subject's body, recording time of 30 s: 1 – position approximately in the middle of the bed, 2 – rolling to the left side of the bed, 3 – position on the left side of the bed, 4 – rolling to the right side, 5 – position on the right side of the bed, 6 – position approximately in the middle of the bed.

significantly from subject to subject, the findings for this measurement unfortunately do not seem to be useful for a comparison of the two methods.

4. Results

We measured several kinds of physiological movements using a sample of subjects in a horizontal position. Tables 2, 3, and 4 demonstrate the extremes in the values for the changes in the strain, for torsional deformation and for bending deformation, respectively. The largest measured values for the change in the deformation are obtained using one of four sensors (i.e., the strain gauge bridge) on the surfaces of the brackets. The data obtained from the deformation sensor placed on the most deformed bracket correspond to the best results.

Table 2 shows that the body weight of an individual subject does not influence the measured heart activity signal. The explanation is that the weight of the subject placed on the bed, as well as the position of the subject's center of mass, produces significantly greater deformation of the bracket than the measured heart activity. The average magnitudes of the change in the strain produced by the heart activity are 1.6 µm/m for both cases (i.e., measurements of the torsional and bending deformations). Surprisingly, the same values were measured both for the change in strain due to torsion and for the change in strain due to bending. We had anticipated that $\varepsilon_{mb} \approx 2\varepsilon_{mt}$. In a similar way, Table 3 illustrates that the weight of the body does not seem to influence the measured breathing activity signals. The average magnitude of the change in the strain caused by movements from breathing is 4.7 µm/m for torsion, and 3.4 µm/m for bending. The results are thus again not as expected. The values for the two approaches again differed from each other for rolling of the body: the average magnitude of the change in the strain due to torsion is 41 µm/m, and the average magnitude of the change in the strain due to bending is 250 µm/m. In addition, Table 4 shows that there is dependence on the weight of the body. Unfortunately, considerably different results had also been expected in this case. We had expected $\varepsilon_{mb} \approx 2\varepsilon_{mt}$, whereas the measured value of the change in the strain due to bending is six times greater than the value for the change in the strain due to torsion.

5. Discussion

Our expectations differed in every case from the findings from the comparison between the measured change in strain due to bending and the measured change in strain due to torsion. For small deformations, the deformation values proved to be almost the same, contrary to our expectations. We had anticipated a greater difference. Conversely, we had expected less significant differences between the methods, which in fact provided deformation values that are remarkably different for large deformations. There are numerous reasons for this finding, one of them being the presence of tangential strains from bending. The tangential stress is the sum of the stress due to bending and the stress due to torsion. The total tangential stress/strain is measured by strain gauge sensors configured to measure the torsional deformation. In addition, the change in strain, which is measured by strain gauges configured to measure the bending deformation of the structure of the bed, was also influenced by the combined stress. Simplified assumptions proved to be yet another shortcoming of this study, e.g., the expected condition of perpendicular parts of the frame that took part in the calculations. Nevertheless, it has been proved that larger values are provided by strain gauges configured to measure the bending deformation when there is a large change in load F_{gi}. It follows from this that a theoretical estimate can be used to identify the suitability of a bedframe.

On the basis of the findings for the measured change in the strain (measured by one strain gauge bridge), the approximate position of the center of the subject's mass can be determined using a single strain gauge, due to the rolling of the subject's body. Half of the measured maximum change in the amplitude of the strain due to the rolling of the subject's body (from left to the right side of the bed) corresponds to the position approximately in the middle of the bed, see Fig. 6. The deformation measurements of the beam of the frame could be an example of the use of our new method, since it is a way to increase the sensitivity of one strain gauge bridge. In addition, the length of the arm and a bracket or a beam influences the maximum distance l_b and l_t. Therefore the dimensions of the frame govern the maximum distances. Figure 2 shows that l_t can be greater than l_b. In general, we can say that it is preferable to use an arrangement based on strain gauge sensors configured to measure the torsional deformation.

6. Conclusions

Anesthesiology, resuscitation and intensive care, long-term care and retirement homes are facilities that could utilize commercially available beds equipped with the proposed strain gauges configured to measure the bending and/or torsion deformation. In this paper, the Eleganza bed-frame with the proposed strain gauges inside the structural design has been used in a comparison of two approaches. Our study has been just a first attempt to compare these two methods with a view to the potential future developments in monitoring bed-ridden patients.

Acknowledgements

This research has been supported by program VG20102015002 (2010–2015, MV0/VG), sponsored by the Ministry of the Interior of the Czech Republic, and CTU in Prague projects SGS14/094/OHK4/1T/17 and SGS14/170/OHK4/2T/17.

References

[1] Zanetti, J.M., Salerno, D.M.: Seismocardiography: a technique for recording precordial acceleration. *Computer-Based Medical Systems – Proceedings of the Fourth Annual IEEE Symposium.* IEEE Comput. Soc. Press, 1991, pp. 4–9.

[2] Diamond, E., Benchimol, G., A. Phonocardiography. *Calif Med.* 1961, vol. 94, no. 3, pp. 139–146.

[3] Alihanka, J., Vaahtoranta, K. A static charge sensitive bed. A new method for recording body movements during sleep. *Electroencephalography and Clinical Neurophysiology.* 1979, vol. 46, no 6, pp. 731–734. DOI:10.1016/0013-4694(79)90113-5

[4] Erne, P. Beyond auscultation–acoustic cardiography in the diagnosis and assessment of cardiac disease. *Swiss Med Wkly.* 2008, vol. 138, no. 31-32, pp. 439–452.

[5] Bruser, Ch. Unobtrusive Non-Contact Detection of Arrhythmias using a "Smart" Bed. *Acta Polytech.* 2011, vol.51, no. 5, pp. 18–23.

[6] Sforza, E., et al. Actigraphy and leg movements during sleep: a validation study. *J. Clin. Neurophysiol.* 1999, vol. 16, no. 2, pp. 154-160. DOI:10.1097/00004691-199903000-00008 PMid:10359501

[7] Watanabe, K., et al. Noninvasive measurement of heartbeat, respiration, snoring and body movements of a subject in bed via a pneumatic method, *Proc. IEEE Trans. Biomed. Eng.* 2005, vol. 52, no. 12, pp. 2100–2107.

[8] Gordon, J. W. Certain Molar Movements of the Human Body produced by the Circulation of the Blood. *J. Anat. Physiol.* 1877, vol. 11, no. 3, pp. 533–536.

[9] Bruser, C., et al. Applying Machine Learning to Detect Individual Heart Beats in Ballistocardiograms. *Proc. 32nd IEEE EMBS,* 2010, pp. 1926–1929.

[10] Chuo, Y., et al. Evaluation of a Novel Integrated Sensor System for Synchronous Measurement of Cardiac Vibrations and Cardiac Potentials. *J. Med. Syst.* 2009, vol. 35, no. 4, pp. 445–455. DOI:10.1007/s10916-009-9380-8 PMid:20703546

[11] Zhu, X., et al. Real-Time Monitoring of Respiration Rhythm and Pulse Rate During Sleep, *IEEE Trans. Biomed. Eng.* 2006, vol. 53, no. 12, pp. 2553-2563. DOI:10.1109/TBME.2006.884641 PMid:17153213

[12] Chee, Y., et al. Air mattress sensor system with balancing tube for unconstrained measurement of respiration and heart beat movements. *Physiol. Meas.* 2005, vol. 26, no. 4, 413-422. DOI:10.1088/0967-3334/26/4/007 PMid:15886436

[13] Spillman, W. B., et al. A "smart" bed for non-intrusive monitoring of patient physiological factors. *Meas. Sci. Technol.* 2004, vol. 15, no. 8, pp. 1614–1620. DOI:10.1088/0957-0233/15/8/032

[14] Junnila, S.,et al. An Electromechanical Film Sensor Based Wireless Ballistocardiographic Chair: Implementation and Performance. *J. Signal Process. Sys.* 2008, vol. 57, no. 3, pp. 305–320. DOI:10.1007/s11265-008-0307-2

[15] Kutilek, P., Hozman, J., Smrcka, P. Identification of patient's physiological movements on the bed by strain gauge sensors detect torsion of the elements of the bed. *Proc. 15th Mechatronika.* 2012, pp. 1–6.

[16] Kutilek, P., Zizka, A., Viteckova, S. Identification of involuntary movements in bed using strain gauge sensors detect bending of the elements of the bed. *Proc. 35th IEEE TSP*, 2012, pp. 484–488.

[17] LANDAU, L. D. *Course of theoretical physics: Theory of elasticity.* 3rd eng. ed., rev. and enl., 2008, viii, 187 pp. ISBN 978-0-7506-2633-0.

[18] Hoffmann, K. *An Introduction to Measurements Using Strain Gages.* Darmstadt: Hottinger Baldwin Messtechnik GmbG, 1989. 1st Edition. ASIN: B004E5T7DI.