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Material selection for femoral component of total knee replacement using comprehensive VIKOR

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ABSTRACT

The increasing trend of total knee replacement (TKR) revision surgery, which is associated with aseptic loosening, makes it a challenging research subject. The concern of loosening can be partially improved by selecting the optimal materials for TKR components. Therefore, this paper considers selection of the best material among the set of alternatives for femoral component of TKR through the multi-criteria decision making approach. The comprehensive VIKOR method was used to select the optimum material, and a systematic technique for sensitivity analysis of weights was introduced to find more reliable results. The obtained ranking order suggested the use of new materials over the existing ones. Porous and dense NiTi shape memory alloys were ranked first and second respectively.

1. Introduction

In recent years, biomaterial development and selection have been two challenging issues due to the essential biological and mechanical requirements [1–3]. Among different biomedical applications, total knee replacement (TKR) has become one of the most critical debates as a result of the simultaneous growing number of replacement [4–7] and revision [4,8] surgeries. The most severe problem associated with revision surgery is aseptic loosening caused by excessive wear between articular surfaces, stress-shielding of the bone by prosthesis, and development of a soft tissue at the interface of bone and implant. Applying the optimal material either for femoral component or the tibial insert can reduce the wear debris and risk of implant loosening. Furthermore, stress-shielding effect is mainly attributed to the material property (elastic modulus) of the components interfacing the bone [9] which are the femoral component on the upper part and the tibial tray in the lower part. Considering this issue for a given design geometry of knee prosthesis, selection of the optimum or best material for femoral part appears to play a significant role in aseptic loosening of the prosthetic joint.

A set of materials is now available which might be suitable to use for femoral component of the knee joint prostheses. However, materials selection of this component has been surrounded by many constraints. To deal with such a difficult problem, one would need to utilize appropriate tools. Traditionally, choosing a new material or replacing an existing one with another whose characteristics provide better performance, was usually carried out by applying trial and error methods or by following of previous experimentation experiences. While it can be dealt with by adopting multiple criteria decision making (MCDM) models [10] to avoid misuse of materials [11] which is associated with huge cost [12]. MCDM provides a foundation for selecting, sorting, and prioritizing materials and helps in the overall assessment. Hence, selection of materials not only requires information about mechanical, physical, biological, electrical, chemical, and manufacturing properties, etc., but also knowledge on MCDM. However, MCDM methods have been widely used in material selection for engineering designs [13–18], and the trend is in growth [10]. In biomedical engineering, most of material selection studies have used finite element analysis as a computer simulation tool [19–21]. Although some have utilized MCDM-based techniques in material selection of hip joint prosthesis [22], and compliant-layer artificial hip joints [23].

This paper discusses a strategy to select suitable material for femoral component of knee prosthesis based on a recently proposed MCDM method, namely comprehensive VIKOR [24], in order to improve the longevity and quality of human life. The scenario starts in Section 2 with theoretical considerations of comprehensive VIKOR approach and a proposed technique for sensitivity analysis of subjective weights, followed by a case study in Section 3. This case study includes a general introduction to TKR components and the required properties of implant materials for femoral component. After good appreciation of the method in Section 2 and the requirements in Section 3, Section 4 offers the solution procedure and discusses selection of the best biomaterials. Section 5 ends the paper with conclusions and remarks.

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2. Theoretical considerations on ranking method

However, several MCDM methods have been proposed to solve material selection problems, there is still a great necessity to use suitable approaches in accordance with the problem nature [25]. In this regard, comprehensive VIKOR was developed in MCDM as an appropriate tool for biomaterial selection applications. It covers all types of criteria in engineering design including beneficial (higher values are desirable), non-beneficial (lower values are desirable), and target values. For implant biomaterial selection, in addition to beneficial and non-beneficial criteria, attributes with target values are desired. An obvious criterion with target value is the elastic modulus of the implant material. Large difference between elastic modulus of implant biomaterial and the surrounding bone can contribute to make severe stress concentration, namely stress-shielding from natural bone. Hence the comprehensive version of VIKOR is a suitable technique to be applied for material selection of prosthetic femur. The process consists of the following steps.

Step 1: Determination of the most favorable values for all criteria.

$$T = \{T_1, T_2, T_3, \ldots, T_j, \ldots, T_n\} = \{\text{Most desirable element } (r_{ij}) \text{ or target value for criteria } j\}$$

where $r_{ij}(i = 1,2,3,\ldots,m$ and $i = 1,2,3,\ldots,n)$ are elements of the decision matrix (alternative *i* respect to criteria *j*).

Step 2: Computation of the values S_i and R_i according to Eqs. (1) and (2), respectively.

$$S_i = \sum_{j=1}^{n} w_j \left(1 - e^{\frac{|r_{ij}-T_j|}{-A_j}}\right) \tag{1}$$

$$R_i = \underset{j}{Max}\left[w_j\left(1 - e^{\frac{|r_{ij}-T_j|}{-A_j}}\right)\right] \tag{2}$$

where $A_j = \{1$ if elements of criteria *j* are normalized between 0 and 1, $\max\{r_j^{\max}, T_j\} - \min\{r_j^{\min}, T_j\}$ otherwise$\}$, $r_j^{\max}$ and $r_j^{\min}$ are maximum and minimum elements in criteria *j* respectively and w_j represents the weight of criterion *j*.

Step 3: Computation of the index values Q_i using Eq. (3).

$$Q_i = \begin{cases} \left[\frac{R_i - R^-}{R^+ - R^-}\right] & \text{if } S^+ = S^- \\ \left[\frac{S_i - S^-}{S^+ - S^-}\right] & \text{if } R^+ = R^- \\ \left[\frac{S_i - S^-}{S^+ - S^-}\right] v + \left[\frac{R_i - R^-}{R^+ - R^-}\right](1 - v) & \text{Otherwise} \end{cases} \tag{3}$$

where S^- = Min S_i, S^+ = Max S_i, R^- = Min R_i, R^+ = Max R_i, and v is introduced as a weight for the strategy of "the majority of criteria" (or "the maximum group utility"), where, $1 - v$ is the weight of the individual regret. The value of v lies in the range of 0–1 and these strategies can be compromised by $v = 0.5$.

Step 4: The results are obtained as three ranking lists by sorting the values *S*, *R*, and *Q* in decreasing order.

Step 5: Proposing the alternative ($A^{(1)}$) which is ranked best by the measure *Q* (minimum) as a compromise solution if the following two conditions are satisfied:

C1: Acceptable advantage (Eq. (4)):

$$Q(A^{(2)}) - Q(A^{(1)}) \geqslant DQ \tag{4}$$

where $A^{(2)}$ is the alternative with second place in the ranking list by *Q*; $DQ = 1/(M - 1)$. *M* is the number of alternatives.

C2: Acceptable stability in decision making:

The alternative $A^{(1)}$ should also be the best ranked by *S* or/and *R*. A set of compromise solutions is proposed as follows, if one of the conditions is not satisfied.

- Alternatives $A^{(1)}$ and $A^{(2)}$ if only C2 is not satisfied, or
- Alternatives $A^{(1)}, A^{(2)}, \ldots, A^{(M)}$ if C1 is not satisfied; $A^{(M)}$ is determined by the relation $Q(A^{(M)}) - Q(A^{(1)}) < DQ$ for maximum *M*.

Table 1
Values of material selection factors in format of 11-point scale.

Qualitative measure of material selection factor	Assigned value
Exceptionally low	0.045
Extremely low	0.135
Very low	0.255
Low	0.335
Below average	0.410
Average	0.500
Above average	0.590
High	0.665
Very high	0.745
Extremely high	0.865
Exceptionally high	0.955

Moreover, the fuzzy conversion scales [26], which systematically converts linguistic terms to their corresponding fuzzy numbers, are applied to assign the values of the attributes on a qualitative scale. Hence, an 11-point scale is used in this paper for better understanding and representation of the qualitative attributes (Table 1).

Furthermore, two subjective methods: modified digital logic approach (MDL) [27], and the revised Simos' weighting method [28] are used to determine weights or importance of criteria. These weights are combined according to the suggested formula in Eq. (5), where w_j^1 and w_j^2 are the pair-wise comparing and direct weights, respectively ($0 \leqslant \lambda \leqslant 1$).

$$W_j = w_j^1 \lambda + w_j^2 (1 - \lambda) \quad j = 1,2,3,\ldots,n \tag{5}$$

In the above equation $\sum_{j=1}^{n} W_j$ would be equal to 1, because of $\sum_{j=1}^{n} w_j^1 = 1$, $\sum_{j=1}^{n} w_j^2 = 1$, and $\lambda + (1 - \lambda) = 1$. Moreover, by changing the λ between 0 and 1, the suggested formula provides an opportunity for sensitivity analysis of weights in MCDM problems.

3. Case study

In engineering design, material selection for a product can be performance-driven or cost-driven which makes a huge difference when choosing materials [22]. In biomedical applications, the material selection process is performance-driven because biomaterials should restore form and function of the replaced biological structures. In the present study, the most significant criteria including strength, Young's modulus, ductility, corrosion resistance, wear resistance and osseointegration are considered.

3.1. Components of TKR and loading conditions

Knee replacements are designed to substitute biological materials of the knee joint that have been damaged. Total knee replacement usually has three main components: femoral component, tibial component (tibial tray and tibial insert), and the patellar component (kneecap) as shown in Fig. 1. Femoral component, that is normally cemented or pressed in the place, replaces the distal fe-

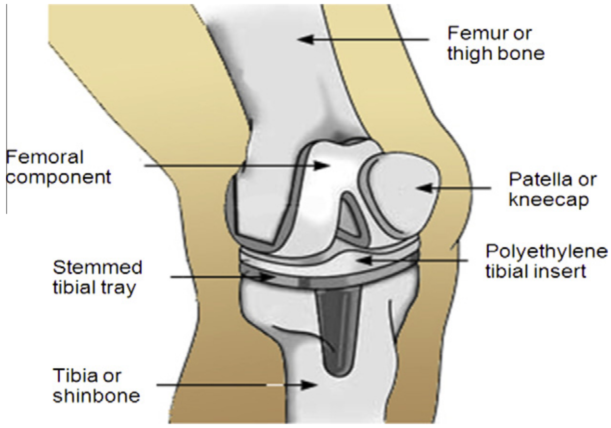

Fig. 1. Components of total knee replacement.

mur. Tibial tray is inserted into the proximal tibia, and the patellar component replaces the back of the patella. The tibial insert and the patellar component are usually made of plastics while the femoral component and the tibial tray are metallic parts. Therefore, the articulating surface is metal on plastic. The tibial insert articulates against the femoral component and tries to reproduce the natural knee constraint and motion. Hence, understanding of the natural knee joint loading is required for various studies of TKR.

The loads acting on the knee joint are comprised of six components: three forces and three moments. When the knee joint is loaded by external forces, the sum is counterbalanced by the forces acting across the joint, i.e. the tibiofemoral contact forces, muscle forces, and forces in soft tissue structures. Furthermore, the moments exerted by muscles, soft tissues, contact forces, and frictional forces also counterbalance the net moment, caused by the external forces. Gait analysis [29,30] and analytical musculoskeletal models [31] were mostly used to estimate these forces and moments about the knee joint which vary considerably for different daily activities. Biomechanical studies on knee joint loading have consistently calculated maximum compressive forces acting on the joint based on the body weight during static (one legged stance, two legged stance) and dynamic (cycling, level walking, stair ascending, stair descending, downhill walking, rising from the chair) daily activities [32–34].

3.2. Requirements of biomaterials

Biomaterials are artificial or natural materials that replace the diseased or damaged organic systems to improve the durability and quality of human life and provide a pain-free life for patients, with a range of motion adequate for daily activities. Biomaterials are chosen to balance some fundamental requirements for an artificial organ to have well performance. However, these requirements vary from one application to another one. The required properties for femoral component are briefly described here.

3.2.1. Adequate strength

Strength of materials influences the fracture of prosthetic knee joint. When the bone–implant interface initiates to fail, a soft fibrous tissue grows at the interface that can produce greater relative motion between the implant component and the bone under loading conditions. This causes pain to the patient, and after a certain period, the implant must be replaced by a revision procedure [35]. Sometimes specific strength (strength/density) is used as a criterion because the weight and density of the biomaterial must be comparable to that of the bone [22].

3.2.2. Elastic modulus

For heavily loaded joint such as total knee replacement, higher yield strength is fundamentally coupled with the necessity of a lower Young's modulus close to that of human bones [36,37]. Large difference between Young's modulus of implant biomaterial and the surrounding bone can contribute to stress-shielding effect. This may weaken the bone, deteriorate the interface of implant-bone and consequently provide loosening and failure of implant [35]. Moreover, lower Young's modulus means higher damping capacity and resilience [22] which can extensively affect the absorption of impact energy and dampening of the peak stress between the bone and the articular prosthesis. Therefore, modulus of implant material is considered as a main factor for selection of TKR materials.

3.2.3. Ductility

Ductility is defined as a mechanical property used to describe the level to which materials can be deformed plastically without fracture. It is essential to avoid brittle failure of the implant under mechanical loading.

3.2.4. Corrosion resistance

Corrosion of metallic biomaterials is an unavoidable issue due to the corrosive body fluid. The implants release undesirable metal ions that are non-biocompatible. The corrosion phenomenon can reduce the implant life and impose revision surgery. Moreover, the human life may be possibly decreased by the corrosion phenomenon because dissolved metal ions either can accumulate in tissues, close to the implant or they may be transported to the other parts of the body [38].

3.2.5. Wear resistance

Low wear resistance or high coefficient of friction can result in implant loosening [39]. Furthermore, wear debris are biologically active and make a severe inflammatory response. This may destruct the healthy bone supporting the actual implant. Also, the friction causes to corrosion which is a big concern as described above.

3.2.6. Biocompatibility

One of the most essential requirements of orthopedic biomaterials is biocompatibility. Biocompatibility refers to the ability of the material to exist in contact with tissues without producing an unacceptable degree of damage to the body. It is not only related to toxicity, but to all the adverse effects of a material in the organic system [40–42]. The biocompatibility factor is considered to screen out unsuitable materials.

3.2.7. Osseointegration

Osseointegration is a fundamental requirement in orthopedic which is related to the process of bone healing. The inability of an implant surface to bond with the surrounding bone and tissues, i.e., due to the micro-motions, leads to the formation of a fibrous tissue around the implant and promotes loosening process [35,43].

It should be pointed out that, fatigue strength is not taken into account because fatigue fracture is a very rare complication for femoral component after total knee arthroplasty [44], but it is frequently reported for hip prostheses causing major problems such as implant loosening, stress-shielding and ultimate implant failure [45].

3.3. Candidate material for knee joint

Implants are fabricated from a wide range of materials, including metals, polymers, ceramics, and their composites. Bone, which the joint replaces, is highly strain rate sensitive and fails under sudden loading. These properties are modest in comparison with those of most metals and engineering alloys. Although some polymers are widely used in implant applications, none of them is strong enough to tolerate the severe mechanical condition acting on the femoral component of the knee joint. Some ceramics can combine good biocompatibility and mechanical strength. Also, it has been found that use of alumina ceramic reduces wear of the polyethylene plate [46]. Although, there exist some restrictions to use ceramics in this application such as lack of toughness, and problems regarding fixation of the components in their bony beds [47]. This study considers candidate materials for femoral component of the knee joint implants including both currently used and promising metallic materials. The currently used metals are stainless steel, Co–Cr-based alloys, titanium and titanium alloys. The promising metals are NiTi shape memory alloys (SMA) including dense and porous NiTi. The candidate materials and their compositions are presented in Table 2 while their properties are shown in Table 3.

4. Results and discussion

In this section, first, Table 4 is presented to show the corresponding numbers to the linguistic terms and median value of interval numbers. Calculations of weights using MDL technique are shown in Table 5. Generated different weights by the combination of pair-wise and direct weight (revised Simos' weighting method) through varying λ within 0–1 are demonstrated in Table 6. Then, these weights were used to obtain S, R, Q, and the final

Table 2
List of candidate materials and their compositions [22,48–50].

Material number	Material name	Composition
1	Stainless steel L316 (annealed)	Fe balancing, 17–20% Cr,10–14% Ni, 2–4% Mo, 0.03–0.08% C, 2% Mn and 0.75% Si
2	Stainless steel L316 (cold worked)	
3	Co–Cr alloys (wrought Co–Ni–Cr–Mo)	Co balancing, 19–21% Cr, 9–11% Ni, 14.6–16% W, 0.13% Mo, 0.05–0.15% C, 0.48% Si and maximum 2% Mn & 3% Fe
4	Co–Cr alloys (cast able Co–Cr–Mo)	Co balancing, 27–30% Cr, 2.5% Ni, 5–7% Mo, 0.75% Fe, 0.36% C and maximum 1% Mn & Si
5	Ti alloys (pure Ti)	0.3% Fe, 0.08% C, 0.13% O_2, 0.07% N_2
6	Ti alloys (Ti–6Al–4V)	Ti balancing, 5.5–6.5% Al, 3.5–4.5% V, 0.25% Fe and 0.08% C
7	Ti–6Al–7Nb (IMI-367 wrought)	Ti balancing, 5.50–6.50% Al, ⩽0.080% C, ⩽0.0090% H, ⩽0.25% Fe, 6.50–7.50% Nb, ⩽0.050% N, ⩽0.20% O, ⩽0.50% Ta
8	Ti–6Al–7Nb (protasul-100 hot-forged)	
9	NiTi shape memory alloy	Ni 55.0–56.0%, Ti 43.835–45.0%, C ⩽ 0.050%, Fe ⩽ 0.050%, O ⩽ 0.050%, H ⩽ 0.0050%, other ⩽ 0.010%
10	Porous NiTi shape memory alloy	Ni–49.0 at.% Ti, 16% porosity

Table 3
Properties of candidate materials for material selection of femoral component (the data were collected from [22,48–53]).

Material number	Density (g/cc)	Tensile Strength (MPa)	Modulus of elasticity (GPa)	Elongation (%)	Corrosion resistance	Wear resistance	Osseointegration
1	8	517	200	40	High	Above average	Above average
2	8	862	200	12	High	Very high	Above average
3	9.13	896	240	10–30	Very high	Extremely high	High
4	8.3	655	240	10–30	Very high	Extremely high	High
5	4.5	550	100	54	Exceptionally high	Above average	Very high
6	4.43	985	112	12	Exceptionally high	High	Very high
7	4.52	⩾900	105–120	⩾10	Exceptionally high	High	Very high
8	4.52	1000–1100	110	10–15	Exceptionally high	High	Very high
9	6.50	⩾1240	⩾48	12	Extremely high	Exceptionally high	Average
10	4.3<	1000	15	12	Very high	Exceptionally high	Exceptionally high

Table 4
Decision matrix with quantitative data.

T_j	1.30	1240.00	16.00	54.00	0.96	0.96	0.96
Material number	Density (g/cc)	Tensile Strength (MPa)	Modulus of elasticity (GPa)	Elongation (%)	Corrosion resistance	Wear resistance	Osseointegration
1	8	517	200	40	0.665	0.59	0.59
2	8	862	200	12	0.665	0.745	0.59
3	9.13	896	240	20	0.745	0.865	0.665
4	8.3	655	240	20	0.745	0.865	0.665
5	4.5	550	100	54	0.955	0.59	0.745
6	4.43	985	112	12	0.955	0.665	0.745
7	4.52	900	112.5	10	0.955	0.665	0.745
8	4.52	1050	110	12.5	0.955	0.665	0.745
9	6.5	1240	48	12	0.955	0.955	0.5
10	4.3	1000	15	12	0.745	0.955	0.955

Table 5
Determination of relative importance of criteria using MDL method.

Criteria	Number of possible decisions [$N = n(n-1)/2$]																					Sum	Weight
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21		
Density	1	1	1	1	1	1																6	0.07
Tensile Strength	3						1	2	1	1	1											9	0.11
Modulus of elasticity		3					3					3	1	1	1							12	0.14
Elongation			3					2				1				1	1	1				9	0.11
Corrosion resistance				3					3				3			3			1	2		15	0.18
Wear resistance					3					3				3			3		3		2	17	0.20
Osseointegration						3					3				3			3		2	2	16	0.19

Table 6
Generated different weights for sensitivity analysis.

	Density (g/cc)	Tensile Strength (MPa)	Modulus of elasticity (GPa)	Elongation (%)	Corrosion resistance	Wear resistance	Osseointegration
Weight of pair-wise comparison	0.071	0.107	0.143	0.107	0.179	0.202	0.190
Direct weighting	0.051	0.103	0.128	0.103	0.179	0.256	0.179
$\lambda = 0$	0.051	0.103	0.128	0.103	0.179	0.256	0.179
$\lambda = 0.1$	0.053	0.103	0.130	0.103	0.179	0.251	0.181
$\lambda = 0.2$	0.055	0.103	0.131	0.103	0.179	0.246	0.182
$\lambda = 0.3$	0.057	0.104	0.133	0.104	0.179	0.240	0.183
$\lambda = 0.4$	0.059	0.104	0.134	0.104	0.179	0.235	0.184
$\lambda = 0.5$	0.061	0.105	0.136	0.105	0.179	0.229	0.185
$\lambda = 0.6$	0.063	0.105	0.137	0.105	0.179	0.224	0.186
$\lambda = 0.7$	0.065	0.106	0.138	0.106	0.179	0.219	0.187
$\lambda = 0.8$	0.067	0.106	0.140	0.106	0.179	0.213	0.188
$\lambda = 0.9$	0.069	0.107	0.141	0.107	0.179	0.208	0.189
$\lambda = 1$	0.071	0.107	0.143	0.107	0.179	0.202	0.190

Table 7
S_i, R_i and Q_i for $\lambda = 0.5$.

Material number	Materials' name	S	R	Q
1	SS L316 (annealed)	0.359127	0.072973	0.7402
2	SS L316 (cold worked)	0.348319	0.072973	0.7157
3	Co–Cr alloy (wrought)	0.306252	0.082651	0.8799
4	Co–Cr alloy (castable)	0.318818	0.082651	0.9084
5	Pure Ti	0.214933	0.07015	0.3368
6	Ti–6Al–4V	0.244171	0.064486	0.2512
7	Ti–6Al–7Nb (wrought)	0.252809	0.06628	0.3190
8	Ti–6Al–7Nb (hot-forged)	0.238354	0.064025	0.2256
9	NiTi (SMA)	0.178931	0.06762	0.1871
10	Porous NiTi (SMA)	0.139047	0.064486	0.0124

ranking results. Table 7 shows these parameters for $\lambda = 0.5$. The ranking orders of materials gained by changing λ in Table 8 are graphically shown in Fig. 2. Based on this graph, it may be concluded that, for the material SS L316 (annealed), the rank of the highest frequency of occurrence is 8. In the results of 11 calculations, the rank 8 occurred eight times; therefore, the material SS L316 (annealed) was assigned the rank 8 with 73% confidence. According to the results of evaluation, a decision may be made that the porous NiTi (SMA) is optimal, and the confidence level of evaluation is 100%. Other alternatives were ranked, and the confidence level of the evaluation was determined in a similar way. Thus, the dense NiTi (SMA) was ranked second with the confidence level of 73%; Ti–6Al–7Nb (hot-forged) was ranked third with 73% confidence, and the Ti–6Al–4V was ranked fourth with 64% confidence. The data obtained in the process of decision making and sensitivity analysis allows the authors to state that the rank of Ti–6Al–7Nb (wrought) is five, with 55% confidence, pure Ti is six, with 45% confidence, and so on.

From the ranking results of sensitivity analysis, it is indicated that the first two ranks belong to the promising and the recently developed biomaterials. Porous NiTi (SMA) has highest and the most stable rank among all ranking orders, and bulk NiTi (SMA) predominantly occupies the second rank. This can be supported by considering the superior properties of these materials including

Table 8
Ranking of materials by varying λ.

Materials' name	λ										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
SS L316 (annealed)	10	10	8	8	8	8	8	8	8	8	8
SS L316 (cold worked)	6	7	7	7	7	7	7	7	7	7	7
Co–Cr alloy (wrought)	8	8	9	9	9	9	9	9	9	9	9
Co–Cr alloy (castable)	9	9	10	10	10	10	10	10	10	10	10
Pure Ti	7	6	6	6	6	6	5	4	2	2	2
Ti–6Al–4V	4	4	4	4	4	4	4	5	5	5	5
Ti–6Al–7Nb (wrought)	5	5	5	5	5	5	6	6	6	6	6
Ti–6Al–7Nb (hot-forged)	3	3	3	3	3	3	3	3	4	4	4
NiTi (SMA)	2	2	2	2	2	2	2	2	3	3	3
Porous NiTi (SMA)	1	1	1	1	1	1	1	1	1	1	1

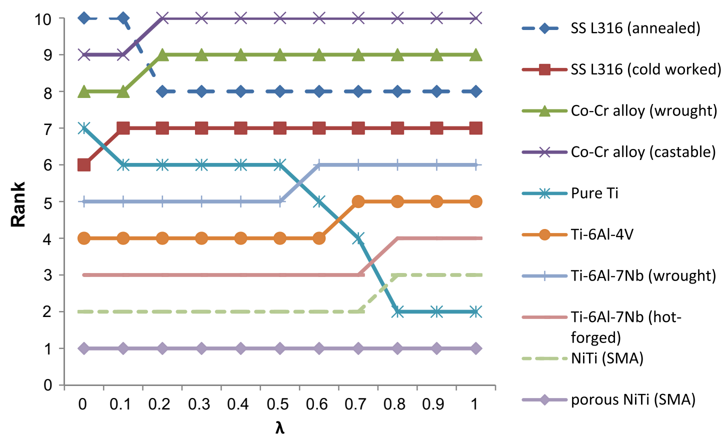

Fig. 2. Stability of materials ranks in different values of λ.

high strength, unique fatigue resistance, good ductility, relatively low modulus, high dampening capacity [35,54], large strain recovery, high wear resistance even more than Co–Cr–Mo alloy, and enhanced biocompatibility [55–58]. Moreover, in the case of porous NiTi, interconnected open pores and large surface area enable transport of body fluids and help to accelerate the healing process. This allows tissue and bone cells to penetrate and integrate with the implant and provides strong anchor between surrounding bone and tissue with the prosthesis. It also promotes long-term fixation, and prevents loosening of implants [35,59–61]. Porous NiTi also shows better osteoconductivity and osteointegration [61], and greater specific damping capacity under dynamic loading in comparison with dense SMAs [62]. Porous NiTi has good biocompatibility, similar to conventional porous stainless steel and titanium implant materials [63]. Furthermore, super-elastic behavior remains after tissue in-growth [64] and shape-recovery behavior can provide good mechanical stability within the host tissue [65]. Moreover, it has been found that an appropriate range of pore sizes and interconnectivity provide the morphology similar to that of bone [60]. Properties of porous NiTi make it suitable for the hard-tissue implants of heavy load-bearing applications [66].

The obtained ranks illustrated that the Ti-based materials are in the higher ranks than stainless steel and Co–Cr-based alloys. This result can be supported by the research work of Geetha et al. [35] who introduced Ti-based materials as the ultimate choice for orthopedic implants. Considering only one criterion like wear resistance, Co–Cr alloys can be ranked highest in the currently used materials. However, the problem of stress-shielding effect still remains which has been determined as a main reason causing bone resorption phenomenon.

From the process of this case study, two main intriguing points can be highlighted as follows. First it should be noted that in the selection of implant materials it is crucial to consider multi-criteria rather than a single criterion. Second, the ranking order might reveal the need for more investigation on new or high potential biomaterials, and treatment of those characteristics in the existing biomaterials that result in better performance of implant. For example, in the case of porous NiTi, the focus should be more on improvement of the corrosion resistance since the Ni release is unavoidable due to the large exposed surface area that directly contacts with adjacent bone and tissue.

5. Conclusions

Comprehensive VIKOR approach was efficiently used to rank the considered candidate materials for femoral component of TKR, and the sensitivity analysis of weights were performed to achieve more reliable results. From this study, the following facts could be concluded:

- Porous NiTi has the highest and most stable rank among the alternatives, followed by dense NiTi which both are new in orthopedic applications. Although the practical use of these materials as femoral component might need more research on surface modification accompanied with tests on animals.
- The data obtained in the process of sensitivity analysis of weights allows designers to announce the rank of materials with a confidence level.
- Results of this paper will provide a systematic procedure for competition of new biomaterials for femoral component of TKR. However, one limitation of this study is that the processability of the considered biomaterials has not been taken into account.

A further research could assess the optimal materials for other parts of knee prosthesis like tibial tray. However, it should be noted that different requirements and target values must be considered in different applications because the material properties are site-specific in human body. This paper should be of value to both scholars who work on biomedical implantation as well as researchers who are interested in the state of the art techniques in material selection.

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