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A MECHATRONIC TOOL FOR REVEALING INVERSE RELATIONSHIPS AMONG HEART'S STROKE VOLUME AND HEAD'S LINEAR ACCELERATION INDUCED BY MOORED BOATS ROLLING IN ELDERLY SAILORS WITH UNCHANGED BODY SIZES: A NON-DRUG ANTI-HYPERTENSIVE ADVANTAGE?

Filippo Tocco[1,9], Roberto Solinas[1], Fernanda Velluzzi[1], Myosotis Massidda[1], Damiano Valerio Mattana[1], Andrea Fois[2], Laura Melis[2], Andrea Manuello Bertetto[3], Elvio Bonisoli[3†], Simone Venturini[3], Pietro Bianco[3], Antonio Hector Dell'Osa[4], Ana Fátima Pereira[5], Salvatore Melis[6,9], Angelo Cerina[7], Lorenzo Loviselli[8], Ricardo Marcello[8], Alberto Concu[8,9]

[1]Department of Medical Sciences and Public Health and University Hospital, University of Cagliari, Italy
[2]Remote Biosignals Acquisition Unit, Nomadyca Ltd, Mulago Hospital, Kampala, Uganda
[3]Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Turin, Italy
[4]Lab Electrónica Aplicada y Biomedicina, Universidad Nacional de Tierra del Fuego, Ushuaia, Argentina
[5]Polytechnic Institute of Setubal, School of Education, Life Quality Research Centre, Rio Maior, Portugal
[6]Sardinia's Schools Direction Office, Physical and Sports Education Unit, Ministry of Education and Merit, Cagliari, Italy
[7]Acquaforte Thalasso & Spa Medical Team, Forte Village Resort, Santa Margherita di Pula, Cagliari, Italy
[8]Lab of Wearable Devices Manufacturing, AC Technologies Ltd, Cagliari, Italy
[9]Lab-Campus for Sciences and Techniques of Physical Exercise, Sport and Preventive Motion Skills, Sardegna Ricerche, Agency for Research &Technological Development, Cagliari, Italy

ABSTRACT

Three aged and skilled sailors, being in a good condition of cardio metabolic compensation, took a seven days coastal sailing cruise. They daily underwent a cardiodynamic assessment by a impedance cardigraphy tool while staying seated on the moored boat. They showed a statistically significant inverse linear regression of beat-to-beat left ventricular stroke volume (LSV) versus the component of the head acceleration along the spatial X-axis, positioning the subject's head so that the X-axis lay along the nose-ocipital direction. In fact, the temporally corresponding values of LSV inversely changed of about 11 ml on average, with an interindividual difference ranging from a minimum of about 6 ml to a maximum of about 14 ml, for each unitary head acceleration change. Since the reduction of left ventricular stroke volume may be due to the already observed vestibulo-sympathetic reflex from which limbs muscle vasodilation may occur, and considering that LSV falling induces a reduction in arterial blood pressure, it is hypothesized that the slow rolling of moored boat might also act as a non-invasive arterial blood pressure attenuator effect.

Keywords: holder sailors, moored boat's rolling, head linear acceleration, cardiodynamic assessment, leg vessels sympathetic control

1 INTRODUCTION

The utricle and saccule otolith organs, inserted in the human vestibular apparatus, contribute to acquire the linear variations of head speed in all directions of space inducing neuromuscular activations which produce specific muscle reactions to realign both the head and body trunk through the nervous action potentials volley travelling along the nervous vestibulo-spinal pathways.

However, in rats were also found nervous fibres from the vestibular nuclear neurons (VNN) which directly project towards the nucleus tractus solitarius (NTS) [1] which

Contact authors: A Concu[1], Andrea Manuello Bertetto[2]

[1]AC Technologies Ltd, Via Pais 12, Cagliari, Italy; [2]Turin Politecnico, Corso Duca degli Abruzzi 24, Torino, Italy
E-mail: aconcu44@gmail.com, andrea.manuello@polito.it

latter, in turn, plays a pivotal role in modulating muscle sympathetic nerve activity (MSNA) in the lower limbs [2], and those changes are significant in maintaining arterial blood pressure since they control smooth muscle tone in these vessels [3], thereby interfering with the extent of peripheral vascular resistance (PVR) upon which the ventricular afterload of the heart depends to peripherally regulate the blood pressure [4].

Cui et al. [4] found that the MSNA activity decreased significantly in subjects submitted to the body sinusoidal linear acceleration applied in antero-posterior or lateral directions, suggesting that dynamic stimulation of otolith organs in humans might directly inhibit MSNA to quickly redistribute blood to muscle during the passively induced postural reflex, so supporting the possibility that otolith organs play such a role in the sympathetic regulation of muscle blood flow.

What which is remarkable is that MSNA activity decreases when the changes in linear acceleration was applied in a sinusoidal mode along the antero-posterior direction which coincided with the X axis of the space, i.e., Gx. It has been shown that when a sinusoidal movement of about 0.1 Hz was applied to subjects seated on a sliding chair, the MSNA mutually decreases with respect to the peak of the applied Gx the more the less the applied acceleration value [4].

When sailboats are moored in the port, they are subject to periodic oscillations due to the residual wave motion of the sea and mainly depending on rolling and pitching movements, so the people who are seated inside the living room of the boat undergo slow oscillations of the head and trunk in harmony with the variations in acceleration of the boat along the three axes of space.

Starting from what discussed above, in this study it has been tested the possibility that the slow and periodic oscillations induced to the body of sailors sitting in the dining room of a moored sailboat may generate cardiodynamic variations of vestibular origin, as well as those above described, which could reach some benefits in elderly people who have been practicing sports at sea for a long time.

2 MATERIALS AND METHODS

2.1 SUBJECTS

Engaged sailboat crew was composed of three male skilled sailors respectively ageing 70 (A), 74 (B the crew captain) and 81 (C) years, hawing respectively 66, 86, 83 kg of body mass and being high 1.65, 1.69, 1.73 m respectively with a Body Mass Index (BMI) value corresponding to a normal weight status: 24.6, 23.6, 24.7 kg/m^2 respectively. Just before a coastal sailing cruise, the sailors reached the University Hospital of Cagliari where they underwent, in turn, anthropometric, nutritional, cardiological and sports medicine visits. Specifically, the anthropometric and nutritional evaluation was performed by an endocrinologist of the department of Medical Sciences and Public Health.

All the three engaged subjects resulted in a good general condition of health. The same controls were repeated immediately after the end of the cruise to confirm or not their maintained good health conditions.

Sailor’s crew embarked on a coastal sailing cruise which lasted 7 days. While cruising they always spent the night sleeping on the moored boat.

2.2 EXPERIMENTAL INSTRUMENTATION

The experimental instrumentation used in this research implemented three devices: an electrical impedance device to assess the cardiodynamic profile of each sailor, beat-to-beat and non-invasively; an accelerometer device to assess changes in the linear accelerations of the subject head; a biosignal tool to remotely acquire all biological signals of any interest from the research team.

2.2.1 ELECTRICAL IMPEDANCE DEVICE

Electrical impedance measurements concern to a lot of biological issues assessment for characterizing both their structurally and functionally properties and changes as resulting from plants, animals and human acquisitions [5, 6, 7, 8, 9, 10].

In this study, trough electrical impedance measurements the cardiodynamic profile of each sailor was beat-to-beat and non-invasively assessed by a custom-made mechatronic tool based on the impedance cardiography technique (E-PhysioIC supplied by a proper power bank therefore unconnected to the electricity net) which consent to detect transthoracic bioimpedance values by means of 4 couples of ECG disposable electrodes.

Briefly, as described in more detail in previous publications [11, 12], to obtain the beat-to-beat values of the thoracic electrical impedance we proceeded as follows: 1) two couples of electrodes for the impedance assessment were placed the one laterally to the neck muscles roots and the other on the thorax laterally to the xiphoid process; 2) five cm externally to each of impedance assessing ones were placed other two couples of electrodes injecting an alternating current of 1 mA constant intensity at 65 kHz.

E-PhysioIC implemented the Sramek-Bernstein equation [13, 14] which consent to non-invasively obtain beat-to-beat the left ventricle stroke volume (LSV). Beat-by-beat analog track from the ECG and the thoracic electrical impedance (Zt) were remotely acquired by the E-PhysioIC tool, digitized and automatically processed to obtain the beat-to-beat LSV by a dedicate software which was previously validated in a master’s degree thesis discussed at the Politecnico di Torino, Italy [15].

The above described E-PhysioIC device has been validated in several previous experimental papers [11, 16, 17].

2.2.2 LINEAR ACCELERATION DEVICE

The boat linear acceleration Gx along the boat transversal axis were acquired with the WitMotion WTI WT901SDCL 9 Axis Sensor (WTI) with a sampling frequency of 5 Hz. The WTI sensor has been validated through comparison

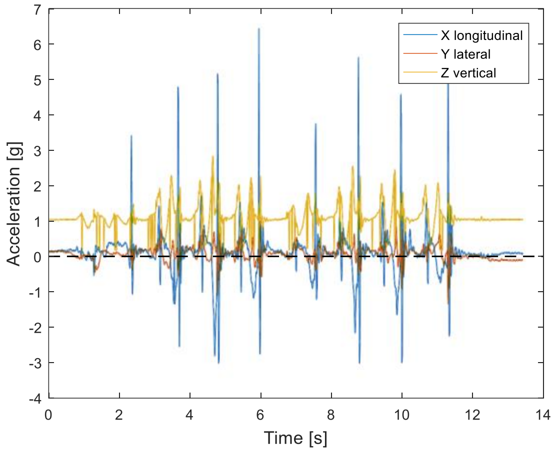

Figure 1 Measured accelerations in Body reference frame: WTI (left) and INEMO-M1 (right) acquisitions.

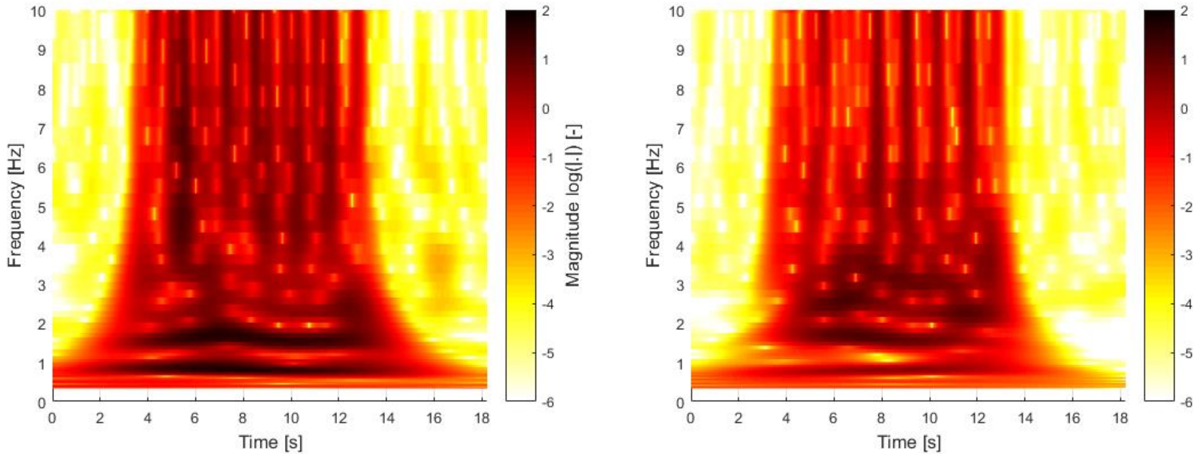

Figure 2 CWT Spectrograms of accelerations from INEMO-M1 test:
X longitudinal direction (left) and Z vertical direction (right).

with the experimental results obtained at Politecnico di Torino, following a common in-door testing protocol.
The protocol has the following requirements (see figure 3):

- 10 m straight walking;
- favourite hand side ankle must be chosen;
- stance period of about 1 second (gait);
- the walker must be barefoot;
- the pavement material must be tile or marble;
- usage of 1 Inertial Measurement Unit (IMU) placed on the ankle of the walker;
- minimum IMU sampling frequency of 100 Hz.

The testing acquisitions with WTI are performed with a sampling frequency of 100 Hz.
The experimental activity at Politecnico di Torino is performed with the STMicroelectronics INEMO-M1 9-axis motion sensor with a sampling frequency of 400 Hz. It is assumed the spatial coordinates are continuous for each instant of time.
In Figure 1 the time histories of the tests with WTI and test#1 with the INEMO-M1 are shown. In both experiments, the sensor measurements in vertical direction present a common offset of the gravity acceleration.
Only x and z axes were chosen for comparison since y axis is assumed to have negligible effect in gait.
The vertical acceleration is consistent between the two accelerometers.
Instead, a sensible difference in the longitudinal peak acceleration can be observed. Since the length of the step is the same, accordingly to the protocol of the test, the difference is due to the different gait style of the two subjects. In fact, the peak value of the acceleration is roughly three times bigger than the peak acceleration of the tests performed at the Politecnico di Torino.
The problem is like "pick and place" procedure in robotics, where two similar robots performing the same task of moving an object at the same time, the accelerations measured on the joints are different, due to different tolerances, time constants of the drives and actuators [19, 20], if not a different kinematic path followed by the robots.

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Figure 3 The Cagliari's testing subject is shown with the WTI accelerometer fixed to the outside of the right ankle, performed without shoes a 10 strides walking task in which each stride was of 71.4 cm and lasted 1 second.

Time-frequency analysis is performed using Continuous Wavelet Transform (CWT). CWT spectrograms allows to contemporarily observe instantaneous variation in frequency content and to maintain frequency resolution [21].

In Figure 2, the acceleration measured by INEMO-M1 test are evaluated. The fundamental frequency of gait (about 1 is visible in both longitudinal and vertical directions as a constant content in time and a further high frequency content at 1.5 Hz of an equivalent inverted pendulum dynamics [22, 23]. In longitudinal direction, the amplitude of gait main frequency is more significant.

The step counting is observable as function of time, by looking at darker vertical bands in the CWT spectrograms.

In longitudinal direction it is observable the number of impulses corresponding to foot contacts for the main foot.

2.2.3 BIOSIGNALS REMOTE ACQUISITION TOOL

In the E-PhysioIC a command-and-control (C&C) block supports the radio frequency communication protocol which enables a totally wireless operation mode of the device. A data transmission block, i.e. a WEB block implemented in the E-PhysioIC device, consents to remotely control it by a personal computer running a proprietary software in such a way to consent, for each recording session, that the beat-by-beat changes in the patient's thoracic bioimpedance could be acquired over a period of 3 minutes. The E-PhysioIC tool has been designed to support complex operational scenarios, characterized by poorly reliable or completely absent internet connectivity. For this reason, the device was designed as a micro-data centre capable of governing digital bio signal acquisition systems and providing command and control interfaces through standard Web tools even in the total absence of connectivity to the Internet. Further insights into the construction and operating characteristics of E-PhysioIC Tool have been comprehensively described in a previous paper [24].

2.3 EXPERIMENTAL PROTOCOL

2.3.1 VARIABLES ACQUISITION PROCEDURES

Each engaged sailor, daily in the morning and after breakfast, while the boat was moored, provided to assess 3 minutes of beat-to-beat LSV changes while he was comfortably seated at the dining desk below deck of the boat. Care was made from subjects for having the naso-ocipital axis of is head just aligned with the X axis of space and therefore undergoing the displacements due to the roll movements of the boat around its longitudinal axis. The WTI device was fixed ensuring that the direction of its x axis was also aligned with the X axis of the boat. All the impedance and accelerometer assed data were wireless acquired from the E-PhysioIC C&C laptop which, in turn, provided to send they toward a remote server for subsequent data conditioning and analysis.

2.3.2 DATA ANALYSIS AND STATISTICS

The MedCalc package Statistics for biomedical research (Mariakerke, Belgium), has been utilized for descriptive, comparative, and predictive measurement of assessed data in considering that the mean, median, and mode are 3 variables concerning the central tendency of a set of data [25].

When data are normally distributed, the distribution is likely a bell-shaped curve, and its mean, median, and mode are all coincident at the centre of the distribution.[26]. In each distribution of data, the degree of variability in the mean of the data is defined by its standard deviation while for the median this information is linked by the inter-quartile range.

Therefore, when appropriate the comparative method of Student's t for mean values and the predictive method of regressions between variables were applied. In the purpose of establish a minimum level of statistical significance when comparing groups of data, a P value < 0.05 was adopted.

3 RESULTS

After disembarked at the cruise end the tree sailors went to the University Hospital of Cagliari where they repeated all the medical controls as those made before cruising from which they resulted to stay in a good general health condition. In particular, their body weight and BMI did not show relevant variations.

A descriptive behaviour of the beat-to-beat assessed values of LSV from each of the 3 tested subjects, along the 7 cruising days, is shown in Figure 3. It can be shown that the total number of samples acquired was different in the 3 subjects tested since the measurements were not made simultaneously among, they but took place in the here assigned alphabetical succession. This could cause a different number of artifacts in the electrical signals acquired during the measurements, which could depend both on inter-individual differences in the inertial

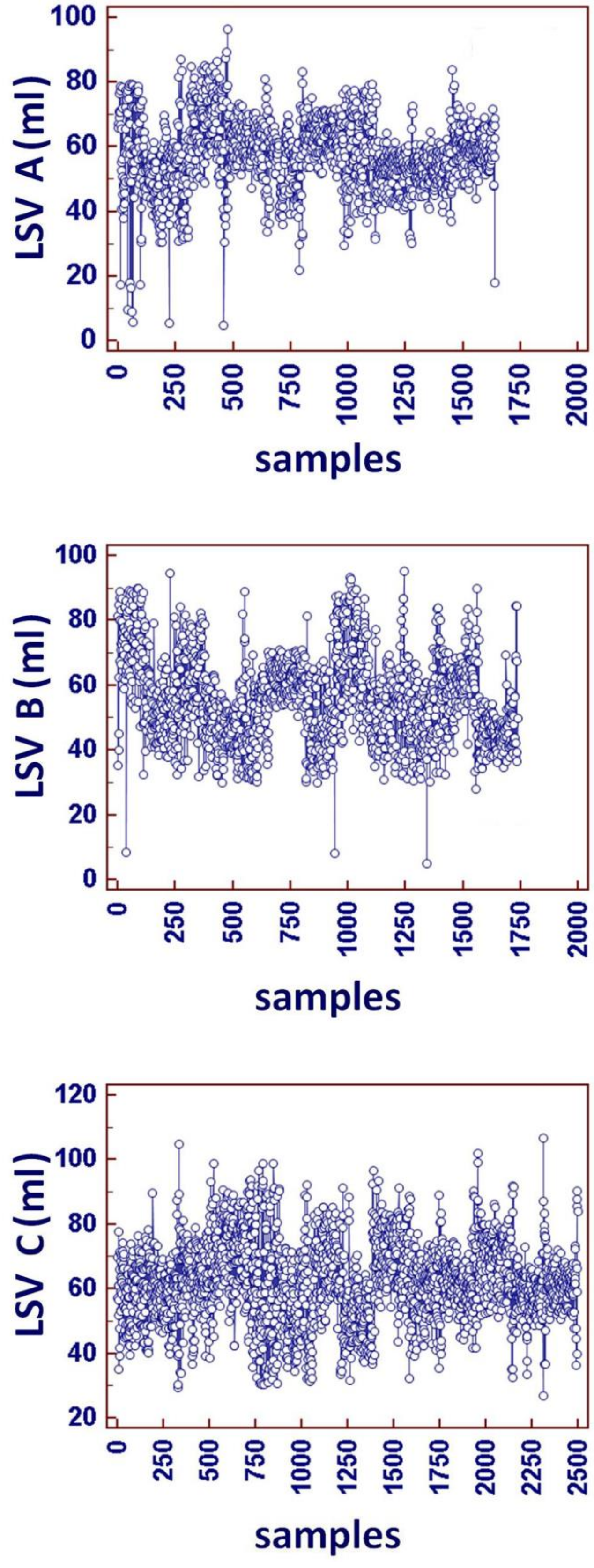

Figure 4 Beat-to-beat LSV distribution assessed from subjects A , B and C.

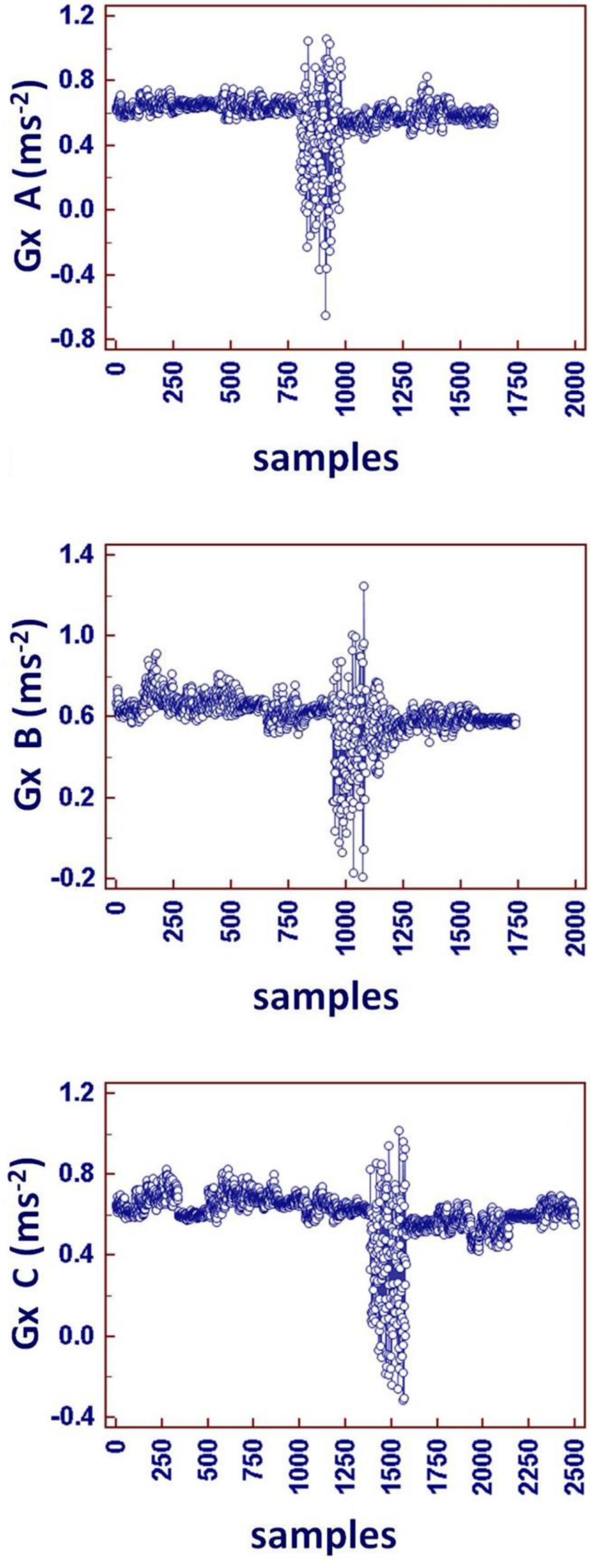

Figure 5 Beat-to-beat Gx distribution assessed from subjects A, B and C.

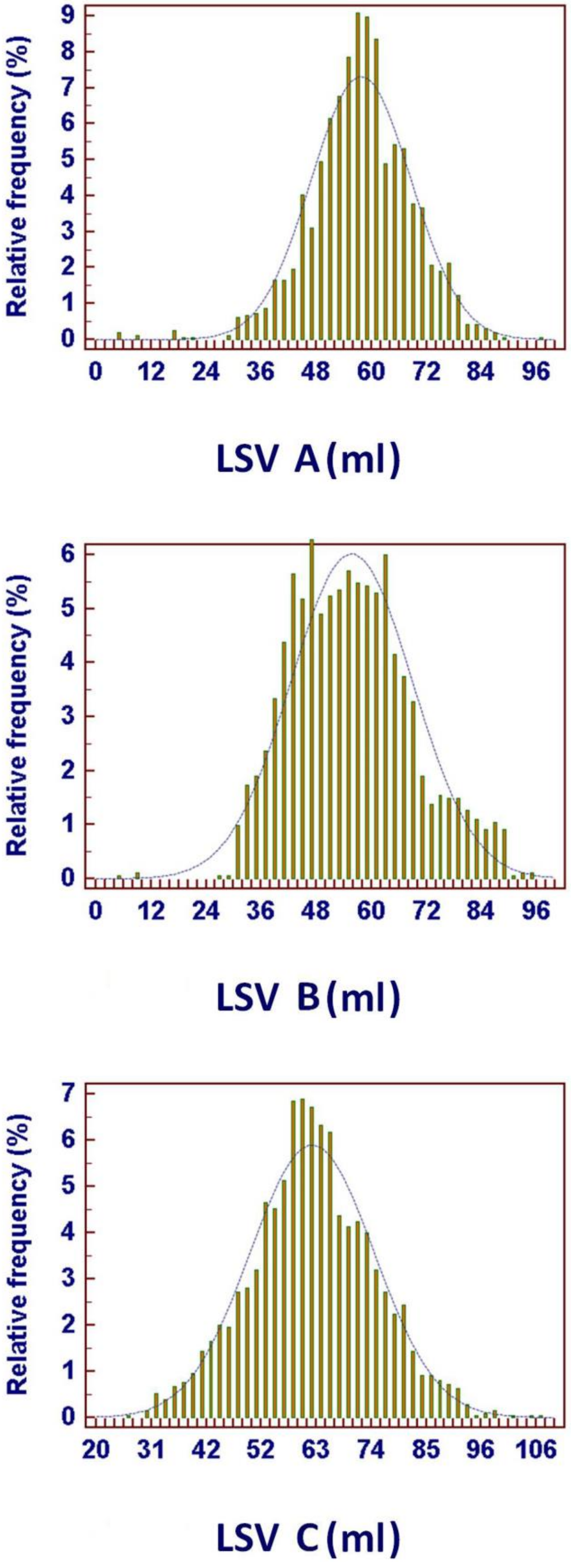

Figure 6 LSV frequency histograms respectively of subjects A, B and C (the number of class distribution is 50).

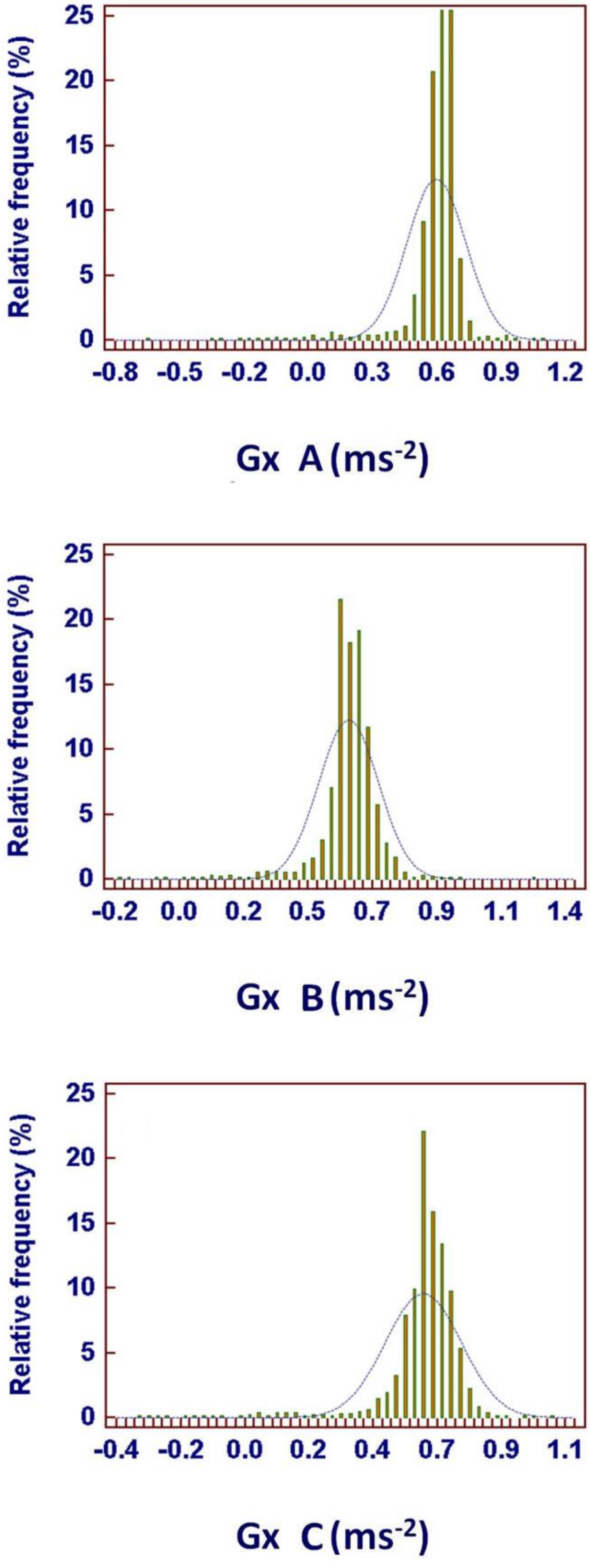

Figure 7 Gx frequency histograms respectively of subjects A, B and C (the number of class distribution is 50).

Table I - Data comparisons among descriptive variables

Subject	LSV (ml)			± Gx (m/s²)		
	mean	median	mode	mean	median	mode
A	57.7 ± 10.9$^{\alpha}$	57.4 (51.4 ÷ 64.7)$^{\beta}$	56.5	0.595 ± 0.13$^{\alpha}$	0.617 (0.57 ÷ 0.65)$^{\beta}$	0.619
B	55.7 ± 13.3$^{\alpha}$	54.8 (45.7 ÷ 63.8)$^{\beta}$	48.0	0.611 ± 0.11$^{\alpha}$	0.622 (0.58 ÷ 0.66)$^{\beta}$	0.625
C	62.4 ± 12.2$^{\alpha}$	62.1 (54.5 ÷ 70.4)$^{\beta}$	60.0	0.603 ± 0.12$^{\alpha}$	0.617 (0.58 ÷ 0.67)$^{\beta}$	0.637
MEAN±SD	**58.6 ± 3.4**	**58.2 ± 3.8**	**54.8 ± 6.2**	**0.603 ± 0.008**	**0.619 ± 0.003**	**0.627 ± 0.009**

In Table I, the following date are supplied:

- LSV: left ventricle stroke volume;
- Gx: head acceleration in the X direction;
- α: standard deviation;
- β: interquartile range;
- In the last row the means ± SD of the variables acquired among the three tested subjects are represented.

characteristics of the body segments subjected to acceleration variations caused, in turn, by the rolling of the boat and on the daily differences between the direction of the sea waves and the position of the moored boat.
The conditioning software of acquired impedance signals could discard some of these in a different proportion between the three subjects tested, from which the different quantity of reliable signals acquired might depend.
However, all 3 graphs in Figure 4 show pseudo-sinusoidal oscillations but without increasing or decreasing drifts in the numerical succession of the LSV values acquired in this way.
It can reasonably be stated that the maximum concentration of LSV values was distributed between 50 ml and 60 ml in all the 3 tested subjects.
The descriptive behaviour of Gx changes in each of the 3 tested subjects, assed in temporal correspondence with the beat-to-beat changes in the LSV values, are shown in Figure 5. In all tested subjects' samples distribution along daily progressive assessment of the Gx values shows a clustering of points almost central with respect to the abscissa axis which extreme values roughly ranged between -0.2 ms^{-2} and +0.9 ms^{-2} in the subject A, -0.1 ms^{-2} and +1.0 ms^{-2} in subject B and -0.3 ms^{-2} and +0.9 ms^{-2} in subject C.
To obtain better information on the type of distribution that characterized the percentage frequencies of the acquired values, both for the LSV (Figure 6) and for the Gx (Figure 7) are show the respective frequency distribution in percentage histograms of these variables obtained from each tested subject.
This in such a way of establishing if or not the distributions in these variables could be considered as normal/parametric ones to establish the possibility of implementing subsequent statistical evaluations within this field, or not. [26, 27].
The statistic variables characterizing the relative frequency of percentage distribution of the beat to beat LSV changes, and of the corresponding ± Gx changes (since the latter had a 5Hz of frequency it has been calculated the average value among those that fell within the time interval into which lasted the corresponding heartbeat), are deductible from the graphs concerning their descriptive representations shown in the frequency histograms of Figures 5 and 6 and expressed as mean, median and mode values for each engaged sailor as shown in Table I.
It could be seen that relative frequency of percentage distribution in beat to beat LSV changes, within the time interval where each sailor proceeded to detect cardiodynamic parameters, i.e., 3 min, was almost symmetrical since values of the mean, the median and the mode were practically coincident.
In fact, the subject A shows a LSV mean value which differ only 0.17% from its median and 2.12% from its mode while the median versus mode difference was of 2.30%; the subject B shows a LSV mean value which differ only 1.64% from is median and 16.1% from is mode while the median versus mode difference was of 14.17%; the subject C shows a LSV mean value which differ only 0.48% from its median and 4.1% from is mode while the median versus mode difference was of 3.5%.
Moreover, applying the comparative Student's t test for paired groups (see next row in Table I), it did not show significant differences in comparing mean values ± SD respectively for the grouped means versus grouped medians (P=0.905) and modes (P=0.408) as well as for median versus mode (P=0.458) So, in agreement with what requested from the descriptive statics method [27], the distributive behaviour of the LSV values in each tested sailor can be considered as of normal or parametric size.
Concerning the boat linear acceleration values assessed along the X axis of space, i.e., the Gx, since the sampling frequency of this variable was 5 Hz, it has been calculated the average value among those values that fell within the time interval of the corresponding heartbeat in such a way of awing comparisons among respective LSV value by a unique Gx value. So, the relative frequency of percentage distribution in Gx changes within the time interval where each sailor proceeded to detect cardiodynamic parameters was calculated. In Table I, data from Gx clearly showed a negative distribution asymmetry in all the three tested subjects (see also graphs in Figure 6).
However, Table I also shows that despite in all three engaged subjects the Gx mode values of distributions were a little higher than the corresponding median values (A: +0.32%, B: +0.48%, C: +3.24%), Student's t test for paired groups did not show significant differences in comparing grouped mode values respectively to the grouped means and

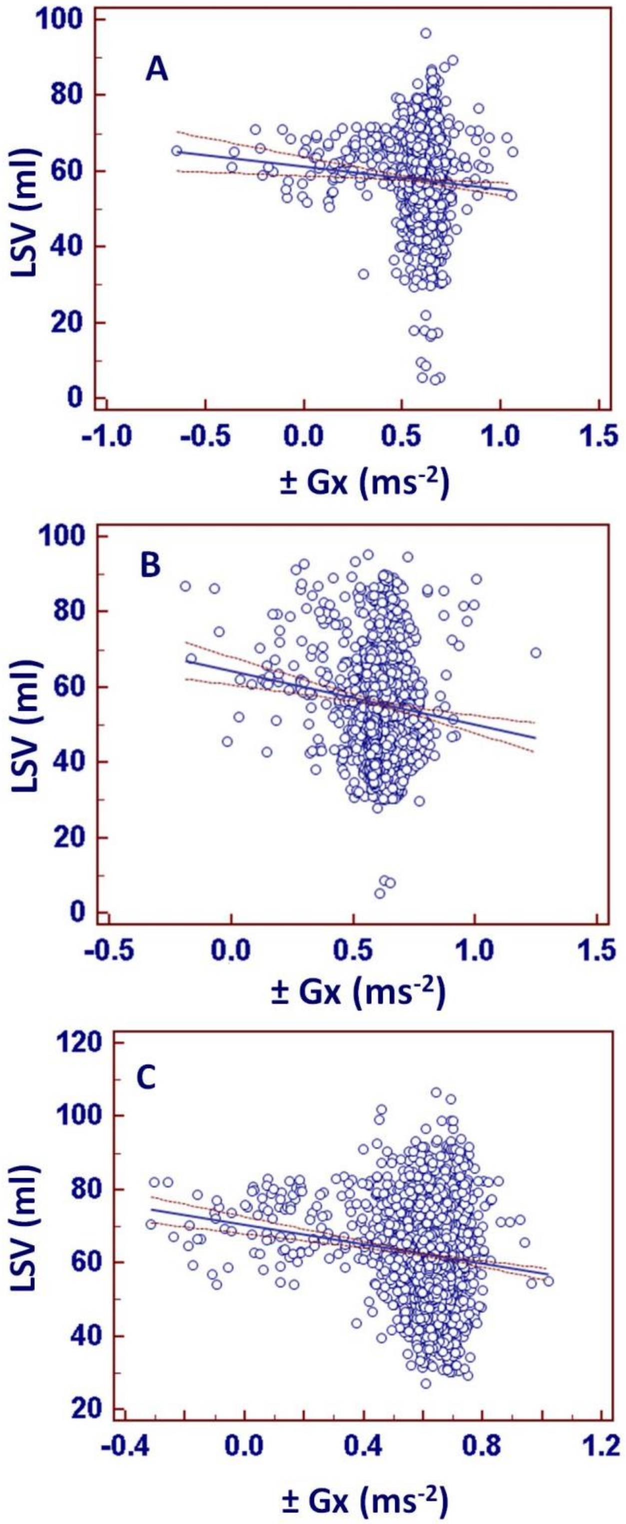

Figure 8 Respectively in tested sailors A, B, and C, shown graphs concern to the linear regression (see the straight lines) of the LSV samples versus Gx samples. Size samples are represented by the empty circles. Dotted orange lines represent the 95% confidence interval. in all three subjects a maximum density of points is observed between 30-90 ml of LSV and 0.4-0.8 ms^{-2} of Gx.

medians since, respectively, there was a P=0.053 and a P=0.289. Moreover, even if the comparison between mediated values of means and medians gave a P=0.041 or a little borderline for statistical significance, it is reasonable to consider also the Gx distribution values in all tested subjects as normal or parametric distributions.

So, since in both LSV and Gx distributions the values of mean, median and mode did not differ significantly, parametric statistical predictive methods could be applied in such a way of reveal possible relationships which consent to individuate some kind of interdependence between behaviour of LSV and Gx variations assessed from our sailors while sitting in the moored boat. The following predictive regression equations could be calculated concerning possible linear dependence of the LSV changes versus Gx ones in each of tested sailors.

$$LSV_A\ (ml) = 61.32 - 6.04 \times Gx_A\ (ms^{-2}) \quad (1)$$

$$LSV_B\ (ml) = 64.35 - 14.19 \times Gx_B\ (ms^{-2}) \quad (2)$$

$$LSV_C\ (ml) = 70.36 - 13.29 \times Gx_C\ (ms^{-2}) \quad (3)$$

Graphs shown in Figure 8 are the geometric representations respectively of the equations (1), (2) and (3). These graphs clearly highlighted the inverse relationship of LSV versus Gx changes, and all these three linear relationships reached a statistical significance since it has been found a P = 0.004 in (1), a P < 0.0001 in (2) and a P < 0.0001 in (3). So, it can be stated that boat rolling gave rise to a LSV fall which in turn might reduce the arterial blood pressure.

4 CONCLUSIONS

What emerges from these results is that, in all three subjects tested, for each unit deviation of the value of Gx, i.e., 1 m/s^2 (equal to about one tenth of the acceleration of terrestrial gravity which, as is known, is about 9.81 m s^{-2}), the dependent LSV value deviates linearly but inversely by about 11 ml on average, with an inter-individual difference ranging from a minimum of about 6 ml to a maximum of about 14 ml.

Several previous papers suggest that vestibular stimulation during linear acceleration applied to the head could produce cardiovascular responses in humans, so supporting the possibility that vestibular system play a role in stabilizing the blood pressure during postural changes [28].

This regulation probably operates through the vestibule sympathetic reflex [29]. In fact, it has been found in humans that the galvanic vestibular stimulation via electrodes over the mastoid processes induced a clear modulation of the limbs MSNA [30] which operated independently of the arterial baroreceptor reflex concerning the blood pressure control [31].

Since it has been found that linear acceleration increases trough naso-ocipital direction induces a MSNA reduction [3] from which a reduction in PVR may also occur [32], this, in turn, could determine the here observed reduction in LSV. Also considering that LSV is the main responsible for the parallel changes in mean arterial blood pressure [4], it could reasonably be speculated that a non-invasive and pleasant antihypertensive effect might be reached by staying seated into a rolling moored boat.

This last speculation could be reasonable if considering that the studied crew was composed by aged sailors being on average 75 years old, and also considering that in a previously published case study concerning an aged (74 years) skilled sailor engaged in a sail boat's coastal cruise and who slept every night in the moored boat [24], it has been found a fall of -3.6% in is mean arterial blood pressure when disembarked.

Moreover, in considering that sarcopenia is characterized by a decline in muscle mass and strength with increasing age [33], the daily boat rolling could induce a postural reflex in our sailors, via the vestibulo-spinal nerve pathways, characterized by an alternating of contracting and relaxing of the trunk and leg muscles even while sitting, which could contribute to limiting the age-dependent sarcopenia. In this regards, we could hypothesize that our sailors did not develop sarcopenia, due to the unchanged body mass and BMI during the cruise [34].

The major limitation of this study may refer to the small number of subjects tested. However, in this type of experimentation, due to the small spaces in which they take place, i.e., the limited living volumes of a sailing boat, those almost represent an objective limit. However, the results of this study suggest the importance of expanding the amount of information, perhaps by engaging in the experimentation a greater number of crews who are willing to undergo these experimental tests.

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