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A Comparison Study of Alternative Materials to Polycarbonate for the Knee Pad Application

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Abstract

This paper conducts a comparative assessment of the suitability of thermoplastic polyurethane (TPU) and thermoplastic elastomer (TPE) as alternatives to polycarbonate for knee pads. The motivation originates from the unacceptably high market price of high-quality knee pads, which limits access for amateur athletes, particularly students, and increases the risk of injury owing to a lack of protective equipment. Knee injuries, particularly in high-impact sports, can result in long-term disabilities and expensive medical procedures. However, many athletes face financial constraints that prevent them from acquiring proper knee protection. To address this, the study investigates if TPU and TPE can provide equivalent or better performance than traditional materials at a cheaper cost. The examination used Finite Element Analysis (FEA) simulations to examine material behaviour under impact, with a focus on von Mises stress and displacement. TPU and TPE demonstrated higher stress endurance and moderate deformation than traditional Ethylene-Vinyl Acetate (EVA), demonstrating their potential as materials that provide a balance of flexibility and structural integrity in protective applications.

1. Introduction

This research focuses on evaluating the materials used in commercial knee pads, with special attention to mechanical performance. The knee joint is one of the most complex and heavily utilized joints in the human body, enabling essential movements such as bending, straightening, and limited rotation. Structurally, it comprises the femur (thighbone), tibia (shinbone), and patella (kneecap), all of which work in coordination to support body weight and enable mobility. Given this functional importance, the knee is highly susceptible to injuries, particularly in sports and occupational settings. Common sports-related injuries include Patellar Tendinitis, Patellofemoral Pain Syndrome (PFPS), Osteoarthritis (OA), Prepatellar Bursitis, and dislocations—conditions that account for approximately 35–47% of chronic musculoskeletal issues among athletes (Schwarze, 2019).

Protective knee pads are widely used to prevent such injuries. However, many commercial knee pads incorporate high-performance polymers such as polycarbonate or polyethylene terephthalate (PET), which contribute to increased production costs. As a result, student athletes and amateur users often find these products financially inaccessible. This study addresses the need to evaluate more accessible materials without compromising safety or performance.

The aim is to develop low-cost knee pads using materials like Thermoplastic Polyurethane (TPU) and Thermoplastic Elastomer (TPE), which offer durability, flexibility, and good energy absorption at a lower cost. The study uses Finite Element Analysis (FEA) to test the strength and performance of these materials, using von

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Mises stress and displacement to measure impact resistance. These methods help ensure the new knee pad designs are both safe and cost-efficient.

While several studies have explored the biomechanics of knee injuries and the design of protective gear (Rodríguez-Parada, 2021), few have specifically compared alternative thermoplastic materials in the context of impact resistance using simulation-based methods. This represents a key research gap that this study aims to address—namely, the lack of comparative simulation data on affordable thermoplastics for knee protection. By filling this gap, the research contributes to the broader goal of making effective knee protection more accessible to at-risk populations (Chanda, 2021).

2. Methodology

2.1 Selected Material

I. Thermoplastic Polyurethane (TPU)
II. Thermoplastic Elastomer (TPE)
III. Ethylene-Vinyl Acetate (EVA) [as benchmark material]
IV. Polyethylene Terephthalate [as benchmark material]
V. Polycarbonate PU [as benchmark material]

First, the knee pad model was designed using SolidWorks software. This included shaping the model to match real-life use and adding features based on actual knee pad designs. Next, material properties such as strength, elasticity, and durability were identified and applied to the model. Once the design and material setup were complete, a Finite Element Analysis (FEA) was run in SolidWorks. This simulation helped predict how the knee pad would respond to a impact force. The results included values for maximum Von Mises stress and displacement, which were used to evaluate the design's performance and safety. This section explains the steps taken, the tools used, and how data was collected throughout the project.

2.2 Alternative Material Mechanical Properties

Table 1 Physical properties of the selected materials. (lookpolymers.com, 2015)

	TPU	TPE	EVA
Elastic Modulus (MPa)	2580	147	93.9
Shear Modulus (MPa)	102	102	35
Tensile Strength (Mpa)	63.3	25	25
Yield Strength (Mpa)	64	39.4	7.13

Table 1 shows the mechanical parameters of the selective materials that is tested in this study: thermoplastic polyurethane (TPU), thermoplastic elastomer (TPE), and ethylene-vinyl acetate (EVA). Elastic Modulus, Shear Modulus, Tensile Strength, and Yield Strength are key indications of a material's behaviour under mechanical strain. TPU has the highest results in most areas, particularly tensile and yield strength, indicating a stronger capacity to endure deformation and structural failure during stress. TPE provides moderate performance, striking a compromise between flexibility and toughness. The benchmark material, EVA, has the lowest values, demonstrating its softer and more flexible character, which may impair structural integrity under repeated impact. These property comparisons are critical in determining the suitability of these materials for use in protective knee pads.

Thermoplastic polyurethane (TPU) and thermoplastic elastomer (TPE) are two promising materials for applications that require a balance of performance and cost. When assessing their potential as knee pad manufacturing alternatives, a thorough assessment of their thermal stability, mechanical qualities, and endurance characteristics yields valuable insights.

2.3 3D Design

Fig. 1 Knee Pad finalised design

Figure 1 illustrates the 3D model of the knee pad designed using SolidWorks 2024, which was based on the Ennui Shock Sleeve Gasket Knee structure. The model incorporates realistic anatomical curvature to fit the human knee, along with strategically placed zones for padding and ventilation. Strap regions and boundary features were modeled to reflect actual usage scenarios and to ensure accurate boundary condition setup in simulation. This design served as the basis for Finite Element Analysis (FEA) to evaluate material behavior under impact, providing a geometrically consistent and simulation-ready representation of a knee pad.

The 3D design of the knee pad is modeled on the basis of the dimensions and the shape of the ENNUI Aly Knee pad, size M. The design was modeled to replicate real-life geometry, including ergonomic curvature and padding zones. The outer shell was contoured to fit the knee anatomically, while interior layers were modeled to accommodate flexible padding zones intended to distribute impact force evenly. Attention was given to maintaining consistent wall thickness and symmetry to ensure accurate simulation results and realistic performance. An estimate of the overall size of the knee pad is around 250 mm (height), 140 mm (width) and 30 mm (thickness at the center point of impact area). The aesthetically obvious locations of fastenings schemes indicate the mounting points of other additional layers or locking systems.

The place that is impacted on the front part of the knee pad is circular and symmetrical. The main protective panel is oval-shaped and about 180 mm coverage over breadth as assessed and 110 mm over height providing the best protection of the patella and soft coverings in the area. The mid-section is the thickest part which is about 30 mm and the margins are narrowed progressively to about 5-10mm. With this design, less material weight is saved without affecting the structural performance. . This profile of curvature is near to a natural 10-15 degree bend where the knee pad can fit snugly on the anatomy of the femoral and tibial regions. The upper loading area is about 8mm away at the mounting surface which gives the necessary deformation space in the impact penetration.

2.4 Simulation

In this study, Finite Element Analysis (FEA) was used because it is a simple and widely used method for such analysis. FEA is a computer-based technique that predicts how a product reacts to forces, heat, vibration, and other conditions. Using SolidWorks software, FEA was used to measure results such as maximum stress, displacement, and strain.

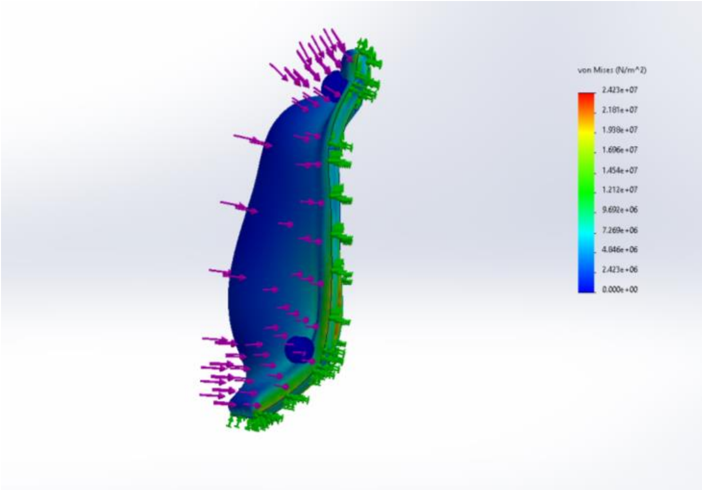

Fig.2 FEA simulation test

Figure 2 shows the simulation result of the von Mises stress distribution on the knee pad model under an applied impact force of 4000 N. The analysis was performed using SolidWorks Simulation, with the force applied to the front impact zone and boundary conditions fixed at the strap areas. The stress distribution indicates regions of high and low concentration, with the highest stresses appearing near the central impact area. This visualization helps identify potential failure zones and evaluate the structural response of the selected material. In this study, Finite Element Analysis (FEA) was used because it is a simple and widely used method for such analysis. FEA is a computer-based technique that predicts how a product reacts to forces, heat, vibration, and other conditions. Using SolidWorks software, FEA was used to measure results such as maximum stress, displacement, and strain.

2.5 Force

Before comparing the performance of different materials, the simulation model was validated by applying the same boundary conditions and load (4000 N) to a knee pad component using a known benchmark material—Ethylene-Vinyl Acetate (EVA). The resulting displacement of 4.61 mm and von Mises stress of 23.28 MPa are consistent with values reported in previous studies on polymer impact behavior (Chanda, 2021; Schwarze, 2019), supporting the accuracy and credibility of the SolidWorks FEA model used. Additionally, the mesh quality, fixture location, and load application were kept uniform across all material tests to ensure simulation consistency. This image shows how a knee pad model was tested in SolidWorks using a 4000 N force. This setup is part of a Finite Element Analysis (FEA) to see how the knee pad reacts to impact, which is common in sports. The purple arrows show how the force is applied directly and evenly onto the center of the knee pad similar to what happens during a fall or hit in sports like volleyball or football.

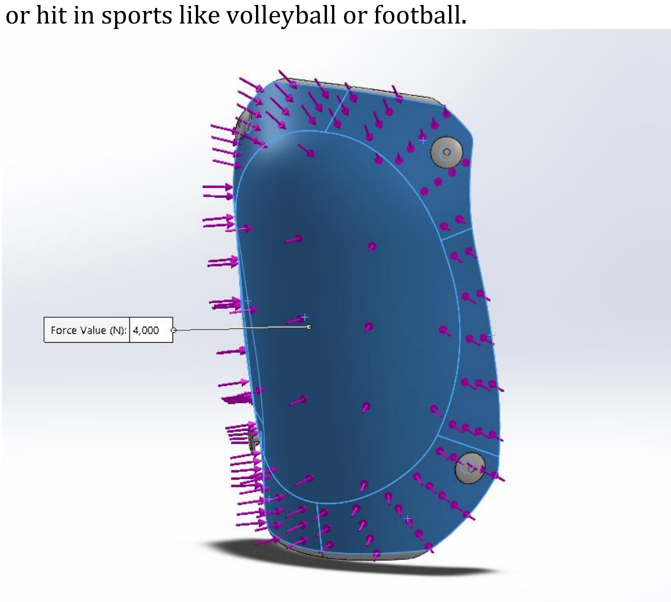

Fig 3 Force applied on the 3D model

Figure 3 shows the pre-simulation setup of the 3D knee pad model in SolidWorks Simulation, where a 4000 N force is applied to the front surface of the pad. The force is oriented perpendicular to the impact zone to simulate a typical sports-related load. Fixed supports are applied at the strap regions to represent realistic attachment points during use. This setup establishes the boundary conditions required for subsequent Finite Element Analysis (FEA) to evaluate material response under impact.

To run the simulation properly, the model needs correct material settings and constraints. A 4000 N force is applied to the front of the knee pad to represent an average impact. The back part, where the knee pad touches the leg, is fixed in place using settings like "Fixed Geometry" or "Roller/Slider" to prevent unrealistic movement. The direction of the force is aimed to mimic a real-life collision.

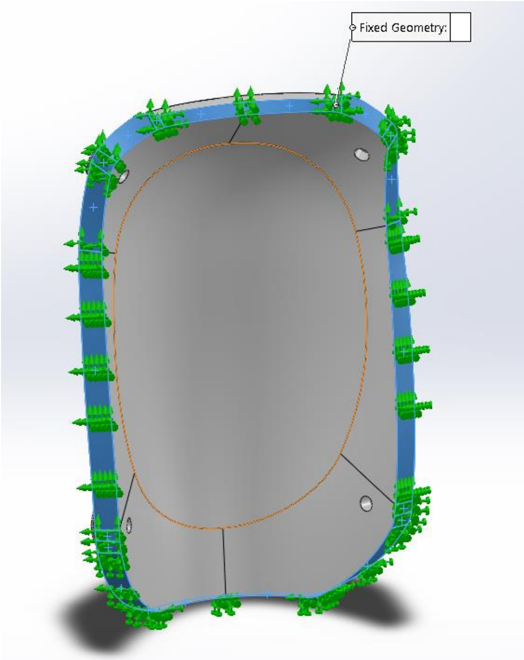

Fig. 4 Fixed geometry on the 3D model

The 4000 N force was chosen based on studies showing that knee impacts can range from 3000 to 8000 N without padding (Schwarze et al., 2019). Actions like soccer kicks and falls also produce forces in this range (Kadirgama et al., 2013). So, 4000 N is a reasonable average for simulating sports-related impacts.

This chapter describes the entire procedure or method for conducting these research. It begins with the selecting the materials, followed by a review of past studies or designs, research for material improvements, and preliminary design. Also, determine the appropriate test to use in the project, plan the research investigations, and finally submit the report and show the results.

3. Results and Analysis

Important information on the mechanical performance of different materials taken into consideration for knee pad applications can be found in the Von Mises stress and displacement analysis. This criterion is crucial for determining the durability and safety of protective gear since it assesses a material's capacity to tolerate complicated loading situations without succumbing.

Table 2 Von mises stress result

Material	Von mises (Mpa)
Thermoplastic Polyurethane (TPUR), Polyester Grade	24.230258
Polyester Thermoplastic Elastomer (TPE)	24.230258
Ethylene Vinyl Acetate Copolymer (EVA)	18.141320
Polycarbonate PU	23.277964
Polyethylene Terephthalate	23.277964

Table 2 presents the simulation results for five materials tested under a uniform 4000 N impact force using Finite Element Analysis (FEA) in SolidWorks. The materials evaluated include TPU, TPE, EVA, Polycarbonate PU, and Polyurethane Terephthalate. The materials evaluated include Polycarbonate PU and Polyethylene Terephthalate, with the table presenting von Mises stress and displacement values for each. TPU and TPE both exhibited high stress tolerance (24.23 MPa), demonstrating a favorable balance between impact resistance and flexibility. Although EVA is commonly used, its high displacement suggests lower structural integrity. Polycarbonate PU and Polyethylene Terephthalate recorded slightly lower stress values (23.27 MPa), indicating greater rigidity but reduced capacity for energy absorption.

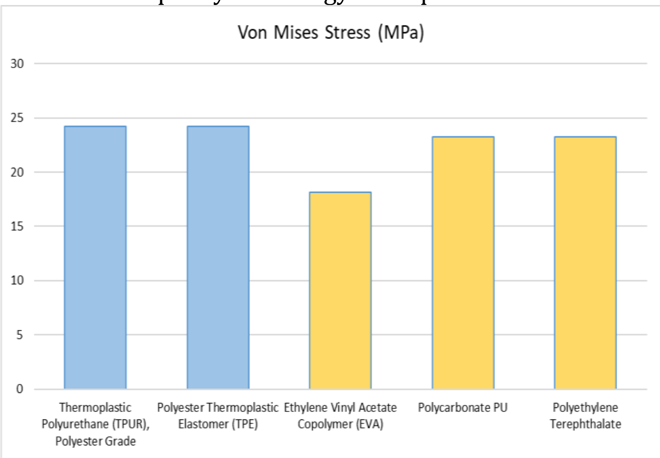

Fig. 5 Von mises graph comparision

Figure 5 presents graph for the von Mises stress values for five different materials subjected to a simulated 4000 N impact load. The results were obtained through Finite Element Analysis (FEA) in SolidWorks. Thermoplastic Polyurethane (TPU) and Polyester Thermoplastic Elastomer (TPE) recorded the highest stress tolerance at 24.23 MPa, indicating superior structural resistance under impact. Polycarbonate PU and Polyethylene Terephthalate (PET) followed closely at 23.27 MPa, reflecting good rigidity but potentially reduced energy absorption. Ethylene Vinyl Acetate (EVA) demonstrated the lowest von Mises stress at 18.14 MPa, suggesting lower structural strength under load. These results help illustrate the comparative mechanical behavior of each material and support the recommendation of TPU for its balance of stress tolerance and elasticity.

Table 3 Displacement result

Material	Displacement(mm)
Thermoplastic Polyurethane (TPUR), Polyester Grade	1.153459
Polyester Thermoplastic Elastomer (TPE)	1.2726
Ethylene Vinyl Acetate Copolymer (EVA)	4.6057
Polyethylene Terephthalate	0.240339
Polycarbonate PU	0.238721

Table 3 presents the displacement values of five materials—Thermoplastic Polyurethane (TPU), Thermoplastic Elastomer (TPE), Ethylene Vinyl Acetate (EVA), Polycarbonate PU, and Polyethylene Terephthalate (PET)—under a simulated 4000 N impact load. These values were generated using Finite Element Analysis (FEA) in SolidWorks. The results indicate that TPU (1.15 mm) and TPE (1.27 mm) undergo moderate deformation, maintaining structural flexibility without compromising integrity. In contrast, EVA recorded the highest displacement (4.61 mm), which may result in reduced protection due to excessive flexibility. Polycarbonate PU and PET showed the least displacement (0.24 mm), reflecting higher stiffness and limited cushioning behavior. These findings highlight TPU's optimal performance in balancing deformation control and impact absorption.

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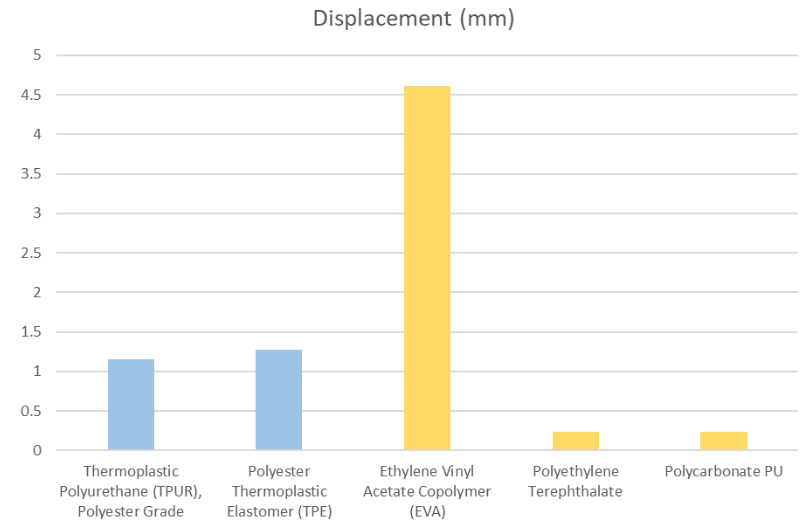

Fig. 6 Displacement graph comparision

Figure 6 illustrates the displacement values of five different materials subjected to a 4000 N impact load, as determined through Finite Element Analysis (FEA). The bar chart compares the deformation behavior of Thermoplastic Polyurethane (TPU), Thermoplastic Elastomer (TPE), Ethylene Vinyl Acetate (EVA), Polycarbonate PU, and Polyethylene Terephthalate (PET). EVA recorded the highest displacement at 4.61 mm, indicating excessive flexibility that may reduce protective performance. TPU (1.15 mm) and TPE (1.27 mm) demonstrated moderate, controlled deformation, balancing comfort and impact resistance. Polycarbonate PU and PET showed minimal displacement (0.24 mm), reflecting higher rigidity but potentially less shock absorption. This comparison highlights TPU as an ideal candidate, offering adequate flexibility while maintaining structural integrity during impact.

In terms of displacement, TPU (1.15 mm) and TPE (1.27 mm) maintained moderate deformation under a 4000 N load, which is desirable in protective gear. Excessive displacement, as seen in EVA (4.61 mm), can reduce protective reliability over time. Low deformation with high stress capacity indicates that TPU and TPE maintain structural integrity while offering cushioning (Chanda, 2021). In contrast, the yellow line represents the current material (likely PET or polycarbonate PU), which has very low displacement at 0.24 mm. This means it's stiff and offers support but absorbs less shock, which may not be ideal for high-impact situations.

These results confirm that TPU, in particular, offers the optimal balance of rigidity and flexibility for knee pad applications, minimizing force transmission to the user's body while resisting permanent deformation.

Table 4 Material result. (lookpolymers.com, 2015)

Material	**Von mises (Mpa)**	**Displacement(mm)**	**Mass Density (kg/m^3)**
Thermoplastic Polyurethane (TPUR), Polyester Grade	24.230258	1.153459	1020
Polyester Thermoplastic Elastomer (TPE)	24.230258	1.2726	1210
Ethylene Vinyl Acetate Copolymer (EVA)	18.14132	4.6057	931
Polycarbonate PU	23.277964	0.238721	1200
Polyethylene Terephthalate	23.277964	0.240339	1380

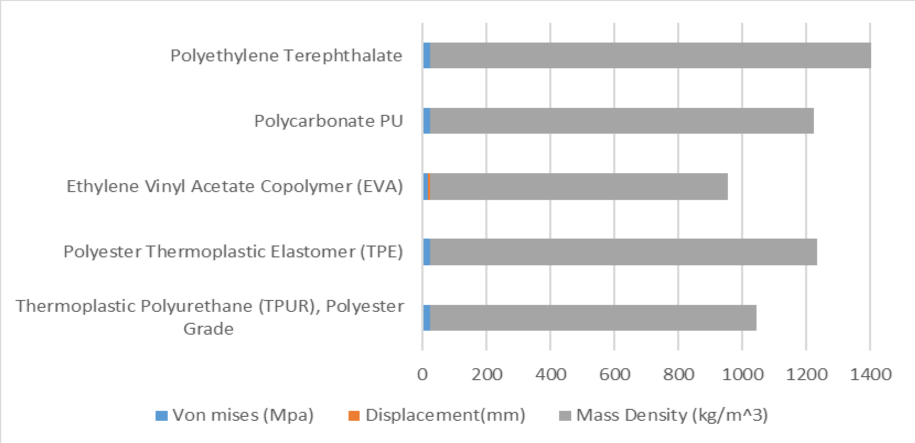

Fig. 7 Material result graph.

Figure 7 presents the simulated performance results for five materials evaluated for use in knee pad applications: Thermoplastic Polyurethane (TPU), Thermoplastic Elastomer (TPE), Ethylene Vinyl Acetate (EVA), Polycarbonate PU, and Polyethylene Terephthalate (PET). The results include von Mises stress, displacement, and mass density.

Among all materials, TPU exhibits the most favorable balance, with a high stress tolerance (24.23 MPa), moderate displacement (1.15 mm), and a relatively low mass density (1020 kg/m^3). In contrast, TPE, while also mechanically strong, has a higher density (1210 kg/m^3), which may increase overall pad weight. Polycarbonate PU and PET, despite their rigidity and low displacement values, show higher mass densities of 1200 and 1380 kg/m^3 respectively, which could negatively affect comfort and mobility.

In knee pad applications, mass density is crucial since materials must not only absorb impact but also be lightweight to avoid fatigue and discomfort during extended use (Schwarze et al., 2019). Excessively dense materials, while physically strong, can limit wearability and increase user strain (Chanda & Roy, 2021). Materials with low density, like EVA (931 kg/m^3), may sacrifice structural integrity for flexibility, resulting in high displacement (4.61 mm) under load.

In this context, TPU is highlighted as the best material due to its effective impact resistance, moderate flexibility, and relatively low mass density, making it both protective and wearable.

3.1 Price difference

Table 5 Material price comparison per kg. (Powerslide, 2025) (exporthub.com) (alibaba.com) (averest.com)

Material	Price (RM) per kg
Thermoplastic Polyurethane (TPUR), Polyester Grade	18
Polyester Thermoplastic Elastomer (TPE)	22.5
Ethylene Vinyl Acetate Copolymer (EVA)	27.6
Polycarbonate PU	21.15
Polyethylene Terephthalate	27

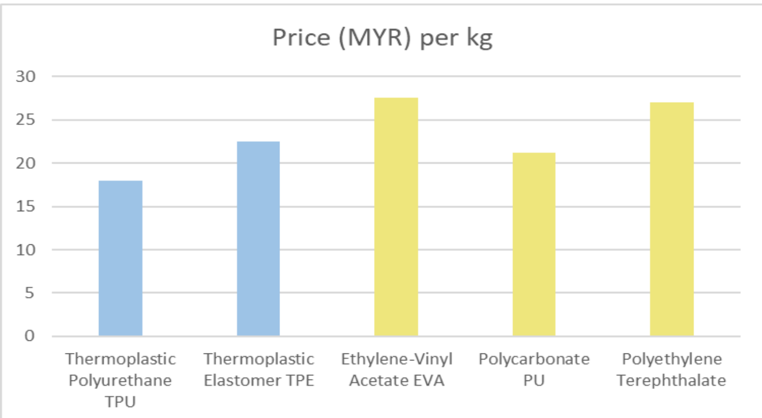

Fig. 8 Price graph comparision

Figure 8 displays a comparison of the estimated material costs for five polymers evaluated in this study: Thermoplastic Polyurethane (TPU), Thermoplastic Elastomer (TPE), Ethylene Vinyl Acetate (EVA), Polycarbonate PU, and Polyethylene Terephthalate (PET). The bar graph reflects the approximate price per 0.5 kg of each material, providing insight into economic feasibility for knee pad production. TPU emerged as the most cost-effective option, priced at around RM18, while still delivering strong mechanical performance. PU follows closely behind, with EVA shows the highest price per kilogram but showing weaker structural properties. Polycarbonate TPE and PET are positioned at the higher end of the cost range, potentially limiting their suitability for low-budget or mass-produced protective gear. This cost comparison supports TPU as the best overall value in terms of both performance and affordability.

In addition to mechanical performance, cost is a critical factor when considering materials for commercial products like knee pads. Thermoplastic Polyurethane (TPU) and Thermoplastic Elastomer (TPE) are significantly more affordable than the materials used in many commercial knee pads, such as polycarbonate composites and high-grade polyethylene terephthalate (PET). TPU, in particular, stands out as the superior option due to its combination of strong mechanical properties and lower raw material cost. TPU filament is widely available for around RM18 per kg, while the estimated material cost for manufacturing a single hard-shell knee pad (weighing approximately 1.5 kg) would only be about RM27 (Ma, 2023). This makes TPU an economically viable material for producing protective gear, especially when affordability is a priority for users such as student athletes and amateur sports participants.

4. Conclusion

This study conducted a comparative simulation of three thermoplastic materials—TPU, TPE, and EVA—for potential use in knee pad applications. Using Finite Element Analysis (FEA), von Mises stress and displacement under impact loading were evaluated. Both TPU and TPE demonstrated higher stress tolerances and moderate displacements compared to EVA, suggesting better performance under short-term impact. While these results indicate that TPU, in particular, may offer promising mechanical behavior for protective gear, it is important to note that the current conclusions are based on unvalidated simulation data. Without empirical testing or experimental calibration, the results cannot be used to conclusively determine material durability, energy absorption capacity, or long-term structural strength.

Nevertheless, TPU remains a strong candidate for further exploration due to its favorable simulated behavior and lower material cost. Future work should focus on experimental validation, fatigue testing, and real-world prototyping to more accurately assess its suitability for impact protection in knee pad applications.

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