DEVELOPMENT OF A TRIAXIAL FORCE PLATFORM FOR THE MEASUREMENT OF FORCE AT A BICYCLE PEDAL

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The main purpose of this work is to present the methodology used to develop a triaxial force platform for the use at a pedal bicycle; this platform is based on the flexion of beams where strain gages are bonded for the measurements of force components FX, FY and FZ, as well as the force moments MX and MY. The theoretical analysis of this force platform was realized by the Finite Element method, with the simulation of 384 combinations of static loads (force and moments) at different directions. Deformation data numerically obtained is related to the position were sensors will be placed. Output signals obtained were numerically organized and graphically analyzed, in order to show the mathematical relation between force and strain, which is used to generate a "calibration matrix", free of mechanical coupling which usually appears in multiaxis systems. At last, a test was made, simulating an input load, and the output signal obtained was practically equal.

KEY WORDS: cycling, pedal force, biomechanics.

INTRODUCTION: The understanding of the forces at the foot/pedal interface during the cycling may be useful for the identification of the technique used by the athlete, and, consequently, show the situations related to reduction or overuse of the knee joints. As a consequence of such measurements, a magnifying of the performance can be achieved with no significant risks involved. For the description of a force platform adapted to a pedal bicycle, the measurement of six components is required: Forces FX, FY and FZ, and force moments, MX, MY and MZ, as shown in *Fig.1*.
The force platform is used to measure the force and force moment components; sensors are adapted to the force platform in order to permit a direct correlation between the load applied and the output signal of the circuitry to where the sensor is connected. These relations can be experimentally obtained by means of a calibration system, which generates a calibration curve.

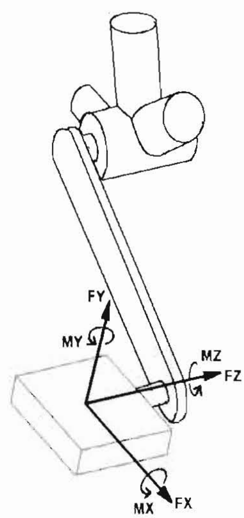

Figure 1. Coordinate systems and the force components at the pedal.

The most important characteristics of a force platform are: (a) high sensibility; (b) high natural frequency in relation to the frequency of the signal to be measured; (c) decoupling of the components of force and force moments (which means that a signal applied only at the x axis cannot generate a signal at the y axis, for example); (d) independence of external factors, such as temperature; (e) facility of manufacturing, and (f) compatible costs. The challenge related to the construction of force platforms is associated to the platform geometry, in order to have the characteristics pointed above and permits the correct measurement of the physical phenomena. Probably, the most usual sensor used in force platforms is the resistance strain gage, which measures directly the relative strain ε, at the point of interest. The geometry of the force platform, the correct geometrical positioning of the sensors and the correct connection at the Wheatstone bridge circuitry are vital to obtain decoupling between force components and force moments at different axis. When decoupling is not achieved by an appropriate geometry, a calibration matrix can be used. In the past, several different systems were used to measure force at the bicycle pedal. It is possible to divide these systems into three classes: (a) piezoelectric or strain gage sensors; (b) number of force components to be measured; (c) shoe/pedal interface. Hull (1981) presented a load cell which permitted the measurement of six load components based on the combination of four orthogonal load cells; these orthogonal load cells can measure independently, normal and tangential components of force. Newmiller (1988) presented an octagonal pedal for the measurement of normal and tangential forces, and force moment at the lateral axis. Brooker (1990) used two multidirectional piezoelectric transducers adapted to the pedal, by offering a high frequency response and avoiding the necessity of decoupling correction. Alvares (1996) presented a load cell based on the flexion of a cylindrical beam with strain gages, in order to measure normal and tangential force components. The main objective of the present project is to show a new geometry, which has nothing to do with the models used in the past. This force platform also uses resistance strain gages and measures triaxial force components and two force moments.

METHODS: The platform developed in this study employs several beams working in flexion, connected in such a way that the behaviour of the platform basis is associated to the decomposition of the force components. In the same way, it is compatible with the standard interface between shoe and pedal. Lywood, 1987, and Roesler, 1998, used this system in triaxial platforms for gait analysis, and Maders (1999) adapted a similar system at a pedal bicycle. Fig. 2 shows two views (top and bottom) of the platform proposed in the present work, where it is possible to identify each of the platform's parts. The manufacturing of this platform is realized from a single Aluminum part with dimensions 105x75x25 mm, and the main geometrical limitations factor is the distance between the pedal axis and the platform basis. The functioning of the platform is based in two beam systems, as it is shown in Fig. 2; the first system it's the peripheral of four beams of rectangular section, used for the measurement of FX, FY and MX (point 1 at *Fig. 2b*), the second system is the central one and consists of four beams of rectangular section, used for the measurement of FZ and MY (point 2 at Fig. *2b*). The MZ component is not measured, because it has the same direction of the rotation axis of the pedal. Strain gages are positioned as indicated in *Fig. 3c*, and preferential positions are based on the orientation of strain calculated by the Finite Element Method (FEM).

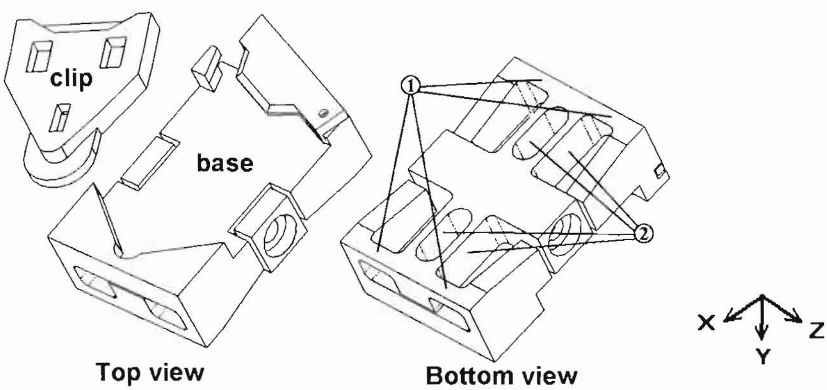

Figure 2. Geometrical aspects of the right pedal. (a) top view, (b) bottom view.

The output signals obtained from the five full Wheatstone bridge circuitries are directly proportional to the force and force moments applied to the pedal. For the validation of the model, the force platform was analyzed using the Finite Element method, employing 8792 solid elements of 4 nodes, this is shown in *Fig. 3a*. Several load levels were simulated and the respective strains were obtained at the places where strain gages would be placed. This procedure, called the static calibration, is used in order to verify the mechanical decoupling (which is related to the quality of the project). From these results, it is possible to obtain the calibration matrix. The numerical tools help this stage of the project, verifying the decoupling without the necessity of building a real platform. For the numerical simulation, nine points of the top of the platform were selected and a force was applied at these points; the values chosen are presented in Table 1. All these values were combined, producing 384 load combinations.

Table 1. Values of force applied to the top part of the force platform.

Direction	FX (N)	FY (N)	FZ (N)	MX (Nm)	MZ (Nm)
Values	0, 300, 600, 900,	0, 300, 600, 900 1200, 1500	0, 300, 600, 900	7.5	4.2

Fig. 3b shows the positions of the forces and force moments application (9 points) and the restrictions of movement using the FEM model. The strain calculated at the selected nodes (which represent strain gages positions) were saved and combined and result in the output signals of the five Wheatstone bridge circuits called VFX, VFY, VFZ, VMX and VMY. These values are ordered and graphically plotted later on, showing the coupling and obtaining the calibration matrix and the visualization of the decoupling.

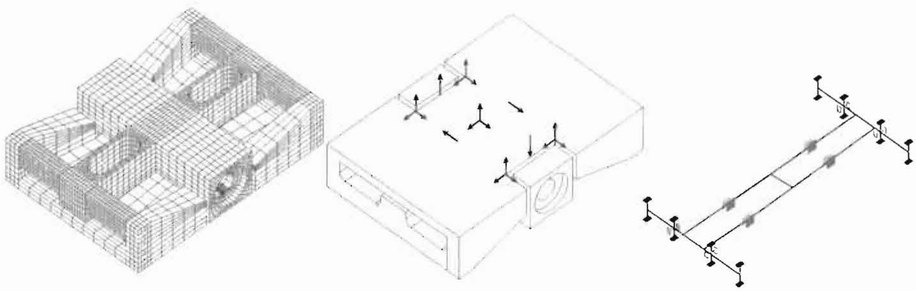

Figure 3. (a) FEM model; (b) location of the applied loads; (c) location of the strain gages sensors.

RESULTS: The FEM method showed coupling in many situations, which are analyzed as follows:

- FX components presented a coupling of 2.67 N for each Nm applied by the force moment MY (2.67 N/Nm), as shown in Fig. 4a.
- FY force components presented a coupling of 1.98 N/Nm, because of the MY moment.
- MX moment presented a coupling of 0.0109 N/Nm (Fig. 4b), because of the force moment FZ.
- FZ components presented a coupling of 13.47 N/Nm, because of the force moment MX.
- MY does not produce any coupling.

The final results (in Newton) are obtained by the force vector components VFX, VFY, VFZ, VMX and VMY (numerically obtained in Volts) multiplied by the calibration matrix.

$$[F] = [V]\,[C] \quad \begin{bmatrix} FX \\ FY \\ FZ \\ MX \\ MY \end{bmatrix} = \begin{bmatrix} vFX & vFY & vFZ & vMX & vMY \end{bmatrix} * \begin{bmatrix} -6810.5 & 0 & 0 & 0 & 0 \\ 0 & 8509.7 & 0 & 0 & 0 \\ 0 & 0 & 475.7 & -502.7 & 0 \\ 0 & 0 & -1750.5 & -5183.7 & 0 \\ 189.1 & -131.0 & 0 & 0 & -4407.2 \end{bmatrix}$$

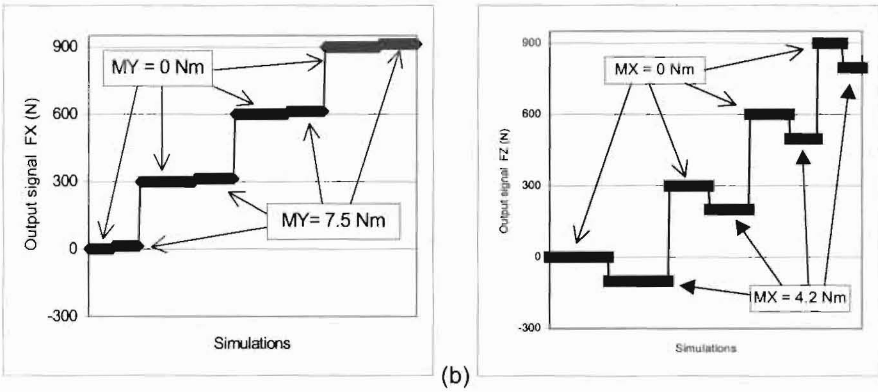

Figure 4. (a) FX values obtained by 384 simulations, showing the coupling caused by the presence of MY force moment of 7.5 Nm; (b) FZ values obtained by 384 simulations, showing a coupling caused by the presence of MX (4.2 Nm).

CONCLUSION: This work presents the steps followed from the design to the calibration matrix of a new geometry bicycle pedal. Numerical simulations results obtained for several loading combinations showed that the coupling matrix permitted the correct calculation of forces in all simulated situations. This fact shows that the methodology developed for decoupling is correct. The authors wish to thank the CNPq governmental agency for partial support.

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