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Development of a Force Table Apparatus for Laboratory Use

Ismaila Olanrewaju Alabi*, Gbenga Collins Famuagun, Adebunmi Peter Okediji, Oluwasanmi Iyiola Alonge and Ahmed Oyedokun Oyefolahan
Department of Mechanical Engineering, Elizade University Ilara-Mokin, Ondo State, Nigeria
*Corresponding Author's E-mail: ismaila.alabi@elizadeuniversity.edu.ng

Abstract
This study presents the design, development, and evaluation of a low-cost, adjustable force table aimed at improving physics education and applied mechanics in resource-constrained settings. Conventional force tables are often expensive, non-portable, ergonomically rigid, and limited in angular accuracy. This project developed a functionally comparable alternative using locally available materials, 3D-printed pulleys, a laminated angular scale, and a height-adjustable tripod stand. The apparatus was tested using repeated three-force equilibrium experiments and benchmarked against a commercial (foreign) model under identical conditions. Performance validation employed statistical tools, including Root Mean Square Deviation (RMSD), standard deviation, paired t-tests, and relative error analysis. Results showed minor deviations from theoretical values, but no statistically significant differences between models at the 95% confidence level ($p > 0.05$). The observed relative error (~5.17%) and angular deviation (≤0.5°) were within acceptable educational limits. Instructional suitability was evaluated based on the device's ability to support hands-on demonstrations of vector addition and equilibrium, promote repeatable student-led experiments, and reinforce Newtonian mechanics through physical validation. Its ergonomic design accommodated different user heights and classroom setups. Preliminary feedback from users (via a structured Likert survey) highlighted strong pedagogical value and ease of use, with recommendations for future digital enhancements. Overall, the study confirms that a validated, affordable, and adaptable force table can effectively support experiential learning in mechanics education.

Keywords: Applied Mechanics Lab, Force table, adjustable, 3D-Printing, error analysis

1. Introduction

The principles of forces and their interactions underpin classical mechanics and are foundational topics in early physics education. A key instructional tool in teaching vector addition and equilibrium is the force table, a device that visually demonstrates the concept that the vector sum of all forces acting on a system in equilibrium is zero (Geddes and Black 2008; Greenslade 2002). Typically, the apparatus comprises a circular platform with angular graduations, pulleys arranged at various angles, and masses suspended via strings. When the forces are correctly balanced, a lightweight central ring remains centered, visibly confirming equilibrium. Despite its pedagogical value, the traditional force table is limited by several design and usability constraints. Many models are fragile, lack adjustability, and are difficult to level accurately. Angular markings often degrade with use, reducing measurement fidelity. Furthermore, most designs are optimized for fixed-height workspaces, disregarding ergonomic needs for users of varying statures. These limitations affect not only experimental accuracy but also hinder learner engagement, particularly in large classrooms or under-resourced institutions where equipment sharing is necessary.

In response to these issues, recent trends in educational technology emphasize low-cost, modular, and student-centered tools, especially within STEM disciplines. Research by Hahn (2016) and Kanwal *et al.* (2022) highlights growing efforts to design affordable, open-source teaching equipment using locally sourced or 3D-printed components. Yet, the force table remains largely absent from this innovation trend, with relatively few modern studies exploring improvements in portability, digital integration, or ergonomic enhancement. Experimental studies, such as Robert (1998) and Dessouki (2022), have validated the instructional utility of force tables, reporting force measurement errors below 5%, which support their continued relevance. However, these studies offer limited exploration of practical refinements in design adaptability, cost-effectiveness, or user interaction.

This study seeks to fill this gap by developing a low-cost, adjustable, and ergonomically enhanced force table built from locally available and 3D-printed materials. Beyond replicating traditional functionality, the design prioritizes improved usability, structural durability, and measurement precision. Performance is validated through controlled three-force equilibrium experiments and benchmarked statistically against a commercial (foreign) model to assess both accuracy and instructional value.

2.0 Materials and methods

This section outlines the systematic approach employed in the design, development, and testing of the force table apparatus. The process was divided into key stages: requirement analysis, conceptual design, material selection, mechanical design, fabrication, and testing; each guided by engineering principles, educational objectives, and cost-effectiveness.

2.1 Requirement Analysis

A review of existing force table designs through literature and local laboratory surveys identified key performance benchmarks:

a) Angular measurement precision (±1° tolerance)
b) Stable, flat surface
c) Low-friction pulley system
d) Adjustable, tripod-based support
e) Durable, low-cost materials
f) Portability and ease of assembly

These requirements were used as benchmarks for the new design.

2.2 Conceptual Design

Initial 2D and 3D sketches (Figures 1 and 2) were developed using AutoCAD to explore different configurations. Key design decisions included:

a) Using a circular platform for even angle distribution
b) Incorporating three to four pulley mounts for vector experiments
c) Integrating adjustable clamps to vary pulley positions

Designs were evaluated for mechanical feasibility, user ergonomics, and classroom suitability.



Figure 1: 2-D Representation of the Developed Force Table

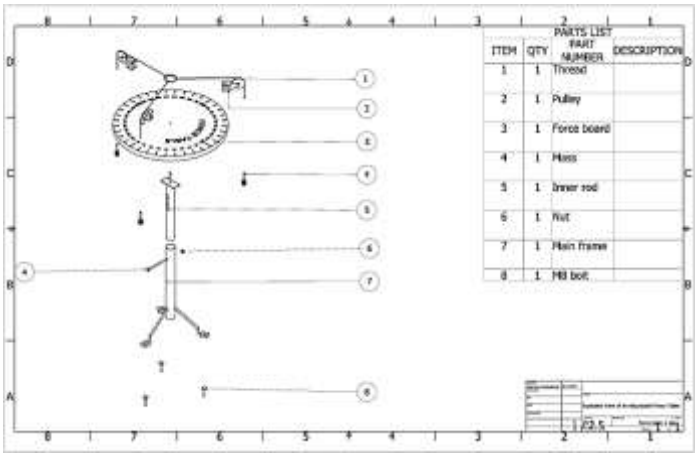


Figure 2: 3-D Representation of the Developed Force Table

2.3 Materials Selection

Material choices were based on availability, strength, machinability, and cost. Table 1 lists the selected materials for each component. All materials, except pulleys (3D-printed), were sourced locally to reduce costs.

2.4 Mechanical Design and Fabrication

The apparatus was built with emphasis on:

a) Availability and cost-efficiency: Locally sourced materials minimized expenses.
b) Structural stability: A tripod stand provided a firm base.
c) Adjustability and ergonomics: The height-adjustable stand accommodated various users.
d) Corrosion resistance: Protective coatings were applied to prevent rust.
e) Aesthetic quality: A neat and professional finish enhanced usability.

Table 1: Force Table Component and Materials Selection

S/N	Component	Material	Reasons
1	Strings	Cotton	Availability, Minimal stretch, good strength
2	Masses	Brass Nickel	Availability, Precision and compatibility
3	Protractor	Polymeric sticker	Cost
4	Pin & Central Rings	stainless	Strength
5	Pulleys	Plastic with ball bearings	Lightness in weight, Low-friction, corrosion-resistant
6	Tripod Stand	Galvanized pipe	Corrosion resistance, cost
7	Tripod Stand Support	High yield steel	Strength, minimal vibration
8	Levelling Screws	Angle iron	Strength
9	Force Table Board	HDF ply board	Lightness in weight, smooth, easy to mark

2.4.1 Platform for the Table

A 360 mm diameter (D) circular platform was cut from HDF ply-board. A laminated angular scale was affixed around the perimeter. A 10 mm central hole enabled free string-ring movement. The circumference was calculated using equation 1, as (Knight, 2017**)**:

$$\text{Circumference}, C_{FT} = \pi D \qquad \text{(Equation 1)}$$

$$C_{FT} = \pi \times 360 = 1130.97 \text{ mm}$$

2.4.2 Pulley Assembly
Custom 3D-printed pulley holders with adjustable clamps were mounted using angle brackets. This ensured smooth string motion and precise angular placement.

2.4.3 Center Ring and Pin
A lightweight 20 mm metallic ring was suspended on a stainless-steel pin at the center to visually assess equilibrium.

2.4.4 Adjustable Support Stand
The stand was built from two concentric galvanized iron pipes (30 mm and 25.4 mm). Vertical height adjustment was achieved through pre-drilled holes. A tripod base, welded from 10 mm mild steel rods, provided stability. Each leg included an M8 bolt-based leveling mechanism.

2.4.5 Calibration and Testing
The apparatus was leveled using a built-in spirit level. Angular accuracy was verified with a digital protractor, and known weight combinations were tested to confirm consistency with theoretical force resolution.



Figure 3: Levelling of Force Table

2.4.6 Safety and Ergonomics
Edges were smoothed to prevent injury. The pulley system was designed to avoid entanglement. Standard workshop safety practices were followed throughout fabrication and testing.

2.4.7 Experimental Determination of Equilibrium with Three Forces
To conduct the three-force equilibrium experiment, the force table was leveled using a bubble spirit level, and the legs were adjusted for stability. Two known masses: 50–300 g (Figure 4) were suspended using strings over pulleys (Figure 5) placed at arbitrary non-zero angles (θ_1 and θ_2). These masses (m_1 and m_2) generated forces F_1 and F_2.
The ring was positioned over the central pin (Figure 6). A third string was then pulled in varying directions until the ring lifted off the pin—indicating equilibrium. At this angle, a third pulley was installed, and the corresponding mass (m_3) was added incrementally until equilibrium was reestablished (Figure 7). This process allowed the determination of F_3 and its direction (θ_3), forming a closed force triangle.



Figure 4: Masses on hangers



Figure 5: Pulley attached to Force Table



Figure 6: Strings attached to the Ring over the Pulleys



(a) Newly Developed Force Table



(b) Foreign Force Table

Figure 7: Experimental setups for the Equilibrium of Forces Experiment

2.4.8 Error Analysis

Error analysis was performed to assess deviations between experimental and theoretical results, and between the constructed and a standard (foreign) force table through Root Mean Square Deviation (RMSD) and Relative error (RE). RMSD was calculated using equation 2 (Holman 2012):

$$\text{RMSD} = \sqrt{\left[\frac{1}{\text{n}}\sum_{i=1}^{n}(x_i - x_m)^2\right]} \qquad \text{(Equation 2)}$$

Where. $x_i - x_m$ is the deviation for each reading
x_i represents each reading taken
n represents the total number of readings taken
the RE was calculated using equation 3 (Dessouki 2022)

$$\text{RE}(\% = \frac{\text{Experimental value} - \text{Theoretical value}}{\text{Theoretical value}} \qquad \text{(Equation 3)}$$

2.4.9 Bill of Engineering Measurement and Evaluation (BEME)

The detailed Bill of Engineering Measurement and Evaluation (BEME) for producing three (3) units of the force table is presented in Table 2.

The total expenditure for producing three units was ₦219,420.00, resulting in an average unit cost of ₦73,140.00. Currency conversion was based on an exchange rate of approximately ₦1,500 to $1 USD (as of June 2025). The comparable imported universal force table costs about $83 (₦124,500.00) per unit in bulk orders.
Additionally, while the foreign units may offer durability, the locally developed force table provides significant cost savings and enhanced educational value by allowing customization and ease of repair with locally sourced materials. Further cost reductions could be realized through use of recycled or surplus materials, depending on availability. Overall, the developed force table represents a cost-effective, adaptable solution suited to the needs of educational institutions in the region.

Table 2: Bill of Engineering Measurement and Evaluation

S/N	Material	Description	Quantity	Unit Price (₦)	Total Price (₦)
1	Plyboard	HDF	1	31,500.00	31,500.00
2	Pipe	Galvanized ½"	1	10,800.00	10,800.00
3	Rod	High steel ½"	1	8,400.00	8,400.00
4	Angle iron	3 mm thick, 50 x 50 mm	1	1,500.00	1,500.00
5	Bolt & Nuts	M8	9	200.00	1,800.00
6	Adjustable Bolt & Nuts	Inner pipe	3	150.00	450.00
7	Electrode	Mild steel (2.5 x 350 mm)	1	2,500.00	2,500.00
8	Abrasive paper/emery cloth	P32 to P800 grain size	1	4,000.00	4,000.00
9	Paint	Auto base	1	4,800.00	4,800.00
10	Paint Brush		1	1,200.00	1,200.00
11	3D-Printed Pulley	Set	3	38,500.00	115,500.00
12	Overhead		-	10,000.00	10,000.00
13	Total Material Cost (TMC)				182,850.00
14	Labour cost	15% of TMC	-	-	27,427.50
15	Lon-term maintenance cost	5% of TMC			9,142.50
	Grand Total				**219,420.00**

3.0 Result and Analysis

The developed adjustable force table was evaluated through controlled three-force equilibrium experiments and compared with a commercial (foreign) force table. Experiments were repeated five times for each setup using identical mass and angular configurations. Results were statistically analyzed to assess accuracy, repeatability, and deviation from theoretical predictions.

3.1 Statistical Summary of Experimental Results

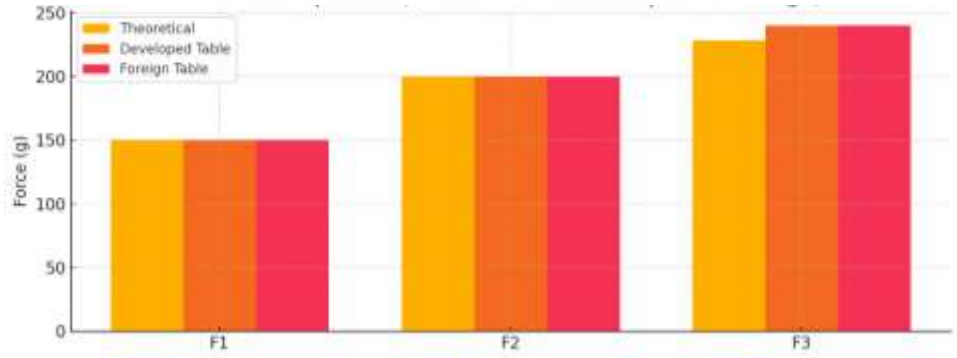
Table 3 summarizes the averaged results across five trials for both the developed and foreign force tables, compared to theoretical values. Standard deviation (SD) and relative error were computed for both force magnitude and angular placement of the equilibrant (F_3, θ_3).

Table 3: Statistical Comparison of Results

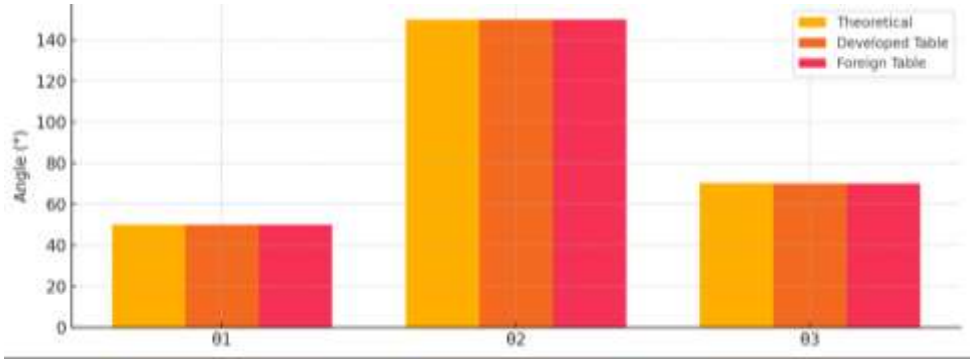
Parameter	Theoretical	Developed Table (Mean ± SD)	Foreign Table (Mean ± SD)	Relative Error (Developed)	Relative Error (Foreign)
F_1 (g)	150	150 ± 0	150 ± 0	0.00%	0.00%
F_2 (g)	200	200 ± 0	200 ± 0	0.00%	0.00%
F_3 (g)	228.2	240 ± 1.58	240 ± 1.58	5.17%	5.17%
θ_1 (°)	50.0	50 ± 0	50 ± 0	0.00%	0.00%
θ_2 (°)	150.0	150 ± 0	150 ± 0	0.00%	0.00%
θ_3 (°)	70.3	70.0 ± 0.5	70.0 ± 0.5	0.43%	0.43%

3.2 Graphical Comparison of Force and Angle Results

Two bar charts shown in Figure 8 compare the theoretical, developed, and foreign force table outcomes for both: force magnitudes (F_1, F_2, F_3) and angular directions (θ_1, θ_2, θ_3). The graphs demonstrate that while F_1 and F_2 matched theoretical values, the measured F_3 slightly deviated, resulting in a 5.17% error in both tables. Angular agreement was strong across all configurations.



(a) Force Comparison



(b) Angle Comparison

Figure 8: Comparison of Theoretical, Developed, and Foreign Force Table

3.3 Error Analysis and Statistical Testing

Root Mean Square Deviation (RMSD) was used to assess deviation from theoretical values: the RMSD for both the developed and foreign force tables is 6.45 g. A paired t-test comparing the developed and foreign table results across five trials revealed no statistically significant difference in F_3 and θ_3 measurements at a 95% confidence level ($p > 0.05$). This supports the claim of experimental equivalence.

3.4 Discussion

The comparative evaluation showed that the developed force table matches the performance of a commercial model with negligible statistical difference. The relative error (≈5.17%) and angular deviations (≤0.5°) fall within acceptable ranges for educational apparatuses (Robert 1998; Dessouki 2022).

However, two critical observations emerged:

i. Pulley friction, though minimized, contributed to overestimation in equilibrant force (F_3).
ii. Manual angle setting introduced small human errors, visible in θ_3.

In terms of usability, informal feedback was collected via a Likert-scale survey from seven users. The average usability score was 8.6/10, with positive remarks on adjustability and visibility of angular markings. However, limitations such as absence of digital measurement and time-consuming setup were noted. Some of the challenges faced during development included ensuring consistent pulley tension, aligning angular markings precisely, and managing cost without compromising accuracy.

4.0. Conclusion and Recommendations

This study successfully designed and validated an adjustable, cost-effective force table suitable for physics education. Constructed using locally sourced materials, the apparatus achieved experimental precision comparable to that of a commercial unit. RMSD, relative error analysis, and statistical testing confirmed its functional equivalence, while usability surveys indicated strong educational value.

To enhance functionality and reduce limitations, future iterations should incorporate:

1. Digital angle encoders to eliminate reading errors and enable real-time calibration.
2. Load cells or force sensors for precise force measurements and integration with data acquisition systems.

3. Quick-lock or magnetic pulley holders for easier repositioning and better repeatability.
4. Mobile app integration or augmented reality (AR) overlays for real-time visualization of vector addition and force diagrams.
5. Formal usability studies, including diverse users and structured surveys, to objectively evaluate ergonomics and user experience.

5.0 Contributions to knowledge

The project contributes to affordable and customizable STEM equipment solutions, especially in resource-limited settings.

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