Dynamic Calibration of Force Platforms by Means of a Parallel Robot

E. Brau[1], J. Cazalilla[2], M. Vallés[2], A. Besa[3], A.Valera[2], V. Mata[3] and A. Page[1,4]
[1]*Instituto de Biomecánica de Valencia, Universitat Politècnica de Valencia, València, Spain*
[2]*Departamento de Ingeniería de Sistemas y Automática, Universitat Politècnica de València, València, Spain*
[3]*Departamento de Ingeniería Mecánica y de Materiales, Universitat Politècnica de València, València, Spain*
[4]*Grupo de Tecnología Sanitaria del IBV, CIBER de Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN V.), València, Spain*

Keywords: Biomechanics, Force Platform, Calibration, Parallel Robot.

Abstract: Force platforms are the basic equipment to measure ground reaction forces and moments in biomechanical studies. So, accurate in situ calibration of force platforms is critical for ensuring the accuracy and precision of the results of experimental studies. Although there are different avaliable approaches for in situ calibration, most of the existing methods do not use realistic and repeteable force patterns to calibrate platforms. In this paper, a new technique based on the use of a 3PRS parallel robot for applying a predefined dynamical load is proposed, where force patterns can be reproduced in a similar way as the used during actual experimental measures. This robot can be programmed to apply force patterns simulating the conditions of human gait, running or jumping. Calibration is performed by comparing the forces measured by the platform and the ones measured by a calibrated load cell. A new algorithm was developed for correcting the sensitivity coefficients, including an estimation of errors in the orientation of the load cell. This method has been validated by means of an specific experiment.

1 INTRODUCTION

Force platforms (FP) are the basic device for measuring forces and moments in biomechanical studies. Along with human movement analysis systems, they provide the information necessary for the development of inverse dynamic models. Hence, its accuracy is critical in the estimation of the variables associated with these models (Hatze, 2002).

A standard FP is composed of a flat top plate supported by four force transducers, usually piezoelectric or based on strain gauges. Each sensor provides voltage signals that are transformed into forces through the sensitivity coefficients obtained by calibration. Once these forces are measured, it is possible to compute the resultant force and torque associated to the ground reaction.

Usually, the sensitivity coefficients of the transducers are obtained in a calibration process before they are mounted on the FP. However, transducers can undergo small changes in their response over time. There also exist other errors associated with the cross-talk effects, the orientation of the transducers or some effects associated to underload deformations. Therefore, it is necessary to recalibrate the platform after assembling, and also periodically, to ensure that measurements are reliable over time (Schmiedmayer and Kastner, 1999); (Chockalingama et al., 2002).

Several approaches to the recalibration of FP have been published. The first attempts were static, based on devices that apply known forces by means of weights (Hall et al., 1996). Although this kind of methods is quite simple, the applied forces are static and they do not reproduce the dynamic effects of forces during the mesument of actual loads.

Different devices have been proposed to apply dynamic loads for calibrating FP. Rabuffeti et al. (2003) used a bar to manually apply a calibration load, whereas the direction and location of such force was measured by photogrammetry. The device proposed by Collins et al. (2009) is similar, but uses an instrumented bar to fully characterize the applied load. Another alternative is proposed by Cedraro et al. (2009) in which a load cell is used to measure the applied forces. Although all these systems allow applying dynamic forces, such loads are manually

Brau E., Cazalilla J., Vallés M., Besa A., Valera A., Mata V. and Page A..
Dynamic Calibration of Force Platforms by Means of a Parallel Robot.
DOI: 10.5220/0004235901320136
In *Proceedings of the International Conference on Biomedical Electronics and Devices* (BIODEVICES-2013), pages 132-136
ISBN: 978-989-8565-34-1

applied, so they are non-reproducible and rather deviate from patterns of actual loads during biomechanical measurements.

Other alternative based on mechanical devices have been proposed to apply repeatable dynamic loads. The simplest devices used a pendulum to generate dynamic loads (Fairburn et al., 2000). Others use motorized systems that generate forces of inertia, as proposed by Hsieh et (2011). Although both systems can reproduce repeteable patterns of dynamical loads, they are barely versatile and generate force patterns quite different of those produced during biomechanical studies, such as movements during gait, running or jumping.

In addition to the type of device to generate the reference load, it is necessary to define a calibration model. The most common used model assumes a linear relationship between the output signals and the applied forces and moments (Cappello et al, 2004). Recently, other non-linear models for the calibration of the COP have been defined (Cappello et al., 2011; Hsieh et al., 2011). The difference between using linear or non-linear models is especially relevant when the loads applied in the calibration are quite different from those actually applied during the experiments.

The use of robots can be useful to solve these problems since they allow a precise and repeatable generation of dynamical load patterns. In particular, parallel robots have some interesting characteristics in terms of accuracy, load capacity and velocity range, which make them particularly suitable to simulate dynamic patterns as those which appear in biomechanical studies (Diaz-Rodriguez et al., 2010).

This paper proposes a method for FP recalibration by means of a parallel robot instrumented with a calibrated load cell. This experimental device allows simulating patterns of forces similar to the ones produced during walking, running or any other gesture used in biomechanical studies. On the other hand, we used a nonlinear calibration model, which includes an algorithm for correction of the alignment of the platform and the reference cell. This algorithm has been validated through a simulation, while the experimental device has been applied to the calibration of a trading platform.

2 MATERIAL AND METHODS

2.1 Calibration Device. Parallel Robot

The calibration tests were performed on a FP Dinascan-IBV (Farhat et al., 2010). A 3PRS parallel robot with three degrees of freedom was used to apply the patterns of forces on the platform (Diaz-Rodriguez et al., 2010). This robot can be programmed to implement any predefined load pattern whitin a wide range of forces and frequencies (Vallés et al., 2011).

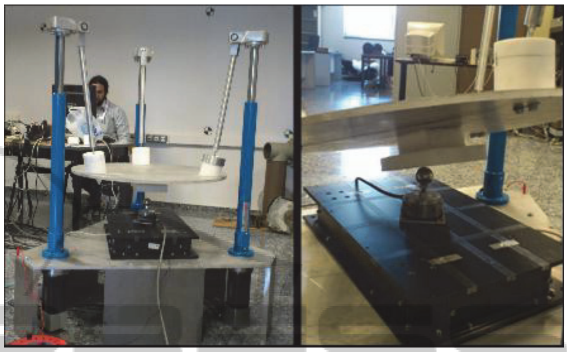

Figure 1: Calibration device. 3PRS parallel robot and calibrated load cell.

The forces were applied on the platform through a calibrated load cell (model Delta, ATI - Industrial Automation), as shown in Figure 1. This cell was placed in seven positions on the platform, defined by a calibration grid. A steel ball was located on the cell to ensure contact at a point. Moreover, a block of teflon was placed in the contact area of the robot actuator to prevent friction-induced oscillations.

Two types of load patterns were applied in this study: a) actual gait patterns, used for the validation of calibration algorithms, and b) calibration load patterns consisting of a sinusoidal load of null minimum value, peak to peak of 500 N and a frequency of 0,5 Hz.

2.2 Platform Model

The modeled FP was a platform DINASCAN-IBV (Farhat et al., 2010). This platform uses four sensors instrumented with strain gauges. Each transducer uses two channels to measure the vertical force and a horizontal force component, respectivley. The equation that relates the applied force and the output sensor for the transducer k is:

$$\begin{bmatrix} V_{Hk} \\ V_{Vk} \end{bmatrix} = \begin{bmatrix} S_{dH} & S_{cH} \\ S_{cV} + S_{mV} & S_{dV} \end{bmatrix}_k \begin{bmatrix} f_{Hk} \\ f_{Vk} \end{bmatrix} = [\mathbf{S}]_k \begin{bmatrix} f_{Hk} \\ f_{Vk} \end{bmatrix} \quad (1)$$

where V_{Hk} and V_{Vk} are the voltage signals measured by the vertical and horizontal channels, respectively. S_{dH} and S_{dV} are the direct sensitivity coefficients, whereas S_{cH} and S_{cV} are the cross-talk sensitivity coefficients. These coefficients are assumed to be constant, which seems to give a linear relationship between applied forces and voltage output. However, S_{mV} is a nonlinear cross-sensitivity coefficient, that models a nonlinear cross-talk effect associated to deformation of transducer when a horizontal force is applied. This deformation affects V_{Vk} in the same way regardless of the direction of the horizontal force f_{Hk}; so, S_{mV} should change its sign when f_{Hk} changes its direction.

Eq. (1) allows to calculate the forces on each sensor from measured V_{Hk} and V_{Vk}. Resultant force and moment can be calculated as:

$$\mathbf{F} = \sum_1^4 f_{Vk} \cdot \mathbf{u}_{Vk} + f_{Hk} \cdot \mathbf{u}_{Hk} \tag{2}$$

$$\mathbf{M}_O = \sum_1^4 \mathbf{r}_k \times (f_{Vk} \cdot \mathbf{u}_{Vk} + f_{Hk} \cdot \mathbf{u}_{Hk}) \tag{3}$$

where $\mathbf{u}_{Vk}$ y $\mathbf{u}_{Hk}$ are the unit vectors corresponding to the vertical direction (OZ axis) and the horizontal direction associated to sensor k (OX or OY axis, depending on the transducer). Vector $\mathbf{r}_k$ is the vector that defines the location of the centre of transducer k with respect to centre of the FP, O.

2.3 Recalibration Algorithm

We assume that the measurements obtained with calibrated load cell are a gold standard. During the recalibration the load cell was placed at m different positions (m=7, in our study), and n load forces have been applied at each position. ${}^j\mathbf{F}_{Ci}$ denotes the force measured by the load cell corresponding to the i-th force (i=1, 2, n) applied at the j-th location (j=1, 2, ..m). ${}^j\mathbf{F}_i$ corresponds to the same force, but measured by the FP. The difference between both values is due to two main sources of error. On the one hand, there are some errors associated with errors in the sensitivity coefficients and also it could be a small error in the alignment of load cell and FP local reference systems.

The error associated with the sensitivity coefficients can be quantified by differentiating (1). Therefore the error in the force measured by sensor k-th is:

$$ {}^j\begin{bmatrix} df_{Hk} \\ df_{Vk} \end{bmatrix}_i = [\mathbf{S}]_k^{-1}\; {}^j\begin{bmatrix} f_H & f_V & 0 & 0 & 0 \\ 0 & 0 & f_H & f_v & \alpha \cdot f_H \end{bmatrix}_{ki} \begin{bmatrix} dS_{dH} \\ dS_{cH} \\ dS_{cV} \\ dS_{dV} \\ dS_{mV} \end{bmatrix}_k \tag{4}$$

where α is coefficient that represents the sign of f_{Hk}.

Having in mind Eq. (2), the difference between force measured by the load cell and the FP is:

$$ {}^j d\mathbf{F}_i = {}^j\mathbf{F}_i - {}^j\mathbf{F}_{Ci} = $$
$$ = \sum [\mathbf{u}_{Hk} \quad \mathbf{u}_{Vk}] \times [\mathbf{S}]_k^{-1}\; {}^j\begin{bmatrix} f_H & f_V & 0 & 0 & 0 \\ 0 & 0 & f_H & f_v & a \cdot f_H \end{bmatrix}_{ki} \begin{bmatrix} dS_{dH} \\ dS_{cH} \\ dS_{cV} \\ dS_{dV} \\ dS_{mV} \end{bmatrix}_k \tag{5}$$

Equation (5) represents a linear system with 3 equations and 5•k=20 unknowns (k = 4 sensors), corresponding to the values of $d\boldsymbol{S}_k$=[dS_{HH}, dS_{HV}, dS_{VH}, dS_{VV} , dS_m] of each sensor. By applying (5) to the n measurements at the m locations of the load cell, we obtain a system with 3×n×m and 20 unknowns that can be solved by least squares. The computed values of $d\boldsymbol{S}_k$ are used to correct the sensitivity coefficients in an iterative process.

In addition to the error associated with the sensitivity coefficients, it is necessary to consider the error of alignement between the FP and the load cell reference systems. This misalignement can be described as a small rotation, ${}^j d\boldsymbol{\theta}$ that propagates as an error in the forces measured by the load cell:

$$ {}^j d\mathbf{F}_{Ci} = {}^j d\boldsymbol{\theta} \times {}^j\mathbf{F}_{Ci} \tag{6}$$

Note that the error associated to the misalignment ${}^j d\boldsymbol{\theta}$ is the same for each location of the load cell, whereas the error in (5) is due to the sensitivity coefficients, and corresponds to the same coefficients for any measurement (i, j). Therefore, ${}^j d\mathbf{F}_{Ci}$ can be estimated as the difference between the measures by the cell and the FP, once the sensitivity coefficients are corrected. The calculation of ${}^j d\boldsymbol{\theta}$ is immediate since it is formally identical to the infinitesimal displacements problem, whose solution is (Page et al., 2009):

$$ {}^j d\boldsymbol{\theta} = {}^j[\mathbf{T}]^{-1} \sum_j [{}^j\mathbf{F}_{Ci} \times \left({}^j\mathbf{F}_{Ci} - {}^j\mathbf{F}_i\right) \tag{7}$$

where, ${}^j[\mathbf{T}]$ is a matrix similar to the tensor of inertia of a point cluster, where the point coordinates are replaced by the components of the forces ${}^j\mathbf{F}_{Ci}$.

The recalibration process consists of an iterative process in which the Eqs. (5) and (7) are consecutively solved until it converges into a stationary solution of the sensitivity coefficients. Two iterations are ussually enough to get a good solution.

2.4 Validation

Two checks have been performed to validate the calibration procedure. First, the recalibration algorithm was validated by means of a simulation that used data from actual measurements of the platform. These data were obtained from real gait and running movements. The "actual" forces were calculated from the nominal values of the sensitivity coefficients and the voltage signals measured by the transducers.Then, a random error of 10% was added to the sensitivity coefficients, thus obtaining the forces corresponding to the "uncalibrated" FP.

Using these data, the proposed recalibration algorithm has been applied, and the results were compared with those obtained with a recalibration matrix as it is proposed in the literature (Collins et al, 2009).

The second validation consisted of an experiment. The platform was recalibrated by applying a senoidal forces with a null minimum value, peak to peak value of 500 N and a frequency of 0.5 Hz. The load cell was placed at seven different positions and loads with different orientations of the horizontal force applied at each location.

3 RESULTS

Figure 2 shows the results of a simulation with a gait force pattern (left side) and a running pattern (right side). The blue dotted line corresponds to the "actual" forces calculated from the nominal sensitivity coefficients and the voltage output of the transducers. Red line represents the forces corresponding to the "uncalibrated FP", calculated after introducing an error in the sensitivity coefficients. These errors are large, especially in the vertical force. Finally, the solid blue line represents the force obtained after correcting the errors in the sensitivity coefficients from the proposed algorithm. Only two iterations were used.

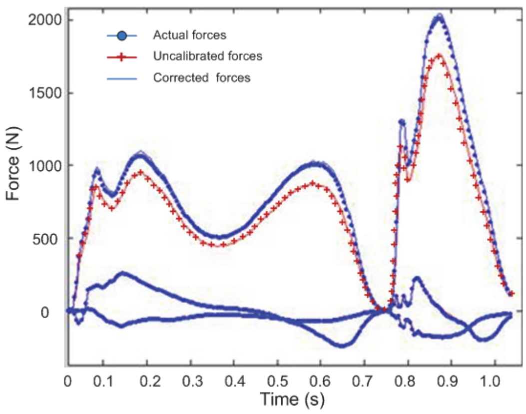

Figure 2: Force patterns in the validation of the calibration algorithm by simulation.

Table 1 shows the rms values of the errors, expressed as a percentage of the actual value. The first column shows the errors in each component of the force. The second one displays the errors that would be obtained if a matrix of recalibration had applied, assuming a linear model. As it can be seen, the linear approximation provides good recalibration; however, important errors remain in the Y component, probably due to the non-linear nature of the S_{mV} coefficient. The X and Z components present smaller errors. When the proposed model of FP is applied, the residual errors are very small, less than 1% in all cases.

Table 1: RMS of errors in force components (% of the actual values).

	Uncalibrated FP	After linear recalibration	After recalibration with the proposed model
X	4.6%	1.8%	0.1%
Y	14.1%	1.1%	0.5%
Z	20.0%	7.6%	0.4%

Table 2 shows the results of the experimental validation. In this case, the nominal sensitivity coefficients of the platform were used as initial data. For these values, the initial error is not too large in absolute values, which indicates that the coefficients used in the previous calibration have not experienced large variations. The greater relative errors of horizontal components are due to the small amplitude of such forces in the experiment (around 60 N). However, after applying the recalibration procedure we obtain an improvement of 30% in the case of the horizontal forces. On the contrary, the improvement in the error in the vertical component is not noticeable. In any case, the results show that the proposed method allows to effectively recalibrating FP by using dynamic force patterns.

Table 2: RMS values of force errors before and after the recalibration process (Newton; in parentheses as a percentage of the peak to peak values).

	Before recalibration	After recalibration
X component	4.8 N (8.1%)	2.9 N (4.9%)
Y component	5.3 N (8.8%)	3.9 N (6.5%)
Z component	7.7 N (1.5%)	6.7 N (1.3%)

4 DISCUSSION AND CONCLUSIONS

This paper presents a device for calibrating FP based on a 3PRS parallel robot. The robot was programmed to apply forces similar to those produced in human gait and running.

Parallel robots can generate dynamic forces in a realistic and repeatable way. In this sense, realism is improved compared to static calibration systems (Hall et al., 1996) or dynamic systems using mechanical devices, which do not represent real efforts during clinical applications (Fairburn et al., 2000); (Hsieh et al., 2011)

Moreover, the system allows programming any kind of force in a wide range of amplitudes and temporal patterns, which improves other manual systems as described by other authors (Rabuffeti et al., 2003); (Collins et al., 2009); (Cedraro et al., 2009). The robot is able to apply cyclic repeatable forces, allowing analyzing effects such as hysteresis or potential drifts of the sensors.

We also propose a recalibration algorithm that allows characterizing the sensitivity coefficients of each sensor. The procedure is not based on a linear recalibration matrix, but performs the calibration of each sensor using a nonlinear model. This model also includes a process for correcting the orientation of the load cell used as a reference. The results obtained show that this procedure offers better results than some systems based on linear models.

In short, parallel robots are robust and versatile devices able to generate dynamic load patterns similar to the forces that appear in biomechanical studies. Combined with a suitable calibration algorithm, they can be very useful for dynamic calibration of FP.

ACKNOWLEDGEMENTS

This work has been funded by the Spanish Government and co-financed by EU FEDER funds (Grants DPI2009-13830-C02-01, DPI2009-13830-C02-02 and IMPIVA IMDEEA/2011/ 93).

REFERENCES

Cappello, A., D. Lenzi, D., Chiari, L., (2004). Periodical in-situ re-calibration of force platforms: a new method for the robust estimation of the calibration matrix. *Medical and Biological Engineering and Computing*, 42, pp. 350–355.

Cappello A., Bagala, F., Cedraro, A., Chiari, L., (2011). Non-linear re-calibration of force platforms. *Gait & Posture* 33, pp: 724–726.

Cedraro, A., Cappello, A., Chiari, L., (2009). A portable system for in-situ re-calibration of force platforms: experimental validation. *Gait & Posture*, 29, pp. 449–453.

Chockalingama, N., Giakasb, and Iossifidoua, A., (2002). Do strain gauge force platforms need in situ correction? *Gait & posture*, 16(3), pp: 233-237.

Collins, S. H., Adamczyk, P. G., Ferris, D. P., Kuo, A. D., (2009). A simple method for calibrating force plates and force treadmills using an instrumented pole. *Gait Posture*. 2009, 29(1): 59–64.

Díaz-Rodríguez, M., Mata, V., Valera, V., Page, A. (2010). A methodology for dynamic parameters identification of 3-DOF parallel robots in terms of relevant parameters. *Mechanisms and Machine Theory*, 45(9), pp 1337–1356.

Fairburn, P. S., Palmer, R., Whybrow, J., Fielden, S., Jones, S., (2000). A prototype system for testing force platform dynamic performance. *Gait and Posture*, pp: 25–33.

Farhat, N., Mata, V., Rosa, D., Fayos, J, (2010). A procedure for estimating the relevant forces in the human knee using a four-bar mechanism. *Computer Methods in Biomechanics and Biomedical Engineering*, 13(5), pp 577-587.

Hall, M. G., Fleming, H. E., Dolan, M. J., Millbank, S. F. D., Paul, J. P., (1996). Static in Situ Calibration of Force Plates. *J. Biomechanics*, 29(5), pp. 659-665, 1996.

Hatze, H., (2002). The fundamental problem of myoskeletal inverse dynamics and its implications. *Journal of Biomechanics*, 35(1), pp 109–115.

Hsieh, H.-J., Lu, T.-W. Chen, S.-H., Chang,C.-M., Hung, C.(2011). A new device for in situ static and dynamic calibration of force platforms. *Gait & Posture* 33, pp: 701–705.

Page, A., de Rosario, H., Mata, V., Atienza, C., (2009). Experimental analysis of rigid body motion. A vector method to determine finite and infinitesimal displacements from point coordinates. *Journal of Mechanical Design* 131, 031005 (8 pp.).

Rabuffetti, M. Ferrarin, M., Mazzoleni, P., Benvenuti, F., Pedotti, A. (2003). Optimised procedure for the calibration of the force platform location. *Gait and Posture* 17, pp: 75-80.

Schmiedmayer, H. B., Kastner, J., (1999). Parameters influencing the accuracy of the point of force application determined with piezoelectric force plates. *J. Biomech*., 32, pp. 1237–1242.

Vallés, M., Díaz-Rodríguez, M., Valera, A., Mata, V., Page, A., (2011) Mechatronic developmentand dynamic control of a 3 dof parallel manipulator. *MUSME 2011, the Int. Symposium on Multibody Systems and Mechatronics*, Valencia, Spain, 25-28 October 2011.