Design, Manufacture, and Testing of a Low-Cost Force Platform with 3-Axis Load Cell

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Abstract. Force platform is an instrument to measure Ground Reaction Force (GRF) and locate Center of Pressure (CoP) in motion analysis. Although it is very useful, the cost of the commercially available force platform is relatively high. Therefore, the objective of this work is to develop a low-cost force platform with 3-axis load cell. The development was initiated with Design Requirement and Objective (DR&O) of the force platform. To measure the force, four 3-axis load cells were placed in each corner of the force platform to measure a maximum force of 1500 N. The dimension of the aluminum 5058 force platform was 500 x 500 mm. After the manufacturing process, the force platform was calibrated to obtain 12 correction factors for the four load cells in the three-axes. It was obtained that the RMSE of the correction factors was 0.87% in z direction and lower than 2% for x and y direction of GRF. The CoP was also tested to ensure the functionality of the developed force platform. The RMSE errors for the CoP were 5 mm and 5.9 mm in x and y coordinates, respectively. With relatively small RMSE, the force platform could be used to obtain GRF and locate the CoP in gait analysis.

Keywords: low-cost, force platform, gait analysis, ground reaction force, center of pressure

1. Introduction

Human daily activities, such as walking or running, have been researched for many purposes for the last decades. Numerous approaches have been made to analyze the living-being movement and apply the results for robotic technology, increase athletic performance, or even diagnose medical injuries. In the movement analysis, a force platform is mostly used to obtain biomechanical parameters, such as Ground Reaction Force (GRF) and Center of Pressure (CoP). The force platform uses a load cell or piezoelectric as its primary sensor to measure GRF and determine the location of CoP that is required for the study. The capacity of the force platform is based on the sensor capability to measure the magnitude and direction of the force. Single-axis load cell gives only the vertical force data. Additionally, the 3-axis load cell is able to monitor force applied in the medio-lateral (Fx), anterior-posterior (Fy), vertical (Fz) direction, and force moment relative to the GRF, Mx, My, and Mz [1,2].

Kistler, Bertec, and AMTI are prominent manufacturers that provide force plates with a wide variety of specifications. These commercial force plates price is relatively high, with an average cost of US$10,000-US$20,000 (140-280 million rupiahs), several even reach the price of US$62,000 (900
million rupiahs) [2]. Vernier may provide a low-priced force platform (US$400). Nevertheless, the specification is significantly inferior to that of Kistler’s or AMTI’s force plates that are capable of measuring 3-axis GRF [3].

There were already several researches in developing low-cost force platforms, such as the research conducted by Silvia et al. [2] and Jaafar et al. [4]. In [2], although the production cost of the force platform was one-tenth of the commercial force platform, it was still not affordable. Moreover, the developed force platform still needed final validation and comparison with the commercial force platform. Another low-cost force platform was developed by Jaafar et al. that could only measure GRF in one dimension [4]. Although, it had large capacity, the force platform resulted in unacceptable error in measuring small GRF.

Because of the costly commercial force platforms and limitations of previous researches, developing a low-cost force platform that could measure GRF in three directions and CoP become the objective of the present work. The current work was initiated by developing an affordable 3-axis load cell by Wicaksono et al. [5]. Then, the 3-axis load cell was used as the force transducer in this research. Subsequently, an affordable force platform was designed and manufactured.

2. Design Requirement and Objective

The first step in designing a low-cost force platform was to determine the design requirement and objective (DR&O). The DR&O consists of demand and wish criteria for the designed force platform. The criteria in the DR&O became the guidance in developing the force platform. Table 1 summarized the DR&O in the present work.

| Category   | Requirement                                                                 | Demand/Wish |
|------------|-----------------------------------------------------------------------------|-------------|
| Cost       | 1. Force platform cost is relatively more affordable than commercial force platform | Demand      |
| Performance| 2. Force platform must be able to measure ground reaction force               | Demand      |
|            | 3. Force platform must be capable of locating the center of pressure          | Demand      |
|            | 4. The maximum load is 1500N                                                | Demand      |
|            | 5. User-friendly data acquisition (Force plate to PC)                         | Wish        |
|            | 6. Force platform is easy to assemble and works fixed or portable             | Wish        |
| Physique   | 7. Maximum overall force platform is less than 30kg                           | Demand      |
|            | 8. The proportional dimension of the force platform                           | Wish        |

As shown in Table 1, one of the demand criteria is the force platform in this work should be affordable. Furthermore, the maximum load of the force platform is to be 1500 N since the average human weight would approximately be 57.5 – 80.7 kg [6] and the ground reaction force (GRF) is up to 1.3 times of weight in walking movement [7].

3. Design of Force Platform

The force platform consists of three essential components, i.e. lower platform, upper platform and force transducer. The lower platform was used to hold the force transducer that are capable to measure forces in three independent directions. In the present work, the load cell developed in previous research was used as the force transducer of the force platform [5]. In total, there are four load cells that were located in each corner of the platform to enhance the accuracy of the force platform. The load cells were bolted to both lower and upper platform. Hence, the forces from the upper platform could be transferred to the load cells.
The dimension of the force platform is determined by the step length of human gait since a ground reaction force is generally measured per foot. This length of step may be estimated at half of the stride length. The spatio-temporal parameters of gait consist of walking speed, stride length, cadence, and cycle time, and is presented in Table 2 for Indonesian subject in the 18 – 49 age group. From Table 2, it may be seen that the average stride length of Indonesian men and women are 1.2 meters and 1.02 meter, respectively. Hence, the force platform dimensions will be 500 x 500 mm, as may be seen in Figure 1. The thickness of the upper and lower platform was 10 mm and 6 mm, respectively.

Table 2 Spatio-temporal gait parameters of subject in 18–49 age-group in Indonesia [8]

| Variables          | Male Mean | Male SD | Female Mean | Female SD |
|--------------------|-----------|---------|-------------|-----------|
| Walking Speed      | 1.09      | 0.11    | 1.02        | 0.12      |
| Stride length (m)  | 1.20      | 0.08    | 1.11        | 0.10      |
| Cadence            | 109.29    | 7.84    | 110.36      | 9.78      |
| Cycle time (s)     | 1.10      | 0.13    | 1.10        | 0.14      |

Figure 1 The isometric view and dimension of force platform

Based on DR&O, the plate should be able to withstand force of 1500 N, but it should be rigid and weighs less than 30 kg. This indicates the material should have low density but high stiffness. There were several materials that fulfilled the criteria, such as stainless steel and aluminum. However, stainless steel has higher density than the aluminum. Therefore, aluminum was chosen as the material for the lower and upper platform. Three types of aluminum were considered, and their mechanical properties and prices are compared. The results are tabulated in Table 3. It may be seen that, aluminum 5058 is the lightest (lowest density) and the cheapest of the three types. While aluminum 7075 has the highest modulus of elasticity. Hence, both aluminum 5058 and 7075 were chosen as the candidates for the platform material.

Table 3 Aluminum mechanical properties [9]

| Parameter                  | Aluminum 5058 | Aluminum 6061 | Aluminum 7075 |
|----------------------------|----------------|----------------|----------------|
| Density (g/cc)             | 2.66           | 2.7            | 2.81           |
| Tensile yield Strength (MPa)| 228            | 276            | 503            |
| Ultimate tensile stress (MPa) | 317            | 310            | 572            |
| Modulus of Elasticity (GPa)| 70.3           | 68.9           | 71.7           |
| Elongation at Break        | 16%            | 12%            | 11%            |
| Poisson’s Ratio            | 0.33           | 0.33           | 0.33           |
| Price                      | 3rd (cheap)    | 2nd            | 1st (expensive)|

The thickness of the upper and lower platform was 10 mm and 6 mm, respectively.
The next step in designing the force platform was to assess the deformation due to the load from the human body on the upper platform. The upper platform should have insignificant deformation since it will affect the movement analysis. Finite element method by ANSYS was used to evaluate the deformation of the upper platform when it was loaded with a force of 2000 N. Figure 2 shows the result of deformation analysis for both aluminum 5058 and 7075. Since they have similar deformation, aluminum 5058 was selected as the material for the lower and upper platforms due to its lower density and price. Then, by using the dimension and material of the platform, it is calculated that the total mass of the designed force platform was 13.81 kg, included the four loadcells as the force transducer.

![Figure 2 Deformation of force platform with (a) aluminum 5058, (b) aluminum 7075](image)

4. **Manufacture of the Force Platform**

Referring to the force platform design, manufacture begins with aluminum 5058 procurement with a dimension of 500 mm × 500 mm with 6 mm and 10 mm thickness. Since each load cell was mounted to the upper and lower platform by four bolts, there should be four holes in each corner of lower and upper platform. In total, 16 holes were drilled in the platform. The final assembly of the force platform was presented in Figure 3. The total cost for the present force platform was around US$1,400.

![Figure 3 Force platform assembly](image)
5. Calibration and Testing Result

The final assembly of the force platform was then calibrated so that it could measure the ground reaction force (GRF) accurately. When the force platform was loaded, the signal from the load cells were acquired by NI 9237 DAQ with the help from SignalExpress software. SignalExpress is a data-logging software from National Instrument and it can acquire signals from many channels simultaneously.

The signal measured by each load cell \( f_{i,j} \) however was not the same with the actual force loaded to the force platform. Hence, there should be a correction factor \( C_{i,j} \) for the measured signal by \( i^{th} \)-load cell in \( j^{th} \)-direction. Since there were four load cells in the force plate, the variable \( i \) was numbered from 1 to 4. Moreover, the variable \( j \) was numbered 1, 2, 3 for \( x \), \( y \), and \( z \) direction, respectively.

The ground reaction force in each direction should be the sum of corrected signal from each load cell in the same direction. Therefore, the relationship between signal from load cell \( f_{i,j} \) and actual force \( F_j \) was depicted in Equation (1) below.

\[
F_j = \sum_{i=1}^{4} C_{i,j} f_{i,j}
\]

As implied in the Equation (1), there are 12 correction factors to be found before the force platform could be utilized. So, there should be at least 4 experiments for each direction with known \( f_{i,j} \) and \( F_j \) to calculate the value of all the correction factor. However, larger number of experiments will increase the accuracy of the correction factors.

The calibration method in \( z \) direction was to apply a static human body weight on the force platform, as illustrated in Figure 4(a). The weight was measured using a scale with a precision of 0.05 kg, or about 0.5 N, and it is assumed as an actual force in \( z \) direction. In the calibration process, the measurement of load cell signal was conducted 12 times to obtain correction factor \( C_{i,3} \) accurately with variation of load and position. The load was varied from 46.75 kg, 49.3 kg, 64.25 kg, 73.35 kg, 86.4 kg, and 99.15 kg. After estimating the correction factor for each load cell and direction, root mean square error (RMSE) was evaluated to assess the accuracy of the ground reaction force measurement by the force platform. The RMSE was calculated from the difference between the actual and measured GRF. The RMSE of GRF in \( z \) direction was 5.22 N. This error was acceptable since it is 0.87% of the average force loaded to the force platform, i.e. 600 N.

The principle of calibration in the \( x \) and \( y \) direction is roughly the same with calibration in \( z \)-direction. However, the arrangement of force platform and its loading should be modified. The loading of the force platform in \( x \) and \( y \) direction was conducted by a string that was guided to \( z \)-direction by a pulley, as can be seen in Figure 4(b). The actual load used was a dead weight, which varies from 1.25 kg, 2.5 kg, 3.75 kg, and 5 kg. The experiments were done 16 times for each \( x \) and \( y \) direction to obtain accurate correction.
factor. From the experiments conducted, it was obtained that the RMSE of the force platform was 0.69 N and 1.27 N, respectively. The RMSE in both directions was tolerable since it was less than 2% compared to the average loading given to the force platform in x and y direction.

After obtaining the correction factors accurately, the next step was to check the force platform performance on locating the Center of Pressure (CoP). The center of pressure (CoP) represents a point of application of the ground reaction force. In checking the CoP, the force platform was loaded by a pointed stick on the pre-determined location. Then, the calculated CoP was compared to the location of the loading in the term of RMSE. The RMSE for locating the CoP in this experiment was 5 mm and 5.9 mm in x and y coordinate, respectively. This number is acceptable because when compared to the dimensions of the force platform and the surface area of the foot, the error value is relatively small.

Since the RMSE of GRF and CoP testing was relatively small, the force platform testing could be continued to measure GRF and CoP of human gait. Two participants with body weight 715.1 N and 614.1 N walked normally and set one foot, either right or left, on the top surface of the force platform. The data acquisition system recorded the GRF and CoP. Moreover, the data will be processed by the MATLAB program. Figure 5 shows the result of GRF and CoP for one of the participants. Note that the x and y direction in the Figure 5(b) is the mediolateral and anteroposterior direction, respectively. As compared to the GRF and CoP in the Whittle [10], the GRF and CoP obtained from the developed force platform was not much different with the references. Therefore, it could be said that the present work in developing the affordable force platform was successful.

6. Conclusion
In the present work, a low-cost force platform that could measure GRF in three direction and CoP have been successfully developed with the cost only around US$1,400. The force platform used the four pre-developed 3-axis load cells in each corner as the force transducer. The total capacity of the force platform was 1500 N. The dimension of the force platform was 500 x 500 mm with thickness 5 mm and 7 mm for lower and upper platform, respectively. The lower and upper platform was made from aluminum 5058 since this material is inexpensive and rigid enough to support the maximum vertical GRF. After the manufacturing process, the force platform was calibrated to obtain correction factor for each load cell in x, y, and z direction. Then, the force platform was evaluated, and it was acquired that the RMSE of GRF in vertical direction was 0.87%. Moreover, the RMSE of GRF for x and y direction was lower than 2%. In addition, the force platform was also investigated to measure the CoP and its RMSE was 5 mm and 5.9 mm in x and y coordinate, respectively. With relatively small RMSE, the force platform could be used to obtain GRF and CoP of gait analysis.

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