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Multi criteria decision making for optimal below knee prosthetic design

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ABSTRACT

In manufacturing prostheses such as blow knee (BK) prostheses, the designer needs to make a proper selection of materials to achieve some requirements according to patient uses prior to fabricating the parts of the prosthesis. Some requirements are low cost, lightweight, durable and withstand the loading environment. Different methods have been used to make such selections based on the optimisation of material properties such as statistical, graphical and computer software. The selection of the optimal material for the socket, shank and foot of BK prostheses is thus considered in this work using the multi-criterion decision-making (MCDM) technique. One of the MCDM strategies is TOPSIS, which was used to choose the ideal material and make a recommendation to design BK prosthesis under different conditions. The common materials used for socket, shank and foot are collected from research works as reference data including polymers, composite, metal alloys, and wood. The results show that pineapple fibre-reinforced composite (PFRC) composite provides light and stiff sockets and PFRC composite provides elastic thought sockets. Titanium alloy (Ti-6Al-4V) provides a stiff shank, and stainless steel (SS 304) alloy provides shock resist shank. Hardwood can be used for low-cost foot, and carbon fibre for shock resistance foot.

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1. Introduction

Below knee (BK) prosthesis is a noteworthy development in the discipline of biomedical engineering that improves human life. It consists of three major parts: socket, shank and foot. However, the prosthesis's most serious complications include excessive strain on the patellar tendon, knee flexion restriction, adventitious bursae, skin abrasions, and prosthesis-bone stress reduction. BK success relies on the successful choice of materials according to the following criteria: the coefficient of elasticity, the strength, the flexibility, the resilience to corrosion, and the wear resistance, biocompatibility, and cost. Humans continue to have prosthesis-related issues despite the wide variety of biomaterials available because BK material has been improperly chosen.

For a specific BK prosthesis design shape, choosing the optimal socket material may help prevent aseptic loosening. Now accessible are knee joint prosthesis socket materials. This component's materials selection is restricted. A challenging issue requires adequate skills. Whether by trial and error or through preliminary

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testing, a superior substance was selected as a replacement for an older one. Stainless steel was formerly considered a viable biomaterial for orthopaedic purposes. However, its usage for implant applications was limited by poor corrosion resistance. Following that, scientists began considering the potential for knee prostheses made from cobalt-based biomaterials [1]. Due to its high elastic modulus (220 GPa), which is higher than bone's (15–30 GPa) and causes stress-shielding, cobalt-based alloys have a poor ability to withstand implantation failure. After that, the researcher discovered pure titanium-based (CP-Ti) biomaterial that were clinically and economically viable for orthopaedic use. However, the elastic modulus of CP-Ti (165 GPa), which was more than that of bone, made the alloy unsuitable for knee implantation. Ti-6L-4V, the most used Ti-based alloy, has a number of disadvantages, including low hardness and poor wear resistance [2]. For knee and orthopaedic applications, researchers have created a variety of high-strength and low-elastic Ti-based alloys, each with unique benefits and drawbacks. In order to solve this issue, choosing the best material for BK prosthesis is crucial. Due to these characteristics of various biomaterials, four different materials were selected based on their availability.

In the body of research, numerous approaches have been put forth to deal with the challenge of material selection and to boost the effectiveness of the design process. Multiple criteria decision-making (MCDM) approaches may be used to choose, filter, and prioritize resources and assist appraise them. Thus, material selection involves an understanding of MCDM and mechanical, physical, biological, electrical, chemical, and manufacturing qualities. MCDM approaches are increasingly employed in engineering design material selection. One of the greatest MCDM strategies is TOPSIS, which was created by Hwang and Yoon in 1981 [3]. TOPSIS chooses the optimal option according to its distance from the positive and negative ideal solutions (NIS). The option that is furthest from the NIS and closest to the PIS will have the highest proximity coefficient.

Many researchers use the selection criteria in different engineering fields. For biomedical and prosthesis applications, the subject is treated by the works of Kumar et al. [4]. They discussed the challenges and strategies for selecting the optimal materials for the total knee replacement (TKR) components. A hybrid MCDM technique was used to pick femoral component material for TKR. The best alternative option was based on five distinct MCDM procedures using the equal weights method (EWM) that assign rankings using various concepts. The five MCDM approaches' rank findings were combined to get the final rank. Eight important features were evaluated for the 11 femoral component materials for TKR. Objective and subjective weights were used for sensitivity analysis. The sensitivity study showed that the femoral component material employing TKR Ti alloys ranks 1 with the standard deviation method (SDM) and fuzzy analytical hierarchy process (FAHP) weight techniques, 2 with the equal weights method (EWM), and 4 with the entropy weights technique (EWT). It possesses a density of 4.5 g/cc, a modulus of elasticity of 100 GPa, a tensile strength of 550 MPa, an elongation of 54%, and extraordinarily strong corrosion resistance. Zr-2.5Nb was last with EWM and SDM and second to last with FAHP. The degree of membership (DoM) yields solid findings using the suggested technique, which is statistically simpler and may provide more accurate results.
With the same objective, Irfan [5] investigated the impact of selecting the best materials associated with aseptic instability and metallosis at the surgery of TKR revision. The TOPSIS technique is used to determine the optimum materials for TKR components. Among a number of available options for the TKR procedure's femoral component, a case study of TKR with a high modulus of elasticity, ductility, wear and corrosion are presented and analyzed.

Taahirah Mangera et al. (2018) [6] investigated the optimal material selection of paediatric knee prostheses with lightweight and low cost by using TOPSIS criteria. Due to their higher cost, titanium alloys were placed below aluminium alloy 7175, the best knee material. Cast aluminium alloys were ranked lowest in terms of structural performance due to their poor performance. A novel MCDM approach (Reference Ideal Method) was utilised by [7] to choose biomaterials for the prosthesis. The approach was evaluated on two literature-based biomaterial selection issues. The findings were compared to literature research. Hip prosthesis material should be Co–Cr alloys-wrought alloy or Ti6Al4V. The optimal materials to use for the femoral componant are NiTi SMA and Porous NiTi SMA. According to research by Ali Jahan et al. [8], material options in engineering design are evaluated using several criteria based on the goals of the issue.

They suggested a novel method to improve the accuracy of material selection results in a variety of applications, specifically biological applications where implanted materials should possess characteristics comparable to those of human tissues. This method was developed to improve the accuracy of material selection results in a variety of applications. This updated version of the VIKOR technique takes into account all possible parameters while placing a priority on finding middle ground solutions. According to [9] , the composite method, which incorporates two or more MCDM methods, could be used for material selection across all application areas. They concluded that the MCDM method is useful for material-choosing options.

In 2021, Kumar et al. [4] examined the optimal TKR femur component materials. This study work uses a hybrid MCDM approach that combines the DoM method with a dynamic system, the weighted sum technique, an evaluation based on distance from the mean solution, and a ranking based on similarity to the optimal solution. The intention of the material selection simulation by Kadhim et al. [10] was to develop hip joint replacements out of lightweight, affordable, and durable materials. Material options for the implant proposed in this research to create a lightweight and less costly joint include aluminium 2024, stainless steel ASIS 410, and titanium alloys (Ti6Al4V). Because of its low cost, low weight, and high efficiency, Al2024 was chosen as the optimal substance. High-density polyethene and hydroxyapatite were combined in varying quantities, and Shankar Swarup Das et al. [11] studied the manufacture of three polymer blends classified as HDHA-10, 20, and 30 before conducting mechanical tests and surface characterisation. From these outcomes, the best one was chosen using a TOPSIS. As a result of its promising qualities, HDHA-30 has been suggested as the ideal mix for acetabular liners of metal-on-plastic hip implants.

In light of the importance of the femur component to BK, this paper explores how a multi-criteria decision-making approach can be employed to choose the most appropriate material. The optimal material was selected using the comprehensive TOPSIS approach.

2. Method

According to the traditional TOPSIS technique, the issue is resolved by a single decision-maker, and the ratings of the options and weights are assumed to be represented by numerical data.

The decision matrix is represented by $X = (x_{ij})$

The weight vector is represented by $W = [w_1, w_2, \dots, w_n]$, where $x_{ij} \in \Re, w_j \in \Re$ and $w_1 + w_2 + \cdots + w_n = 1$.

Normalisation is used to convert different attribute dimensions into non-dimensional characteristics. Various methods exist for normalising values. The following approaches [8] are used to calculate the normalised value n_{ij} [8]:

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (1)$$

$$n_{ij} = \frac{x_{ij}}{\max_i x_{ij}}, \quad (2)$$

$$n_{ij} = \begin{cases} \frac{x_{ij} - \min_i x_{ij}}{\max_i ij - \min_i ij} & \text{if } C_i \text{ is a benefit criterion} \\ \frac{\max_i ij - x_{ij}}{\max_i ij - \min_i ij} & \text{if } C_i \text{ is a cost criterion} \end{cases} \quad (3)$$

for $i = 1, \dots, m; j = 1, \dots, n$.

The following expression defines the calculation for the weighted normalised number v_{ij} :

$v_{ij} = w_j n_{ij}$ for $i = 1, \dots, m; j = 1, \dots, n.$ (4)

Where w_j is the weight of the j-th criterion, $\sum_{j=1}^{n} w_j = 1$.

The optimum negative solution maximises the cost criterion while decreasing the benefit criterion. On the other hand, the optimal positive solution aims to maximise the benefit criterion while simultaneously decreasing the cost criterion.

The form of the positive ideal solution, denoted by the letter (A^+), is:

$$A^+ = (v_1^+, v_2^+, \dots, v_n^+) = \left(\left(\max_i v_{ij} \,\middle|\, j \in I\right), \left(\min_i v_{ij} \,\middle|\, j \in J\right)\right). \quad (5)$$

The form of the negative ideal solution, denoted by the letter (A^-), is:

$$A^- = (v_1^-, v_2^-, \dots, v_n^-) = \left(\left(\min_i v_{ij} \,\middle|\, j \in I\right), \left(\max_i v_{ij} \,\middle|\, j \in J\right)\right) \quad (6)$$

i is linked to the benefit criterion, where (i = 1, … , m).

j is linked to the cost criterion, where (j = 1, … , n).

When using the TOPSIS technique, a variety of distance metrics may be used to determine how far apart each option is from the optimum answer.

$$d_i^+ = \left(\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^p\right)^{1/p}, \; i=1,2,\dots, m. \quad (7)$$

According to the following formula, each option is distinguished from the negative ideal solution:

$$d_i^- = \left(\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^p\right)^{1/p}, \; i=1,2,\dots, m. \quad (8)$$

The following formula determines how closely the i-th choice, Aj, is related to A^+:

$$R_i = \frac{d_i^-}{d_i^- + d_i^+}, \quad (9)$$

where $0 \le R_i \le 1$, $i = 1,2, \dots, m$.

Now, it is possible to sort a list of options by decreasing R_i value.

3. Results and discussion

3.1. Socket materials selection

The primary materials used in the manufacture of sockets and their mechanical characteristics are shown in Table 1.Table 1. The material properties of socket and cost for socket materials [12-14].

Socket Materials	Density (Kg/m^3)	Modulus of elasticity (Gpa)	Yield strength (Mpa)	Impact strength (J)	Relative price
CFRC	0.74	40.7	36.4	20.5	1.94
GFRC	0.65	11.4	34.3	13.3	1.8
PFRC	0.78	40.4	58.8	6.5	1.5
AFRC	0.84	27.3	49.6	4.2	1.5

CFRC=carbon fiber-reinforced composite; GFRC=glass fiber-reinforced composite; PFRC=pineapple fiber-reinforced composite; AFRC= abaca fiber-reinforced composite. The next section provides a detailed solution for selecting materials of stiff and affordable socket materials First, rank the attributes (max rank = 9, min rank = 1); the results are shown in the table below.

Table 2. The material's key attributes

Socket Materials	Density (kg/m^3)	Modulus of Elasticity (Gpa)	Yield strength (Mpa)	Relative price
CFRC	7	9	7	9
GFRC	6	6	6	8
PFRC	8	8	9	7
AFRC	9	7	8	7

Second, weight the desired property with high value. In this case, 0.4 is attributed to the modulus of elasticity since it is the favorite, and the price is weighted by 0.1to reduce cost. The total weight must equal to one, so the remaining 0.5 is now distributed equally across the remaining properties. In Table 3, each attribute's weights are shown.

Table 3. Matrix using quantitative data, while turning intangibles into numbers and giving each criterion a certain amount of weight

	Density (kg/m^3)	Modulus of elasticity (Gpa)	Yield strength (Mpa)	Relative price
weight	0.25	0.4	0.25	0.1

Third, applying the TOPSIS analysis as follows:

Step 1: To determine rij, figure out $(\sum x^2_{ij})^{1/2}$ for each column and divide each column by that.

Table 4. Decision matrix of the socket material

Socket Materials	Density (kg/m^3)	Modulus of elasticity (Gpa)	Yield strength (Mpa)	Relative price
CFRC	0.46157	0.593	0.46157	0.577
GFRC	0.39563	0.396	0.39563	0.513
PFRC	0.5275	0.528	0.59344	0.449
AFRC	0.59344	0.462	0.5275	0.449

Step 2: To get V_{ij}, multiply each column by w_j.

Table 5. Matrix with each element's weight multiplied by its corresponding column

Socket Materials	Density (Kg/m^3)	Modulus of elasticity (Gpa)	Yield strength (Mpa)	Relative price
CFRC	0.09231	0.237	0.13847	0.058
GFRC	0.07913	0.158	0.11869	0.051
PFRC	0.1055	0.211	0.17803	0.045
AFRC	0.11869	0.185	0.15825	0.045

Step 3: From the output of the previous step, the ideal positive solution (A^+) and negative solution (A^-) are determined, respectively, as shown below.

A^+ = {0.11869, 0.237, 0.17803, 0.045}

A^- = {0.07913, 0.158, 0.11869, 0.058}

Step 4: Separation from the ideal solution is determined according to the following equation:

$\mathbf{S_i^* = [\sum (v_j^* - v_{ij})^2]^{1/2}}$ for each row ^{j}.

Table 6: Matrix measuring relative separation values

Socket Materials	$S_i^* = [\sum (v_j^* - v_{ij})^2]^{1/2}$
CFRC	0.04924915
GFRC	0.10671916
PFRC	0.02948839
AFRC	0.05633749

Step 5: Separation from the ideal negative solution ($\mathbf{S_i^-}$) is determined according to the following equation:

$\mathbf{S_i- = \ [\sum (v_j - v_{ij})^2]^{1/2}}$ for each row ^{j}.

Table 7. Matrix measuring negative separation values (S_i^-).

Socket Materials	$S_i- = \ [\sum (v_j - v_{ij})^2]^{1/2}$
CFRC	0.08262014
GFRC	0.006415
PFRC	0.08464401
AFRC	0.06317196

Step 6: The calculation used to determine how close the actual solution is to the optimal solution is as follows: $Ci^* = \mathbf{S_i^-} / (\mathbf{S_i^*} + \mathbf{S_i^-})$, and presented in Table 8.

Table 8. A matrix that measures the degree of proportional proximity to the optimal solution.

Socket Materials	Ci^*
CFRC	0.62653
GFRC	0.0567
PFRC	0.74163
AFRC	0.52859

The highest Ci* value is chosen for the best material, which is 0.74163 for (PFRC) material, and the lowest value for the worst material (GFRC), which is 0.0567. In this instance, the attributes are weighted in accordance with the preferences outlined in Table 2. Five cases are considered for selecting socket material based on MCDM. The preferences listed in Table 9 are taken into consideration while weighing each attribute.

Table 9. MCDM weighting for the socket material properties

Case	Preferences	Density (kg/m^3)	Modulus of Elasticity (Gpa)	Yield strength (Mpa)	Relative price
1	Stiff and low cost	0.25	0.4	0.25	0.1
2	Elastic and Tough	0.4	0.3	0.1	0.2
3	Light and Low cost	0.4	0.15	0.15	0.3
4	Shock Resistive	0.2	0.2	0.4	0.2
5	Traditional	0.25	0.25	0.25	0.25

The results of TOPSIS for Ci^* for best materials are presented in Table 10.

Table 10. Results of TOPSIS for the optimal choice of socket material.

Case	Ci^* for best solution	Material
1	0.74163	PFRC
2	0.69025	PFRC
3	0.80401	AFRC
4	0.70851	CFRC
5	0.6097	(CFRC)

3.2. Shank materials selection

Material property values for pylon tube are as presented in Table 11.

Table 11. Material properties and cost of shank materials [15, 16]

Pylon tube Materials	Density (Kg/m^3)	Modulus of elasticity (Gpa)	Yield strength (Mpa)	Impact strength (J)	Relative price
Ti-6Al-4V	1.23	25.9	200	3.9	3.2
Al6061-T6	0.97	25.6	102.2	9.3	2.66
SS 304	1.55	24.1	26.9	40.6	2.86
CFRC	0.65	40.7	36.4	2.7	1.94

In this case the selected weights are as shown in the Table 12.

Table 12. MCDM weighting for shank material properties

Case	Optimum	Density (Kg/m^3)	Modulus of elasticity (Gpa)	Yield strength (Mpa)	Relative price
1	Stiff and low cost	0.2	0.4	0.3	0.1
2	Elastic and Tough	0.4	0.3	0.1	0.2
3	Light and Low cost	0.4	0.15	0.15	0.3
4	Shock Resistive	0.2	0.2	0.4	0.2
5	Traditional	0.25	0.25	0.25	0.25

Now by applying TOPSIS procedure the final values of Ci^* are as shown in Table 13.

Table 13. TOPSIS solution for best materials.

Case	Ci^* for best solution	Material
1	0.70204	Ti-6Al-4V
2	0.57205	Ti-6Al-4V
3	0.58579	SS 304
4	0.65291	SS 304
5	0.54729	Ti-6Al-4V

3.3. Foot materials selection

Table 14 gives material properties and costs for foot materials.

Table 14. Material properties and cost of foot materials

Foot Materials	Density (kg/m^3)	Modulus of elasticity (Gpa)	Yield strength (Mpa)	Impact strength (J)	Relative price
Hard wood	760	12.5	30.14	4.5	0.76
Polymer	932	2.41	56.5	8.44	2.3
Carbon fiber	1336.3	22.8	12.5	12.65	6.7
Hard rubber	1100	0.05	2.4	9.76	1.56

In this case, the selected weights are shown in Table 15.

Table 15. MCDM weighting for foot material properties

Case	Optimum	Density (kg/m^3)	Modulus of elasticity (Gpa)	Yield strength (Mpa)	Relative price
1	Cheap with average properties	0.3	0.3	0.3	0.1
2	Flexible	0.2	0.4	0.3	0.1
3	Shock resistive	0.2	0.2	0.4	0.2
4	Traditional	0.25	0.25	0.25	0.25

By applying the TOPSIS procedure, the final values of Ci^* are shown in Table 10.

Table 16. TOPSIS results for Foot materials.

Case	Ci^* for the best solution	Material
1	0.751648384	Hard wood
2	0.672065577	Carbon fibre
3	0.710102051	Carbon fibre
4	0.633974596	Carbon fibre

The decision making can be enhanced by artificial intelligence (neural networks), Arduino and proper antennas (sensors) and filters to get the most optimal results [17-23].

4. Conclusions

TOPSIS analysis is an effective tools used to select optimal requirement for material of prosthesis parts. Chosen of materials depend on the designer demand and preferences as wish or the patient order and conditions for wide variety applications of cases such as; low cost, flexible, durable, light weight. The results of TOPSIS technique show that; PFRC composite provide light and stiff socket and PFRC composite provide elastic thought socket. Ti-6Al-4V alloy provide stiff shank and SS 304 steel alloy provide shock resist shank. Hard wood can be used for low cost foot and carbon fiber for shock resistance foot.

Declaration of competing interest

The authors of this article declare that they do not have any known financial or non-financial conflicting interests in any of the topics that are covered in this study.

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