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Design and Analytical Study of a Force Plate for Ground Reaction Forces (GRF) and Center of Pressure (CoP) Measurement

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Abstrak

Force plate digunakan dalam analisis pergerakan manusia untuk mengukur gaya reaksi tanah (GRF), pusat tekanan (CoP) dan turunan besaran kinetik yang diperlukan dalam bidang rehabilitasi medik. Penerapan force plate di berbagai bidang biomekanik, seperti analisis gaya berjalan, telah banyak disarankan dan diteliti di masa lalu. Penelitian ini bertujuan untuk merancang force plate yang ekonomis namun memiliki keandalan yang serupa dengan produk komersial. Force plate dirancang menggunakan sistem load cell sebagai penerima beban bila digunakan untuk mengukur gaya reaksi tanah yang terjadi pada saat manusia melakukan gerak berjalan. Terdapat empat load cell yang diterapkan pada force plate yang dirancang, dimana masing-masing load cell mampu menerima beban sebesar 50 kg, sehingga total beban yang dapat diterima force plate tersebut adalah 200 kg atau 2000N. Kekuatan load cell dalam menahan beban disimulasikan menggunakan metode elemen hingga. Hasil menunjukkan bahwa load cell 3 memiliki beban tertinggi di semua titik beban, kecuali titik beban 2 dan 6. Load cell 4 memiliki beban terendah di semua titik beban, kecuali titik beban 2 dan 6. Hasil perancangan ini diharapkan dapat diimplementasikan dan memiliki keandalan yang serupa dengan produk komersial.

Kata kunci : Force Plate; Gait Analysis; Load Cell; Ground Reaction Force; Center of Pressure

Abstract

Force plates are used in the analysis of human movement to measure ground reaction forces (GRF), center of pressure (CoP) and kinetic magnitude derivatives required in the field of medical rehabilitation. The application of force plates in various fields of biomechanics, such as gait analysis, has been extensively suggested and investigated in the past. This study aims to design an economical plate force but with reliability similar to commercial products. Plate force is designed using a load cell system as a load receiver when used to measure the ground reaction force that occurs during human walking motion. There are four load cells applied to the designed force plate, where each load cell is capable of receiving a load of 50 kg, so the total load that can be accepted by the force plate is 200 kg or 2000N. The strength of the load cell in holding the load is simulated using the finite element method. The results demonstrate that load cell 3 exhibits the highest load across all load points, with the exceptions of load points 2 and 6. Conversely, load cell 4 consistently registers the lowest load at all load points, except load points 2 and 6. The results of this design are expected to be implemented in products and have reliability similar to commercial products.

Keywords: *Force Plate; Gait Analysis; Load Cell; Ground Reaction Force; Center of Pressure*

1. Introduction

Forces are generated by all movements in biomechanical activity [1]. Measuring and quantifying the forces involved in the activity allows us to better understand and assess this mechanics of movement. The analysis of human gait, also known as gait cycle analysis, is one of the activities that is frequently performed [2]. The gait cycle refers to the period of time between when one foot makes contact with the ground and when the same foot makes contact with the ground again on the same side of the body [3](Figure 1). A single gait cycle comprises of two distinct phases: the stance phase, during which one foot makes contact with the ground, and the swing phase, during which one foot swings or is not in contact with the ground [4]. Typically, the initial point of contact with the ground is the heel of the foot.

Recently, force plates are commonly used for diagnostic purposes for orthopedic or neurological diseases e.g. diagnosis of Parkinson's disease [12], gait analysis [13–15], sport movement performances [16], postural analysis [17], and rehabilitation assistance [18]. Through the force plate, it is possible to measure, process, and interpret the total force arising from the contact between the body and the ground during the movement process. Some researchers have also used force plates for several purposes, one of which is gait analysis. a prototype force plate was designed and built with a modular sensor to measure the reaction force of the limbs generated when starting swimming activities [19]. A force plate was also developed and validated to measure ground reaction force by athletes at the Malaysia National Sports Institute [20]. Furthermore, the analysis and characterization of flight time and body posture of volleyball athletes have been carried out with a multiaxial extensometric force plate [21]. In their simplest form, force plates are designed to measure strictly axial forces using various geometries and various sensor technologies such as piezoelectricity, capacitance metering [22] and piezoresistivity [23]. The geometric shapes of force plates that are used in general are square and small-dimensional rectangles. For example, a square force plate with dimensions of 0.6 x 0.6 m is used in physics and sports [24]. In addition, a force plate with a rectangular shape with dimensions of 0.914 x 0.46 m is used to analyze the validity and reliability of a simple calculation method to evaluate speed, force, and output power during the back-jump movement [25].

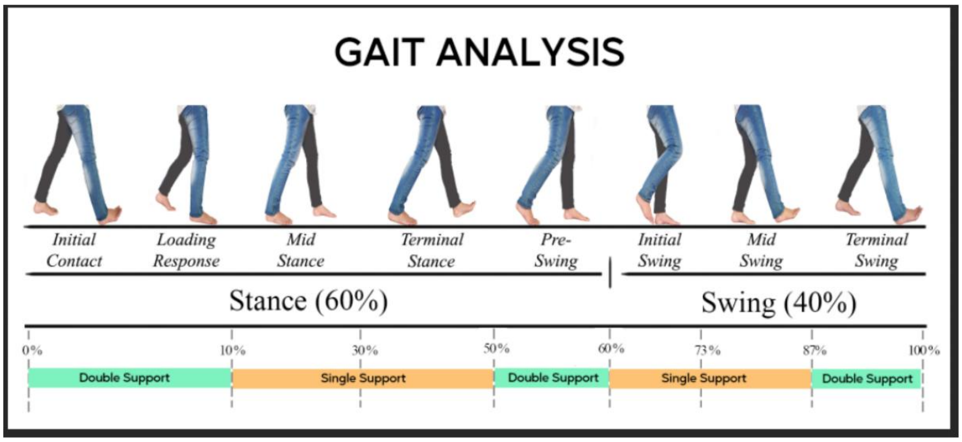

Figure 1. Gait cycle in normal walking [HKI EC00202253707]

This article presents a detailed exploration of the design and analytical aspects of a force plate specifically tailored for the measurement of GRF and CoP. The methodology employed in crafting this force plate is discussed, along with the theoretical underpinnings and engineering considerations. Additionally, the article delves into the significance of accurate force measurement, highlighting the implications for advancing research in biomechanics and related fields, using cheaper and more portable force plates, and and detailed measurement of balancing ability. The aim is to provide a comprehensive resource for researchers, engineers, and professionals interested in the nuanced study of human movement dynamics through the lens of force plate technology.

2. Materials and Method

This research begins with a literature study related to the force plate and its function as a tool for analyzing human walking motion. Next is to determine some of the criteria that will be used as the basis for making force plates. Force plate design criteria are shown in table 1.

In this study, the force plate was designed in a compact form because in use it was installed flush with the floor height so that subjects walking on it could walk naturally. Furthermore, the maximum load of the force platform is to be 2000 N since the average human weight would approximately be 57.5 – 80.7 kg [26] and the ground reaction force (GRF) is up to 1.3 times of weight in walking movement [27].

Table 1. Design Criteria of Force Plate

No.	Criteria
1.	Force plate cost is relatively more affordable than commercial force plate
2.	Force plate must be able to measure ground reaction force value in the vertical direction
3.	Force plate must be capable of locating the center of pressure.
4.	Able to be used for subjects with a maximum weight of 150 kg.
5.	User-friendly data acquisition (Force plate to PC)
6.	Force plate is easy to assemble and works fixed or portable
7.	Maximum overall force platform is less than 30kg
8.	Has dimensions that are wide enough, so that both feet can be in the force plate area

2.1. Force Plate Design

Based on the predetermined criteria, the force plate design is then obtained as shown in Figure 2. The force plate design is made with the help of Solidwork software. The force plate prototype developed in this study is square in shape with dimensions of 600 mm x 400 mm. force plates are constructed with load cells, all with their axes vertical, supporting a plate. Four load cells are used with located in each corner of the platform to enhance accuracy of the force plate. Load cells use what are called strain gauges, which essentially are variable resistors that change their resistance relative to their strain (basically how much they stretch) [14]. By measuring the resistance, and calibrating each load cell so that the resistance is meaningful in proportion to force. The load acting on the force plate must be less than 2000N in the vertical direction. The maximum work load must not cause the load cell as the main component of the force plate to experience plastic deformation.

The force plate prototype in this research uses a commercial load cell with a capacity of 50 kg. Based on criteria, the force plate should be able to witstand force of 1500 N, but it should be rigid weights 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 lower and upper force plate.

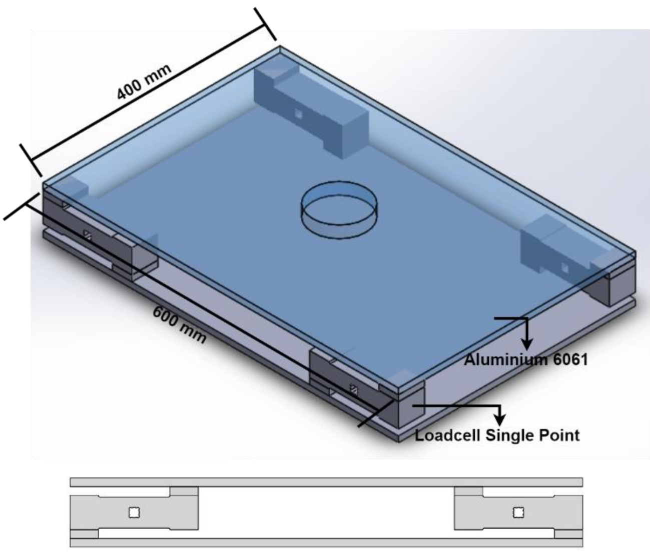

Figure 2. Force Plate Design

2.2. Finite Elemen Model

Simulations were carried out to determine the strength level of the design material along with the forces acting on the load cell when it receives an object load using the help of the finite element method. The software used to carry out the simulation is Ansys software. The meshing settings and boundary conditions are shown in Figure 3 and Figure 4. The elastic properties of Young's Modulus (YM), Poison Ratio (PR), and Density (ρ) of each material used in the analysis are shown in Table 2. Element used beam element simulation, to analyze deformation. The number of elements obtained is 54556 elements dan the number of nodes obtained is 208085 nodes.

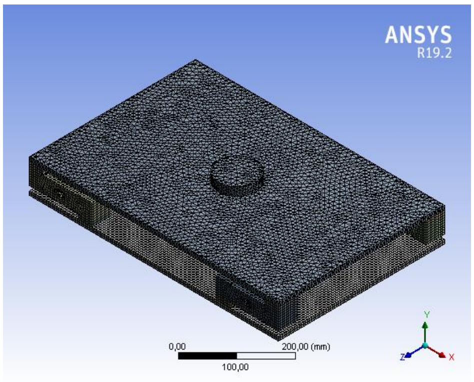

Figure 3. Meshing Process

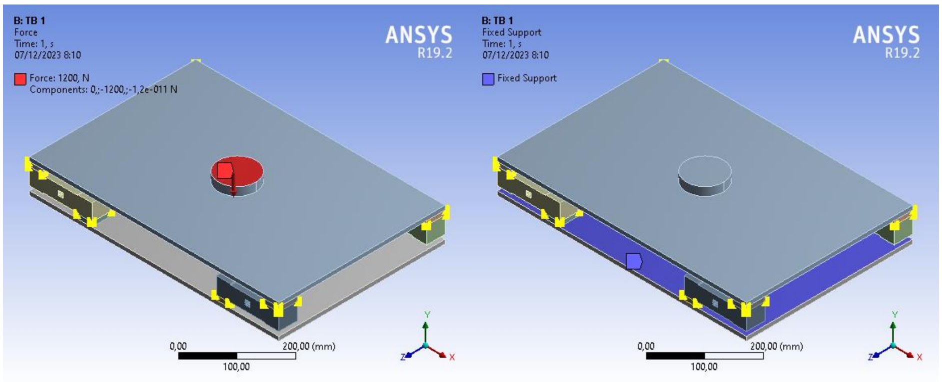

Figure 4. Boundary Condition Settings

Table 2. Materials Properties of Aluminum 6061

Parameters	Properties
Density (g/cc)	2.7
Tensile yield strength (MPa)	276
Ultimate tensile stress (MPa)	310
Modulus of Elasticity (GPa)	68.9
Elongation at /break	12%
Poisson's Ratio	0.33

The FEM simulation conducted in this study aimed to analyze the force distribution as measured by individual load cells. Simulations were conducted at nine distinct locations (Figure 5) to assess whether the measured force distribution aligns with the corresponding load application points on the model. A uniform load of 1500 N (150 kg) was applied at each designated point for consistency.

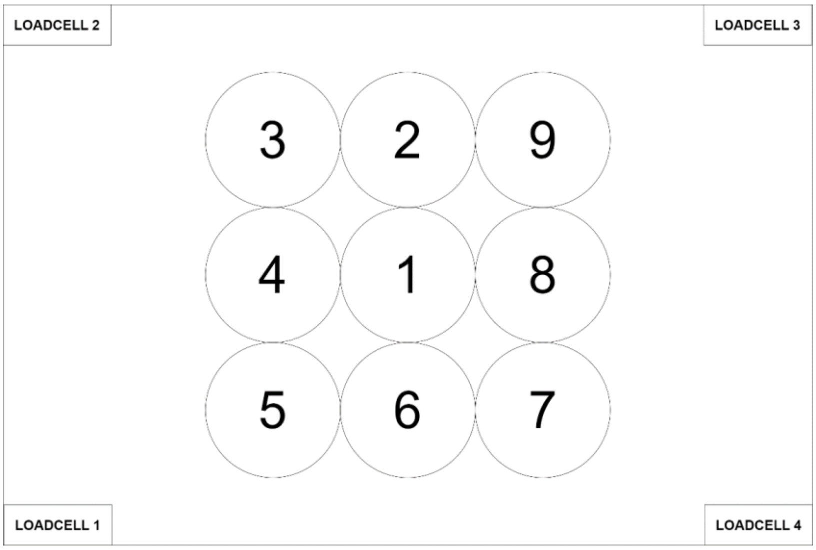

Figure 5. Location of nine points for testing

2.3 CoP Calculation

The next test is a test in measuring CoP. This test follows the following formula. The results of the CoP calculation are shown in Table 3.

- CoPx

$$\boldsymbol{CoPx} = \frac{1}{2} \cdot \frac{(\mathrm{F2+F1})-(F3+F4)}{\mathrm{F1+F2+F3+F4}} \quad (1)$$

- CoPy

$$\boldsymbol{CoPy} = \frac{1}{2} \cdot \frac{(\mathrm{F2+F3})-(F1+F4)}{\mathrm{F1+F2+F3+F4}} \quad (2)$$

3. Result and Discussion

The force plate was employed to analyze the dynamic changes in GRF and CoP throughout the gait cycle. The data obtained highlighted distinctive patterns during the stance and swing phases. The temporal and spatial variations in GRF and CoP provided valuable insights into the intricate mechanics of human walking. These findings contribute to a deeper understanding of gait dynamics, essential for designing interventions in areas such as orthopedics and sports science. Numerical modeling based on the finite element method is usually used to provide objective and quantitative indicators to analyze and optimize the design process. The data taken from the simulation is data from force reaction or loadcell, then the results of the numbers from the force reaction simulation come out and are processed in excel to obtain graphical results. The simulation was carried out with the help of Ansys Workbench software using static linear analysis. The simulation results can be seen in Figure 6.

The test aimed to validate the functionality of the force plate, assessing whether the load cells accurately register varying loads at different points. Specifically, it was investigated whether the load cell closest to the applied load would register a relatively higher force compared to others. Testing was conducted at nine specific points, incrementally increasing the load from 10 kg to 70 kg in 10 kg intervals. Notably, at the first point— the midpoint— there was a significant variance in the load distribution among load cells. Table 2 presents the detailed test results. Despite minor discrepancies, the load measured by each load cell from the second to the ninth test points aligned with expectations, as depicted in Figure 6. The observed error likely stemmed from either a manufacturing defect or suboptimal quality of the load cell, with the strain gage cable being particularly susceptible to breakage due to its minute diameter.

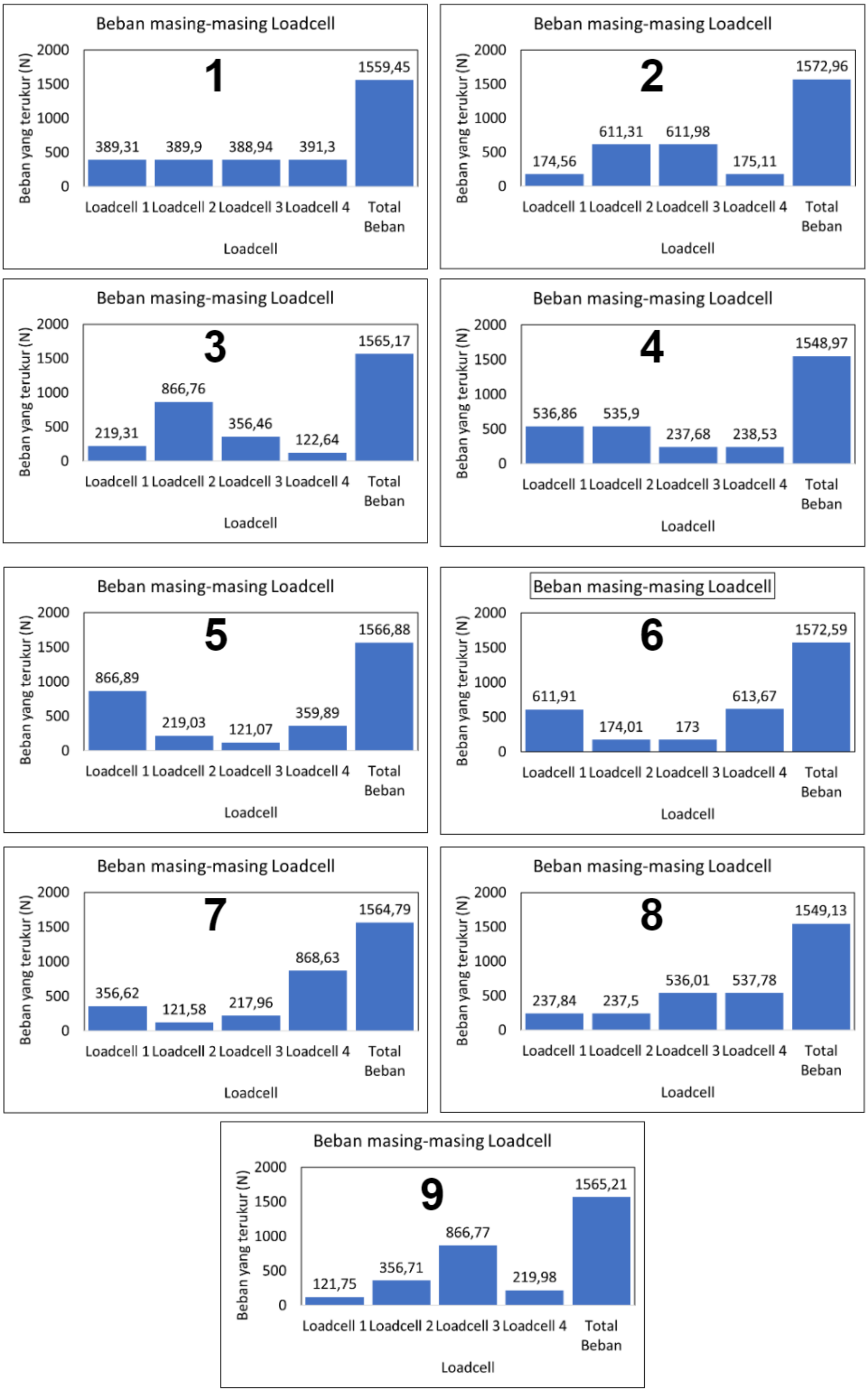

Figure 6. Test Results at Nine Load Points

Table 2. Total from load points 1 to 9 on Loadcell

	Loadcell 1	**Loadcell 2**	**Loadcell 3**	**Loadcell 4**	**Total Load**
Load Point 1	389,31	389,9	388,94	391,3	1559,45
Load Point 2	174,56	611,31	611,98	175,11	1572,96
Load Point 3	219,31	866,76	356,46	122,64	1565,17
Load Point 4	536,86	535,9	237,68	238,53	1548,97
Load Point 5	866,89	219,03	121,07	359,89	1566,88
Load Point 6	611,91	174,01	173	613,67	1572,59
Load Point 7	356,62	121,58	217,96	868,63	1564,79
Load Point 8	237,84	237,5	536,01	537,78	1549,13
Load Point 9	121,75	356,71	866,77	219,98	1565,21

Table 3. Calculation results of COPx and COPy at the load point

	CoPx	**CoPy**
Load Point 1	-0.00033	-0,0006
Load Point 2	-0,00039	0,277699
Load Point 3	0,1938	0,2815
Load Point 4	0,1925	-0,0006
Load Point 5	0,19305	-0,2829
Load Point 6	-0,0002	-0,2793
Load Point 7	-0,1944	-0,283
Load Point 8	-0,1932	-0,0007
Load Point 9	-0,1943	0,28167

4. Conclusion

In conclusion, the design and analysis of the force plate presented in this study provide a comprehensive and reliable platform for measuring GRF and CoP. The implications of these findings extend across multiple disciplines, offering researchers and practitioners a valuable tool for advancing biomechanics research and applications. The results presented here pave the way for future research avenues and potential enhancements to the force plate design. Addressing limitations and exploring opportunities for further refinement will contribute to the continuous evolution of biomechanics tools, fostering advancements in the understanding of human movement and function.

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