Periodical *in-situ* re-calibration of force platforms: a new method for the robust estimation of the calibration matrix

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Abstract—*The paper provides a new technique based on a least-squares approach for the accurate estimation of a force platform calibration matrix using simple manual procedures, when the direction of the applied loads cannot be perfectly aligned with the axes of the platform. This new procedure can be applied to all force platforms and allows the combined application of vertical and horizontal forces, both static and time-varying. The robust calibration method includes the angular errors in the least-squares parameter vector, thus reducing the bias in the estimated calibration matrix parameters. The performance of the robust method was compared with the conventional one, using a numerical simulation approach starting from a known calibration matrix. With the conventional approach, in noiseless conditions, the maximum error due to load misalignment (SD = 3°) was 6% for the direct terms and over 10% for the cross-talk terms. With the robust method, these errors reduced to zero and were always below 0.4%, even when realistic noise was superimposed on the measures. With perfectly aligned loads and realistic output noise, the confidence intervals of the calibration matrix parameters were very similar for the two methods, demonstrating that the increased number of parameters did not affect the reliability of the estimate.*

Keywords—*Force platform, Calibration matrix, Robust estimation, Movement analysis, Spot-check*

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1 Introduction

FORCE PLATES are the standard kinetic measurement devices in balance assessment and are commonly used to measure ground reaction forces (GRFs) and the trajectory of the centre of pressure (COP) during walking or balance-related tasks. They are complex, precision instruments and require an accurate calibration process that is usually accomplished by the manufacturer prior to delivery.

Exposure, age and *in-situ* installation procedures can cause changes in instruments' sensitivity over time and undesired cross-talk between measured variables, leading to a general lack of accuracy (CHOCKALINGAM *et al.*, 2002). This can cause systematic errors on the measured GRFs and COP, which are particularly important when the signal variability is small (BOBBERT and SCHAMHARDT, 1990; MITA *et al.*, 1993; HALL *et al.*, 1996; BROWNE and O'HARE, 2000). These errors can propagate to the accuracy of quantities such as joint forces and moments, which are estimated from kinetic and kinematic data through an inverse dynamics approach (CAPPOZZO, 1984; WINTER, 1991) or the location of body centre of mass (COM), which is often obtained by double integrating the measured GRF (LENZI *et al.*, 2003).

For this reason, a quality control is advisable to determine any appreciable deviation from stated measurement accuracy. This control includes initial testing and revisions to the calibration on every conventional or experiment-specific installation (e.g. when force plates are moved or when stairs or a seat are attached to the platform) and routine *in-situ* monitoring through standard measurements (*spot-check*) (FLEMING *et al.*, 1997; GILL and O'CONNOR, 1997; BROWNE and O'HARE, 2000) to check that the measurement system continues to measure correctly. The estimation of the calibration matrix and the comparison with the one provided by the manufacturer, which is unique for each plate, may be a valid spot-check of functionality and good calibration (HALL *et al.*, 1996).

In particular, the calibration performed with the platform *in situ* allows evaluation of the system as it will be used, eliminating possible inaccuracies due to preloading of the plates during mounting. *In-situ* calibration also minimises disturbance to the routine working of the laboratory.

Proposals for calibration and testing procedures have been made by GOLA (1980), HALL *et al.* (1996), FAIRBURN *et al.* (2000) and the CAMARC II (1994) partners. Calibrated weights or accurate load cells and grids applied to the platform surface can be used easily and accurately to control the

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magnitude and the application point of the applied load. On the contrary, control of the orientation of the applied loads with respect to the platform reference frame is rather difficult, and, when the procedure is performed manually or by non-technical personnel, this is a largely critical point.

All tests proposed so far for quality assessment need to ensure 'pure' loads acting in a known direction only (HALL *et al.*, 1996; CAMARC II, 1994), which is particularly difficult for horizontal directions. Hence, these procedures suggest using complicated rigs that make the tests accurate but also complex and time-consuming. In contrast, in the clinical or laboratory setting, calibration and testing procedures should be simple enough to be easily performed by non-technical personnel and fast enough to minimise disturbance to the working of the laboratory. The use of complicated rigs and the relative mounting (GILL and O'CONNOR, 1997), un-mounting and fine-tuning procedures should be avoided. As a consequence, the majority of laboratories do not assess force platforms' accuracy *in situ* on a regular basis (CHOCKALINGAM *et al.*, 2002).

The aim of this study was to provide a new technique based on a least-squares approach for the accurate estimation of a force platform calibration matrix using simple, manual procedures, even when the direction of the applied loads is only approximately known.

2 Methods

2.1 *Basic method*

Several models have been proposed in the literature for a force platform input–output relationship. Some models consider both linear and non-linear terms, using non-linear terms to account for elastic deformations of the transducers (DUBOIS, 1981) or of the top of the platform (SCHMIEDMAYER and KASTNER, 1999; 2000) when a load is applied. As new commercial platforms guarantee a small non-linearity error, only linear terms are generally considered in common practice.

A six-component platform has six outputs. If the outputs were proportional to the three components of the applied force and to the three moments about the origin of the plate, the calibration process would be reduced to the estimation of each proportionality coefficient. Unfortunately, this is only approximately true, and cross-talk between measured variables is generally present. All the output signals differ from zero, even if pure horizontal or vertical forces are applied. This relationship can be expressed as

$$\boldsymbol{V} = \boldsymbol{S}\boldsymbol{L} \tag{1}$$

where $\boldsymbol{L} = [F_X, F_Y, F_Z, M_X, M_Y, M_Z]^{\mathrm{T}}$ is the load vector, $\boldsymbol{V} = [V_1, \ldots, V_6]^T$ is the corresponding output signal vector, and $\boldsymbol{S}$ is the $[6 \times 6]$ non-diagonal sensitivity matrix.

As a consequence, each load component can be calculated as a linear combination of all the outputs

$$\boldsymbol{L} = \boldsymbol{C}\boldsymbol{V} \tag{2}$$

where $\boldsymbol{C} = \boldsymbol{S}^{-1}$ is the calibration matrix of the measurement system. The diagonal terms of $\boldsymbol{C}$ are the direct calibration coefficients between each load component and the corresponding output. The off-diagonal terms quantify the cross-talk among the channels and are generally considerably smaller than the direct coefficients by construction.

Calibration is generally achieved by applying known forces and moments to the plate and recording the output signals of the force plate and amplifier system. Then, for each set of loads, (2) can be written with the elements of $\boldsymbol{C}$ as the unknown coefficients (BERME, 1990). If N linearly independent load and output signal sets are combined in the same equation, then (2) can be written as

$$\boldsymbol{L} = \begin{bmatrix} F_X^1 \\ \vdots \\ F_X^N \\ \vdots \\ M_Z^1 \\ \vdots \\ M_Z^N \end{bmatrix} = \begin{bmatrix} \boldsymbol{U} & 0 & 0 & 0 & 0 & 0 \\ 0 & \boldsymbol{U} & 0 & 0 & 0 & 0 \\ 0 & 0 & \boldsymbol{U} & 0 & 0 & 0 \\ 0 & 0 & 0 & \boldsymbol{U} & 0 & 0 \\ 0 & 0 & 0 & 0 & \boldsymbol{U} & 0 \\ 0 & 0 & 0 & 0 & 0 & \boldsymbol{U} \end{bmatrix} \begin{bmatrix} C_{11} \\ \vdots \\ C_{16} \\ \vdots \\ C_{61} \\ \vdots \\ C_{66} \end{bmatrix}$$

$$= \boldsymbol{S}_U \boldsymbol{\theta} \quad \boldsymbol{U} = \begin{bmatrix} V_1^1 & \cdots & V_6^1 \\ \vdots & \vdots & \vdots \\ V_1^N & \cdots & V_6^N \end{bmatrix} \tag{3}$$

where $\boldsymbol{L}$ $(6N \times 1)$ contains the load components applied to the plate in each set, and U_{ij} $(i = 1, \ldots, N; j = 1, \ldots, 6)$ is the value of the jth output signal in the ith set. The (36×1) parameter vector $\boldsymbol{\theta}$ contains the calibration coefficients (i.e. the elements of $\boldsymbol{C}$) ordered by row.

To solve (3), both sides are pre-multiplied by the pseudo-inverse matrix $(\boldsymbol{S}_U^T \boldsymbol{S}_U)^{-1} \boldsymbol{S}_U^T$

$$\boldsymbol{\theta} = (\boldsymbol{S}_U^T \boldsymbol{S}_U)^{-1} \boldsymbol{S}_U^T \boldsymbol{L} \tag{4}$$

To determine $\boldsymbol{\theta}$, the sensitivity matrix $\boldsymbol{S}_U$ must have a number of rows $6N \geq 36$. Then, a minimum number of six linearly independent tests are needed. However, to minimise the effect of errors, which are always present and statistical in nature, more than six load sets are usually adopted (BERME, 1990). In this case, (4) corresponds to the least-squares estimate of $\boldsymbol{\theta}$. The sensitivity matrix $\boldsymbol{S}_U$ allows for the computation of the covariance matrix of the parameter $\Sigma(\boldsymbol{\theta})$ that can be regarded as an estimate of parameter accuracy (DRAPER and SMITH, 1966).

2.2 *Robust calibration method*

In general, calibration tests require the application of several loading configurations to the platform in static or dynamic conditions. To provide independent sets of load components, the combination of a known vertical force F_V and a known horizontal force F_H can be applied to given points on the platform surface, orienting F_H along one of the two horizontal axes in the platform reference frame (Fig. 1). Instantaneous values of moment components applied to the platform can be calculated from the knowledge of the force components, which can be time-varying in general, and the point of application of the resultant force $\boldsymbol{F}$.

If the orientation of calibration forces in each loading configuration is obtained manually, without the use of complicated precision rigs, errors in the alignment with respect to the

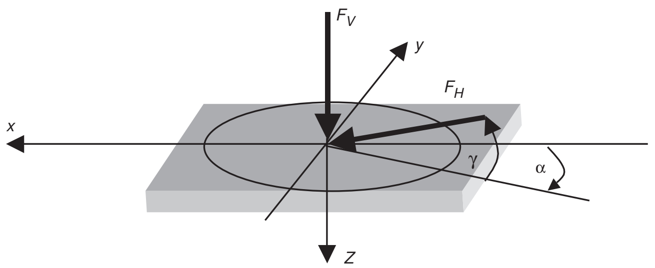

Fig. 1 *Errors (magnified for better visualisation) on orientation of calibration force. Elevation γ and azimuth α of horizontal component with respect to force platform reference frame xyz*

platform reference frame can cause inaccuracies in the estimation of calibration coefficients. In particular, the direction of the horizontal component can be affected by an angular error in azimuth and elevation (Fig. 1). We assume stability of the load, and, hence, this horizontal misalignment error can be considered constant during data acquisition in each loading configuration. The vertical component is generally produced through gravity and is considered free from orientation errors.

If small errors γ and α in the orientation of the horizontal calibration force are considered, then the components of the force effectively applied to the platform are

$$\begin{aligned} F_X &= F_H \cos(\alpha)\cos(\gamma) \approx F_H \\ F_Y &= F_H \sin(\alpha)\cos(\gamma) \approx F_H\alpha \\ F_Z &= F_V + F_H \sin(\gamma) \approx F_V + F_H\gamma \end{aligned} \tag{5}$$

when the force is oriented along the x-axis (α is the angular error with respect to the x-axis), or

$$\begin{aligned} F_X &= F_H \sin(\alpha)\cos(\gamma) \approx F_H\alpha \\ F_Y &= F_H \cos(\alpha)\cos(\gamma) \approx F_H \\ F_Z &= F_V + F_H \sin(\gamma) \approx F_V + F_H\gamma \end{aligned} \tag{6}$$

when the force is oriented along the y-axis (α is, here, the angular error with respect to the y-axis).

Moment components depend on alignment errors through force components

$$\begin{aligned} M_X &= F_Z Y_{COP} + hF_Y \\ M_Y &= -F_Z X_{COP} - hF_X \\ M_Z &= -F_X Y_{COP} + F_Y X_{COP} \end{aligned} \tag{7}$$

where X_{COP}, Y_{COP} and h are the co-ordinates of the point of application of $\boldsymbol{F}$ in the platform reference frame.

From (5)–(7), each force and moment can be expressed as

$$\begin{aligned} F &= F_0 + F_\alpha \alpha + F_\gamma \gamma \\ M &= M_0 + M_\alpha \alpha + M_\gamma \gamma \end{aligned} \tag{8}$$

where F_0, F_α, F_γ, M_0, M_α, M_γ depend on F_H, F_V, X_{COP}, Y_{COP}, h and on the x- or y-direction of the horizontal load.

In the case of N independent loads, (8) can be written in matrix form as

$$\boldsymbol{L} = \boldsymbol{L}_0 + \boldsymbol{L}_\alpha \boldsymbol{\alpha} + \boldsymbol{L}_\gamma \boldsymbol{\gamma} \tag{9}$$

where $\boldsymbol{\alpha}$, $\boldsymbol{\gamma}$ are the $(N \times 1)$ alignment error vectors, $\boldsymbol{L}_0$ is a $(6N \times 1)$ vector representing the load components applied in the absence of alignment errors, and $\boldsymbol{L}_\alpha$ and $\boldsymbol{L}_\gamma$ are $(6N \times N)$ matrices representing the load sensitivity to alignment errors.

From (3) and (9), we obtain

$$\begin{aligned} \boldsymbol{L}_0 = \boldsymbol{S}_U\boldsymbol{\theta} - \boldsymbol{L}_\alpha\boldsymbol{\alpha} - \boldsymbol{L}_\gamma\boldsymbol{\gamma} &= \begin{bmatrix} \boldsymbol{S}_U & -\boldsymbol{L}_\alpha & -\boldsymbol{L}_\gamma \end{bmatrix} \begin{bmatrix} \boldsymbol{\theta} \\ \boldsymbol{\alpha} \\ \boldsymbol{\gamma} \end{bmatrix} \\ &= \boldsymbol{S}_A\boldsymbol{\theta}_A \end{aligned} \tag{10}$$

where $\boldsymbol{S}_A$ and $\boldsymbol{\theta}_A$ are the augmented $(6N \times (36 + 2N))$ sensitivity matrix and the augmented $((36 + 2N) \times 1)$ parameter vector.

The least-squares solution of (10) is

$$\boldsymbol{\theta}_A = \left(\boldsymbol{S}_A^T\boldsymbol{S}_A\right)^{-1}\boldsymbol{S}_A^T\boldsymbol{L}_0 \tag{11}$$

The minimum number of linearly independent load sets required to determine $\boldsymbol{\theta}_A$ can be demonstrated to be 9. In fact, the number of rows $6N$ of the augmented sensitivity matrix must be greater than or equal to the dimension of the augmented parameter vector $36 + 2N$. In practice, five test points, as shown in Fig. 2, with two load directions each, seem to be a good choice.

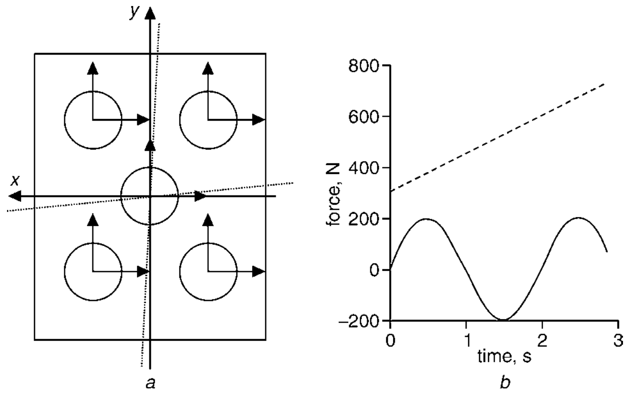

Fig. 2 *(a) Top view of points and directions of application of horizontal and vertical loads; (b) time course of (—) horizontal F_H and (– – –) vertical F_V loads*

As noise affecting the outputs $\boldsymbol{V}$ of the measurement system (and then $\boldsymbol{S}_U$) is always present, the estimates given by (11) are, in general, biased. To obtain an unbiased estimate of $\boldsymbol{\theta}_A$, the relationship should be inverted, assuming $\boldsymbol{V}$ as the output. Taking into account (2) and (9), we obtain

$$\boldsymbol{V} = \boldsymbol{C}^{-1}\boldsymbol{L} = \boldsymbol{C}(\boldsymbol{\theta})^{-1}(\boldsymbol{L}_0 + \boldsymbol{L}_\alpha\boldsymbol{\alpha} + \boldsymbol{L}_\gamma\boldsymbol{\gamma}) + \boldsymbol{\varepsilon} = \boldsymbol{f}(\boldsymbol{\theta}_A) + \boldsymbol{\varepsilon} \tag{12}$$

where $\boldsymbol{f}$ is a non-linear vector function and $\boldsymbol{\varepsilon}$ is the noise vector affecting the outputs $\boldsymbol{V}$.

An iterative non-linear weighted-least-squares method (DRAPER and SMITH, 1966; CAPPELLO *et al.*, 1996) is then applied, choosing the estimate given by (11) as an initial guess for the parameters $\boldsymbol{\theta}_A$. At each iteration, the function $\boldsymbol{f}$ is linearised by numerical differentiation about the current value of $\boldsymbol{\theta}_A$, producing the corresponding sensitivity matrix $\boldsymbol{S}_V(\boldsymbol{\theta}_A) = \partial\boldsymbol{f}/\partial\boldsymbol{\theta}_A$. The parameter vector $\boldsymbol{\theta}_A$ is then updated by addition of the maximum likelihood adjustment term

$$\Delta\boldsymbol{\theta}_A = (\boldsymbol{S}_V^T\boldsymbol{W}\boldsymbol{S}_V)^{-1}\boldsymbol{S}_V^T\boldsymbol{W}(\boldsymbol{f}(\boldsymbol{\theta}_A) - \boldsymbol{V}) \tag{13}$$

where $\boldsymbol{V}$ is the measured output, $\boldsymbol{f}(\boldsymbol{\theta}_A)$ is the output of the non-linear model (12) corresponding to the current estimate of $\boldsymbol{\theta}_A$, and $\boldsymbol{W}$ is the $(6N \times 6N)$ weighting matrix that allows us to take into account different variances and cross-correlations between noise components. If the noise is normally distributed, and its six components are not cross-correlated, $\boldsymbol{W}$ is diagonal and is made up of six matrices $\boldsymbol{W}_i = \sigma_n^2/\sigma_i^2\boldsymbol{I}$, lined along its diagonal, where $\boldsymbol{I}$ is the $(N \times N)$ identity matrix, σ_i^2 is the variance of the ith noise component, and σ_n^2 is the value chosen for normalisation.

The iterative correction of the parameter estimates determines a gradual decrease in the cost function, $(\boldsymbol{f}(\boldsymbol{\theta}_A) - \boldsymbol{V})^T\boldsymbol{W}(\boldsymbol{f}(\boldsymbol{\theta}_A) - \boldsymbol{V})$. The iteration is stopped, and the value of $\boldsymbol{\theta}_A$ is taken as the final estimate, when $\Delta\boldsymbol{\theta}_A$ becomes negligible, in norm, with respect to the previous iteration.

The sensitivity matrix $\boldsymbol{S}_V$ plays a dominant role in the procedure described above, as it allows calculation of the $\boldsymbol{\theta}_A$ covariance matrix

$$\Sigma(\boldsymbol{\theta}_A) = (\boldsymbol{S}_V^T\boldsymbol{W}\boldsymbol{S}_V)^{-1}\sigma_n^2 \tag{14}$$

which can be regarded as a measure of the estimation process accuracy.

2.3 *Simulated calibration procedure*

To evaluate the performance of the new estimation method, the calibration procedure was simulated on a hypothetical platform with a known calibration matrix. For this purpose, we considered the calibration matrix given for a commercial strain

Table 1 Percentage error on calibration parameters estimated with basic calibration method, when errors on alignment of calibration load are present: simulated calibration matrix and maximum error on calibration coefficients estimated through basic method. Error on each calibration parameter is expressed as percentage of relative direct calibration coefficient (principal diagonal, on same row) and refers to worst case obtained over 500 simulations

$\boldsymbol{C}$						Max $\Delta\boldsymbol{C}$%					
1279.9	7.4	−13.8	2.5	−1.5	10.6	0.49	7.74	0.05	2.46	0.87	10.59
−33.8	1278.7	−0.8	−5.9	11.2	−15.6	6.9	0.34	0.09	0.29	0.82	9.35
−18.6	8.4	1904.7	−8.7	−10.7	8.1	5.82	5.11	0.08	1.58	0.8	9.5
0.6	−51.1	−6	709.7	−1.2	0.7	1.45	1.29	0.02	0.36	0.26	2.39
55.2	4.2	−0.3	−0.4	501.3	2.4	1.72	2.02	0.03	0.63	0.27	3.42
3.2	−5.7	1.6	−1.9	3.4	298.7	3.56	3.25	0.04	0.96	0.58	6.04

Table 2 95% confidence intervals for calibration matrix parameter estimates in case of noisy outputs and perfect alignment between calibration force and force plate reference frame

Basic method, $CI_{95}(\theta)$						Robust method, $CI_{95}(\theta_A)$					
0.05	0.05	0.05	0.2	0.14	0.08	0.05	0.14	0.05	0.2	0.14	0.11
0.05	0.05	0.05	0.2	0.14	0.08	0.14	0.05	0.05	0.2	0.14	0.1
0.06	0.06	0.06	0.2	0.16	0.09	0.09	0.09	0.06	0.2	0.16	0.15
0.02	0.02	0.02	0.09	0.07	0.04	0.03	0.02	0.02	0.1	0.07	0.04
0.03	0.03	0.02	0.1	0.07	0.04	0.03	0.03	0.02	0.1	0.07	0.06
0.06	0.06	0.05	0.2	0.16	0.09	0.06	0.06	0.05	0.2	0.16	0.1

Table 3 Combined effect of noise and misalignment error. Maximum errors are expressed as in Table 1

Basic method, Max $\Delta\boldsymbol{C}$%						Robust method, Max $\Delta\boldsymbol{C}$%					
0.47	6.23	0.098	1.72	0.91	11.2	0.08	0.23	0.08	0.29	0.20	0.16
8.02	0.42	0.13	0.55	0.88	13.7	0.25	0.07	0.07	0.3	0.25	0.15
4.84	4.66	0.11	1.65	0.88	8.28	0.13	0.14	0.09	0.38	0.25	0.25
1.34	1.39	0.036	0.44	0.23	2.58	0.04	0.04	0.03	0.13	0.11	0.07
1.62	1.69	0.048	0.65	0.29	2.98	0.05	0.05	0.04	0.17	0.12	0.09
3.28	2.30	0.09	0.97	0.55	6.40	0.10	0.09	0.08	0.40	0.22	0.15

gauge platform*. A simulated force with known, time-varying, horizontal and vertical components was applied at five different points on the surface of the platform (Fig. 2*a*). The patterns of the two force components, shown in Fig. 2*b*, though indicative, were selected according to design criteria including realistic range for most motor/postural tasks and easy reproducibility in practice. The horizontal component was assumed to be oriented, in separate tests, along the two horizontal axes of the reference frame. A total of ten tests were simulated, each lasting 30 s. The outputs were simulated from the given calibration matrix and sampled at 20 Hz.

The effect of misalignment errors on the estimates of the calibration coefficients was evaluated by simulation of a random angular deviation between the applied force and the platform reference frame. The procedure was repeated 500 times, considering a Gaussian distribution for the misalignment errors with zero mean and a standard deviation of 3°. The estimates given by the new and the basic estimation methods were then compared in terms of differences with the corresponding coefficients in the known calibration matrix. In particular, differences were considered for each calibration coefficient as a percentage of the relative direct calibration coefficient (principal diagonal term on the corresponding row of the calibration matrix).

When noise is present in the outputs of a system, a larger number of parameters often lead to a higher dispersion, i.e. lower accuracy, in their estimates. To evaluate the effect of the larger number of parameters on the estimates, we superimposed Gaussian noise on the six outputs with zero mean and realistic variances, as measured on the commercial platform. Normalised 95% confidence intervals (DRAPER and SMITH, 1966) of the estimates were calculated for the new and the basic methods in the absence of misalignment errors. For the *i*th coefficient, the normalised 95% confidence interval can be expressed as

$$CI_{95}(\theta_{Ai}) = \frac{\sqrt{\Sigma_{i,i}}}{\theta_i} t(df, 1 - 0.025) \tag{15}$$

where *df* is the number of degrees of freedom, *t* is the Student's *t*-distribution, and Σ is the parameter covariance matrix (14).

The combined effect of misalignments and noise was finally evaluated.

3 Results

Table 1 reports the calibration matrix considered for the simulation and the errors obtained on the estimates of calibration coefficients, if the basic estimation method (4) is used in the presence of a misalignment error in each calibration test and with noiseless outputs. Errors are given as a percentage of the corresponding direct sensitivity coefficient's true value, reported in Table 1. Misalignment errors propagate to the elements of $\boldsymbol{C}$, and, when $\boldsymbol{C}$ is estimated by the basic method, the error reaches 6% on the direct sensitivity coefficients and 10.6% on the cross-talk coefficients (this may correspond to huge errors, larger than 1000%, if compared with the actual value of the off-diagonal terms). With the robust method, the estimation error due to misalignment is zero.

*Bertec, model 4060-08

In Table 2, the 95% confidence interval for each calibration coefficient is reported when noise is superimposed on the output signals and the calibration force is applied in the absence of misalignment errors. The results show that, in ideal alignment conditions, the robust method and basic method achieve very similar accuracy on the estimates.

Finally, in Table 3, the combined effect of output noise and alignment errors is considered, and the maximum percentage error on each element of $\boldsymbol{C}$ over the 500 trials is reported. In this general condition, the robust method behaves significantly better than the basic one, and the percentage error is always below 0.4%.

4 Discussion

In movement analysis, the importance of accurate measurements is critical when inverse dynamics is used to compute joint forces and torques. Errors in the determination of moments about the horizontal axes and, more importantly, errors in the vertical force can propagate to the COP. Horizontal forces contribute to the estimates of joint moments with large moment arms. Their contribution is significant, and errors propagate with a coefficient given by the moment arm on each joint. Furthermore, in balance-related studies, the difference between COM and COP is important and is usually small. COP measure and COM estimation, which depend on horizontal forces, should be accurate (LENZI *et al.*, 2003). Some authors showed that the force plate manufacturer's specifications, especially on cross-talk, can permit large errors on some measured values (HALL *et al.*, 1996). To ensure accurate force plate performance, clinical and research laboratories should adopt quality control procedures on a regular basis.

The aim of this study was to provide a new least-squares algorithm for the accurate estimation of a force platform calibration matrix, even in the case of simple, manual procedures when the direction of the applied loads cannot be perfectly aligned with the axes of the platform. We only considered errors in the alignment of the horizontal component. The proposed algorithm may reduce the complexity of the rigs needed for quality assessment and recalibration of the force platform. It may also allow the use of manual procedures that can be applied by non-technical personnel.

This was accomplished by including the angular deviations in the parameter vector. In the basic method, the elements of $\boldsymbol{L}$ can be considered separately when estimating the calibration parameters in the regression equation (2). The inclusion of the angular errors in the model makes this impracticable, as the number of unknowns becomes higher than the number of regression coefficients. This analysis is possible only if we jointly solve these equations, which are related to each other through the misalignment angles. The robust approach permits the specific information carried by each load component in every test to be included in a single multivariate regression analysis, while adjustment is made for the correlation between calibration force components.

A larger number of parameters usually induce a greater dispersion in the estimates. The robust estimator, however, showed very similar estimation accuracy (expressed as 95% confidence intervals on the calibration coefficient estimates) with respect to the basic method, even in ideal experimental conditions when the calibration force is applied without misalignment errors.

The application of pure vertical or horizontal forces can cause inaccuracies in the determination of the calibration matrix (DUBOIS, 1981; CAMARC II, 1994; FLEMING *et al.*, 1997). As an alternative, this new method considers applied forces with both a vertical and a horizontal component. Moreover, forces can also vary in time, and hence, loading conditions can be recreated where dynamic patterns of the load can explore the whole range of gait and balance control dynamics.

In the calibration procedure, the point of application of the force was considered to be known. This problem has already been addressed in the literature, and grids or rigs have been proposed (BOBBERT and SCHAMHARDT, 1990; GILL and O'CONNOR, 1997) for force application to the platform surface. Even if the applied forces are time-varying, the samples in the same trials are not linearly independent, and nine trials are needed. The redundancy of information is important to reduce the effect of noise.

The proposed algorithm is completely independent from the particular output units of the measurement system. If only force and moment components are directly accessible as outputs, the calibration matrix obtained by the new calibration method is dimensionless and should be applied to the output to obtain a calibrated measure of ground reactions.

5 Conclusions

A new method was presented for the robust estimation of a force platform calibration matrix. This method can be applied to all force platforms, as the representation of the input–output relationship with a calibration matrix is of general validity and can also be applied to piezo-electric platforms. The estimation of the calibration matrix allows for quantification of and, eventually, compensation for direct sensitivity and cross-talk errors. The comparison between the new method and the basic estimator, which does not consider the misalignment error, showed that the basic estimator is less accurate, especially in the estimation of cross-talk elements. Furthermore, this method allows the application of combined and time-varying calibration loads, avoiding inaccuracies due to the application of pure loads and, potentially, friction. Consequently, the basic estimator can be used only for re-calibration of the direct calibration coefficients. The robust method gives an accurate estimation of the whole calibration matrix.

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References

BERME, N. (1990): 'Load transducers', in BERME, N., and CAPPOZZO, A. (Eds): '*Biomechanics of human movement, applications in rehabilitation, sports and ergonomics*' (Bertec, Washington, 1990), pp. 140–149

BOBBERT, M. F., and SCHAMHARDT, H. C. (1990): 'Accuracy of determining the point of force application with piezoelectric force plates', *J. Biomech.*, **23**, pp. 705–710

BROWNE, J., and O'HARE, N. (2000): 'A quality control procedure for force platform', *Physiol. Meas.*, **21**, pp. 515–524

CAMARC II (1994): 'Standards for instrumentation and specifications', Technical Report, AIM Project A2002

CAPPELLO, A., LA PALOMBARA, P. F., and LEARDINI, A. (1996): 'Optimization and smoothing techniques in movement analysis', *Int. J. Biomed. Comput.*, **41**, pp. 137–151

CAPPOZZO, A. (1984): 'Gait analysis methodology', *Hum. Mov. Sci.*, **2**, pp. 27–50

CHOCKALINGAM, N., GIAKAS, G., and IOSSIFIDOU, A. (2002): 'Do strain gauge force platforms need in situ correction?', *Gait Posture*, **16**, pp. 233–237

DRAPER, N., and SMITH, H. (1966): '*Applied regression analysis*' (John Wiley & Sons, Inc., 1966)

DUBOIS, M. (1981): 'Six-component strain-gauge balances for large wind tunnels', *Proc. Soc. Exp. Stress Anal.*, **38**, pp. 401–407

FAIRBURN, P. S., PALMER, R., WHYBROW, J., FIELDEN, S., and JONES, S. (2000): 'A prototype system for testing force platform dynamic performance', *Gait Posture*, **12**, pp. 25–33

FLEMING, H. E., HALL, M. G., DOLAN, M. J., and PAUL, J. P. (1997): 'Quality framework for force plate testing', *Proc. Inst. Mech. Eng. (H)*, **211**, pp. 213–219

GILL, H. S., and O'CONNOR, J. J. (1997): 'A new testing rig for force platform calibration and accuracy tests', *Gait Posture*, **5**, pp. 228–232

GOLA, M. M. (1980): 'A calibration procedure of a new platform', *Acta Orthop. Belg.*, **46**, pp. 522–533

HALL, M. G., FLEMING, H. E., DOLAN, M. J., MILLBANK, S. F. D., and PAUL, J. P. (1996): 'Static in situ calibration of force plates', *J. Biomech.*, **29**, pp. 659–665

LENZI, D., CAPPELLO, A., and CHIARI, L. (2003): 'Influence of body segment parameters and modeling assumptions on the estimate of center of mass trajectory', *J. Biomech.*, **36**, pp. 1335–1341

MITA, K., AKATAKI, K., ITOH, K., NOGAMI, H., KATOH, R., NINOMI, S., WATAKABE, M., and SUZUKI, N. (1993): 'An investigation of the accuracy in measuring the body centre of pressure in a standing posture with a force plate', *Front. Med. Biol. Eng.*, **5**, pp. 201–213

SCHMIEDMAYER, H. B., and KASTNER, J. (1999): 'Parameters influencing the accuracy of the point of force application determined with piezoelectric force plates', *J. Biomech.*, **32**, pp. 1237–1242

SCHMIEDMAYER, H. B., and KASTNER, J. (2000): 'Enhancements in the accuracy of the center of pressure (COP) determined with piezoelectric force plates are dependent on the load distribution', *ASME J. Biomech. Eng.*, **122**, pp. 523–527

WINTER, D. A. (1991): 'Biomechanics and motor control of human gait, 2nd edn' (University of Waterloo Press, Waterloo, 1991)

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