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METROLOGICAL CHARACTERIZATION OF ROCKING BOARDS AND POSTURAL READERS TO ASSESS SINGLE STANCE STABILITY IN HUMAN SUBJECTS

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Abstract: The study of posture and movement control in humans requires technological supports able to provide accurate, reproducible and repeatable information on displacement and/or position in real-time.

A methodology used in rehabilitation and in sports medicine involves the use of rocking boards on which the subjects must keep their balance, in different operating conditions. The use of rocking boards combined with displacement and position sensors allocated at specific points of the human body, can provide information on the single stance stability and contribute to reprogramming the postural and proprioceptive control of healthy and pathological subjects (orthopaedic and neurological patients), mitigating the risk of falling in older subjects and decreasing the risk of injuries in sport athletes.

This paper describes the procedure used for the characterization of rocking boards (uniaxial and triaxial) and wearable sensors as postural readers, in terms of angular position. In the first step both measuring systems are characterized by a reference accelerometer, in order to accurately determine the angular positions.

A metrological approach in biomechanical measurements is necessary since it provides more accurate and reproducible data on which evaluations related to human health and wellbeing can be achieved.

Keywords: biomechanical measurements, angular position, rocking boards, postural control, proprioceptive boards.

1. INTRODUCTION

Health and wellbeing in human life are indubitably a matter of priority. Any scientific instrumentation or technical tool adopted in any field of medicine should fulfill metrological requirements in order to provide accurate and reproducible data and to guarantee a reliable exchange of information worldwide. Actually, in recent years, an increased demand for metrological characterization of medical systems, materials or tools in general, has been observed.

In this work a metrological characterization of a system for reprogramming single stance stability is described. Single stance stability and its proprioceptive sensory component have been recently hypothesized as promising early predictor of the risk of falling in older subjects [1]. Several studies [2, 3] have highlighted that falls and unstable balance in older people are a growing problem of the developed countries. In order to prevent falls, hospitalization and loss of independence, effective tools and systems able to mitigate the risk of falling should be developed [4 - 7]. Tests performed on an electronic rocking board, by World and Olympic champions of different sport disciplines, have shown very refined single stance stability confirming its importance in the effectiveness of the antigravity movements [8].

Therefore, it is necessary to have a technological supports able to create conditions of controllable instability and wearable sensors of angular position, allocated at specific points of the human body (e.g. sternum, head, knees), in order to monitor the stability performance of the subject. The real time visualization of the inclination of the board on an external screen and the related postural feedback allow the reprogramming of the vertical control.

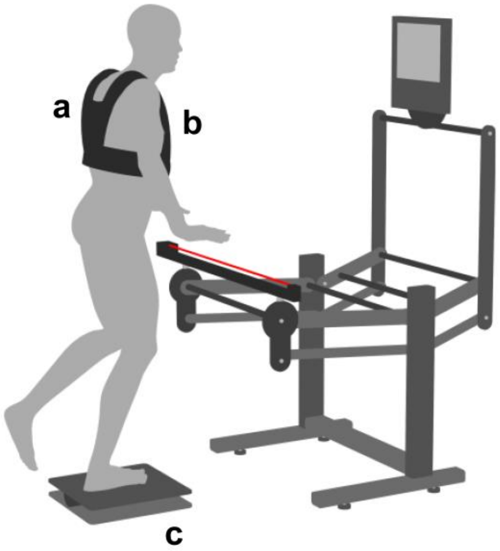

Figure 1. The postural proprioceptive station. The red line represents the infrared ray of the sensorized bar. Vest (a) to support the “postural reader”, (b) a two-dimensional accelerometer unit, in sternal position. Rocking board (c).

The accuracy of data is a requirement of paramount importance in biomechanical measurements. The possibility to perform analysis using reproducible data allows both to formulate very accurate functional assessment and also to exchange information with high reliability. The metrological characterization of the measurement system here presented provides for the determination of the inclination angles of the rocking boards and of the postural readers.

2. OVERVIEW OF THE SINGLE STANCE POSTURAL STABILITY TEST SYSTEM

The tests are performed by monitoring the single stance stability of a subject in balance on rocking boards, as depicted in Figure 1. Two kinds of rocking boards (here denoted with A and B) were designed and realized with reproducible technical features. The rocking board and the postural reader are parts of an electronic postural proprioceptive system (DPPS, Delos, Turin, Italy) Figure 2 and are connected to a PC with a specific software (DPPS 5.0). The main purpose of the rocking board is to generate instability in a defined range. The first typology of rocking board (A) creates instability around a single axis, moving on an horizontal plane. The support on the ground is a section of a cylinder that constrains the rolling motions along the frontal plane (*x*-plane). The second typology of rocking board (B) causes instability in the frontal and sagittal plane (*x*-*y* plane), using as rolling support the section of a sphere.

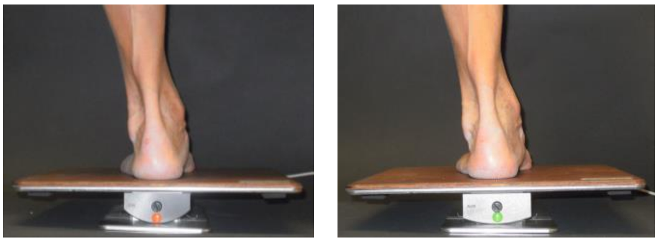

Figure 2. Rocking boards with two different radius of the semi-cylindrical supports.

It is possible to use, as support, sections of cylinders or spheres with different radius (55mm, 80mm, 110 mm) in order to generate different instability. The decreasing of the radius increases the instabilities of the rocking boards.

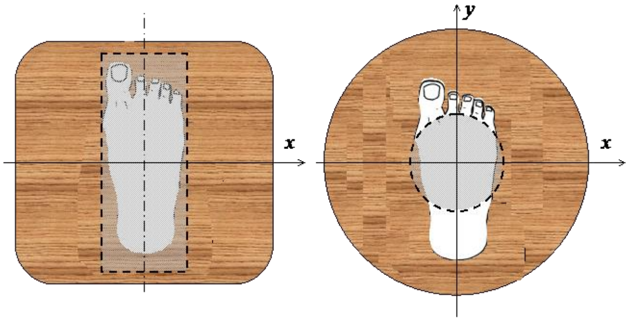

Figure 3. Schematic representation of the rocking boards. (Left) The rocking board A creates instability in the frontal plane (*x*-axis) and (right) the rocking board B creates instability in the frontal and sagittal planes (*x*-y axes).

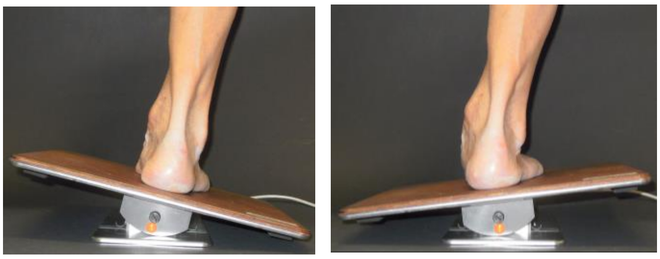

Figure 4. The subject manages different inclinations of the rocking board. Left: supination. Right: pronation.

In the case of the rocking board A, the movements are possible only in the frontal plane, i.e. *x*-axis, Figure 3 (a). In the case of the rocking board B the movements are possible in the frontal and sagittal planes *(x y*-axes), Figure 3 (b).

The subject on the rocking board manages the rocking instability by means of a series of postural adjustments, as shown in Figure 4.

Moreover a displacement sensor, applied to the sternum, measures the trunk inclination of the subject during the test. Output data from the rocking board coupled with the output data from the wearable sensor on the sternum allow one to evaluate the single stance subject stability, in high instability conditions. On a PC screen in real time, the trace of the inclination of the rocking board and the trace of the postural adaptations on the plane *x*, *y* and *x*-*y* in different combinations are displayed, Figure 5.

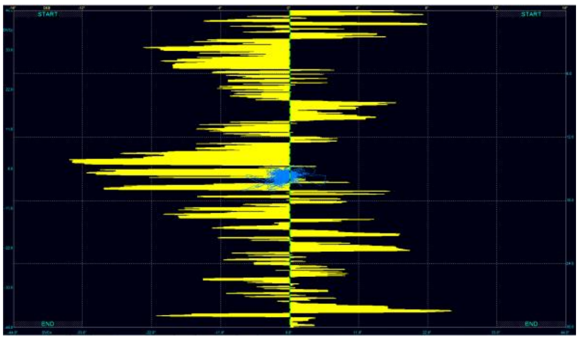

Figure 5. The real time trace of the rocking board A (yellow bars) and the trace of the postural reader (blue line).

3. CHARACTERIZATION OF THE REFERENCE SENSOR – MEMS ACCELEROMETER

In the system under analysis, the rocking board A is equipped with a potentiometer connected to a PC and the rocking board B is equipped with an accelerometer wireless-connected (Bluetooth system) to a PC. The output signal is sampled at 100 Hz. The analyzed output signals are the inclination angles of the rocking board, as a function of time, and the related direction of the inclination. The maximum width of inclination is within a 30° angle, i.e. $-15^\circ \leq \alpha \leq 15^\circ$. The requested accuracy is 0.5°.

For this purpose a triaxial MEMS accelerometer is used as a reference to measure the angle inclination of the rocking boards. The reference accelerometer (able to perform measurement from DC) was first calibrated on a rotating table at INRIM with a resolution of 0.01°. The measurements performed on the rocking boards can be expressed with an uncertainty of 0.1° within the operative and calibration ranges.

The internal integrated amplifier of the reference accelerometer gives values of –4.9016 V at -30° and 4.9076 V at 30°. The absolute average value (4.9045 V), obtained from the values measured at 30° and at -30°, was taken into account in order to calculate the expected values of output voltage as a function of inclination angles. The sensitivity of the accelerometer was measured for the three axes. A calibration factor, expressed as volt per degree, was calculated, as a function of the inclination angle, on the rotating table for the three axes. It should be noted that the range of interest for the characterization of the proposed system is limited between -20° and 20°.

As an example for only *x*-axis, in Figure 6, the values obtained of the calibration factor as a function of inclination angles are depicted.

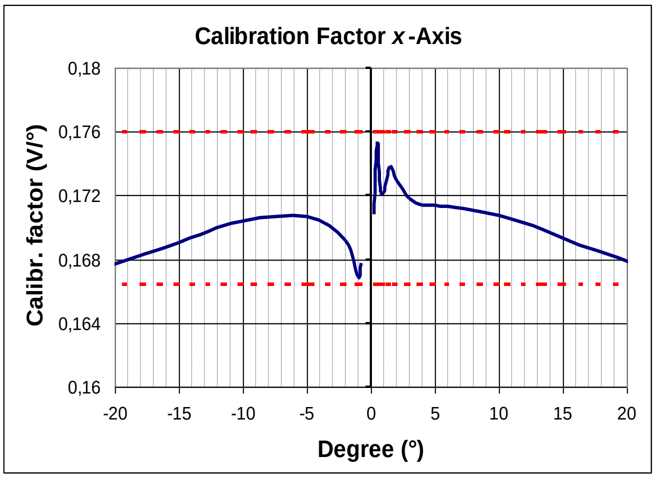

Figure 6. Calibration factor (*x*-axis) of the accelerometer determined between -20° and 20° of inclination angle.

In Figure 7, for *x*-axis, the difference between expected and measured values, as a function of inclination angles, are depicted. The difference presented here is only in the range of interest. In this range it is possible to note that the difference between expected and measured values is markedly less than 0.01 V per degree. The expected values are obtained from the following relation:

$$4.9045 \cdot \sin\alpha_i \qquad \mathrm{V} \quad (1)$$

in which α_i is the value, in radians, of the inclination angle of the rotating table during the calibration.

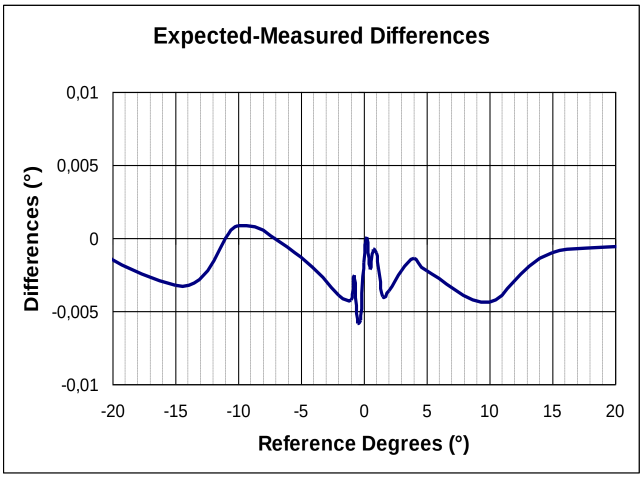

Figure 7. Difference between the measured values and expected values as a function of inclination angle (*x*-axis).

Once the triaxial MEMS reference accelerometer has been calibrated, the characterization of the two rocking boards, equipped with all the different support systems, was performed. The main aim of this characterization was to verify if the response of the sensors of the rocking boards can be considered accurate and repeatable.

4. METROLOGICAL CHARACTERIZATION OF THE ROCKING BOARDS

The triaxial MEMS reference accelerometer was fixed on the center of the rocking boards. The signal output was acquired simultaneously both from MEMS and from the sensor of the rocking boards. The sampling rate used was 100 Hz. The sampling of the MEMS signal output was about 8 kHz. In Figure 8 a drawing of the system is shown. Previously both the horizontal position (0°) and the maximum possible inclination (~15°) were detected. Then, by using three different spacers put underneath the board, three different angles (both positive and negative) were characterized (±4°, ±8° and ±12°).

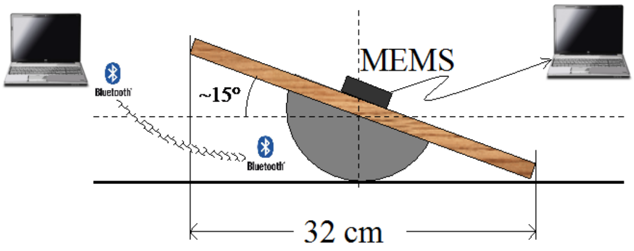

Figure 8. Schematic drawing of the characterization of the rocking board.

In order to characterize the rocking board B, the measurements were performed separately for the *x*-axis and *y*-axis, by constraining the motion along a single axis. The constrains were two semi-spheres fixed on the ground. In Figure 9 a schematic diagram is depicted.

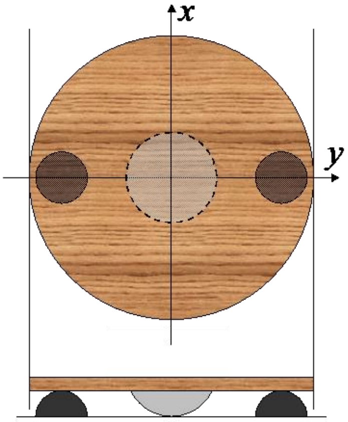

Figure 9: The constrains along *y*-axis allow to perform measurements of inclination angle only on *x*-axis.

In the graph of Figure 10, a series of measured angles performed with the rocking board A are depicted. The measurements were collected as a function of inclination angle. Actual measurements were performed randomly (i.e. by using supports with different radius and reaching the position angle both from 0° and from the maximum inclination).

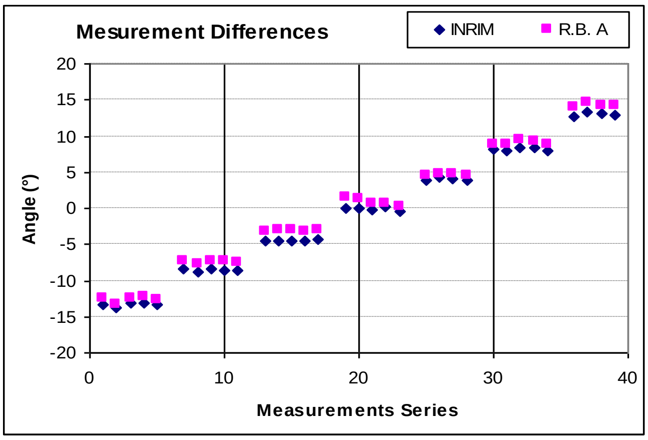

Figure 10. Rocking board A: comparison between measured angles (blue points with calibrated INRIM accelerometer).

In the following graph the differences between angles measured with the reference accelerometer and the angles measured with the sensor of the rocking board A are depicted. Two systematic effects are highlighted. The first one shows an average linear over estimation of ~1° (0.98° ± 0.3°) on the whole range of the rocking board inclination. The latter shows a sinusoidal behavior as a function of the rocking board angle inclination, probably due to a friction wear. The data variation is within 0.4°. From –15° to –5° and from +5° and +15° some increasing in overestimation is observed. Around 0° a more severe dispersion is observed. The best fit among the data is a sinusoidal function, as detected in the graph of Figure 11.

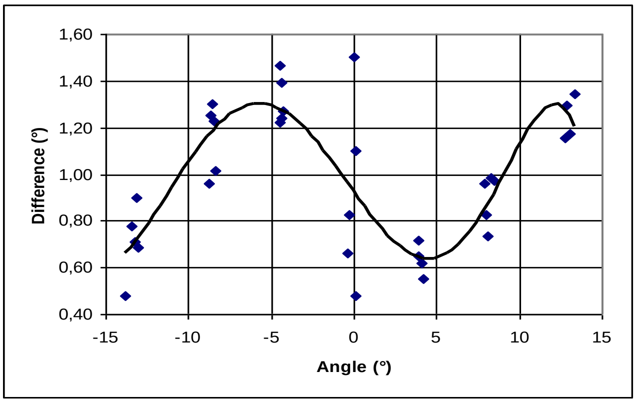

Figure 11. Differences between angles and best fit data.

This analysis allows to define the compensation of the systematic effects of the measured angles for the rocking board A. The best compensation, in order to estimate correctly the angles measured with the potentiometer of the rocking board, is achieved by minimizing the systematic effects by subtracting both the average linear overestimation (here denoted with δ°) and the observed sinusoidal drift (here denoted with ε°), as follows:

$$x^\circ_{\text{eff}} = x^\circ_{\text{meas}} - \left(\delta^\circ + \varepsilon^\circ\right) \qquad \text{deg} \qquad (2)$$

in which x°_{eff} is the best angle value, x°_{meas} is the value of the inclination angle measured by the medical system, δ° is the averaged overestimation, i.e. $\delta^\circ=1^\circ$ and ε° is derived from the best fit analysis as follows:

$$\varepsilon^\circ = 0.4\cdot\sin\left[x^\circ_{\text{meas}}\cdot\frac{34\pi}{360}+\pi\right] \qquad \text{deg} \qquad (3a)$$

for negative values of the measured angle ($x^\circ_{\text{meas}} < 1^\circ$), and:

$$\varepsilon^\circ = 0.4\cdot\sin\left[x^\circ_{\text{meas}}\cdot\frac{42\pi}{360}+\pi\right] \qquad \text{deg} \qquad (3b)$$

for positive values of the measured angle ($x^\circ_{\text{meas}} > 1^\circ$).

In order to make things easier it is proposed to use a single mean compensation of the systematic effects for the whole range of inclination angles (except for the 0° value that has to be considered separately). The proposed compensation allows to evaluate the inclination angles with an accuracy of 0.2° as well as relation (3a) and (3b). The differences between values measured with relations (3a) and (3b) and the following relation (4) are less than 0.01°. The proposed simplified compensation is:

$$\varepsilon^\circ = 0.4\cdot\sin\left[x^\circ_{\text{meas}}\cdot\frac{\pi}{10}+\pi\right] \qquad \text{deg} \qquad (4)$$

In the graph of Figure 12, the differences between measured values by the reference accelerometer and the measured angles with Rocking board A, with and without the proposed correction, is depicted. As it is shown the difference between the values of inclination angles measured with the proposed correction is within 0.2°.

It is important to underline that variation around 0° does not follow this behavior, then the availability of the proposed relations has to be considered limited for positive angles up to 1° and for negative angles below –1°. As a matter of fact, around the horizontal position at 0° a more severe dispersion, not characterized by any systematic effect, has been observed. The dispersion of the random distribution is of about ± 0.4°, i.e. less than the request accuracy of 0.5°.

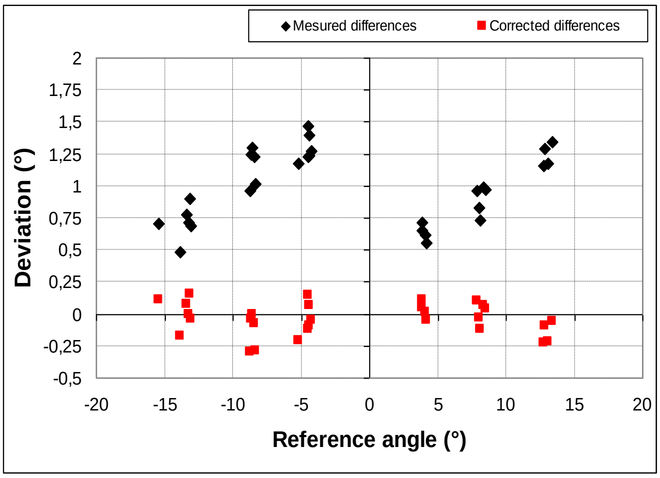

Figure 12. Difference between measured values without any compensation (black points) and measured values with the proposed compensation (red points) by using relation (2) and relation (4) for the rocking board A.

Similar comparison has been performed on rocking board B. In the graph of Figure 13 and Figure 14 one of the series of measured angles, both on *x*-direction and on *y*-direction are depicted. The measurements has been performed randomly.

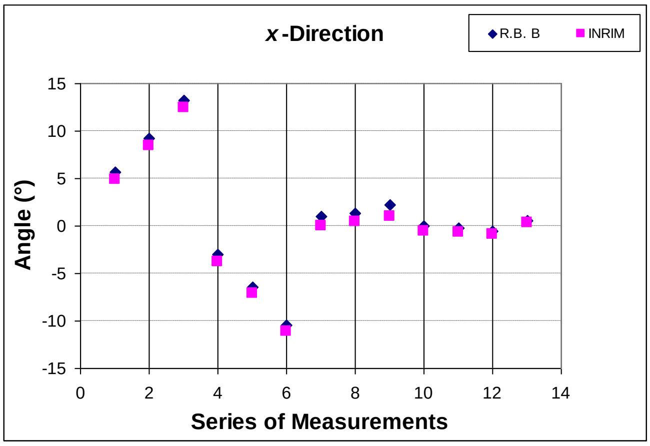

Figure 13. Rocking board B (R.B. B): comparison between measured angles on *x*-direction

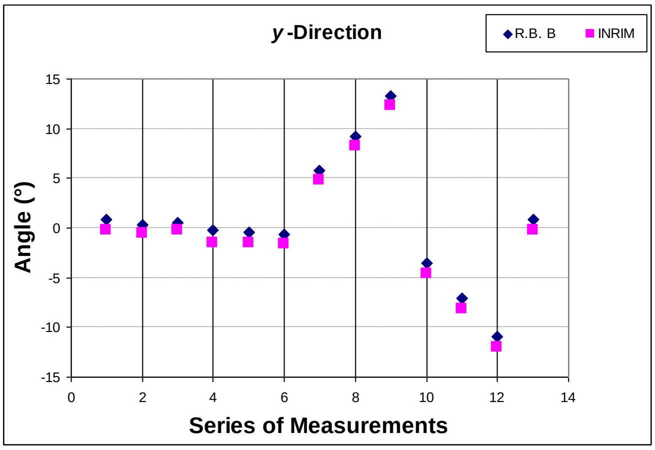

Figure 14. Rocking board B (R.B. B): comparison between measured angles on *y*-direction.

The differences among angles detected on the rocking board B, on both directions, can be considered mainly linear, with a systematic overestimation of 0.9° ± 0.2° for *x*-direction within the range –15° to +15° (except around 0° where the overestimation is 0.4° ± 0.1°) and 1° ± 0.2° for *y*-direction over the same range.

By applying this simple correction directly to the measured angles by the Rocking board B, it is possible to obtain reliable output data of inclination angles. In the following graphs of Figure 15 and Figure 16, the difference between measured values by the reference accelerometer and the measured angles by the sensor of the rocking board B, with and without the proposed correction, are depicted.

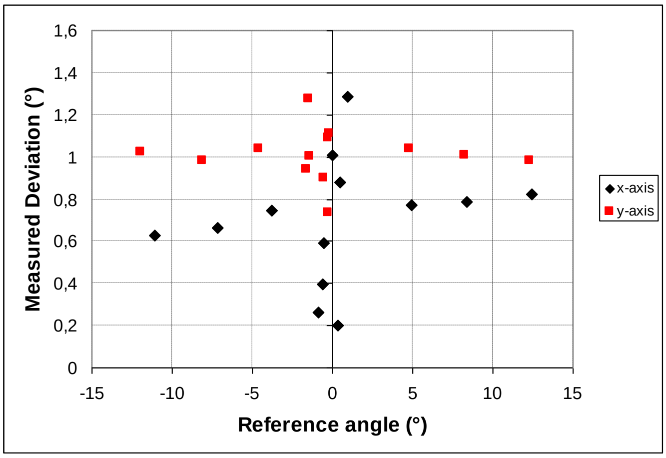

Figure 15. Differences between angles measured by R.B. B and reference accelerometer, as a function of the reference angle, for *x*-direction (black points) and *y*-direction (red points).

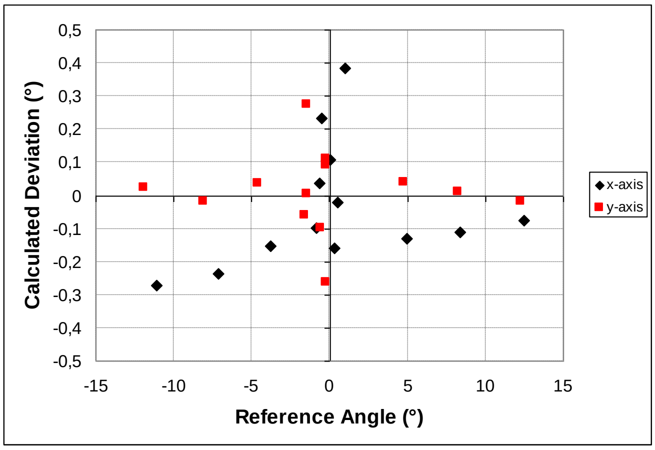

Figure 16. Corrected differences between angles measured by R.B. B and reference accelerometer, as a function of the reference angle, for *x*-direction (black points) and *y*-direction (red points).

As it is shown the difference between the values of inclination angles measured with the proposed correction is largely less than 0.5° for both *x*-direction and *y*-direction, as required.

5. METROLOGICAL CHARACTERIZATION OF THE POSTURAL READERS

In single stance the trunk of the subject moves as a segment of a broken line with multiple joints [1]. The analyzed output value is the inclination angle of the trunk itself during the test, measured by means of proper postural readers applied at specific points of the human body (e.g. sternum, pelvis, knee). The postural reader is equipped with a bi-axial MEMS accelerometer.

As a first step, a simple vertical rigid bar has been fixed on the rocking board, equipped with the postural reader and the reference tri-axial MEMS accelerometer fixed on a proper support. The supports allocated on the bar allow to set the accelerometer position at different heights in order to investigate the influence of different accelerations in the same angle measurement.

It has to be underlined that this measurement does not simulate the actual behavior of a human body during the test. This analysis allow to evaluate, at first, the output angle values of the postural readers in comparison to the reference accelerometer.

Measurements of different inclination angles have been taken by moving the rocking board B along both *x*-direction and *y*-direction, constraining the motion along a single axis, as previously reported. The signal output was acquired simultaneously both from reference and from the postural reader connected to the PC of the electronic postural proprioceptive system. The test rig is depicted in Figure 17. In the Figure 18 the reference accelerometer and the postural reader fixed on the support at the vertical bar are shown.

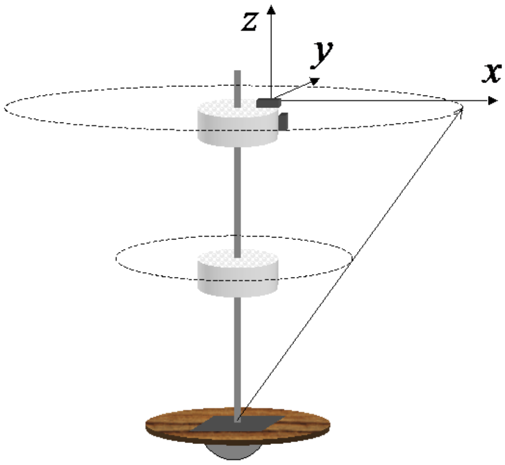

Figure 17. Schematic draw of the vertical bar for postural readers characterization.

Figure 18. Tri-axial MEMS reference accelerometer and the postural reader fixed on the support at the vertical bar.

In the graph of Figure 19, as an example, a series of difference among angles measured on the vertical bar in a particular work condition, are depicted. The differences are expressed as a function of the reference angle. Actually measurements were performed randomly.

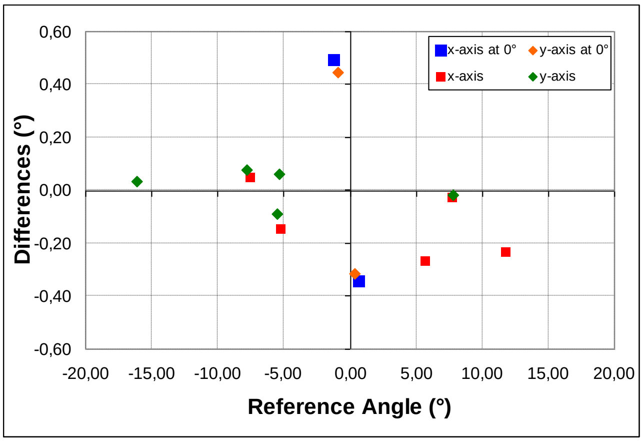

Figure 19. Calculated differences between angles measured by the postural reader and the reference accelerometer, as a function of the reference angle, for *x*-direction (black points) and *y*-direction (red points).

As it is shown, the differences range within ± 0.5° around the horizontal position (0° for both for *x*-direction and *y*-direction) and within ± 0.3° between -15° and +15° , without any compensation. On the basis of these consideration for the postural reader under analysis no correction was proposed.

6. CONCLUSIONS

In this work a procedure to characterize rocking boards and postural readers used in rehabilitation and in sports medicine has been presented. The use of rocking boards and postural readers allocated at specific points of the human body can provide information on the single stance stability and contribute to reprogramming the postural and proprioceptive control of healthy and pathological subjects (orthopaedic and neurological patients), mitigating the risk of falling in older subjects and decreasing the risk of injuries in sport athletes.

As next step, after a detailed measurement uncertainty budget definition, in order to quantify accuracy, repeatability and reproducibility, the proposed procedure will allow to directly calibrate the systems in-situ, simply by using a calibrated accelerometer as reference. Once the reference accelerometer is calibrated, e.g. by means of a rotating table, with enough accuracy with the respect of expected accuracy in working condition, the whole electronic postural proprioceptive system can be considered traceable in metrological terms.

A metrological approach in biomechanical measurements allows to achieve more accurate and reproducible data. As a consequence, very accurate functional assessment can be formulated and the exchange of clinical/medical information, with high reliability worldwide, can be guaranteed by the traceability of calibrated instrumentation.

7. CONFLICT OF INTERESTS

Dario Riva is the scientific director of Delos, and he holds Company equity. The other authors declare that they have no conflict of interest.

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