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LOW COST DEVICE FOR GROUND REACTION FORCE MEASUREMENTS IN BIOMECHANICS

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Abstract: *The term biomechanics or bio engineering has become synonymous with high cost measurement apparatus. This contribution focuses on force plate devices and challenges the current high cost trends of this technology by designing a low cost alternative capable of obtaining comparably accurate results. The design uses a simple and unique configuration of beam elements measured through strain gauges. The contribution explains the alternative devices evolution from concept to FEA calculations of active structural members, to the realization and testing of prototype. The data obtained from the prototype are compared to those from an established force plate manufacturer. The comparison of results shows that the prototype force plate obtains data that are comparable to the results acquired from high cost technologies, proving that the low cost alternative is capable of providing similar levels of accuracy at a fraction of current prices.*
Keywords: *force plate, ground reaction forces, strain gauge, finite element analysis, gait*

INTRODUCTION

The evolution of biomechanics has accelerated rapidly in past decades as new technologies have become available. An important device in the analysis of human motion is force plate technology. This apparatus measured reaction forces when a patient stands, walks or even jumps on its measuring surface. It is a very useful tool in determining postural discrepancies and GRF (ground reaction forces) which can later be used to determine approximate JRF (joint reaction forces) through the application of inverse dynamics. An example of this can be seen in figure 1 where the approximate JRF at the knee can be determined by the following relations [1]:

$$R_x + F_x = m_t a_x$$
$$R_y + F_y - m_t g = m_t a_y \qquad (1)$$

where m_t is the mass of the shank and foot, a_x and a_y are the linear accelerations of the COM (centre of mass) and g is gravity.

These forces are a valuable indicator of a patients state of locomotion, especially when compared to results from a sample of statistically similar healthy individuals. On top of this the technology is capable of determining the direction of the reaction vector and COP (centre of pressure) during a certain activity.

The problem is that accurate systems capable of determining all of the above parameters continue to be costly especially considering that the measurement technology is already quite well established. At many teaching institutions, force plates are an exceptional tool for demonstrating how key biomechanical parameters effect a patients locomotion however they are often times financially unobtainable. This article challenges current high cost trends in biomechanical apparatus by designing and testing a simple apparatus that is capable of obtaining many of the same parameters at a fraction of current costs.

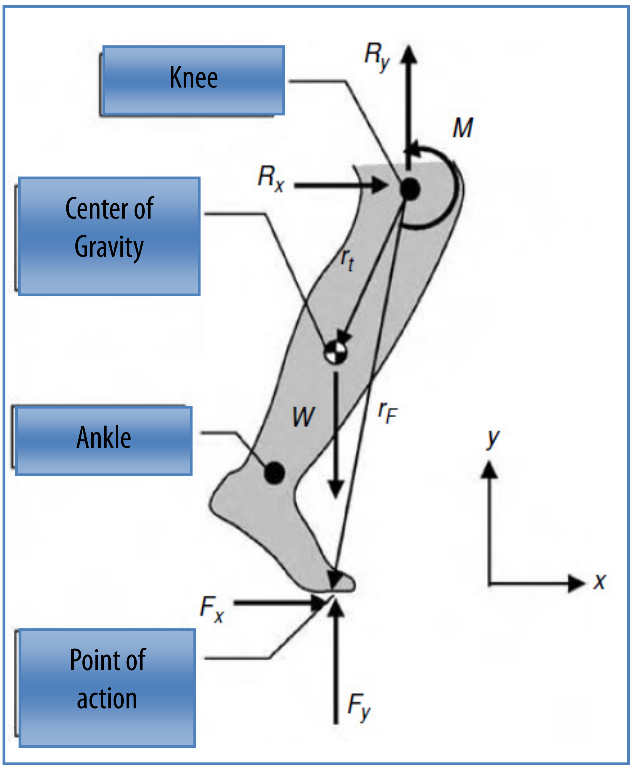

Figure 1: Free body diagram of reaction forces on the knee [1]

STRAIN GUAGE

Strain gauges are a reliable and well established technology that can accurately measure the deformation of structural members. They are constructed of an active grid configuration sandwiched between a flexible foil carrier. When glued to a structure that is loaded, the internal grid structure deforms and changes the output resistance. The sensitivity to change is known as the gage factor.

In practice, measurable strain is very small (often expressed in millistrain) thus it is important to be able to measure small changes in resistance which requires an excitation voltage V_{EX} across a bridge configuration like the one seen in figure 2.

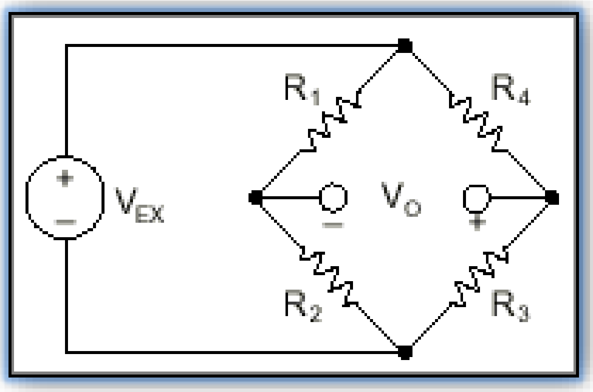

Figure 2: Wheatstone bridge configuration

The output voltage V_O across the bridge is then measured as:

$$V_O = [\frac{R_3}{R_3+R_4} - \frac{R_2}{R_1+R_2}] \cdot V_{EX} \quad (2)$$

where one or more of the resistances R_1, R_2, R_3, R_4 in the bridge are substituted by the strain gage itself with a similar gage factor. With no change in resistance, the bridge is balanced and thus a zero voltage results. As soon as the gage is stressed a measurable nonzero voltage will result. In this way we can quantify the deflection of simple beam elements when subject to a known force.

DESIGN OF ACTIVE BEAM ELEMENT

Strain gages come in many configurations and specifications. In the intention of keeping costs low, a quarter bridge configuration is used for each measuring point. The active member is a simple beam element with circular cross section. The beam geometry is optimized to maximize sensitivity to deflection while remaining within the measurement range of the strain gage.

The proposed design utilizes strain gages from Vishay industries which have a particular measurement range up to 3% deflection along the measurement direction. Using this limitation as one of the design considerations and knowing that typical gait analysis encounter up to 2.5 to 3g of loading [2], a FEA (Finite Element Analysis) was constructed using a beam element with circular cross sectional area.

Loading the beam to the limiting case of a 100kg patient acting on the loading point of the member at3g allowed for optimization of geometry to obtain no more than 3% strain between corresponding elements along the measurement direction (Figure 3).

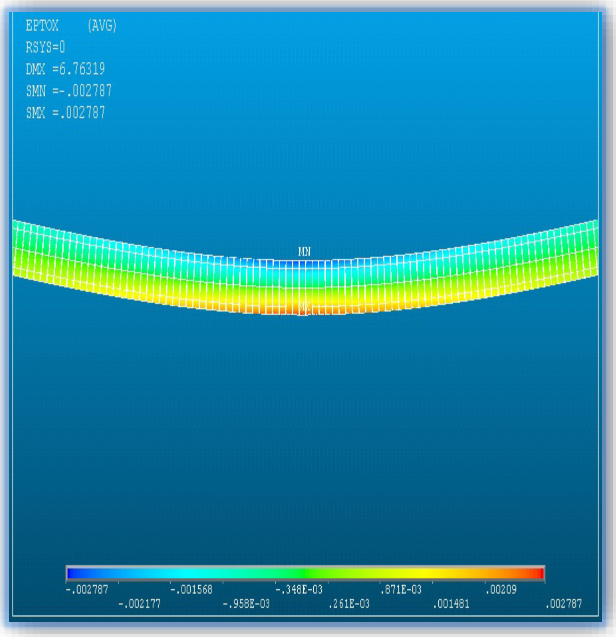

Figure 3: Analysis of total strain in the x direction (along axis of beam)

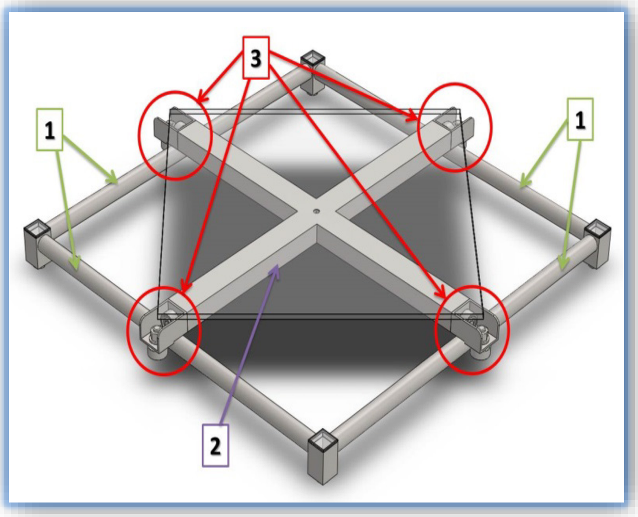

Figure 4: Model of 1 – active members, 2 – area of action, 3 – load points

Since there are four active members, this provides a large factor of safety since the patients weight is distributed over four beam elements. According to the FEA results, a model of the prototype was constructed with design considerations for loading points, ergonometric, and ease of data post processing (Figure 4).

DATA PROCESSING METHODOLOGY

The design configuration ensures that the active members are loaded in a controlled manner. The strain gages are mounted to measure tension on the beam underside in the area of maximum strain.

The quarter bridge for each gage were mounted on a standalone card with minimal lead length. The gages are excited by a stabilized 5V DC source. Voltage signals are fed through an ADC (analog to digital converter) to obtain data in a PC environment. Data acquisition was structured in labview software.

Firstly the unloaded signals were passed through an averaging block in order to detrend (zero) the signals in the unloaded state. Each loaded member is then calibrated using a 10, 20, and 30 kg mass respectively. the sensitivity is determined through the average difference in each loaded state from the reference detrended signal. After the calibration is completed, each signal is multiplied by its corresponding sensitivity and then summed to obtain the total vertical reaction force.

These values are then saved into .txt format after measurement completion for further data processing and interpretation. The constructed prototype can be seen in figure 5.

Figure 5: Prototype force plate design

RESULTS

The results of prototype measurements were compared to measurements obtained from a well-established force plate manufacturer used as a benchmark for comparison. Both force plates measured vertical GRF for the same test subject during gait. 10 measurements were performed for each force plate. An overlay of the results for the prototype force plate and benchmark force plate can be seen in figure 5.

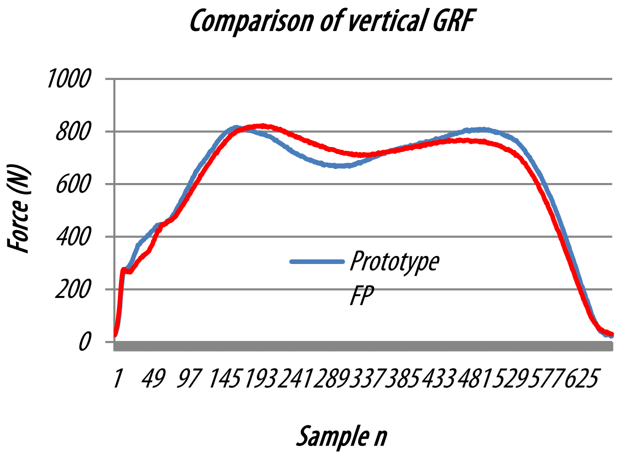

Figure 6: Comparison of averaged GRF measurements between prototype FP (force plate) and established FP apparatus

To quantify the strength of association between both sets of measurement, the linear correlation coefficient between the two results were calculated by the formula:

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2}\sqrt{n(\sum y^2) - (\sum y)^2}} \quad (3)$$

Where n is the sample size, x are values of one measurement, and y are the values for comparison. The coefficient returns values from -1 (negative correlation) to 1 (complete correlation). Comparison between the two measurements resulted in a correlation of 0.984. However a more accurate representation of how well the prototype measurements correspond to the measurements taken by the benchmark force plate was to calculate the RMSE (Root Mean Squared Error):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \quad (4)$$

which returned an error of28.24 N compared to results from the benchmark force plate.

CONCLUSIONS

The preliminary results measured for this contribution show that the prototype design is more than capable of obtaining accurate results (provided some conditions are met), when compared to an industry standard device which measures the same physical quantities. It should be noted that the prototype is still in the alpha stages of development. The final design should be capable of determining the COP (Centre of Pressure) and with an additional four strain gages, should also provide reaction measurements in the horizontal direction. Together, the measurement data should be able to calculate the approximate direction of the resulting force vector.

However, there are some drawbacks to the proposed design. The active beam elements must be deflected in a precise area, else the tensile strain changes relative to the actual applied mass, thus the results are effected. Simultaneous contact must be ensured between the plate and beams or else the resulting vector be affected. The association between perpendicular beam elements may affect deflection. A floating beam would eliminate this problem. The diamond configuration results in a device which is larger than the area of action, requiring a runway to be built around it.

Finally, the beams are susceptible to plastic deformation if overloaded which can cause the strain gage to delaminate or change the characteristics of the measurements. Although it is true that most force plate designs utilize strain gages, they are less likely to be permanently damaged if overloaded.

Regardless the current prototype force plate performs well and costs much less to comparable systems. It is debatable which system is more accurate, but considering the results, low cost systems have the potential to perform just as well as the current high cost alternatives.

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