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DYNAMIC VALIDATION OF A NUMERICAL MODEL OF FORCE PLATFORM FOR HUMAN GAIT ANALYSIS

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Abstract. *The load due to a pedestrian acting on the structure has been obtained from investigations in platforms, instrumented treadmills, gait machines or even prototype footbridges, in which the applied force by a pedestrian is pursued. Force platforms are devices designed to measure the forces exerted by a body in an external surface, the contact surface. The designed platform consists of two plates placed side by side, each instrumented with three ring-type load cells. Any force platform should allow the measurement of loads compatible with the frequencies involved in its application and must have sufficient stiffness to prevent unwanted vibration that may undermine measured values. It was used a unidirectional accelerometer to measure the natural frequencies. The structure was subjected to an excitation by an impact hammer, and a value of 30.1 Hz was found for the frequency corresponding to the first vibration mode. Similar results were obtained by the load cells. A finite element model was fitted to reproduce the dynamic features of the platform. The observed frequencies resulted in values very close to the experimental ones and confirmed the adequacy of the design, since the frequencies were reasonably higher than the frequencies involved for walking pedestrians. So, the designed platform presented a resonant dynamic response far from the range of force frequencies developed in walking, thus minimizing the chances of measurement errors due to interaction or amplification.*

Keywords: *force platform, biomechanics, experimental measurements, vibration.*

1. INTRODUCTION

Walking, running and jumping on footbridges produce dynamic forces which can activate appreciable vibrations. These vibrations can cause discomfort to pedestrians and deterioration of the footbridge's structural integrity. The human body may interact with the structures and these interactions are developed through the application of forces due to movement. A structure may undergo changes in their dynamic behavior when subjected to loads. Several cases of excessive vibration in vertical direction on footbridges due to human-induced loads have been reported, being usually related to crowd condition. Until recently, the load due to a pedestrian acting on the structure has been obtained from investigations in platforms, gait machines or even prototype footbridges, in which the applied force is that produced by a walking pedestrian. A combination of those individual applied forces is considered for groups of pedestrians or crowds. Thus, the design load is a force model. However, attention is drawn in some recent publications (Barker and Mackenzie, 2008; Kim, *et al*., 2008; Zivanovic, *et al*., 2010) regarding the potential effect of the dynamic interaction between pedestrians and structure while crossing footbridges in crowd situations. Barker and Mackenzie (2008) called attention to studies that suggested that in crowded situations pedestrians might increase the damping of the system and thus reduce the structural response. Kim, *et al*., 2008 investigated the effect of the dynamics of pedestrians walking along a footbridge. Each pedestrian was represented as a biodynamic system, presenting equivalent mass, stiffness and damping. They observed differences on the response of the structure between force and biodynamic models for the pedestrian action. Zivanovic, *et al*., 2010 explored the strategy of an arbitrary increase of damping of the system to account for human-structure interaction and pointed out a strong need for further research on quantification of human-structure interaction. Kala, *et al*., 2009 affirms that many footbridges have natural frequencies that coincide with the dominant frequencies of the pedestrian-induced load and therefore they have a potential to suffer excessive vibrations under dynamic loads induced by pedestrians. According to Hauksson (2005) excessive vibrations can be caused by resonance between pedestrian loading and one or more natural frequencies of the structure. The reason for this is that the range of footbridge natural frequencies often coincides with the dominant frequencies of the pedestrian-induced load. Agreeing to Zivanovic, *et al*., 2009 structures that accommodate pedestrians, such as footbridges and floors, could be exposed to excessive vibrations under walking-induced dynamic excitation. Since humans are quite sensitive vibration receivers (threshold motion perception 0.5~1.0 mili-g), this situation leads to pedestrians' interaction with the structure. Qin, *et al*., 2013 suggests that because of the dynamic interaction, pedestrians need to impose more external

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energy and change the walking pattern to maintain the steady gait and a uniform dynamic behavior of the center of mass of the body in each step cycle.

Zuo, *et al*., 2012 affirms that engineering projects such as footbridges sometimes have large spans. As a result, these structures have lower natural frequencies (close to 1 Hz). It is observed that these structures do not present a suitable project, generating large amplitudes of vibration when subjected to pedestrians loading. Zuo, *et al*., 2012 concluded that the pedestrians walking on the footbridges have an effect of added mass that can affect the vibration frequency of the footbridges, and that the evolution of the footbridges vibration frequency is an indication of the level of synchronization of pedestrian footfalls. In this context, Alam and Amin (2010) argue that in the last few years, the trend in footbridge design has been changed towards larger spans and less weight. Once followed, such trend gives increased flexibility in dynamic behavior. As a consequence, stiffness and mass sometimes decrease and lead to smaller natural frequencies, these structures are more sensitive to dynamic imposed pedestrian loads or wind loads. In practice, such footbridge has particularly been found to be more sensitive to dynamically imposed pedestrian loads.

The aforementioned studies provided evidence that in structures subjected to a flow of pedestrians (e.g. footbridges in urban areas), the dynamics of the pedestrian body should be considered in order to define the design load or even to investigate its effects properly. To evaluate this dynamic interaction between pedestrian and structure, in this paper it was used a force platform. This designed device should have natural frequencies different from the frequencies involved in human gait, avoiding possibility of resonance phenomena, changing the values of the pedestrian loading and inducing errors in the measurements. The aim of this paper is to design and obtain the natural frequencies and vibration modes of a force platform, using experimental measurements and a Finite Element numerical model.

2. FORCE PLATFORM

Force platforms are devices designed to measure the forces exerted by a body in an external surface, the contact surface. One of the variables most commonly investigated during human walking is the Ground Reaction Force (GRF) and this is measured using force platform. For the experimental measurements two independent instrumented plates were used, being mounted side by side. Each plate has three ring-type load cells instrumented with 4 strain gauges in a full Wheatstone bridge configuration. The design of the load cells was meant to cover a specific range of loads with maximum sensitivity, eliminating moments and horizontal forces influences. It was also used a data acquisition board and a signal conditioner/amplifier circuit. Figure 1 shows the main dimensions of the force platform. Figure 2 shows the acceleration and deceleration plates (these are not instrumented) used just to stabilize the pace and minimize the influence of fluctuations in the step cadence due to subject’s visual feedback. Figure 3 shows structural details of the designed device.

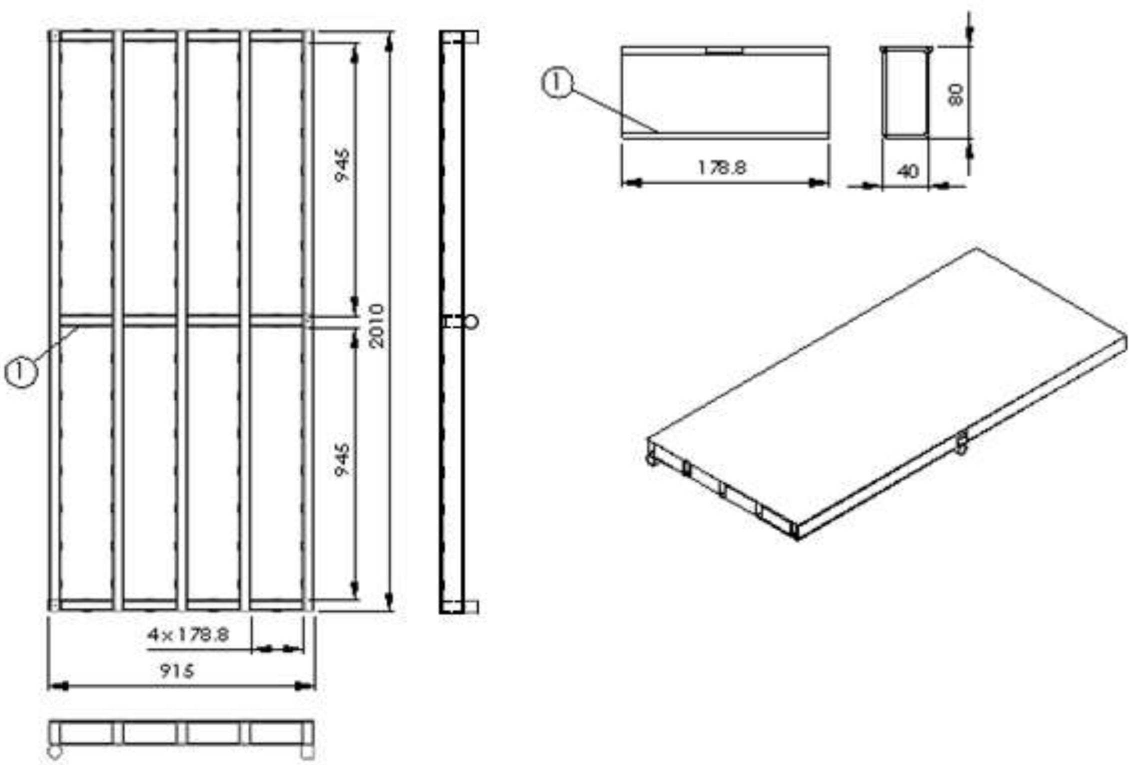

Figure 1. The main dimensions of the force platform.

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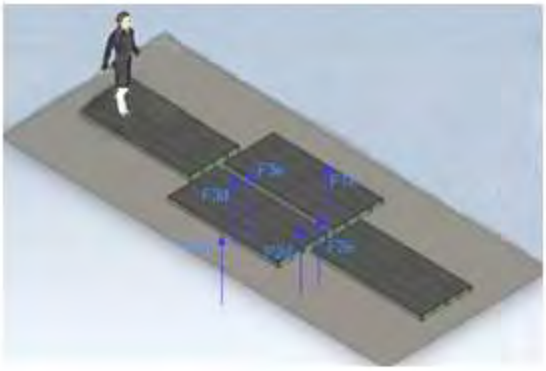

Figure 2. Model of force platform for gait analysis (blue arrows means force reaction from load cells).

Figure 3. Structural details (bottom side view) with ribs to comply with natural frequency requirements.

Further details regarding the design and development of the force platform can be found in other publication Toso (2012).

2.1 Vertical ground reaction force and static equilibrium equations

In the design of the force platform it was considered the acquisition of only vertical forces. Zivanovic, *et al*., 2005 affirm that the vertical component of the GRF is the one that has the highest magnitude, and hence the more important and consequently the most studied, primarily in research which aims quantifying the forces of the movement interacting with structures. The force platform provides electrical signals proportional to the forces applied to the structure. These signals allow evaluate the position and the resultant forces on the platform. Figure 4 shows a schematic view of the left platform (intended to capture the left step force) with the respective load cells and their position in relation to the coordinate axes (x, y).

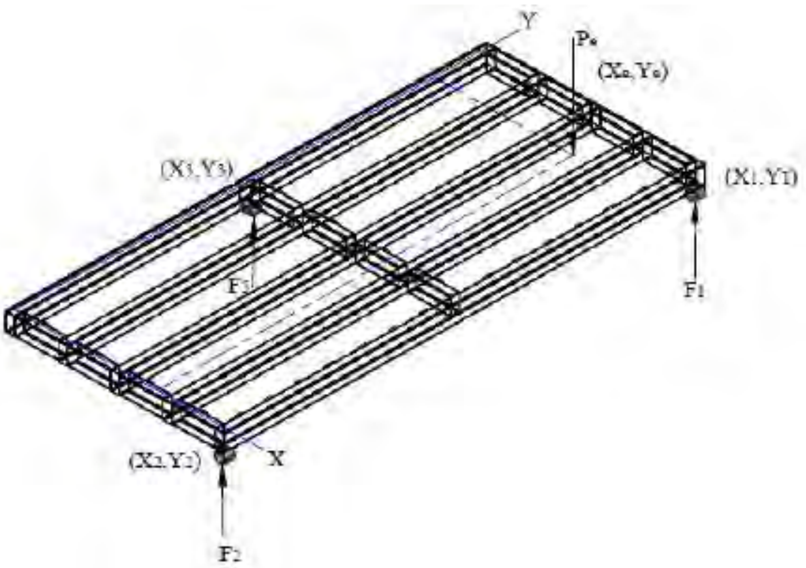

Figure 4. Positioning of the load cells in the left force platform.

According to the scheme in Fig. 4, the static equilibrium equations allow writing:

$$P_e = F_1 + F_2 + F_3 \tag{1}$$

$$F_2 y_e + F_3 (y_e - y_3) - F_1 (y_1 - y_e) = 0 \tag{2}$$

$$F_3 x_e - F_1(x_1 - x_e) - F_2(x_2 - x_e) = 0 \tag{3}$$

Solving the previous system for the variables P_e, x_e and y_e one has:

$$P_e = F_1 + F_2 + F_3 \tag{4}$$

$$x_e = \frac{F_1 x_1 + F_2 x_2}{P_e} \tag{5}$$

$$y_e = \frac{F_1 y_1 + F_3 y_3}{P_e} \tag{6}$$

Thus, knowing the F1, F2 and F3 loads, the coordinates x_e and y_e of the applied load is obtained using Eq. (5) and (6). Inversely, knowing P_e, x_e and y_e, one can obtain the values of the forces in the three load cells:

$$F_1 = \frac{P_e(x_2 y_e + x_e y_3 - x_2 y_3)}{x_2 y_1 + x_1 y_3 - x_2 y_3} \tag{7}$$

$$F_2 = \frac{P_e(x_e y_1 - x_1 y_e - x_e y_3 + x_1 y_3)}{x_2 y_1 + x_1 y_3 - x_2 y_3} \tag{8}$$

$$F_3 = -\frac{P_e(x_e y_1 - x_1 y_e + x_2 y_e - x_2 y_1)}{x_2 y_1 + x_1 y_3 - x_2 y_3} \tag{9}$$

Similar equations to the above ones can be developed for the calculation of the P_d force and x_d and y_d positioning for a the right platform.

3. NATURAL FREQUENCIES OF THE FORCE PLATFORM

Force platforms should allow the measurement of loads compatible with the frequencies involved in its application, in order not to produce a resonant dynamic response, changing the values of loading and inducing measurement errors. The first natural frequency of the force platform should be greater than the maximum frequency contained in the measurement, in order to avoid that part of the acquired signal is amplified by the mechanical system. This is a critical condition, because it relates directly to the platform stiffness, which is proportional to the natural frequency and mass of the platform, which is inversely proportional to this same frequency. The vibration modes determine the dynamic behavior of the force platform. The proximity between the vibrations of the movement and its fundamental frequency can interfere in the transducer measurements. In this sense, platforms with maximum stiffness combined with minimum mass are often pursued. The required high stiffness aims to reduce the bending of the surfaces during the use of the platform, ensuring a complete transmission of the loads received by the upper surface to the load cells beneath the platform.

3.1 Experimental measurements

To perform the data signal processing it was used the Agilent Vee 7.5 software, this consists of a graphical programming language geared towards test and measurement, having advanced features for data analysis and processing. An unidirectional accelerometer was used to measure the natural frequencies of the force platform (model 8312B10 nominal sensitivity of 200 mV/g measuring frequency range 0-180 Hz, Kistler company's data). The structure was subjected to an excitation by an impact hammer, and a value of 30.1 Hz was found for the frequency corresponding to the first vibration mode. The frequency spectrum of the signal from the accelerometer is shown in Fig. 5.

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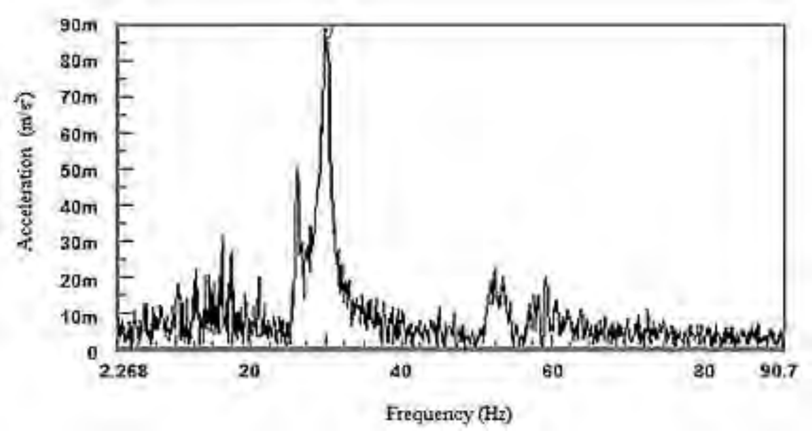

Figure 5. Acceleration frequency spectrum.

Analyzing the results of the Fig. 5, one can notice a second frequency with smaller amplitude of acceleration, around 25 Hz. This frequency may be associated with the bending of the upper plate, where the accelerometer was placed (local frequency), this is not the frequency of the whole structure in the vertical direction.

Another way used to confirm that measurement was using the signals from the load cells. Figure 6 shows the force load cell signal in the frequency domain. Note that the value obtained (30.1 Hz) is the same value measured previously with the use of the accelerometer. There is a smoothness of the force spectra due to the mechanical filtering of the platform system.

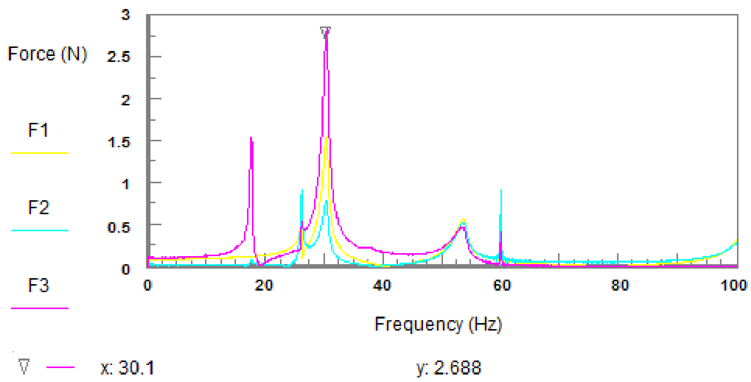

Figure 6. Force frequency spectrum.

The data in Fig. 6 show a second frequency with smaller acceleration amplitude, a frequency close to 20 Hz. This frequency may be associated with the frequency of the load cell in another direction (horizontal), this is not associated with the vertical direction.

Although further studies are needed to investigate the frequencies using both the accelerometer and the signals from the load cells, it is noteworthy that the fundamental frequencies of the force platform are still far from the range of frequencies involved in its application. According to Zivanovic, *et al*., 2005 and Kala, *et al*., 2009 the frequencies of the human gait are of the order of 0.5 to 10 Hz considering the sub-harmonic of the frequency spectrum. The frequency results previously obtained (using the accelerometer and load cells) are sufficient information to show that the force platform should not suffer interference from resonance, are not necessary others analyses such as a frequency response function to obtain these conclusions.

3.2 Numerical model of the force platform

The 3D linear elastic finite element model of the force platform was constructed using a commercial software. In this paper, the program was used to determine the dynamic characteristics based on its physical and mechanical properties. The values of parameters used in modal analysis of the force platform are given in Tab. 1.

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Table 1. Material Properties used in analyses of the force platform.

Denomination	Parameter
Material	AISI Steel 1020
Poisson's ratio	0.3
Density	7850 kg/m³
Elastic Modulus	210 GPa

A program of CAD (Computer Aided Design) was used to build the 3-D geometric model. To obtain the natural frequencies and the vibration modes, the load cells were fixed (in directions x, y, z) in the regions in which they were in contact with the ground. The movements of the force platform were restricted in the directions x and z because only vertical displacements were considered. The contacts between the structural parts were added, adopting as default the bonded contact that does not allow relative sliding between the surfaces or the loss of contact between them.

Regarding the finite element mesh, firstly it was used the standard mesh automatically generated by software, without refinement. This mesh is composed by ten nodes tetrahedral elements. It was used the Lanczos method for the eigenvalues (natural frequencies) and eigenvectors (mode shapes) extraction due to the fast convergence rate. Table 2 shows the convergence for the first natural frequency along mesh refinement.

Table 2. Convergence for the first natural frequency along mesh refinement.

Mesh	Number of elements	1st Mode frequency (Hz)
Standard mesh	40783	45.5
1	114400	40.3
2	163914	37.5
3	176987	33.6
4	187158	30.9

Table 2 shows different values of the first natural frequency according the number of elements. Therefore, it was used 187158 tetrahedral elements corresponding to a frequency of 30.9 Hz. It is observed that from the fourth case, has a good convergence rate of the results. With the increasing of the number of elements, the results not significantly changed, but generated a great increase in the computation time.

Natural frequencies and corresponding vibration modes are important dynamic properties and have a significant effect on the dynamic performance of structures. Figure 7 shows the first vibration mode of the force platform, using a scale with 10x amplification compared with the original displacement of the structure. It is noticed that the first natural frequency/mode shape is related to the bending of the ring load cells, thus if necessary, this value can be increased using a stiffer load cell despite the loss of sensitivity of the force measurements.

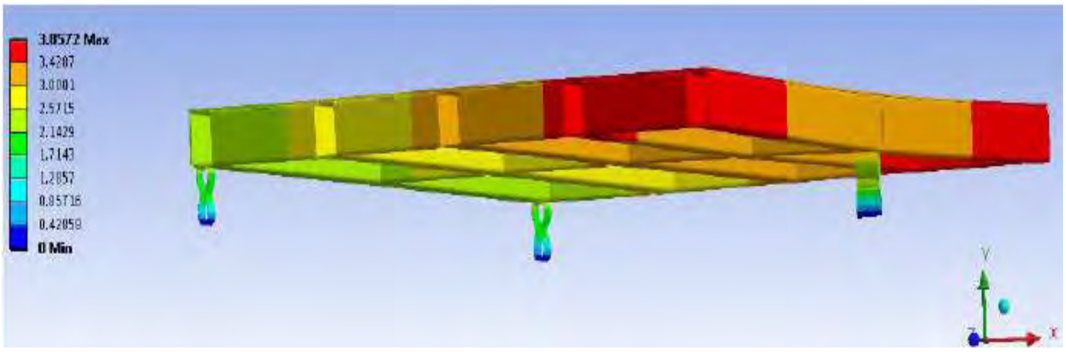

Figure 7. First vibration mode of the force platform.

3.3 Results of natural frequencies and mode shapes

According to Bayraktar, *et al.*, 2009 it is generally expected that finite element models present uncertainties, such as stiffness of supports and nonstructural elements, clearances, material properties, uncertainties in the structural geometry, boundary conditions and inevitable differences between the properties of the designed and as-built structure, these uncertainties may influence in the results of an analysis.

The numerical result shows frequencies values fairly close to those obtained in the experimental analysis. The numerical model shows 30.9 Hz for the first vibration mode while the experimental test indicates 30.1 Hz. The force platform is designed in order to be compatible with the frequencies involved in the measurements which are in the range of 0.5-10 Hz. So, it was confirmed numerically and experimentally that the design presented a resonant dynamic response far from the range of walking frequencies, thus minimizing the chances of measurement errors due to load amplification.

4. GROUND REACTION FORCE (GRF)

To conclude this paper, it is presented a measurement of Ground Reaction Force (GRF) of a pedestrian. Figure 8 shows the GRF data collected during the measurements, considering a person with a body weight of 75 kg, 1.81 m tall, walking normally and considering a dynamic amplification of about 25%.

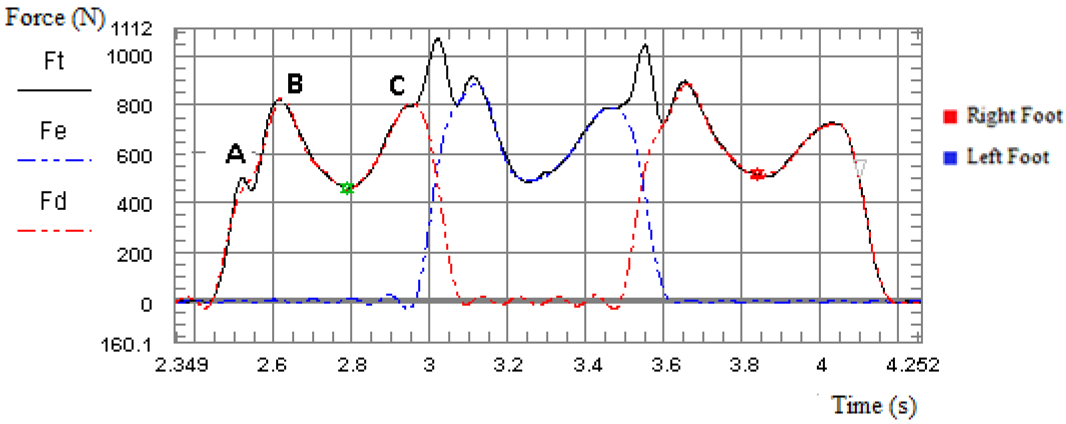

Figure 8. Data for Ground Reaction Force (GRF).

The vertical component of the GRF is characterized by two peaks and a valley, and usually these peaks have a magnitude greater than the body weight. For each leg, the first peak (B) is observed during the first half of the support and features the support leg receiving all body weight. This occurs after the contact of the foot with the ground (Larish, *et al.*, 1988). The second peak (C) is observed in the existing end of the support and represents the impulse against the ground to begin the next step. The valley between two peaks is slightly smaller in magnitude than the body weight and occurs when the foot is in flat position at the ground (Hamill and Knutzen, 2012). Also, there is a peak (A) in the first milliseconds (ms) of the support, and this peak is not always evident. This refers to the impact force, which results from the collision between two bodies (the foot and the ground). The total force (Ft) represents a sum of the forces of the left foot (Fe) and right foot (Fd), at the exact moment when both feet are in contact with the ground. Further details regarding the characteristics of the GRF can be found in other publication, Toso and Gomes (2013). Additional information about the human movement can be found in Vaughan, *et al.*, (1992) and Winter (2009).

5. CONCLUSIONS

In this paper, the analytical modeling and experimental testing for modal evaluation of a force platform was presented. A 3 D finite element model (FEM) of the force platform was developed using a commercial software. Considering the design data and the modal parameters such as frequencies and mode shapes were determined. It was identified the load cells bending mode as responsible for this frequency. The FEM was updated to reproduce the dynamic features of the force platform. The frequency result it is a value fairly close to the experimental ones and confirmed the adequacy of the design, since the frequencies were reasonably higher than the frequencies involved for walking pedestrians. So, the designed force platform presented a resonant dynamic response far from the range of force frequencies developed in human walking, thus minimizing the chances of measurement errors due to interaction or amplification. The obtained biodynamic parameters were consistent with those indicated by the literature.

6. ACKNOWLEDGEMENTS

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