PRIN

Mechanical measurements for the musculoskeletal apparatus: novel and standardizable methodologies for metrological assessment of measurement systems.

WP3
Metrological characteristics and requirements

Date: February 2015

Introduction

The objective of this project is the development of procedures and instrumentation to test the quality of measurements conducted in motion analysis laboratories and to define a methodology to obtain repeatable and reproducible measurements.

The types of measurements considered for this project are:

- Human kinematics and gait analysis, conducted through a Motion Capture System (OS)
- Forces, conducted through force plates.
- Mechanics of breathing and respiratory volumes by optoelectronic plethysmography (OEP).

Metrological characteristics and requirements

In this document the metrological characteristics of the instrumentation are discussed. Moreover, the preliminary requirements and criticalities on the design of protocol and instrumentation are exposed.

Human kinematics, gait analysis and integration with force plates

Andrea Ancillao, Roberto Di Marco, Stefano Rossi, Fabrizio Patanè, Paolo Cappa.
Dept. Of Mechanical and Aerospace Engineering, Sapienza University of Rome, Roma, IT

From the literature analysis, previously presented in the deliverable D2, it is emerged that the most common methods to assess the metrological performances of Optoelectronic systems (OS) consist in the use of *ad-hoc* built systems. To evaluate OS accuracy and precision, experimental trials are conducted by imposing known marker trajectories and by comparing them with positions estimated by OS.

As it is known, given a marker moving in the laboratory, the OS is able to reconstruct the 3D time history position relative to a fixed reference frame (LabFrame). Looking at the same reference, the position, the orientation and the optical characteristics (addressed as *calibration parameters*) of each camera can be considered time invariant and have been calculated with the calibration procedure. As the calibration data are collected, the reconstruction algorithm performs a fitting process and provides "residual errors" as output. The calibration algorithms for the main commercial OS are based on: the collinearity equation (CESNO) [1] and the direct linear transformation (DLT) [2], [3].

The reconstruction uncertainty of the marker position is associated with centroid estimate, camera calibration and data processing as highlighted by Burner and Liu [4]. The authors showed that the uncertainty in target centroid measurement is associated with camera noise, target dimension and spatial quantization of the CCD sensor. For this reason, the random error related to the camera noise can be collectively represented by the centroid variations for spatially fixed targets. A practical method for quantifying this fluctuation is to track fixed points at a known distance and compare it to the mean value and the standard deviation of the distance reconstructed by OS (Fig. 1).

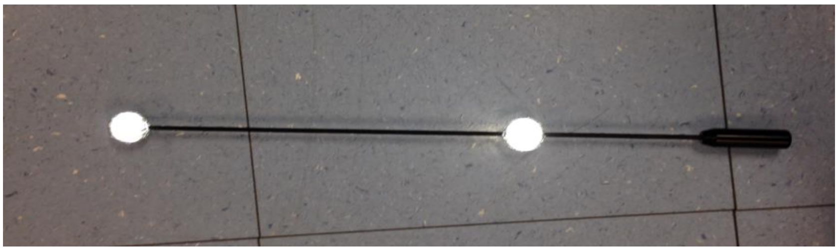

Figure 1: Markerized wand.

The technical characteristics of the instrumentation in use is summarized into table 1:

Table 1: technical characteristics of motion analysis systems in use.

		URLS		
Optoelectronic system	*Model*	Vicon MX		
	Sample frequency	200 Hz		
	Marker size/type	Spherical 10 mm		
	Marker protocol	P.i.G.		
Force Platform	*Model*	AMTI OR6-6 1000		
	Output channel	6 components (Fx, Fy, Fz, Mx, My, Mz)		
	Sample frequency	1000 Hz		
	FSO	4450 N (Fz)		
EMG	*Model*	Cometa Zero Wire		
	Channels	16 - analog		
	Sample frequency	1000 Hz		
	Protocol	SENIAM		

Considering the technical characteristics of the available instrumentation, we proposed the following preliminary requirements for devices and protocols to be developed.

Optoelectronic System OS:

A spot check of the functionality/accuracy of the OS can be performed by means of a fixed length wand equipped with reflective markers (Fig. 1). An effective example of this wand is the calibration wand itself, which is equipped with 5 active/passive markers at a known distance between each other.

Moreover, the full acquisition volume can be tested by recording multiple walking trials performed by healthy subjects. Also subject preparation should be performed by different trained operators in order to test inter-operator repeatability.

Recorded data should be pre-processed according to the operation usually performed in a clinical context:

- Filtering;
- Fill gap;
- Labeling;
- Static and Dynamic Kinematics, and Kinetics pipelines.

Data should be analyzed with and without pre-processing.

The following parameters are computed and studied for repeatability and reliability:

- Joint angles (Kinematics);
- Joint moments (Kinetics);

Force Platforms

Force platforms should be tested both statically and dynamically. For the static tests, a device equipped with a 6-component load cell will be used. The device (Fig. 2) is equipped with reflective markers to allow the OS to track the position of the load cell with respect to the fixed force platform and absolute reference system.

The device should be applied on several points on the surface of the force platform (Figure 3). Random forces through different directions are applied by the operator on the load cell and on the force platform. The 6-component load cell is assumed as the gold standard to test and compare the output of the force platform, in terms of force components and moment components.

In the processing phase, the forces and moments measured by using the load cell will be projected onto the coordinate frame composed with the markers depicted by Figure 2. Then, the vectors force and moments will be compared with the reaction vectors measured by the force platforms.

Figure 2 – The device developed to test the force platform.

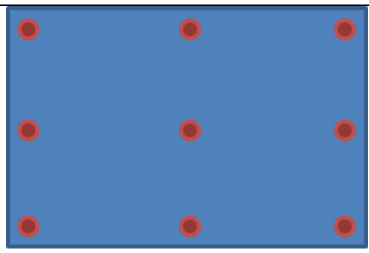

Figure 3: Test points over the surface of the force platform.

References

[1] F. Gazzani, "Comparative assessment of two algorithms for calibrating stereophotogrammetric systems," *J. Biomech.*, vol. 26, no. 12, pp. 1449–1454, 1993.

[2] Y. I. Abdel-Aziz and H. M. Karara, "Direct linear transformation from comparator coordinates into object space coordinates in close-range photogrammetry," *Proc. Symp. Close-Range Photogramm. Am. Soc. Photogramm.*, 1971.

[3] T. Huang, S. Blostein, and E. Margerum, "Least-squares estimation of motion parameters from 3-D point correspondences," *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, pp. 24–26, 1986.

[4] A. Burner and T. Liu, "Videogrammetric model deformation measurement technique," *J. Aircr.*, vol. 38, pp. 745–754, 2001.

Mechanics of breathing and Respiratory volumes investigated by OEP

Carlo Massaroni, Emiliano Schena, Paola Saccomandi, Sergio Silvestri.
Unit of Mechanical and Thermal Measurements and Biomedical Instrumentation, Campus Bio-Medico di Roma University, Rome - IT

OEP is an motion analysis system that allow the evaluation of mechanics of breathing by the non-invasive measurement of the chest wall surface motion. As widely described in literature, OEP is reliably and validated to (i) map the functionality of chest wall compartments, (ii) investigate the chest wall coordination and (iii) track the improving of respiratory functionality after clinical treatment or surgery. The breathing assessment by mouthpiece and flowmeter or by spirometer is extremely difficult in children or uncooperative adults; Spirometer as well as total-body plethysmograph cannot be used during sleep, to analyze phonation, and during weaning from mechanical ventilation. These problems are widely overcome by the measure of chest wall kinematic considering that displacements of the lung are transmitted to the chest wall and vice versa, and, therefore, measurements of thoraco-abdominal surface movement can be used to estimate lung volume variations.
OEP's working principle is based on the tracking of a large number of markers (i.e., 89 marker) during the time in the 3D space. The validation of the method has been obtained by comparing the lung volume changes obtained by volumetric measures obtained from spirometers and chest wall total volumes by optoelectronic plethysmography during different maneuvers.
As it is known OEP is able to reconstruct the 3D coordinates of each marker relative to a fixed reference frame after a calibration procedure identical to a standard OS one. By connecting a triplet of markers in order to form a triangle is possible to obtain an elementary surface. The volume contained in this surface can be calculated using the Gauss theorem.
The computed volume uncertainty is associated on the one hand to 3D reconstruction uncertainty of each marker (e.g., camera and workspace noise, target dimension, OEP calibration) and on the other hand to the volume computation algorithm error. A practical method for quantifying this systematic error is to impose well-known variable and reproducible volumes during the time.

Table I: Optoelectronic system adopted by campus bio-medico di roma university

		RUCBM
Optoelectronic System	Model	OEP System
	Sample frequency	60 Hz
	Marker size/type	Emi-spherical 6/10 mm Spherical 6/10 mm
	Marker protocol	89-marker
Force Platform	Model	BTS P6000

		RUCBM
		(strain gage tech)
	Output Channel	6 components (Fx, Fy, Fz, Mx, My, Mz)
	Sample Frequency	1000 Hz
	FSO	2000 N (F_z)
Surface EMG	**Model**	BTS FreeEMG (8 probes)
	Acquisition Frequency	4kHz

Considering the technical characteristics of the available instrumentation, we proposed the following preliminary requirements for devices and protocols to be developed.

Optoelectronic Plethysmography (OEP)

To assess metrological performances of OEP can be useful the use of *ad-hoc* built simulator which can reproduce human chest wall in dimension and kinematic features (displacements, speeds and acceleration). Simulator should be realized with a minimum of 2 compartment (for total volume assessment) and a maximum of 8 compartments (2 compartments simulating upper thorax, 1 simulating rib cage zone and 1 simulating abdominal zone, for back and front of the chest wall).

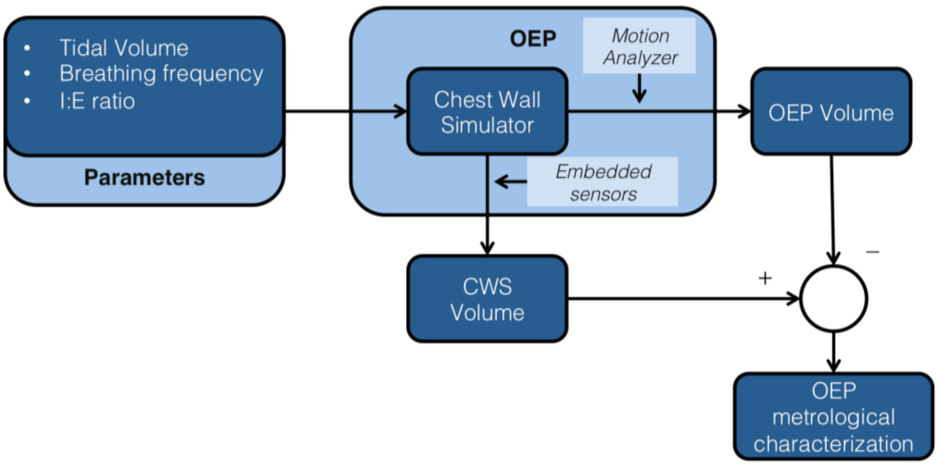

FIGURE I: OEP METROLOGICAL CHARACTERIZATION PROOF OF CONCEPT

The design should be based on anthropometric measurements of thoracic wall: compartments size and trajectories should be designed on literature reviews and experimental data from healthy subjects which should be underwent to OEP exam.

OEP accuracy, precision, reproducibility experimental trials will be conducted by imposing known volumes by simulator underwent OEP and by comparing this volume with total volumes estimated by OEP system.
Different volume within the physiological range will be tested (i.e., from 300 mL up to 1300 mL) during quiet breathing simulating breathing frequencies from 8 breathing per minute (bpm) to 30 bpm. I:E ratio should be easily set as a parameters during the programming phase.
Recorded data should be pre-processed according to the operation usually performed in a clinical context: evaluation of total volume and evaluation of compartmental volumes (pulmonary rib cage volume, abdominal rib cage volume and abdominal volume).

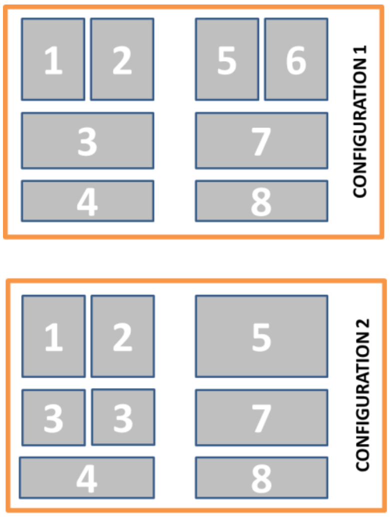

Fig. 2: SIMULATOR COMPARTMENT REPRESENTATION IN TWO DIFFERENT CONFIGURATION (1,2) AIMING AT REPRODUCE THORACO-ABDOMINAL ZONE OF A HUMAN CHEST WALL

The simulator should allow to assess:

- systematic error influencing factor (i.e., number of cameras in the workspace, position of cameras into the OEP room, room ambient noise)
- OEP repeatability and reliability in measuring small movement (i.e. from 0 to 12 mm), at different imposing frequencies (i.e., from 0 to 1 Hz)
- OEP repeatability and reliability in measuring static and dynamic volumes;

Temperature and ambient light sensors will be embedded into the simulator.

References

[1] A. De Groote, M. Wantier, G. Cheron, M. Estenne, and M. Paiva, "Chest wall motion during tidal breathing.," Journal of Applied Physiology, pp. 1531-1537, 1997.
[2] Ehara, Y., et al. "Comparison of the performance of 3D camera systems." Gait & Posture, Vol. 3, pp. 166-169, 1995.
[3] Ehara Y, Fujimoto H, et al. "Comparison of the performance of 3D cameras systems II " Gait Posture. Vol. 5, pp 251-255, 1997.

[4] Klein PJ, Dehaven JJ. "Accuracy of three dimensional linear and angular estimates obtained with the Ariel performance analysis system" Arch Phys Med Rehabil. Vol. 76, pp 183-9, 1995.
[5] Vander Linden DW, Carlson SJ, et al. "Reproducibility and accuracy of angle measurements obtained under static conditions with Motion Analysis system" Phys Ther, Vol. 72, pp. 300-5, 1992.
[6] Thornton, Matthew J., Matthew C. Morrissey, and Fiona J. Coutts. "Some effects of camera placement on the accuracy of the Kinemetrix three-dimensional motion analysis system." Clinical Biomechanics Vol.13, pp. 452-454, 1998.
[7] Bobrowitsch et al. "Digital stereophotogrammetry based on circular markers and zooming camera: evaluation of a method for 3D analysis of small motion in orthopaedic reasearch" Biomedical Engineering Online. Vol. 10, 2011.
[8] Richards J.G. "The measurements of human motion: A comparison of commercially available systems" Human Movement Science. Vol. 18, pp 589-602, 1999.

Design and development of a new dynamic calibration system for force plates

Andrea Scorza, Fabio Botta, Giulia Lupi, Salvatore Andrea Sciuto.

Department of Engineering, Roma TRE University, Rome - IT

Accurate measurements of ground reaction force (GRF) from force platforms are important in many areas of biomechanics research, as motion analysis and postural control in both normal and pathological situations. In a movement analysis laboratory, stereophotogrammetric motion capture systems and force platforms should share one absolute reference frame that allows the computation of joint moments and powers. The correct calibration of the platform location identifies the transformation between force plate and absolute reference systems, which determines the spatial coherence among the equipment's measurements [1] . Despite reliable calibrations of the stand-alone stereophotogrammetric system and force platform, several errors may affect the platform location calibration [2]. Therefore the estimation of resultant join forces and moments from gait analysis data heavily depends on the accuracy of ground reaction force (GRF) measurements. Typically, multicomponent force platforms are used to measure GRF's components and the center of pressure (COP) position [3]. Apart from the measured kinematic data, it has been shown that the accuracy of the GRFs and COP measured by force plates has a significant impact on the calculated joint kinetics (kinematic and force plates data are necessary for computing joint forces, moments and powers using inverse dynamics techniques) . Since errors in force plates applications may occur as a result of improper installation, aging or other damages, in situ calibration is required to ensure the accuracy of kinetic and dynamic measurements as well of gait analysis results. In literature, many approach are used for force platforms calibration: a first classification is based on methods and devices that perform calibration only for one direction [5, 6], and those used for three dimensional forces and moments calibration [7, 9]. Other studies consider a correction equation applied on a known calibration procedure [1, 5, 7 – 10], while some other works focus on the design and development of innovative calibration devices. As shown in literature many approaches have been considered to provide static calibration of force platforms while dynamic calibration methods are not well established yet. Recently, requirements for measuring dynamic forces have been more severe and varied in many industrial and research applications and so dynamic calibration of force platforms, which are usually calibrated under static conditions, becomes more important [11]: few methods and device have been proposed but they have some drawbacks, i.e. for the arbitrary [12] or very narrow [13] frequency range of force solicitations as well for their amplitudes, not adequate to adult gait measurements, and direction, limited to the vertical one [14].

From considerations above some improvements are needed to design a new testing device for dynamic calibration of force platforms, to provide frequency, amplitude and direction range of force solicitations suitable for adult gait and posture analysis.

Table 1: technical characteristics of motion analysis systems in use at URLS and RUCBM.

		RULS	RUCBM
Optoelectronic system	*Model*	Vicon MX	OEP System
	Sample frequency	200 Hz	60 Hz
	Marker size/type	Spherical 10 mm	Emi-spherical 6/10 mm Spherical 6/10 mm
	Marker protocol	P.i.G.	89-marker
Force Platform	*Model*	AMTI OR6-6 1000	BTS P6000 (strain gage tech)
	Output channel	6 components (Fx, Fy, Fz, Mx, My, Mz)	6 components (Fx, Fy, Fz, Mx, My, Mz)
	Sample frequency	1000 Hz	1000 Hz
	FSO	4450 N (Fz)	2000 N (Fz)

Considering the technical characteristics of the available instrumentation (table 1) used by the other research units, “La Sapienza” (RULS) and “Campus Biomedico” University (RUCBM), we proposed the following preliminary requirements for devices and protocols to be developed.

Dynamic Calibration System for Force Platforms (DCSFP)

A simplified scheme of the Dynamic Calibration System (DCSFP) is shown in figure 1.

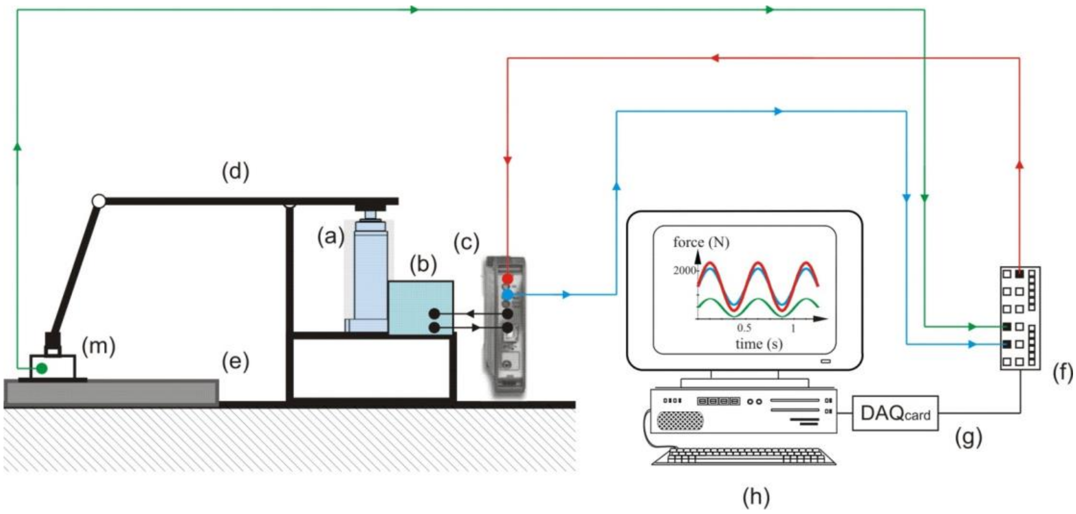

FIGURE I: DCSFP scheme. (a) Linear actuator, (b) Motor, (c) Drive unit, (d) Leverage mechanism, (e) Force platform under dynamic calibration, (f) shielded connector block (e.g. National Instruments BNC 2120), (g) Data Acquisition Card (e.g. National Instruments DAQCard-6062E), (h) Desktop PC, (m) Load cell.

In figure 1 a linear actuator (a) is connected to a leverage mechanism (d) that pushes on the surface of a force plate (e) with a sinusoidal controlled force (i.e. preload, force amplitude and frequency are controlled). A multi-axial load cell (m) is interposed between the force plate (e) and mechanism (d) to provide a feedback and direction of the impressed force. The leverage mechanism (d) could weigh up to 20 kg_f. The actuator (a) is moved by a motor (b) and drive (c), that should be programmable and controlled by a desktop PC (h) through a data acquisition system (f, g), e.g. National Instruments hardware/software and / or manufacturer hardware/software.

Moreover it has to be able to provide stress cycles, even if displacements are very small, between 150N (peak-to-peak) and 2000N (peak-to-peak) along a single direction (i.e it must be force controlled) with frequencies from 0.1Hz up to 10 Hz. A calibration task could take up to 1 hour without interruption.

The DCSFP should allow to assess Dynamic Calibration of Force Platforms:

a) Up to a 2000N load, with a resolution of 1N and accuracy about 1% of full scale range
b) For a frequency range between 0.1Hz and 10Hz (sinusoidal pattern)
c) By means of an oscillating force superimposed on an adjustable preload
d) Along different force direction, i.e between 0° (vertical, perpendicular to force platform plane) to about 60° in the elevational plane (e.g. y-z), and at different coordinates (x,y) on the force platform

Critical issues on the design and development of the device are:

1. Actuator selection
2. Leverage mechanism design and development
3. System Portability
4. Software development for excitation control and measurement data acquisition (i.e. a force controlled feedback should be implemented)
5. Delays in instrumentation buying and delivery.

The leverage mechanism

A detailed scheme of the leverage mechanism to transmit forces between the actuator and force platform is shown in figure 2.

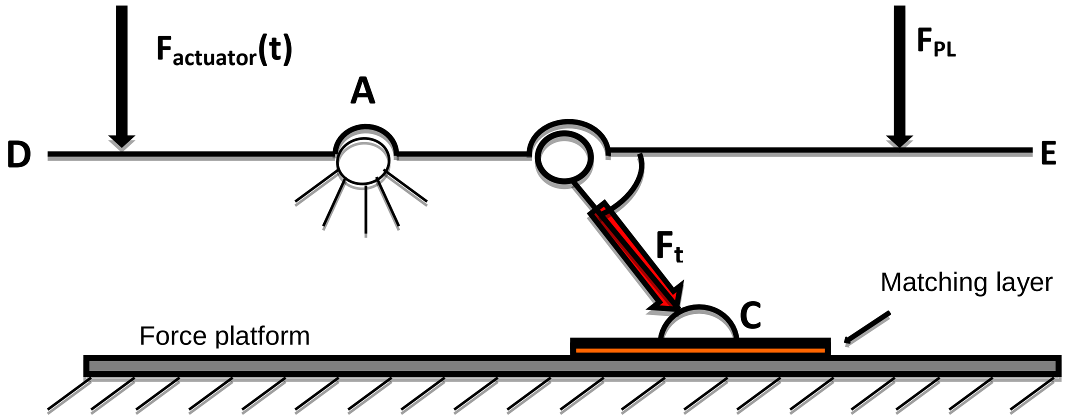

FIGURE 2: Leverage mechanism scheme (y-z plane). $F_{actuator}(t)$: force from the actuator (e.g. shaker, linear actuator, etc.), F_{PL} : preload force , F_t: transmitted force . C: load cell

In figure 2 the mechanical system provides a transmitted force F_t that can be oriented between 0° to about 60° in the elevation plane (i.e. y-z). Moreover the system can transmit an oscillating F_t (e.g. ±700N) superimposed on a static adjustable preload (e.g. +500N), even if forces from the actuator are of low amplitude (e.g. ±150N).

Critical issues on the design and development of the device are:

1. The frame stiffness
2. The displacement of the point application of the actuator excitation ($F_{actuator}$) ,
3. The stiffness of the base where is placed the actuator,
4. The joints friction
5. The force direction should be in the elevation plane (perpendicular to force platform plane)
6. The frame weight and its portability: to exclude frame displacements during calibration (due to reaction forces from the platform) stabilizing masses should be applied, with a total weight up to 2500N.
7. Load cell fixing to force platform by means of a high friction layer (matching layer in figure 2)
8. Design of the frame can be time consuming
9. Delays in frame manufacturing

References

[1] M. Rabuffetti, M. Ferrarin, F. Benvenuti. “Spot check of the calibrated force platform location”. Med. Bio. Eng. Comput., 2001, 39, 638-643.

[2] Y. Ehara, H. Fujimoto, S. Miyazaki, M. Mochimaru, S. Tanaka, S. Yamamoto. “Comparison of the performance of 3D camera systems II”. Gait and Posture, 1997, 5, 251-255.

[3] J. Middelton, P. Sinclair, R. Patton. “Accuracy of centre of pressure measurement using a piezoelectric force platform”. Clinical Biomechanics, 1999, 14, 357-360.

[4] S.T. McCaw, P. DeVita, “Errors in alignement of center of pressure and foot coordinates affect predicted lower extremity torques”. J. Biomech, 1995, 28, 985-8.

[5] M. F. Bobbert, H. C. Schamhardt. “Accuracy of determining the point of force application with piezoelectric force plates”. J. Biomech.,1990, 23, 705 -710.

[6] H. S. Gill, J. J. O’Connor. “A new testing rig for force platform calibration and accuracy tests”. Gait and posture, 1997,5,228-232.

[7] S. H. Collins, P. G. Adamczyk, D. P. Ferris, A. D. Kuo. “A simple method for calibrating force plates and force treadmills using an instrumented pole”. Gait and posture, 2009, 29, 59-64.

[8] M. Rabuffetti, M. Ferrarin, P. Mazzoleni, F.Benvenuti, A. Pedotti. “Optimised procedure for the calibration of the force platform location”. Gait and Posture, 2003, 17, 75-80.

[9] S. R. Goldberg, T. M. Kepple, S. J. Stanhope. “In situ calibration and motion capture transformation optimization improve instrumented tredmill measurements”. Journal of applied biomechanics, 2009, 25, 401-406.

[10] A. Cappello , D. lenzi, L. Chiari. “Periodicalin-situ re-calibration of force platforms: A new method for the robust estimation of the calibration matrix”. Medical and Biological Engineering and Computing , 2004, 42, 350-355.

[11] Y. Fujii, H. Fujimoto. “Proposal for an impulse response evaluation method for force transducers”. Meas. Sci. Technol., 1999, 10, 31-33.

[12] Y. Fujii, H. Fujimoto. “Proposal for an impulse response evaluation method for force transducers”. Meas. Sci. Technol., 1999, 10, 31-33.

[13] P.S. Fairburn, R. Palmer, J. Whybrow, S. Fielden, S. Jones, “A prototype system for testing force platform dynamic

performance”, Gait and Posture 12 (2000) 25–33

[14] Hong-Jung Hsieh, Tung-Wu Lu, Sheng-Chang Chen, Chia-Min Chang b, Chinghua Hung, “A new device for in situ static and dynamic calibration of force platforms” Gait & Posture 33 (2011) 701–705,