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Design, development, and calibration of bipedal force-plate for post prosthesis gait rehabilitation

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ABSTRACT

There is a large demand for gait balancing devices for the above knee and below knee amputees after the installation of prostheses globally due to rehabilitation problems associated with prosthesis they occupied. Conventionally various methods used for this purpose those not affordable and not accessible easily and are not feasible generally as they need a lot of space and a well-qualified trainer which is not possible. So for it is required to design and develop an in-house transient force sensing device for lower limb amputees to get balanced in their gait cycle after wearing a prosthesis. Objectives of this research is to design and develop an affordable, accessible, easy to adopt and in-house force-plate for lower limb amputees to balance in gait cycle in four successive stride length after wearing prosthesis and improve their center of pressure line and to get quality of life. A force plate is designed via cad software and fabricated by the author. In this work, researchers passed through all the faces of such as design, modeling, fabrication electronic circuitry, interfacing, programming, and calibration. With the help of this force plate, an amputee can improve their gait cycle in five stride lengths one by one. Finally we have been designed and fabricated an in-house force-plate for lower limb amputees to get balanced in their gait cycle after wearing a prosthesis. A maximum deviation of 0.4 N was found from the tare value after experiments. From this limited study we conclude that the plate designed and fabricate can be used to improve the amputee's gait cycle and it has the potential to get easy access, affordability, less space occupying features.

1. Introduction

An inexpensive force plate in an important tool to find out ground reaction forces during the gait cycle of lower limb amputees [1].A force plate assess the postural stability during normal standing[2]. Force-plate is a simple method[3] that is often used to assess postural control[4]. Currently, the assessment of gait pattern can only be found out using costly force plates, that makes it difficult to application in most clinical settings [5]. Barela and M. Duarte explained that we cannot see forces and are unable to measure them in the course of a clinical evaluation. However, the GRF can be measured [6]with a force plate, which is an instrument used for gait analysis in many gait labs. We can acquire data with the help of a force plate, which describes some gait characteristics and is not detectable through visual inspection [7]. It is challenging to acquire valuable force plate data for an amputee in a limited amount of time [8]. Balance testing is a crucial component in gait cycle treatment and planning [9]. Vertical jump height is thought to get a valuable index of muscular power, which is an important factor in assessing the mobility [10], gait performance and functional capacity of lower limb [11]. Buckthorpe et al. described a method to determine the validity and reliability of a portable force plate when analysing landing and jumping tasks [12].

Collins et al. proposed a new method for calibrating force plates to minimise errors in the moments centre of pressure locations and forces. These errors may be occurred by the improper mounting of force plates to the ground or by the installation of a treadmill atop a force plate, which may cause distorting loads. The method termed as Post-Installation Least-Squares (PILS) calibration, consists functions of several previous methods into a simple procedure [13]. Kinser et al. tested the reliability and validated an algometer (1000-Hz sampling rate) by applying pressure on a force plate manually (500-Hz sampling rate): 10 sets of 5 applications to

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80 N and 1 set of 5 applications to each force level: 20, 30, 40, 50, 60, 70, 80, 90, 100, and 110 N[14].

Glatthorn et al. were to evaluated concurrent reliability and validity of the Optojump photocell system (Microgate, Bolzano, Italy) with the help of force plate measurements for assessing vertical jump height. Twenty subjects were asked to perform countermovement jumps and maximal squat jumps, and flight time-derived jump heights was obtained by the force plate compared with those provided by Optojump, to examine its concurrent (criterion-related) validity [15]. Running and walking on the level presumes external mechanical work, even when speed averaged over a complete stride remains constant [16]. Force plates are useful for examining the kinetic characteristics of movements of an amputee. They provide information regarding the external forces involved in the movement that can aid a lower limb amputee to evaluate his gait cycle quality [17].A. R. Altman and I. S. Davis was to quantify the continuum of foot strike patterns using an easily attainable kinematic measure and compare it to the strike index measure [18].To explain the relation between force plate measurement and clinical assessment of gait pattern control after stroke when selected to estimate tasks are performed under similar spatial and temporal conditions, and to examine the inter-rater agreement of assessment of weight distribution during quiet stance in subjects with stroke [19]. The importance of force plate studies of gait cycle in lower limb amputees has grown recently with the increasing applications of prosthesis foot [20,21].

The current work aimed to design and develop an in-house dynamic force sensing device for lower limb amputees to balance in their gait cycle after wearing prosthesis and improve their centre of the pressure line. This force plate would be the core concept of an extended dynamometric device, built by its simple reproduction in the proper location. Using such an arrangement it would be possible to map completely the limb ground reaction forces (GRF) produced in the gait cycle, allowing more qualitative gait patterns.

2. Materials and method

A force plate for lower limb gait analysis was designed via cad software and fabricated in the lab. For that researchers passed through all the faces of such as design, modelling, fabrication electronic circuitry, interfacing, programming, and calibration. With the help of this plate, amputees can enhance the quality of their gait cycle and can balance weight between both legs after some practice.

2.1. Mathematical modelling

An analytical model was used with the experimental results are discussed for comparison. In this section, the mathematical model was used to obtain the analytical deformation of the cantilever beam under bending is presented. The stress and strain models used in this paper are widely explored in the literature, both analytical methods [22–25] and methods wad based on finite elements analysis [26–27]. In the given force plate two rectangular plates having strain gauges on the top and bottom surface were used as load cells were used in the position of the cantilever beam.

For the beam fixed at one end and free at the other, we have the expression described below for the tension at the surface of the beam, [28]

$$\sigma = M \rho / I \tag{1}$$

where M is the resulting bending moment, I is the moment of inertia of the cross-sectional area, and rho is the distance from the neutral line to the point of interest. The moment of inertia is given by

$$I = bh3/12 \tag{2}$$

where b is the width of the beam and h is its thickness. Substituting Equation (2) into Equation (1) and c for h/2 we have

$$\sigma max = 6\ M/\ bh2 \tag{3}$$

which corresponds to the tension σmax on the surface of the beam when subjected to a bending moment M. It is known that the deformation ϵ can be obtained employing the Equation (4), known as the Hooke's Law, where E is the modulus of elasticity of the material.

$$\epsilon = E\sigma \tag{4}$$

Substituting Equation (3) into Equation (4) gives the equation for the deformation at the beam surface when subjected to bending, Equation (5).

$$\epsilon = E\ 6\ M/\ bh2 \tag{5}$$

2.2. Finite element analysis

Two leaf spring elements (150 mm*30 mm*5mm) each of ASTM A228 Steel having density 7800 kg/m3, poisson's ratio 0.313 and modulus of elasticity of 210 GPa was attached to base frame in such a way that they form a cantilever beam. One end of each leaf spring was fixed with base frame and another free end was mounted with footrests. Two downward loads of 800 N were applied on the top surface of each footrest and the whole frame was considered as fixed support. Transient structural finite element analysis was performed using 15.0Ansys workbench. A Cartesian coordinate system in Mechanical APDL solver preference was used. 1*10–3 sized tetrahedron mesh was generated. Ansys design modeller was used for modelling of force plate with a fully defined state and element control was program-controlled. The 3d model of the force plate has 21 faces, 12,617 nodes, and 5506 elements. Advanced size function was not used and medium relevance centre and medium smoothing were used.

2.3. Fabrication

In the hardware part a base frame of rectangular shape having 80 cm length and 45 cm width with a channel of 10 cm width weighing 50 g per mm, it has four legs having 40 cm height one at each corner of the rectangular base. One of the two footrests (30 cm*15 cm*1cm) of the acrylic sheet is mounted on the long edges of the rectangular base frame with the help of two leaf springs to place amputees foot to balance their weights easily. One end of the leaf spring is mounted to the acrylic footrest and another end is mounted with the help of a nut and bolt on the hole of the rectangular base. The second footrest (Left footrest) was mounted on one of the holes drilled on the left edge of the rectangular base. Four holes were drilled on the longer left edge of the rectangular base to facilitate changes in the stride length of the amputee as described and shown in Fig. 1(a) and (b).

2.4. Electronic hardware and connections

Four 350 O strain gauges were used to sense the applied force, two on each of the leaf springs. one is in the lower surface of the leaf spring to accommodate the compression force, and one on the top surface to accommodate tensile force on the spring. On the application of the force, tension will take place at the upper surface of the leaf spring and this tensile force will create tension in the strain gauge.

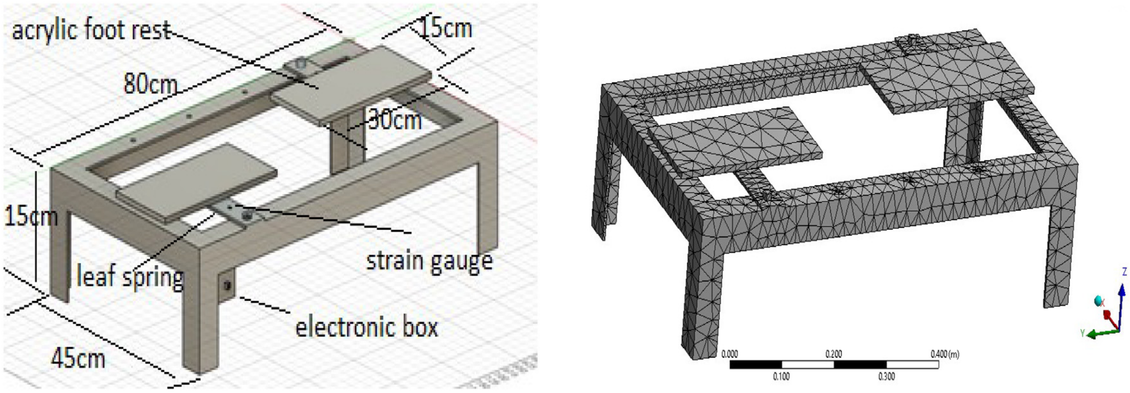

Fig. 1. (a) Force plate with dimension (b) 3D model of force plate with mesh.

Due to the tension in the strain gauge dimensions of the fine conductors of the strain gauge will also change and this change in the dimension will cause the change of resistance of the strain gauge and also a change if the voltage will take place proportional to the change in resistance. Although this change is in millivolts to, convert it into the human-readable form it is required to amplify this very fine voltage with the help of the HX711 amplifier module also a balanced Wheatstone bridge circuit was prepared to read the change in resistance. HX711 having six pins at the input and four pins at the output, four pins E+, E-, A+, and A- of the input side was connected to the Wheatstone bridge, and two pins B + and B-left vacant. on another end that is the output end, there were four pins one for GND, one for + 5 V, one DT connected to digital pin 5 of Arduino UNO, and one SCK pin which was connected to digital pin 6 of Arduino UNO hardware. The Arduino Uno hardware board was connected to the laptop through a 1.5 m long printer cable via a serial port.

2.5. Software installation and programming

To process and receive the data and to convert it into the human-readable format an open-source software integrated development environment was used. Arduino IDE was download and installed on the laptop and a library for amplifier HX711 was installed to activate its functions. There is a need to receive data from HX711 and process it in the required format for that an Arduino program was written which convert voltage input into weight in kilogram up to two decimal points and send it to the serial monitor. In Arduino programming, the HX711 ADC header file was used to enable the Arduino to read data from HX711 and to convert it in a usable format. "EEPROM.h" header file was used to save the information related to calibration. Then digital pins 2,3,4,5 was set as input. In void setup section 9600 baud rate was set and delay of 10 ms was set. Then serial print line function was used to get data into the serial monitor. In the void loop section also a serial print function was used to get sensor data with an interval of 10 ms.

2.6. Calibration

To calibrate the force plate, Open the Calibration example in Arduino IDE that came with the "HX711_ADC" library. Run the example code to your Arduino. It should run without any modifications if you connected the DT output of the HX711 module to the Arduino pin 4, and pin SCK to the Arduino pin 5. Open the Arduino IDE Serial Monitor. Follow the instructions in the terminal window. It gives you a message to put a known mass onto the load cells and then enter the actual weight of that item. That was the process of calibration to the force plate. Then it starts outputting the actual value of the weight on the scale. It should be remembered that serial port, serial monitor, and parallax data acquisition tool could not be open simultaneously. So that only one tool should be open at a time. The final developed model is represented in Fig. 2.

Fig. 2. Force plate test setup.

2.7. Data processing

To receive data from the serial port and access it into Microsoft excel sheet a parallax data acquisition tool was used. The parallax data acquisition tool enables us to see the change online in the form of curves, which is easy to analyze the changes during the gait cycle balancing and accommodate the changes required.

3. Results and discussion

A maximum strain of 0.002146 mm was found at the top surface of the spring and it is the location to place strain gauges as in Fig. 3(a) and maximum deformation of 0.009131 mm was found at the hanging inner sides of acrylic plates as in Fig. 3(b). Ansys results were satisfactory and meet our strain and deformation requirements. Hence design is safe and feasible for fabrication.

Force plate calibration was a necessary step in force measurement and hence we calibrated our force plate by taking ideal force readings for one thousand milliseconds of duration. The deviation

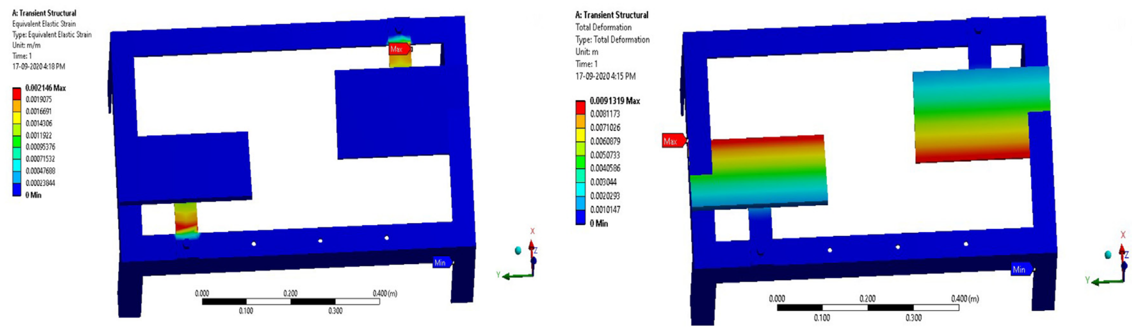

Fig. 3. Transient Structural analysis showing maximum and minimum strain location (b) Transient Structural analysis showing maximum and minimum deformation.

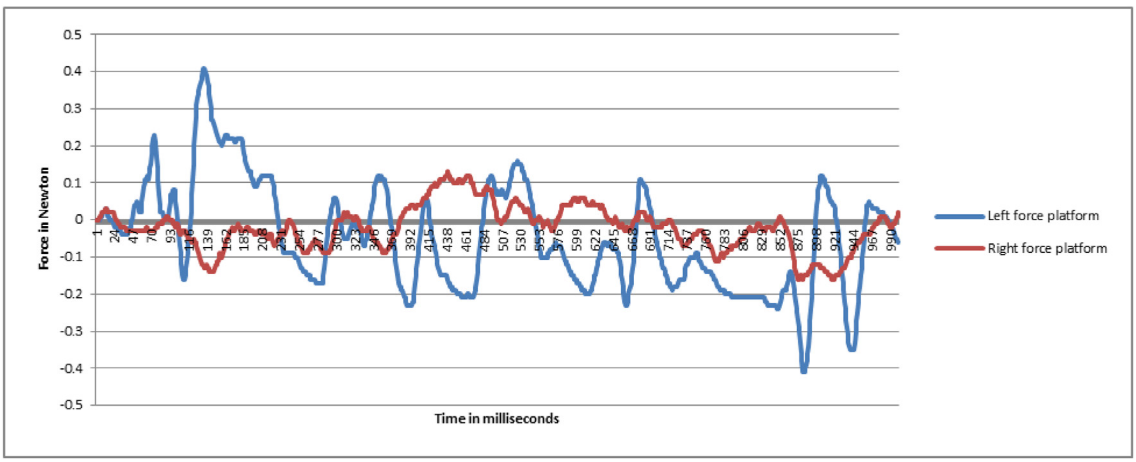

Fig. 4. Deviations in force values of left and right force platforms for one minute of ideal condition.

of force values in ideal condition for the left force platform and shows the deviation of force values in ideal condition for right force plate form shown in as in Fig. 4. The maximum deviation of + 0.4 N was shown at 140^{th}ms and −0.4 N was shown at 880th ms for the left force platform and the maximum deviation of + 0.12 N was shown at 440^{th}ms and −0.16 N was shown at 880^{th}-ms for the right force platform. This results are aligned with the result shown by the force plate designed and fabricated [1]. S. Wardoyo used TEKSCAN made flexy-force pressure sensor with the microcontroller chip ATmega 328. This configuration generated an output voltage of 50 mV per Newton[7].We used Arduino uno board which has smaller no of pin configuration and enough to handle electronic circuitry and Similar range of voltage variation with the variation in force is shown by the our prototype force plate. Other advantages of the prototype are flexible, light, and portable for outdoor usage.

4. Conclusion

An affordable, accessible, easy to adopt and in-house force-plate for lower limb amputees to balance the gait cycle in four successive stride length after wearing prosthesis and improve their center of pressure line and to get quality of life. The force plate is designed via cad software and fabricated. Design, modeling, fabrication electronic circuitry, interfacing, programming, and calibration was covered in this research paper. This newly designed and fabricated force-plate will be an aid for lower limb amputees to get balanced in their gait cycle post prosthesis. From this limited study we conclude that the plate designed and fabricate can be used to improve the amputee's gait cycle and it has the potential to get easy access, affordability, less space occupying features. It has been shown that a force plate with affordable budget of force plate can be fabricated to provide vertical component forces data that is similar in quality to commercial versions of force plate. Such a plate can be used as an aid in gait cycle training post prosthesis. A 3d cad model was analysed with the aid of Ansys 15.0 workbench. The Strain shown by the Ansys workbench 15.0 is within the range of the measurement capability of the strain gauge used in the force plate. The location of the maximum strain shown by the Ansys15.0 workbench is also in the middle of the spring elements of the designed model of the force plate. The location of maximum deflection is at the open ends of the spring elements and maximum deflection is also with in the elastic limit of the spring material which allow the spring element to regain the initial position after the release of load and so it proves that the model designed is feasible for fabrication. Our first prototype of the force plate was able to give quantitative experiments in standing and running. A maximum deviation from of 0.4 N was found from the tare value after experiments. Above prototype of the force plate is able to give the real-time force of quantitative experiments in standing and balancing. For future works, improvement in design and sensitivity of sensors configuration may able to increase the quality of dynamic force measurements and minimize the force deviation and leg time in signal processing.

CRediT authorship contribution statement

Radheshyam Rathore: Conceptualization, Methodology, Writing - original draft, Resources, Data curation, Software, Validation, Investigation, Formal analysis. **Amit Kumar Singh:** Supervision, Writing - review & editing. **Himanshu Choudhary:** Formal analysis, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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