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A portable system for *in-situ* re-calibration of force platforms: Experimental validation

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ABSTRACT

A system for the *in-situ* re-calibration of six-component force platforms is presented. The system consists of a device, a data-acquisition procedure and an algorithm. The device, simple and lightweight, is composed of a high-precision, 3-D load cell, loaded through a triangular stage, and precisely positioned on the force platform under re-calibration by means of a template. The data-acquisition procedure lasts about 1 h and requires up to 13 measurements consisting of manual positioning the load cell on the force platform, and then having the operator exerting loads on both load cell and force platform by his/her body movement. As a result, the procedure makes use of loads in the same range of posture and gait tests. The algorithm estimates the local or global six-by-six re-calibration matrix of the force platform through a least-squares optimization, and is presented in detail in a separate paper [Cedraro A, Cappello A, Chiari L. A portable system for *in-situ* re-calibration of force platforms: Theoretical validation. Gait Posture 2008;28:488–94].

The system was validated on four commercial force platforms (Amti OR6, Bertec 4060–08, Bertec 4080–10, and Kistler 9286A). The average accuracy in the measurement of the center of pressure were 2.3 ± 1.4 mm, 2.6 ± 1.5 mm, 11.8 ± 4.3 mm, 14.0 ± 2.5 mm before re-calibration, 1.1 ± 0.6 mm, 1.8 ± 1.1 mm, 1.0 ± 0.6 mm, 3.2 ± 1.1 mm after global re-calibration, and 0.7 ± 0.4 mm, 0.8 ± 0.5 mm, 0.5 ± 0.3 mm, 2.0 ± 1.2 mm after local re-calibration (results presented in random order).

The force platform re-calibration influenced the value, sign, and timing of net joint moments, estimated during a gait task through an inverse dynamics approach.

1. Introduction

Force platforms, FPs, are precision instruments used in human movement analysis to measure the ground reaction force, GRF, and the center of pressure, COP. From the FP data, other kinetic quantities are calculated, such as: (i) the location of the body center-of-mass [1]; (ii) energy quantities, such as work or power [2]; and (iii) net joint forces and moments, determined from kinetic and kinematic data through an inverse dynamics approach [3,4].

Due to *in-situ* installation procedures, usage and aging, the accuracy of the FP data may decrease [5]. This lack of accuracy may propagate to calculated kinetic quantities [6].

Some groups developed systems to assess the accuracy of the FP data, using *ad hoc* designed devices comprising: instrumented poles [7,8], a framework-attached pendulum [9], a passive moveable plate [10], rectangular steel feet [11], or orthogonal rails and trolleys [12].

Morasso et al. [13] developed a system, comprising two metal masses manually set in rotation. This system minimized COP errors by a linear transformation that compensated FP anisotropy. Hall et al. [14] developed a system, comprising orthogonal rails and pulleys. This system estimated the six-by-six re-calibration matrix, **C**, by an algorithm based on static 2-D loads that required accurate alignment with the FP axes.

Recently, Cappello et al. [15] presented an iterative, weighted-least-squares algorithm that estimated **C** with time-varying 2-D loads laying on planes approximately aligned with the FP axes and perpendicular to the FP itself.

More recently, in the first paper of this series, Cedraro et al. [16] revised the Cappello et al. algorithm [15] with the aim of developing a simple and robust re-calibration device and an associated data-acquisition procedure. The main advantage of the revised algorithm is that it is based on time-varying 3-D loads, without any alignment restrictions.

In this paper, we present the design and the experimental validation of the new system, which consists of the re-calibration

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device and the data-acquisition procedure, to efficiently implement the algorithm presented in [16].

2. Materials and methods

2.1. Revised algorithm

The first article in this series [16] provides a detailed description of the revised algorithm that we proposed for the estimation of the re-calibration matrix **C**. The main diagonal elements of matrix **C** quantify the sensitivities of the FP signals and the off-diagonal elements quantify the crosstalk between any couple of FP output signals.

The algorithm estimates **C** using 5 or more measurement sites. Each measurement consists of data coming from the simultaneous loading of the FP and a triaxial load cell, LC, by a force in sites of known coordinates. For each measurement, the LC reference frame is re-aligned to the FP reference frame by a proper rotation matrix, estimated by minimizing the difference between the LC and FP output signals. If the sites chosen for the re-calibration cover an area smaller than the entire FP surface, the corresponding **C** may be defined "local", since the elements of **C** reflect the mechanical properties of the loaded FP area. If the sites chosen cover most of the FP surface, the corresponding **C** may be instead defined "global". Local and global **C** can be useful to quantify the FP non-linearity.

2.2. Re-calibration device

The re-calibration device (Fig. 1) consists of 3 major components: a custom triaxial load cell, a triangular stage, and a template.

The load cell is made of aluminum and steel (Laumas Elettronica, Italy). Technical specifications follow: full scale (FS) ±500 N for shear forces and 1000 N for vertical force; hysteresis 0.06% FS; non-linearity 0.05% FS. The load cell works with 3 Wheatstone bridges, each one sensitive mainly to the force applied along the relevant axis of an orthogonal reference frame, TLN (T = transverse, L = longitudinal; N = normal). The load cell was calibrated with the assistance of a metrological center (Cermet, certificate number: 0709020FRI) using precision weights, ranging up to 600 N for vertical force and from −150 N to 150 N for shear forces. The metrological center ran single and multi-axis calibrations to characterize the non-linear behavior of the LC, assuming a quadratic calibration model:

$$F_i = \mathbf{A}_i^T\mathbf{V} + \mathbf{V}^T\mathbf{B}_i\mathbf{V} \tag{1}$$

where $F_i = F_\mathrm{T}, F_\mathrm{L}, F_\mathrm{N}$ and $\mathbf{V} = [V_\mathrm{T}\ V_\mathrm{L}\ V_\mathrm{N}]^T$ is the LC output voltage. Vectors $\mathbf{A}_i$ (3×1) and matrices $\mathbf{B}_i$ (3×3) were estimated by a least-squares method from LC outputs and the applied loads. The load cell has a circular base of support (Ø = 100 mm) to reduce inaccuracies caused by FP deformation, due to a point source loading [11,17,18]. A steel cone is screwed on the LC top.

The *triangular stage* is equilateral with a 600 mm side and a 16 mm thickness. It consists of an aluminum plate with a honeycomb internal structure and results lightweight (2 kg), easy to move, but suitably rigid to support the operator's weight. In this way, the FP is loaded in or near its usual working range. Two feet, made of commercial-grade steel and brass, are screwed on two corners of the stage. The feet terminate with ball bearings, to concentrate shear force transmission to the LC. In the third corner of the stage there is a steel, conical socket that easily joins with the LC top. The vertex of the LC top is the only point of contact with the socket; hence, the vertex is the point of force transfer to the FP (COP). The torque applied to the LC can be considered negligible, since it was minimized by the mechanical uncoupling between the stage and the LC.

The *template* is a 400 mm × 600 mm sheet of plastic, placed on the FP during the data-acquisition procedure, and used to locate easily and precisely the LC on the FP. The template has 13 holes (Ø = 100 mm) centered at the measurement sites and distributed on the whole surface. The minimum number and minimum reciprocal distance of the measurement sites to be used for re-calibration were determined via a simulation approach in the first paper [16].

The load cell bends when loaded, causing a variation in the COP coordinates. We determined the maximal LC flexion that we may expect by using a finite element simulation (Visual Nastran, MNC), in which the LC was loaded at its top with a horizontal force up to 200 N while the LC basement was blocked. The maximal COP displacement induced was less than 0.14 mm. This uncertainty on COP position was considered negligible, based on tests in which the LC bending was included in a simulated re-calibration procedure.

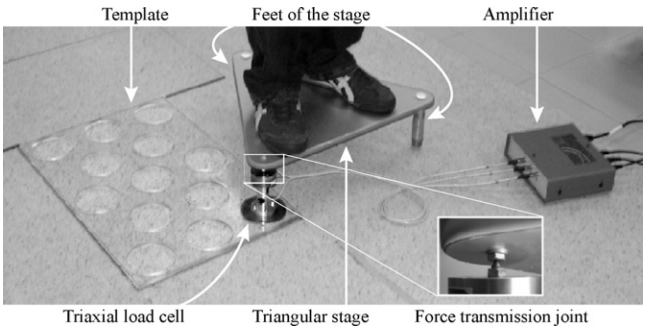

Fig. 1. View of the re-calibration device.

The LC output voltages were amplified by three customized voltage-amplifiers and then A/D converted using a NI-DAQPad6020E (National Instruments) acquisition board.

2.3. Data-acquisition procedure

The data-acquisition procedure is summarized as follows:

(1) Both FP and LC electrical hardware are turned on, and a warm-up time is waited according to manufacturers' specifications.
(2) The template is manually positioned on the FP surface.
(3) The LC is manually placed in one of the measurement sites. The placement of the template and of the LC causes a static offset in the FP output. Both FP and LC outputs are zeroed before proceeding.
(4) The stage is placed as shown in Fig. 1: the socket is placed on the LC top and the feet are placed outside the FP surface.
(5) The operator stands on the stage and sways his/her body with circular movements with rapid changes in his/her rotational speed, generating a time-varying 3-D load.
(6) The LC and FP output are acquired for 30 s. The LC and FP acquisition systems are not synchronized and work independently.
(7) Steps 3/6 are repeated for all the chosen measurement sites.
(8) After data-acquisition, the LC and FP signals are off-line synchronized, by finding the best cross-correlation between the vertical forces measured by the LC and FP. The a-posteriori time-synchronization error corresponds, at worst, to half of the sampling period. By keeping a sampling frequency ≥1000 Hz, such error is negligible (as proven by a simulation test).
(9) After synchronization, **C** can be estimated by the algorithm described in [16].
(10) The FP output vector **L** is then calibrated by:

$$\mathbf{L}_C = \mathbf{CL} \tag{2}$$

2.4. Experimental tests and outcome measures

The new system was tested on 4 commercial FPs, three of which were strain-gauge FPs: AMTI OR6, size 464 mm × 508 mm (Advanced Medical Technology Inc., Watertown, MA, USA), Bertec 4060–08, size 400 mm × 600 mm, and 4080–10, size 400 mm × 800 mm (Bertec Corporation, Columbus, OH, USA); one FP was piezo-electric: Kistler 9286A, size 400 mm × 600 mm (Kistler Instrumente AG, Winterthur, CH). These FPs were routinely used in clinical and research laboratories for gait and balance analysis and the FPs signals were calibrated by the manufacturers' calibration matrix. The FPs age was 5 ± 3 years.

Due to the different factor-form and size of the FPs, we chose partially different placement and number of the measurement sites, as reported in the following. We kept the reciprocal distance between each couple of sites greater than the minimum distance of 100 mm identified in [16].

AMTI OR6

$$\begin{cases} X_\mathrm{COP} = (0, 70, 70, -70, -70, 0, 0, 140, -140, 194, 194, -194, -194)\ \mathrm{mm} \\ Y_\mathrm{COP} = (0, 120, -120, 120, -120, 182, 182, 0, 0, 182, -182, 182, -182)\ \mathrm{mm} \end{cases} \tag{3}$$

Bertec 4060 − 08
Kistler 9286A

$$\begin{cases} X_\mathrm{COP} = (0, 70, 70, -70, -70, 0, 0, 140, -140, 140, 140, -140, -140)\mathrm{mm} \\ Y_\mathrm{COP} = (0, 120, -120, 120, -120, 240, -240, 0, 0, 240, -240, 240, -240)\mathrm{mm} \end{cases} \tag{4}$$

Bertec 4080−

$$\{\text{Bertec 4060 08 COPs}\} + \begin{cases} X_\mathrm{COP} = (70, 70, -70, -70)\ \mathrm{mm} \\ Y_\mathrm{COP} = (340, -340, 340, -340)\ \mathrm{mm} \end{cases} \tag{5}$$

For all the measurements, $Z_\mathrm{COP} = -124$ mm, that corresponds to the height of the LC.

In the following, the FP manufacturers are omitted, since no comparison between the manufacturers was intended, also due to different age, usage and installation of the FPs, that prevent any possibility to draw general conclusions from this limited sample. Each FP will be addressed by a unique identifier such as FP#1, #2, #3, and #4.

The forces used in re-calibrating all the FPs ranged from −80 N to 80 N for the horizontal components and from 200 N to 600 N for the vertical component.

The above described range was defined in a separate test, where a calibration procedure was performed on FP#2 with forces ranging ±200 N (horizontal) and 400/1000 N (vertical). Then, global re-calibration matrices were estimated using only the