JMHT: Journal of Medicine and Health Technology
Vol. 02, No. 02, Nov., 2025, pp. 12-22
ISSN: 3046-6865
DOI: 10.12962/j30466865.v2i2.2625

Numerical Analysis of the Failure of a 3D-Printed Knee Joint for a Transfemoral Amputee

Amelia Arsyl Majid[1] and Achmad Syaifudin[2,3]
[1]Department of Mechanical Engineering, Institut Teknologi Sepuluh Nopember (ITS), Surabaya 60111, Indonesia
[2]Department of Medical Technology, Institut Teknologi Sepuluh Nopember (ITS), Surabaya 60111, Indonesia
[2]Laboratory of Solid Mechanics, Department of Mechanical Engineering, Institut Teknologi Sepuluh Nopember (ITS), Surabaya 60111, Indonesia

Corresponding Author: syaifudin@its.ac.id

Abstract —A leg prosthesis is a tool that can help people with disabilities due to amputation or birth defects. Prosthetic leg products created through the 3D printing process on the knee joint have been reported to have cracked after two months of use. The purpose of this study was to observe the causes of failure of knee joints in prosthetic legs printed using the 3D printing method. The numerical method based on the finite element method, ANSYS Workbench 2023, was chosen to complete the structural simulation. The model parameters observed in the simulation were the printing orientation, model position, and equivalent plastic strain of PETG, ABS, and PLA. Several print-direction positions were considered in this simulation, namely 0°, 45°, and 90°. Static simulation of the structure was performed because only the static forces acted on the knee joint. Static forces were obtained by applying the principle of static equilibrium to rigid objects. The results of the numerical simulation showed that damage to the knee joint made of PTEG was caused by the plane of 90°. The orientation position causes the force received in the perpendicular direction of the knee joint component; thus, it tends to break the printing layers. The ideal printing orientation for the knee joint is 0° orientation. This orientation is considered suitable because it has the highest safety factor compared to other orientations.

Keywords— *Knee joint; ABS; PLA; PETG*

How to cite: Majid AA, Syaifudin A. Numerical Analysis of the Failure of a 3D-Printed Knee Joint for a Transfemoral Amputee. Journal of Medicine and Health Technology. 2025;2(2):12-22. doi:10.12962/j30466865.v2i2.2625

Manuscript received 28 January 2025; revised 17 February 2025; accepted 3 May 2025. Date of publication 10 November 2025.

INTRODUCTION

Globally, approximately 57.7 million people experience limb amputation due to trauma, with falls and road injuries being the leading causes. [1]. The demand for prostheses is expected to continue to increase, and the number of amputees is expected to double by 2050 [2]. However, this technology may not be accessible to all groups within the population. Data collected routinely from prosthetic clinics to help tailor services can provide valuable insights into the changing needs of the disabled population [3]. In Indonesia, the population of individuals with disabilities was 2.45%, as recorded in the 2012 population census [4]. The data show that 33.74% of the population had physical disabilities, making them the largest disabled population in Indonesia. This percentage is equivalent to 717,312 disabled people. Meanwhile, in 2018, 14.2% of the Indonesian population with disabilities or around 30.38 million people [5]. According to the latest data [6], approximately 0.4% of Indonesia's population are physically disabled people who may need prosthetic legs. With Indonesia's population of approximately 273 million, this means that approximately 1.1 million people may need prosthetic legs. Physically disabled or disabled limbs refers to people with disabilities who have weaknesses in both upper and lower limbs. This large population of physically disabled people has certainly led to a great demand for prosthetic limbs.

According to the Health Minister, medical device products in Indonesia are still dominated by imported products. The dominance of imported products shows a high dependence on foreign technology and raw materials in the medical device industry [7]. This is due to the limited capabilities of the national pharmaceutical industry in managing the availability of raw materials and regulations that are not yet optimal [8]. In addition, the lack of technology transfer and investment in R&D also contributes to obstacles in creating competitive local products [9]. Based on data from the Directorate General of Pharmaceuticals and Medical Devices of the Ministry of Health until the end of the first semester of 2023, total national medical device transactions via e-catalog were still dominated by imported products, reaching 88% [10]. Most prosthetic leg products in Indonesia are imported because imported products have good final quality, so their price is also expensive.

Imported prosthetic legs are generally sold at a high price of up to 23 million rupiah per unit [11]. On the other hand, not all people who need it have sufficient economic capacity to buy it. Therefore, it is necessary to develop more affordable prosthetic legs. The price of prosthetic legs is influenced by the manufacturing technology. It is made of metal, especially aluminum and medium-strength steel alloys, which makes its price more expensive. The use of 3D printing manufacturing technology provides the possibility of making prosthetic legs at a cheaper price[12].

A prosthetic leg consists of at least 4 components, namely the socket, knee joint, pylon, and sole of the foot [13]. The knee joint is the most expensive and critical component of a prosthesis, as it receives the largest proportion of the load. Prosthetic knee joints generally use a combination of materials to optimize performance and longevity. One combination of materials used is metal, specifically aluminum alloy, which has been identified as the optimal material for pediatric prosthetic knees due to its light weight and structural strength [14-15]. For adult knee and hip replacements, metals and biocompatible polymers are typically used, with ongoing research into self-lubricating coatings [16]. Ceramics have also emerged as an alternative material to metals by providing excellent biocompatibility and reducing wear rates [17]. Recent research has explored nonmetallic materials such as ULTEM 1010 for potential use in knee prostheses [18]. Several studies have also explored various composite materials, including PLA-CF, PETG-CF, and PLA-MWCNT, to improve the flexural strength and durability of 3D-printed prosthetic sockets [19].

Many studies have attempted to utilize 3D printing methods in prosthetic leg manufacturing. Pentek et al. observed the use of PLA and ABS for upper limb prosthetics, and their results showed that 3D printing parameters significantly affected the mechanical and electrical properties of PLA and ABS carbon composites [20]. From several existing studies, PLA exhibits superior mechanical properties, including high yield strength and tensile strength, making it suitable for structural components [21-22]. On the other hand, Silva and Guilhon studied the use of PETG as a connector material. The results showed that PETG-based connectors made by the 3D printing method have good flexibility and resistance to cracking [23]. Other researchers found that socket and pylon components made of 3D-printed ABS demonstrated acceptable durability during different gait phases [24]. With various materials for 3D printing technology, it is possible to produce customized and affordable prostheses with enhanced functionality [25], [26]. However, the use of 3D printing for the manufacture of knee joint prostheses does not provide good results. As a result, there is still crack failure in one component of the knee joint, as reported by Bagaskara (2019) [27]. The presence of cracks in the prosthesis components can be identified using the finite element method. This study was conducted to determine the exact cause of failure of a knee joint component made using the 3D printing method.

METHODS

Structural static analysis was used in this study to analyze the damage to one of the knee joint components by the 3D printing method. ANSYS Workbench 2023 was chosen as the software to perform the numerical calculations. The forces applied to the knee joint were taken from the highest forces that occur during the gait cycle. Humans walk by repeating the same movements in sequence. In general, it consists of the stance phase and the swing phase [28]. **Fig. 1** shows the amount of force supported by the foot during walking. It can be seen how the greatest force occurs when one leg provides support for the overall body weight, which is 1.19 of the body weight [28].

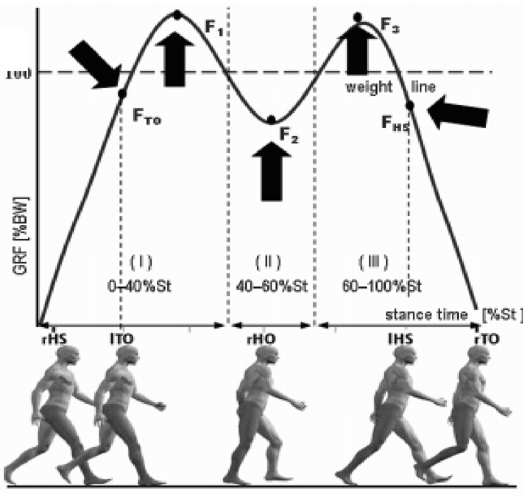


Fig. 1. The ground force reaction [28]

The materials used in this numerical simulation were PETG, ABS, and PLA. ABS is a type of 3D printing material that experiences failure of knee joint components [27]. As a comparative analysis, two types of 3D printing materials that are commonly used and cheap are chosen, namely PLA and PETG. These three types of materials are widely available on the Indonesian market. The material parameters required in the numerical simulation comprise the mechanical properties of the materials and the material model. The mechanical properties of the material in the form of stress-strain curves and Poisson's ratio are displayed in **Fig. 2** . Meanwhile, the Poisson ratio value and material failure criteria in the form of strain at failure in percentage are shown in **Table 1** for PETG, **Table 2** for ABS, and **Table 3** for PLA. All materials were modeled as isotropic in the numerical simulations because the anisotropic data were not completely known.

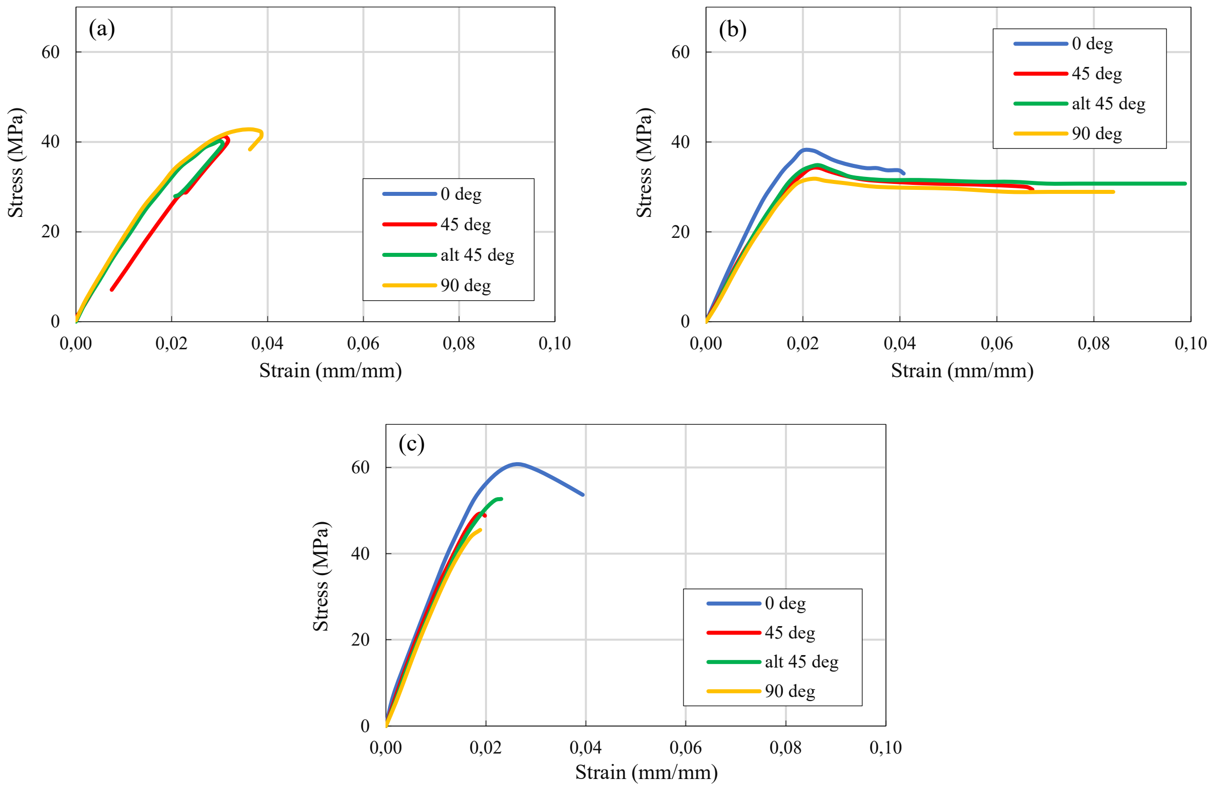


Fig. 2. Stress-strain curve for a) PETG [4], b) ABS [6], and c) PLA.

Table 1. 3D printed mechanical properties for PETG [29]

Properties	[+45/-45] Flat	[0/90] Flat	[+45/-45] On-Edge	[0/90] On-Edge	[+45/-45] Upright	[0/90] Upright
Poison's Ratio	0.36 ± 0.02	0.37 ± 0.03	0.35 ± 0.02	0.36 ± 0.03	0.34 ± 0.03	0.35 ± 0.02
Young's Modulus (MPa)	1900 ± 80	2000 ± 100	1850 ± 110	1950 ± 90	1600 ± 120	1700 ± 130
Ultimate strength (MPa)	46.0 ± 1.0	48.5 ± 1.2	44.0 ± 1.1	42.5 ± 1.3	38.0 ± 1.5	40.0 ± 1.4
Strain at failure (%)	6.8 ± 0.9	7.5 ± 1.0	5.2 ± 0.8	4.8 ± 1.0	3.5 ± 0.7	3.8 ± 0.6

Table 2. 3D printed mechanical properties for ABS [29]

Properties	[+45/-45] Flat	[0/90] Flat	[+45/-45] On-Edge	[0/90] On-Edge	[+45/-45] Upright	[0/90] Upright
Poison's Ratio	0.36 ± 0.03	0.37 ± 0.04	0.38 ± 0.03	0.36 ± 0.02	0.36 ± 0.03	0.36 ± 0.03
Young's Modulus (MPa)	1960 ± 60	2020 ± 60	2020 ± 110	1910 ± 60	2040 ± 90	2020 ± 110
Ultimate strength (MPa)	32.8 ± 0.6	33.5 ± 0.5	31.9 ± 0.9	30.7 ± 0.7	30.0 ± 0.8	30.9 ± 1.3
Strain at failure (%)	8.89 ± 2.34	7.14 ± 2.79	5.41 ± 1.13	5.82 ± 1.26	1.72 ± 0.16	1.84 ± 0.15

Table 3. 3D printed mechanical properties for PLA [25],[31], [32], [33], [34]

Properties	Flat (0°)	Edge (90°)	Upright (90°)
Poison's Ratio	0.30 ± 00	0.39 ± 00	0.30 ± 00
Young's Modulus (MPa)	3360 ± 50	3200 ± 60	3100 ± 70
Ultimate strength (MPa)	57.8 ± 1.2	52.5 ± 1.5	48.3 ± 1.8
Strain at failure (%)	6.5 ± 0.5	5.8 ± 0.6	5.2 ± 0.7

3D printing patterns with various orientations are intended to determine the appropriate materials and patterns to be applied to the knee joints of prostheses. The knee joint is a connection between the tibia (thigh bone) and femur (calf bone). The knee joint in transfemoral prostheses is divided into two types: monocentric and polycentric. The monocentric system only has a rotation on one axis, whereas the other type has two rotations on one axis [27]. In this study, the type of knee joint observed was the polycentric type, as shown in **Fig. 3a**. Meanwhile, **Fig. 3b** shows a knee joint made using the 3D printing method, which shows that failure occurred around the pin connecting to the femur (pointed in figure).

(a) (b)

Fig. 3. a) Polycentric knee joints [35], b) 3d-printed polycentric knee joints

The model was discretized by selecting the default settings in ANSYS Workbench software to obtain good meshing quality and achieve a balance between accurate results and fast calculation time. There are 2 types of contact between components used in this simulation: 1) contact due to rotational movement between components but translational movement is limited (defined as no separation contact) and 2) contact between components that have absolutely no relative movement (defined as bonded contact. A load of 60 kg (688 N heel contact, or equivalent to 1.19 of the body weight) was applied over the knee joint surface, and a fixed support was arranged in the pylon cavity at the bottom of the knee joint. The simulation results taken for analysis were the equivalent plastic strain of the observed knee joint components, with the aim of comparing them to the strain at failure values of each material and orientation. The equivalent plastic strain is a value indicating the magnitude of the resulting plastic strain from all directions. This quantity represents the total plastic strain before fracture.

The most important part of the numerical simulation is defining the printing orientation. The 3d printing process referred to here is often referred to as Fused Deposition Modeling (FDM). FDM adds heated material to the printed part layer by layer. As a result, FDM often prints components with lower mechanical properties than conventional manufacturing methods. The mechanical properties of FDM products are not only controlled by the original filament material but are also significantly affected by the direction-dependent production process that creates components with anisotropic characteristics. [29]. In terms of 3d printing product modeling, numerical simulation cannot distinguish the print orientation that is achieved through the 3d printing process. Thus, what must be done is to take the numerical simulation results that match the 3d printing print orientation and compare them with the available failure criteria.

The printing orientation patterns of 0°, 45°, and 90° affected the tensile test value. The printing orientation pattern of 0° has a bimodal strain pattern in the vertical direction; thus, the specimen made with a printing orientation of 0° will receive a force parallel to the specimen layer. The printing orientation pattern of 45° can form a uniform strain pattern. As a result, the specimen with a printing orientation of 45° will receive a perpendicular force, where the specimen layer forms an angle of 45°. The 90° printing orientation pattern can form a bimodal strain pattern in the horizontal direction, so the resulting specimen will receive a force perpendicular to the specimen layer. The 3D printing orientation patterns are shown in **Fig. 4.** [36].

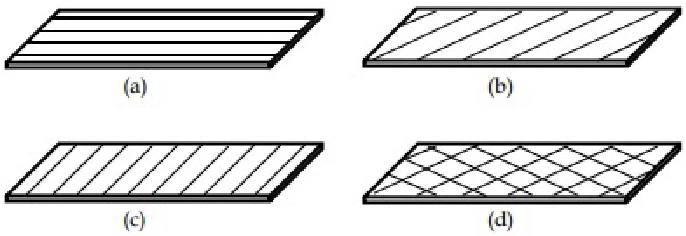


Fig. 4. Display printing orientation: a) 0 deg, (b) 45 deg, (c) 90°, and alt 45° [36]

The focus of this study is the selection of materials and orientations for application to prosthetic knee joints. The previously applied material that failed was PETG, so analysis is needed to determine the cause of knee joint damage. Then alternative materials, ABS and PLA, are given to be analyzed to determine whether they meet the safety limits for application to the knee joint. The variations in the print orientation are 0°, 45°, and 90°. The 3D printing orientation of the knee joint is illustrated in **Fig. 5**.

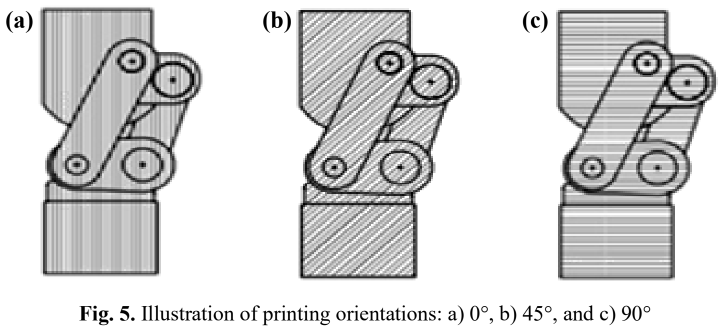


Fig. 5. Illustration of printing orientations: a) 0°, b) 45°, and c) 90°

RESULTS AND DISCUSSION

The simulation results were analyzed and displayed in the form of a graph of the relationship between equivalent plastic strain and printing orientation, as shown in **Fig. 6**.

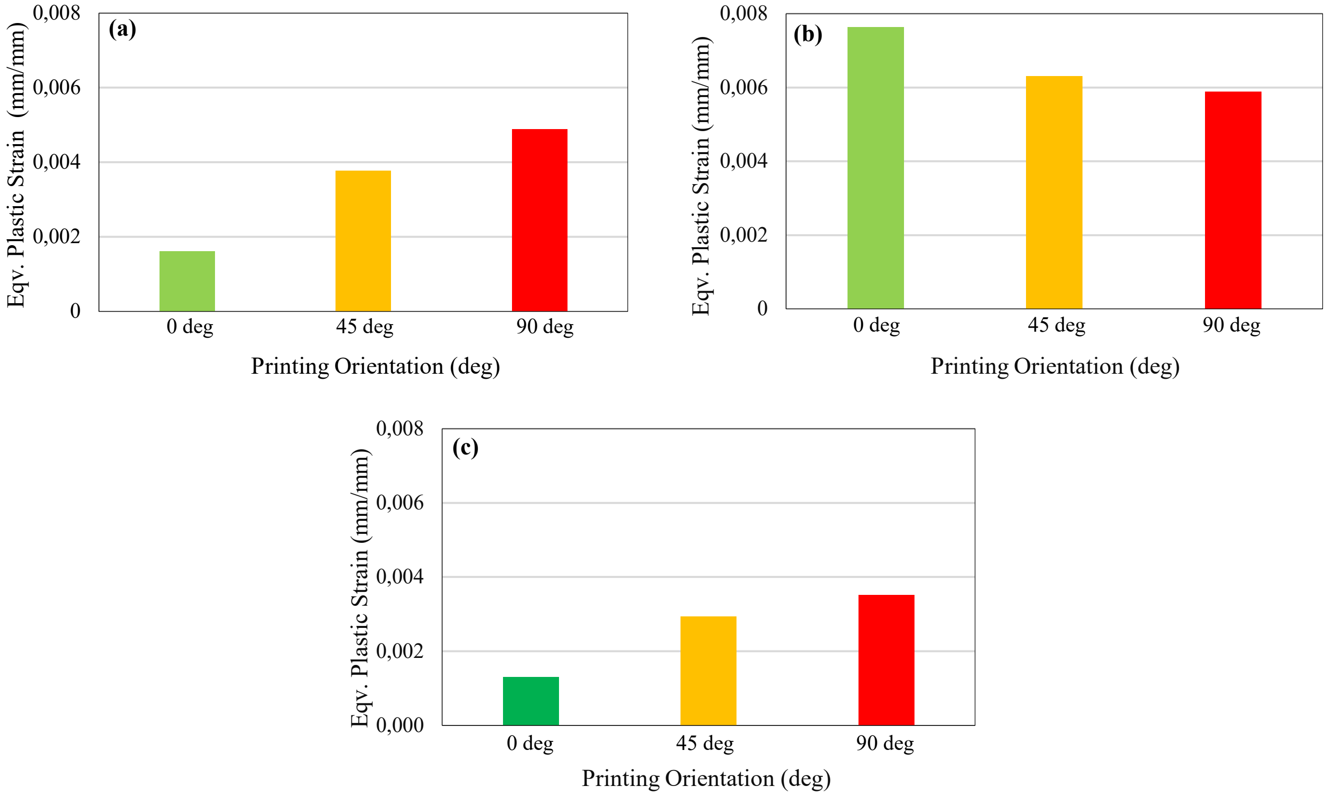


Fig. 6. Equivalent plastic strain from the simulation for a) PETG, b) ABS, and c) PLA

Fig. 6a shows the equivalent plastic strain for each printing orientation of PETG. The 90° printing orientation produces the largest equivalent plastic strain. Compared with the strain at failure of PETG, the overall safe status for each printing orientation was obtained. At the printing orientations of 0°, 45°, and 90°, the strain at failure limits for PETG were 0.02301, 0.02733, and 0.030579 mm/mm, respectively. Thus, with the equivalent plastic strain values of 0.0016102 mm/mm, 0.0037745 mm/mm, and 0.0049858 mm/mm for the printing orientations of 0°, 45°, and 90°, respectively, it can be stated that there is no safety issue related to the printing orientation for PETG.

Fig. 6b shows the equivalent plastic strain for each printing orientation of ABS. In contrast to PETG, the highest equivalent plastic strain for ABS occurs at the 0° printing orientation. Meanwhile, there is no significant difference in the equivalent plastic strain value between 45 deg and 90°. However, ABS has the same characteristics as PETG in terms of structural integrity, namely that overall various printing orientations do not have the potential to cause failure. The comparison between equivalent plastic strain and strain at failure at each printing orientation is 0.0063368 mm/mm compared to 8.34 mm/mm for the 0° flat position direction, 0.0063071 mm/mm compared to 5.34 mm/mm for the 45° tilted position direction, and 0.0049858 mm/mm compared to 1.74 mm/mm for the 90° vertical position direction.

Fig. 6c shows the equivalent plastic strain for each printing orientation of PLA. It is clear that PLA exhibits the same tendency as PETG, namely, the highest equivalent plastic strain value at 90° orientation and the lowest equivalent strain value at 0° orientation. In terms of strain at failure, PLA also has the same results, namely that the equivalent plastic strain value produced by the knee joint components is still below the strain at failure limit. At 0° orientation, the maximum equivalent plastic strain of 0.0013047 mm/mm was still below the strain at failure of 0.01285 mm/mm. At 45° orientation, the maximum equivalent plastic strain of 0.0029322 mm/mm was also below the strain at failure of 0.01702 mm/mm. At 90° orientation, the maximum equivalent plastic strain value of 0.0035175 mm/mm remained below the strain at failure of 0.01134 mm/mm.

Although all simulation results showed that the maximum equivalent plastic strain value for all types of 3D printing materials, both PETG, ABS, and PLA, was still below the strain at the failure limit, it could not be concluded that all types of materials had the same strength. To determine this, it is necessary to calculate the safety factor for each material with various printing orientation variations. The formulation of the safety factor is analogous to the formulation of the safety factor for structures, which is obtained by comparing the stress to material strength. Therefore, in this study, a formulation of the safety factor for structures manufactured by 3D printing is proposed based on the comparison between equivalent plastic strain and strain at failure:

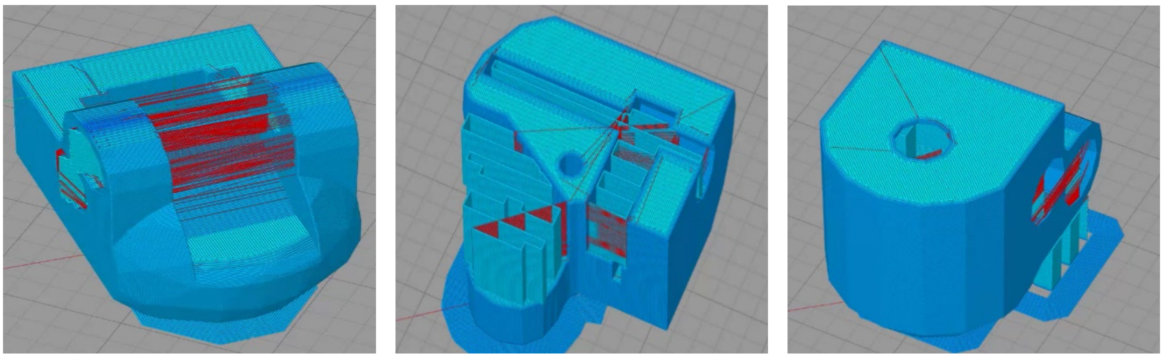
$$SF = \frac{strain\ at\ failure}{equivalent\ plastic\ strain} \quad (1)$$

where SF is the safety factor (dimensionless), the strain at failure, and equivalent plastic strain are expressed in mm/mm. Using Equation 1, the SFs for all material variations and printing orientations are summarized in **Table 4**.

Table 4. Safety factors of each material and printing orientation

Material	0 deg	45 deg	90 deg
PETG	14.3	7.2	6,1
ABS	1,315.8	846.6	348.9
PLA	9.8	5.8	3.2

Table 4 shows the safety factor resulting from the comparison between the strain at the failure limit and the equivalent plastic strain. It can be seen that ABS is very dominant compared to PETG and PLA, namely, with a huge SF value, up to thousands of times. This can be easily understood because this behavior is in sync with the mechanical properties of ABS, which are very superior in terms of plastic strain (**Fig. 2**). Considering the high safety factor value, it is unlikely that static failure is the main cause of knee joint component failure. In general, if failure still occurs in the range of large safety factor values, it can be concluded that the failure occurred due to repeated dynamic loads. Meanwhile, when viewed from the perspective of printing orientation variations, the 0° printing orientation provides a higher level of safety for all types of material variations, whereas the 90° printing orientation produces the lowest level of safety. Therefore, it is recommended to choose a 90° printing orientation in the printing components with filaments made of PETG, ABS, or PLA.



(a) (b) (c)

Fig. 7. Printing pattern in (a) 0°, (b) 45°, and (c) 90°

The simulation results and analysis of the influence of printing orientation on the strength of various materials were conducted. This study did not directly prove why failure occurred in the 3D printed knee joint component because all simulation variations stated that all simulation models were safe. However, the results of this study show that the possibility of failure is caused by a printing orientation that does not match the direction of the force acting on the component. In the meantime, if we pay attention to the pattern formed from each printing orientation, as shown in **Fig. 8**, then the greatest possibility of failure will occur in the 90° printing orientation because the force that appears will cause the bonds between the 3D printed layers to be far apart. Compared to the 0° orientation, the force that appears actually occurs in a direction parallel to the printing direction. Thus, the possibility of failure is reduced. This is in line with the smallest safety factor of the 90° printing orientation.

The results of this study indicate that the material and printing orientation of the prosthetic knee joint greatly affect its safety during bearing loads. Based on the simulation results, ABS is a 3D-printed filament material with the greatest tensile strength, which is demonstrated by its superior safety factor compared to PETG and PLA. The simulation results also indicate that the 0° printing orientation is highly recommended for product printing because it produces a higher safety factor than other printing orientations. A study by Adi and Dharmastiti also showed that the printing orientation greatly affects the distribution of forces on the prosthetic knee joint [37]. The 0° orientation of the PETG material used in this study resulted in faster failure because of the force received parallel to the printed layer. The results of Adi and Dharmastiti's study strengthen the findings in this study that the 0° printing orientation has significant structural weaknesses, especially when facing repeated force cycles, such as when walking. The same result was also reported by Hidayat et al. They emphasized the importance of optimizing the printing orientation to increase the durability of 3D printing-based prosthetics [38]. This demonstrates that a design approach that considers the proper printing orientation can result in a more durable and cost-effective prosthesis.

In addition, this study also provides important contributions for evaluating other materials such as PLA and PETG. PLA, although it has a relatively high maximum tensile strength of 57.8 MPa in flat orientation, shows a lower equivalent plastic strain value compared to ABS. Therefore, PLA may be more suitable for applications requiring high stiffness but that do not involve significant dynamic loads. In contrast, PETG exhibits better flexibility than PLA, but the 0-degree printing orientation used is a major drawback, as also reported in other previous studies. These studies emphasize that the optimal combination of materials and manufacturing techniques is essential for improving the durability and performance of prostheses, especially for users with high activity.

This research has direct implications for clinical practice, particularly in the selection of materials and 3D printing methods for prosthetic knee joints. Based on the simulations conducted, a 90° printing orientation has a higher risk of failure compared to other orientations. This is due to the tensile forces acting perpendicular to the printed layers, which can lead to delamination and reduced structural durability. Conversely, a 0° printing orientation is recommended as it provides the highest safety factor and better stress distribution in prosthetic knee joints [39].

From a clinical perspective, material selection directly impacts the comfort, durability, and functionality of prosthetics. ABS has the highest safety factor, demonstrating superior resistance to mechanical loads and repeated usage cycles, making it more suitable for users with high activity levels. PLA and PETG offer advantages in flexibility and lighter weight but require additional structural design optimization to be effectively used in prosthetic applications [40]. Therefore, in clinical practice, material selection should be tailored to the user's activity level, comfort needs, and expected mechanical durability.

As a recommendation, in addition to material selection, the type of load must also be considered, as this simulation study proves that failure in Bagaskara's prosthetic limb case was not due to static load but rather dynamic load. This is evident from the still very high safety factor. Material failure due to dynamic loading, or fatigue failure, can occur because of small loads that are applied repeatedly at a relatively high frequency.

Nevertheless, the simulations in this study still use isotropic properties. Ideally, for 3D-printed components, the anisotropic nature of the material should be considered. Studies show that incorporating anisotropic and elastoplastic material behavior in simulations yields more accurate predictions of mechanical properties and failure modes [41]. However, some research suggests that isotropic models can adequately describe the behavior of 3D-printed ABS parts, regardless of infill strategy [42]. Manufacturing parameters, particularly infill percentage and layer thickness, significantly affect mechanical properties, with PLA generally exhibiting higher tensile strength and rigidity than ABS [43-44].

CONCLUSIONS

Static simulations of knee joints made of PLA, PETG, and ABS with various printing orientations were conducted. The research results are as follows:

i. The cause of damage to the knee joint is that the PTEG material is printed with a 90° orientation because the simulation results show that this printing orientation produces the smallest safety factor. The same applies to ABS and PLA materials. Compared with PETG and PLA, ABS has a superior safety factor for various printing orientations.
ii. The best printing orientation is 0°. This orientation is suitable for all types of 3d printing filament materials because it produces a higher safety factor than other printing orientations.

CONFLICTS OF INTEREST

The authors declare there are no conflicts of interest.

REFERENCES

[1] C. L. McDonald, S. Westcott-Mccoy, M. R. Weaver, J. Haagsma, and D. Kartin, “Global prevalence of traumatic non-fatal limb amputation,” Prosthet Orthot Int, vol. 45, no. 2, pp. 105–114, Apr. 2021, doi: 10.1177/0309364620972258.
[2] B. Wodlinger, J. E. Downey, E. C. Tyler-Kabara, A. B. Schwartz, M. L. Boninger, and J. L. Collinger, “Ten-dimensional anthropomorphic arm control in a human brain-machine interface: Difficulties, solutions, and limitations,” J Neural Eng, vol. 12, no. 1, Feb. 2015, doi: 10.1088/1741-2560/12/1/016011.
[3] Dickinson A, Gates L, Metcalf C, Owen C, Kheng S, Harte C, Bunthoeun S, Simpson S, Worsley P, Ostler C, Donovan-Hall M. Learning about the changing needs for prosthetics service provision from routinely collected digital centre management data: an exemplar study across three clinics in Cambodia. Journal of Global Health. 2022 Oct 30;12:04083.
[4] Kementerian Kesehatan RI. Situasi Penyandang Disabilitas. Jakarta: Kementerian Kesehatan RI; 2014.
[5] Liputan6.com, “Jumlah Penyandang Disabilitas di Indonesia Menurut Kementerian Sosial,” https://www.liputan6.com/disabilitas/read/4351496/jumlah-penyandang-disabilitas-di-indonesia-menurut-kementerian-sosial.
[6] BPS Indonesia, “Potret Penyandang Disabilitas di Indonesia: Hasil Long Form Sensus Penduduk 2020,” Jakarta, Dec. 2024.
[7] antaranews.com, “Merangkai Masa Depan Melalui Industrialisasi: Peluang dan Tantangan di Era Transformasi,” https://www.antaranews.com/berita/4571134/merangkai-masa-depan-melalui-industrialisasi-peluang-dan-tantangan-di-era-transformasi.
[8] “Kemenkes: Bahan Baku Impor Dominasi Produksi Alat Kesehatan |Republika Online,” https://news.republika.co.id/berita/qyn1x3366/kemenkes-bahan-baku-impor-dominasi-produksi-alat-kesehatan.
[9] “Kemenperin: Jamin Demand Belanja Dalam Negeri, TKDN Terbukti Tingkatkan Investasi dan Produktivitas Industri,” https://kemenperin.go.id/artikel/25613/ghs.
[10] Kumparan.com, “Produk Alat Kesehatan RI Masih Didominasi Impor, Nilainya Capai Rp 40 T,” https://kumparan.com/kumparanbisnis/produk-alat-kesehatan-ri-masih-didominasi-impor-nilainya-capai-rp-40-t-21pZ2mf11u2.
[11] S. Mihradi, “Pengembangan Prototipe kaki palsu Atas Lutut Endoskeletal Dalam negeri Yang berdaya saing,” https://research.lppm.itb.ac.id/proyek/pengembangan-prototipe-kaki-palsu-atas-lutut-endoskeletal-dalam-negeri-yang-berdaya-saing?utm.
[12] T. Suteja, D. Rahmawan, and S. Tjandra, “Investigasi Flexural Properties Hasil Cetak 3D Printer Berbahan Carbon Fiber Polylactic Acid untuk Pembuatan Telapak Kaki Palsu,” https://ejournal.undiksha.ac.id/index.php/JST/article/view/84387/31027, 2024.
[13] G. K. Kamacı and K. Aydemir, “Lower limb prosthetic prescription,” 2023, Turkish Society of Physical Medicine and Rehabilitation. doi: 10.5606/tftrd.2023.12988.

[14] Syaifudin A, Suryandari DA, Agustin HC. Strength Assessment of Prosthetic Pylon Considering the Geometric of Raw Material. Journal of Medicine and Health Technology. 2024;1(1):50-8.

[15] T. Mangera, "Optimal material selection for the construction of a paediatric prosthetic knee," 2018, doi: 10.1177/1464420715620228Corpus.

[16] Hussain O, Saleem S, Ahmad B. Implant materials for knee and hip joint replacement: A review from the tribological perspective. In: IOP Conference Series: Materials Science and Engineering. Volume 561. Bristol (UK): Institute of Physics Publishing; 2019. p. 012007. doi: 10.1088/1757-899X/561/1/012007.

[17] M. N. Rahaman, A. Yao, B. S. Bal, J. P. Garino, and M. D. Ries, "Ceramics for prosthetic hip and knee joint replacement," Journal of the American Ceramic Society, vol. 90, no. 7, pp. 1965–1988, Jul. 2007, doi: 10.1111/j.1551-2916.2007.01725.x.

[18] M. Suffo and C. Revenga, "Biomechanical analysis of non-metallic biomaterial in the manufacture of a new knee prosthesis," Materials, vol. 14, no. 20, Oct. 2021, doi: 10.3390/ma14205951.

[19] B. Tyagi, A. Sahai, and R. S. Sharma, "Augmenting the flexural strength of polymer composites for stronger and more durable prosthetic sockets," Polym Compos, vol. 44, pp. 5656–5674, Sep. 2023, doi: 10.1002/pc.27517.

[20] A. Pentek et al., "The effect of printing parameters on electrical conductivity and mechanical properties of PLA and ABS based carbon composites in additive manufacturing of upper limb prosthetics," Crystals (Basel), vol. 10, no. 5, May 2020, doi: 10.3390/cryst10050398.

[21] S. H. Mian, E. Abouel Nasr, K. Moiduddin, M. Saleh, and H. Alkhalefah, "An Insight into the Characteristics of 3D Printed Polymer Materials for Orthoses Applications: Experimental Study," Polymers (Basel), vol. 16, no. 3, Feb. 2024, doi: 10.3390/polym16030403.

[22] A. Coelho Figliolia, E. Tobaro, G. Gonçalves, H. Mello, F. Eika Sandnes, and F. Orsi Medola, "The Influence of Filament Type and Number of Layers on Mechanical Resistance: Contributions for the Development of 3D Printed Prosthesis," in Additive Manufacturing, Modeling Systems and 3D Prototyping, AHFE International, 2022. doi: 10.54941/ahfe1001588.

[23] A. Silva and D. Guilhon, "Comparative analysis of ankle prosthesis connector adapters in 3D printed using PLA and PETG," in IFMBE Proceedings, Springer Verlag, 2019, pp. 155–161. doi: 10.1007/978-981-13-2119-1_24.

[24] M. H. Baharuddin, A. M. Ab Rashid, N. N. A. A. Abdullah, and M. H. Ramlee, "Patient-Specific Design of Prosthesis for Below Knee Amputee: Analysis Between Different Gait," International Journal of Integrated Engineering, vol. 16, no. 5, pp. 214–223, 2024, doi: 10.30880/ijie.2024.16.05.017.

[25] H. Kamel, O. Harraz, K. Azab, and T. Attia, "Developing an Optimized Low-Cost Transtibial Energy Storage and Release Prosthetic Foot Using Three-Dimensional Printing," J Eng Sci Med Diagn Ther, vol. 3, May 2020, doi: 10.1115/1.4046319.

[26] S. S. Karibeeran, P. K. Murugesan, and J. Jayakumar, "DESIGN AND DEVELOPMENT OF A LOW-COST PROSTHETIC LEG FOR BELOW-KNEE AMPUTATIONS," in ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE), American Society of Mechanical Engineers (ASME), 2023. doi: 10.1115/IMECE2023-112039.

[27] I. Bagaskara, "Desain Kaki Prosthetic Untuk Transfemoral Amputi Dengan Aktivitas Tinggi di Indonesia," Feb. 2019.

[28] S. Winiarski and A. Rutkowska-Kucharska, "Estimated ground reaction force in normal and pathological gait," Acta Bioeng Biomech, vol. 11, no. 1, 2009.

[29] J. Cantrell et al., "Experimental characterization of the mechanical properties of 3D printed ABS and polycarbonate parts," Conference Proceedings of the Society for Experimental Mechanics Series, vol. 3, pp. 89–105, 2017, doi: 10.1007/978-3-319-41600-7_11/FIGURES/12.

[30] "(PDF) The effect of orientation on tensile strength 3D printing with ABS and PLA materials." Accessed: Jan. 19, 2025. [Online]. Available: https://www.researchgate.net/publication/374592854_The_effect_of_orientation_on_tensile_strength_3D_printing_with_ABS_and_PLA_materials

[31] A. Alhuzaim, "Article ID: IJMET_15_02_004 Cite this Article: Abdullah Alhuzaim, Investigating the Mechanical Properties of PLA Polymer Tensile Test Samples Produced Via 3D Printing in Various Orientations: Flat, Vertical, and 45 Degrees," International Journal of Mechanical Engineering and Technology (IJMET), vol. 15, no. 2, pp. 35–42, Accessed: Jan. 19, 2025. [Online]. Available: https://iaeme.com/MasterAdmin/Journal_uploads/IJMET/VOLUME_15_ISSUE_2/IJMET_15_02_004.pdfAbdullahAlhuzaimhttps://iaeme.com/Home/journal/IJMET36

[32] M. R. Khosravani, F. Berto, M. R. Ayatollahi, and T. Reinicke, "Characterization of 3D-printed PLA parts with different raster orientations and printing speeds," Scientific Reports 2022 12:1, vol. 12, no. 1, pp. 1–9, Jan. 2022, doi: 10.1038/s41598-022-05005-4.

[33] L. Auffray, P. A. Gouge, and L. Hattali, "Design of experiment analysis on tensile properties of PLA samples produced by fused filament fabrication," International Journal of Advanced Manufacturing Technology, vol. 118, no. 11–12, pp. 4123–4137, Feb. 2022, doi: 10.1007/S00170-021-08216-7/FIGURES/10.

[34] T. Appalsamy, S. L. Hamilton, and M. J. Kgaphola, "Tensile Test Analysis of 3D Printed Specimens with Varying Print Orientation and Infill Density," Journal of Composites Science 2024, Vol. 8, Page 121, vol. 8, no. 4, p. 121, Mar. 2024, doi: 10.3390/JCS8040121.

[35] K. Jha, "Polycentric prosthetic knee | 3D CAD Model Library | GrabCAD." Accessed: Jan. 28, 2025. [Online]. Available: https://grabcad.com/library/polycentric-prosthetic-knee-1

[36] D. Jiang and D. E. Smith, "Anisotropic mechanical properties of oriented carbon fiber filled polymer composites produced with fused filament fabrication," Addit Manuf, vol. 18, pp. 84–94, Dec. 2017, doi: 10.1016/J.ADDMA.2017.08.006.

[37] C. W. ADI and C. W. ADI, “Evaluasi Lower Limb Prosthetics Produk Pusat Rehabilitasi Yakkum Yogyakarta,” https://etd.repository.ugm.ac.id/penelitian/detail/115104?utm_source=chatgpt.com.

[38] R. F. Hidayat, W. Nugroho, and C. Budiyantoro, “ANALISIS PENGARUH PARAMETER PROSES 3D-PRINTING MATERIAL PETG TERHADAP RESPON AKURASI DIMENSI DAN KEKUATAN TARIK MENGGUNAKAN METODE TAGUCHI.” [Online]. Available: http://journal.umy.ac.id/index.php/jmpm

[39] M. R. Khosravani, F. Berto, M. R. Ayatollahi, and T. Reinicke, “Characterization of 3D-printed PLA parts with different raster orientations and printing speeds,” Scientific Reports |, vol. 12, p. 1016, 123AD, doi: 10.1038/s41598-022-05005-4.

[40] A. Coelho Figliolia, E. Tobaro, G. Gonçalves, H. Mello, F. Eika Sandnes, and F. Orsi Medola, “The Influence of Filament Type and Number of Layers on Mechanical Resistance: Contributions for the Development of 3D Printed Prosthesis,” Additive Manufacturing, Modeling Systems and 3D Prototyping, vol. 34, 2022, doi: 10.54941/AHFE1001588.

[41] F. Ferrano, M. Fateri, M. Merkel, and J. Hertel, “Simulating Elastoplastic and Anisotropic Behavior in Thermoplastic Additively Manufactured Components: An Application-Oriented Modeling Approach,” Polymers (Basel), vol. 16, May 2024, doi: 10.3390/polym16091234.

[42] A. Kasmi, J. Marae Djouda, and F. Hild, “On elastic anisotropy of 3D printed acrylonitrile butadiene styrene structures,” Polymer (Guildf), vol. 254, Jul. 2022, doi: 10.1016/j.polymer.2022.125032.

[43] A. Rodríguez-Panes, J. Claver, and A. M. Camacho, “The influence of manufacturing parameters on the mechanical behaviour of PLA and ABS pieces manufactured by FDM: A comparative analysis,” Materials, vol. 11, no. 8, Aug. 2018, doi: 10.3390/ma11081333.

[44] M. Bembenek, Ł. Kowalski, and A. Kosoń-Schab, “Research on the Influence of Processing Parameters on the Specific Tensile Strength of FDM Additive Manufactured PET-G and PLA Materials,” Polymers (Basel), vol. 14, no. 12, Jun. 2022, doi: 10.3390/polym14122446.