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A new device for *in situ* static and dynamic calibration of force platforms

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ABSTRACT

In human motion analysis, *in situ* calibration of the force plate is necessary to improve the accuracy of the measured ground reaction force (GRF) and center of pressure (COP). Few existing devices are capable of both static and dynamic calibration of the usually non-linear GRF and COP errors, while are also easy to move and/or set up without damaging the building. The current study developed a small device (160 cm × 88 cm × 43 cm) with a mass of 50 kg, equipped with auxiliary wheels and fixing suction pads for rapid deployment and easy set-up. A PC-based controller enabled quick movement and accurate positioning of the applied force to the calibration point. Static calibration at 100 validation points and dynamic calibration of a force plate were performed using the device. After correction by an artificial neural network (ANN) trained with the static data from another 121 points, the mean errors for the GRF were all reduced from a maximum of 0.64% to less than 0.01%, while those for the COP were all reduced from a maximum of about 1.37 mm to less than 0.04 mm. For dynamic calibration, the mean errors for the GRF were reduced from a maximum of 0.46% to less than 0.28%, while those for the COP were reduced from a maximum of 0.95 mm to less than 0.11 mm. The results suggest that the calibration device with the ANN method will be useful for obtaining more accurate GRF and COP measurements in human motion analysis.

1. Introduction

Gait analysis has been widely used in the diagnosis of neuromusculoskeletal pathology and the assessment of the outcome of subsequent treatment [1–7]. Generally, kinematic and force plate data are necessary for computing the joint forces, moments and powers using inverse dynamics techniques [8–10]. Apart from the measured kinematic data, it has been shown that the accuracy of the ground reaction forces (GRF) and the center of pressure (COP) measured by the force plate has a significant impact on the calculated joint kinetics [11–13]. Since inaccuracies of the force plate mounted flush with the floor may occur as a result of improper installation, aging, or other damages [14,15], *in situ* calibration is required to ensure the accuracy of the measurements, and thus the gait analysis results.

Several calibration devices for *in situ* calibration of force plates have been described in the literature [16–19]. Bobbert and Schamhardt designed a calibration device to apply static vertical forces at 117 calibration points to quantify the measured COP errors that were then corrected using polynomial regression equations. Dynamic calibration was performed only for COP but not GRF. Hall et al. [18] performed a static vertical and horizontal force calibration using a point loader and a pulley rig, and cross-sensitivity matrices were obtained for correcting errors in the measured forces and COP positions. It is noted that both devices required extensive structural changes to the laboratory building and did not allow dynamic force calibration. To overcome the problem of damage to the floor, Gill and O'Connor [17] designed a device (mass: 400 kg; volume: 1.71 m × 1.54 m × 0.8 m) which enabled the application of known static vertical forces at several calibration points using a manually controlled lever system, making it difficult to ensure the accuracy and speed of positioning. The correction of measurement errors was not described. Collins et al. reported a linear, least-squares calibration method for force plates and treadmills using data from arbitrary calibration points [20] but only static calibration was performed for the force plate. Goldberg et al. increased the accuracy of an instrumented treadmill's measurement of center of pressure and force data by calibrating statically the transformation between the coordinate systems motion capture and treadmill force plate [21].

Until now, few existing devices are capable of both static and dynamic calibration of GRF and COP errors with high positioning accuracy, while are also easy to move and/or set up without damaging the building. Since there is a significant correlation between measured forces and COP positions that are also non-

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linear across the force plate [16,17], using linear cross-sensitivity matrices for error correction is restricted. A correction procedure considering the coupling and non-linear nature of the GRF and COP is necessary for accurate force plate measurements. The purposes of this study were to build a new *in situ* force plate calibration device that has the above-mentioned features, and to develop a correction method based on an artificial neural network (ANN) for correcting the measured force plate data.

2. Materials and methods

2.1. Calibration device

The current calibration device uses the principle of leverage to control the magnitudes and positions of the forces applied to the force plate under test. The device consists of a base secured to the floor by eight industrial suction pads, an arm that rotates about and moves along an axis relative to the base, a loading rod that moves along the arm, and a carrier that carries calibrating weights and moves along the arm on a ball screw, Fig. 1. A ball bearing of 15 mm diameter at the end of the loading rod was used to transmit the load to the force plate. The suction pads were used to counter-balance the forces applied to the force plate, whereas previous devices achieved this by fixing themselves to the floor [16,18] or by their weights [17]. This design significantly reduced the weight and volume of the device (mass: 50 kg; volume: 160 cm × 88 cm × 43 cm) and thus enabled rapid mounting without damaging the floor. For accurate positioning of a calibration point, each moving axis of the device was driven by a step motor and controlled by a PC-based controller, and measured using encoders with an accuracy of 0.00125 mm.

For a given calibration point, the force applied to the force plate is determined by considering moment equilibrium at the base axis as follows (Fig. 1):

$$R = \frac{Wl + W_a l_a + W_p d}{d} \tag{1}$$

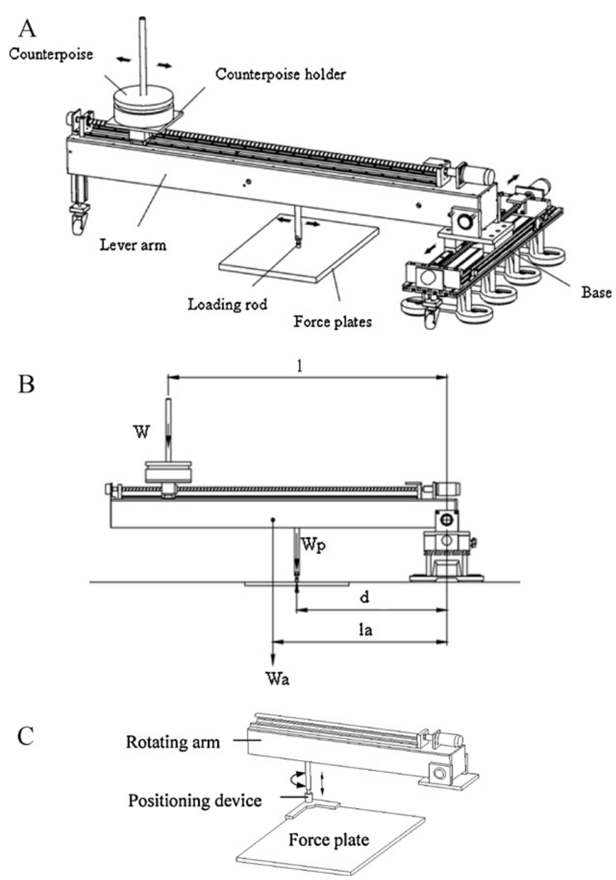

Fig. 1. (A) Setup of the device for calibrating a force plate. (B) Force diagram showing the determination of the calibration loads (W_p) from the weight of the counterpoise (W), the weight of the lever-arm (W_a) and their respective positions d, l and l_a. The wheel at the left endpoint of the lever-arm did not touch the floor during force plate calibration. (C) A height-adjustable positioning device with its two L-shaped legs aligned with the two edges of a corner of the force plate for the definition of the position of the corner.

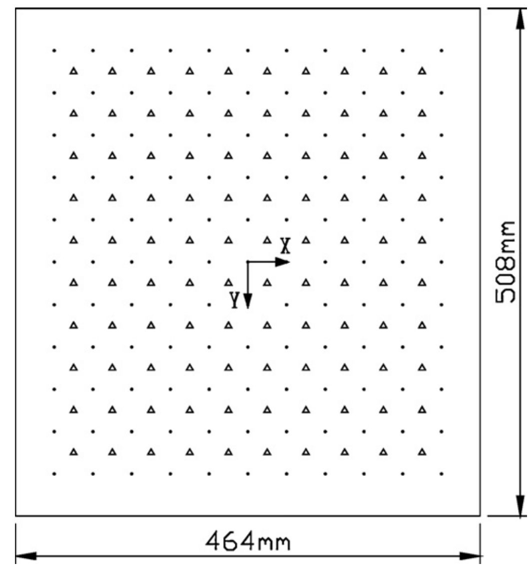

Fig. 2. The positions of 121 calibration points (dot) and 100 validation points (triangle) on the force plate.

where R is the GRF; W is the calibration weight; W_p is the weight of the loading rod (17.07 N); and W_a is the weight of the rotating arm, with lever-arm lengths of l, d and l_a, respectively. All lever-arm lengths were measured by encoders, while the force plate data were collected simultaneously through an A/D converter at a sampling rate of 120 Hz (National Instruments, USA). The accuracy of the calibration load was less than 0.007 N, estimated experimentally using a load-cell (capacity 2000 N; precision 0.0045 N; Sensotec Inc., USA).

2.2. Static calibration tests

A force plate (OR6-7-1000, AMTI, USA) was tested by the calibration device that was positioned next to the force plate with the rotating arm parallel to its short edge. The coordinates of the four corners of the force plate were digitized five times using a positioning device based on the load rod (Fig. 2), and the averaged coordinates used for determining the coordinate transformations between the calibration device and force plate. The calibration system then generated a grid of 121 calibration points (Fig. 2). At each point, vertical loads of 650 N, 800 N and 1000 N were applied while the measured forces and moments, and COP were collected at a sampling rate of 120 Hz for two seconds. Data were also obtained for another grid of 100 validation points (Fig. 2).

2.3. Dynamic calibration tests

Dynamic calibration was performed at the center of the force plate. The dynamic loading history was created by moving a 20 kgf weight on the counterpoise holder forward and backward over a range of 100 cm at speeds of 7.5 cm/s and 25.0 cm/s, with the applied force varying linearly between 987 and 523 N. This enabled the calibration of not only the COP position, but also the loading values under dynamic conditions. For calibration of COP position at higher dynamic loads, a young subject with a body mass of 60 kg was asked to stand with one leg on the counterpoise holder, and the other on a platform with the same height placed outside the force plate. By shifting from two-leg stance to single-leg stance on the counterpoise holder, the dynamic condition during walking could be simulated. This type of dynamic calibration was performed at three different counterpoise holder positions, to simulate three vertical loading ranges, namely 800–1400 N, 650–800 N and 450–650 N. Owing to the problems with the calculated COP positions under small vertical forces during initial and terminal ground contact [14,16], only the data within the three force ranges were used for quantifying the mean and standard deviation of the errors in the COP position. The forces and moments measured by the force plate were collected at a sampling rate of 1000 Hz.

2.4. Calculation of COP position

The COP position was described relative to the force plate coordinate system, originating at the geometric center of the plate, with the X-axis along the short edge and the Y-axis along the long edge (Fig. 1). Given the measured forces $\mathbf{F} = (F_x, F_y, F_z)$ and moments $\mathbf{M} = (M_x, M_y, M_z)$ about the origin, the COP position $\mathbf{P} = (P_x, P_y, P_z)$ was calculated as follows:

$$P_x = \frac{P_z F_x - M_y}{F_z} \tag{2}$$