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ARTICLE

Graph Theory and Matrix Approach (GTMA) Model for the Selection of the Femoral-Component of Total Knee Joint Replacement

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ABSTRACT

Total Knee Replacement (TKR) is the increasing trend now a day, in revision surgery which is associated with aseptic loosening, which is a challenging research for the TKR component. The selection of optimal material loosening can be controlled at some limits. This paper is going to consider the best material selected among a number of alternative materials for the femoral component (FC) by using Graph Theory. Here GTMA process used for optimization of material and a systematic technique introduced through sensitivity analysis to find out the more reliable result. Obtained ranking suggests the use of optimized material over the other existing material. By following GTMA Co_Cr-alloys (wrought-Co-Ni-Cr-Mo) and Co_Cr-alloys (cast-able-Co-Cr-Mo)are on the 1st and 2nd position respectively.

1. Introduction

Due to the biological and mechanical requirements, major problems for orthopedic biomaterials are their development/design and selection for particular application. Among existing applications of orthopedic biomaterials, total knee replacement (TKR) is a challenging and debating one because of simultaneous replacement and revision surgical procedure. The major severe responsible factors (for TKR revision surgery) are the aseptic loosening and tissue growth at interface of implanted region. The risk of implant loosening and wear debris can be minimized while choosing the optimized material for femoral part of the implant or femoral-component (FC) or tibial insert. Stress shielding (Young's Modulus) mostly depend upon the material which is directly attached or interfacing the bone like femoral-component (FC) on the upper side and tibial try on the lower side. By taking under consideration this issue given design geometry of knee prosthesis, optimal and best material for the femoral part plays an important role in the aseptic loosening of prosthetic joint [1-4].

Recent days many materials are accessible which might be useful for knee joint femoral-component (FC) usage. However there are some limitations to select the material for this component, to resolve this critical problem there should be a proper tool for the selection of femoral-component (FC). To solve this critical problem there should be a proper tool for the selection of material. Usually a new material or replacement of a material with another material having better working characteristics, applied after testing and error methods or after getting experience from already done experiments. Whereas it can be han-

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dled by using Multiple Criteria Decision Making (MCDM) model, misuse of material having heavy cost. MCDM is the basics of selection, grouping, prioritizing, sorting and helpful during the whole assessment of material selection process. For the selection of material not only biological, chemical, physical, electrical, mechanical and manufacturing characteristics necessary but also the knowledge of MCDM. However, the method of MCDM used widely for the material selection in engineering design and somehow in the biological engineering which is growing simultaneously [5-10].

In this paper there is discussion about a method to select a femoral-component (FC) for TKR. This method having 11 scale point, totally based upon MCDM, its compressive name GTMA (Graph Theory with Matrix Approach) which is used for the betterment of durability and quality of human life by selecting an appropriate material for the femoral-component (FC) of knee joint aseptic.

2. GTMA Theoretical Explanation

2.1 Graphical Illustration of Properties

For the illustration of graph there are two main components i.e. "anchor points" and "path" associated with them. One anchor point defines a specific property of material and path associated with this point defines its relationship with other properties. Number of anchor points always depends upon the number of properties on the basis of which a material is going to be selected. If a property 'p' has relative importance on the other property 'q' then there will be an arrow head on path indicating relative importance of 'p' upon 'q'.

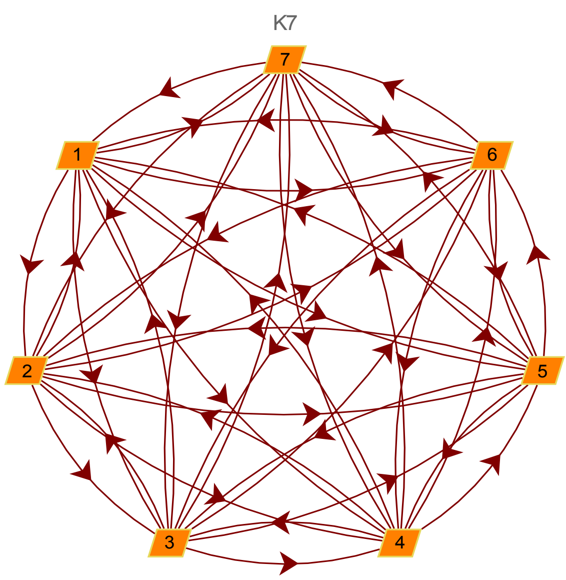

Figure 1. General Graphical Illustration

Similarly if property 'q' has a relative importance on other property 'p' then the direction of path of relative importance will be from 'q' to 'p'. To explain this graph in a better way, let's take an example of material selection for TKR. There should be some properties depending upon which a material will be selected i.e.

P1, P2, P3... P7. Here seven properties are considered so there will be seven anchor points respectively for each property. Path of relative importance will be in both directions because, if a property 'p' has relative importance upon 'q' then then there will be a relative importance of 'q' upon 'p' which is similar for the relative importance between all other properties. Graphical illustration is quick view of properties and their relative importance upon each other. If there are more anchor points or more number of properties then there will be a complex graphical illustration, therefore matrix illustration will be used to avoid this situation.

2.2 Matrix Illustration

Whenever a graph becomes more complex then matrix illustration is more helpful. Size of matrix depends upon number of anchor points. If there are N numbers of properties important for the material selection then the size of matrix will be NxN. Therefore it will be always a square matrix.

$$\begin{bmatrix} Properties & P1 & P2 & P3 & P4 & P5 & P6 & P7 \\ P1 & R1 & r_{12} & r_{13} & r_{14} & r_{15} & r_{16} & r_{17} \\ P2 & r_{21} & R2 & r_{23} & r_{24} & r_{25} & r_{26} & r_{27} \\ P3 & r_{31} & r_{32} & R3 & r_{34} & r_{35} & r_{36} & r_{37} \\ P4 & r_{41} & r_{42} & r_{43} & R4 & r_{45} & r_{46} & r_{47} \\ P5 & r_{51} & r_{52} & r_{53} & r_{54} & R5 & r_{56} & r_{57} \\ P6 & r_{61} & r_{62} & r_{63} & r_{64} & r_{65} & R6 & r_{67} \\ P7 & r_{71} & r_{72} & r_{73} & r_{74} & r_{75} & r_{76} & R7 \end{bmatrix}$$

It always depends upon the numeric values of properties (R_p) and their relative importance (r_{pq}). Here Rp is the value of property 'p' and r_{pq} is the relative importance of 'p' upon 'q'. Permanent of matrix 'Z' symbolically i.e. per (Z) is also known as material selection properties function. While using this permanent there is no minus sign used, so there will no any part disappear [11-13]. Permanent of matrix is actually its determinant but taking all terms positive. Its mathematical expression is as follows.

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$$
\begin{aligned}
&\prod_{i=1}^{N} Ri \\
&+\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \ldots \\
&\times \sum_{N=t+1}^{N} (r_{ij}r_{ji}) R_k R_l R_m R_n R_o \ldots R_t R_N \\
&+\sum_{i=1}^{N-2}\sum_{j=i+1}^{N-1}\sum_{k=j+1}^{N} \ldots \times \sum_{N=t+1}^{N} (r_{ij}r_{jk}r_{ki} + r_{ik}r_{kj}r_{ji}) \times R_k R_l R_m R_n R_o \ldots R_t R_N \\
&+\left(\sum_{i=1}^{N-3}\sum_{j=i+1}^{N}\sum_{k=i+1}^{N-1}\sum_{l=i+2}^{N} \ldots \times \sum_{N=t+1}^{N} (r_{ij}r_{jk}r_{kl}r_{li} + r_{il}r_{lk}r_{kj}r_{ji}) \times R_k R_l R_m R_n R_o \ldots R_t R_N\right) \\
&+\left(\sum_{i=1}^{N-2}\sum_{j=i+1}^{N-1}\sum_{k=j+1}^{N}\sum_{l=1}^{N-1}\sum_{m=l+1}^{N} \ldots \sum_{N=t+1}^{N} (r_{ij}r_{jk}r_{ki} + r_{ik}r_{kj}r_{ji})(r_{lm}r_{ml}) \times R_n R_o \ldots R_t R_N\right. \\
&\left.+\sum_{i=1}^{N-4}\sum_{j=i+1}^{N-1}\sum_{k=i+1}^{N}\sum_{l=i+1}^{N}\sum_{m=j+1}^{N} \ldots \times \sum_{N=t+1}^{N} (r_{ij}r_{jk}r_{kl}r_{lm}r_{li} + r_{im}r_{ml}r_{lk}r_{kj}r_{ji}) \times R_n R_o \ldots R_t R_N\right) \\
&+\left(\sum_{i=1}^{N-3}\sum_{j=i+1}^{N-1}\sum_{k=j+1}^{N}\sum_{l=j+1}^{N}\sum_{m=1}^{N-1}\sum_{n=m+1}^{N} \ldots \times \sum_{N=t+1}^{N} (r_{ij}r_{jk}r_{kl}r_{li} + r_{il}r_{lk}r_{kj}r_{ji})(r_{mn}r_{nm})\right. \\
&\times R_o \ldots R_t R_N + \sum_{i=l}^{N-5}\sum_{j=i+1}^{N-1}\sum_{k=j+1}^{N}\sum_{l=1}^{N-2}\sum_{m=l+1}^{N-1}\sum_{n=m+1}^{N} \ldots \sum_{N=t+1}^{N} (r_{ij}r_{jk}r_{ki} + r_{ik}r_{kj}r_{ji})(r_{lm}r_{mn}r_{nl} \\
&+ r_{ln}r_{nm}r_{ml}) \times R_o \ldots R_t R_N \\
&+\sum_{i=1}^{N-5}\sum_{j=i+1}^{N}\sum_{k=i+1}^{N-3}\sum_{l=i+2}^{N}\sum_{m=k+1}^{N-1}\sum_{n=k+2}^{N} \ldots \sum_{N=t+1}^{N} (r_{ij}r_{ji})(r_{kl}r_{lk})(r_{mn}r_{nm}) R_o \ldots R_t R_N \\
&+\sum_{i=1}^{N-5}\sum_{j=i+1}^{N-1}\sum_{k=i+1}^{N}\sum_{l=i+1}^{N}\sum_{m=i+1}^{N}\sum_{n=j+1}^{N} \ldots\ldots \sum_{N=t+1}^{N} (r_{ij}r_{jk}r_{kl}r_{lm}r_{mn}r_{nl} + r_{ln}r_{nm}r_{ml}r_{lk}r_{kj}r_{ji}) \\
&\left.\times R_o \ldots R_t R_N\right) + \cdots
\end{aligned}
$$

For the calculation of permanent of matrix there is a programmed developed in computer by using C++ language to calculate suitability index.

3. Suitability Index for the Material

Material suitability index is actually a numeric measurement of a material to check in which extent this material can be selected. In the equation given above there is a material selection property function which contains measurement of properties and their correlations which is essential for the Material suitability index. Numeric value of material selection property function is known as the material suitability index. Such as material selection property function has only positive terms so that the highest value of Rp and their relative importance r_{pq} results greater value of material suitability index, to find out this index numeric values of Rp can be obtained from the data available. After obtaining these values there normalized values calculated corresponding to each property. To solve vp/vq here vp is the value of property 'p' and vq is the value of property q which is greater than vp. This ratio is suitable for most obligatory property. Here most obligatory property means its higher values are beneficial for selected material, whereas least obligatory properties are those which are beneficial while having low numeric values. There relative normal values can be calculated by vq/vp, in this situation the value of vq is less than that of vp as well as from all other properties.

If there is no numeric values are available for some properties then there values can be adopted by fuzzy conversion scale. By using fuzzy set theory first of all find property Rp find in linguistic terms and then into fuzzy numbers. Chang & Hawng [14] discovered a numerical approximation system in which a linguistic term automatically converted into numeric value. It consists of eight conversion scale, whereas in present work eleven point scales is used as given in the table below.

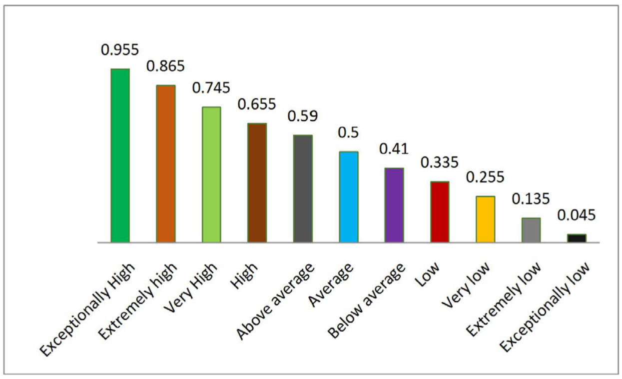

Figure 2. Eleven Point Scale for Correlation

Material suitability index evaluated for the different available choices by using the equation given above and by substituting the values of Rp and relative importance r_{pq}. Material having greater suitability index will be the best choice for utilization.

4. Evaluation of Femoral-component (FC) for TKR

Stage 1

At first stage to find out the properties upon which selection of femoral-component (FC) for TKR dependent as well as enlist the available choices of materials which are suitable for the femoral-component (FC) of TKR, which satisfied all the requirements of knee joint aseptic. There are some properties depending upon which we are going to select a material for femoral-component(FC) i.e. Tensile Strength(TS MPa), Density ($\rho g/cc$) , Elasticity Modulus (EM GPa), Elongation (%), Wear Resistance(WR), Corrosion Resistance (CR), Osseointegration.

There are some limitations for every selected property either qualitatively or quantitatively which will be suitable for the femoral-component (FC). Here are the listed material and their properties for femoral-component (FC).

Stage 2

After shortlisting find out the material relative importance relation among properties and normalize the values according to most and least obligatory properties.

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Table 1. Selected materials and their Compositions for the femoral-component(FC) [9,15-20]

Material Number	Material name	Material Composition	TS (Mpa)	EM (Gpa)	Density (g/cc)	Elongation (%)	WR	CR	Osseointegration
1	**Ni_Ti shape-memory-alloy**	Titanium 43.835-45.0%,Nickle 55.0-56.0%, Hydrogen≤ 6 0.0050%,Carbon ≤ 6 0.050%,Oxyegen≤ 6 0.050%, iron≤ 6 0.050%, other≤ 6 0.010%	1240	48	6.5	12	0.955	0.955	0.5
2	**Porous-Ni_Ti-shape-memory-alloy**	Titanium, 16%-porosity-Nickle-49.0	1000	15	4.3	12	0.955	0.745	0.955
3	**6Al-Ti-7Nb-(protasul-100 hot_forged)**		1000-1100	110	4.52	10—15	0.665	0.955	0.745
4	**6Al-Ti-7Nb (IMI_367_ wrought)**	Titanium balancing, 5.50-6.50% Aluminum, 60.080% Nb, 60.050%Carbon, 60.0090% Hydrogen, 60.25% Nitrogen,60.20% Oxygen,60.50%Ta	900	105-120	4.52	10	0.665	0.955	0.745
5	**stainless_steel_ L316 (annealed)**	Fe-balancing,17-20% Molybdenum, 0.03-0.08% Cromium,10-14% Ni, 2-4% Carbon,2% Mn and 0.75% Silicon	517	200	8	40	0.59	0.665	0.59
6	**stainless_steel_ L316_(cold-worked)**		862	200	8	12	0.745	0.665	0.59
7	**Co_Cr-alloys (wrought-Co-Ni-Cr-Mo)**	Cobalt-balancing, 19-21% Chromium, 9-11% Nickel, 14.6-16% W, 0.13% Molybdenum, 0.05-0.15% Carbon, 0.48% Silicon & maximum-2%-Mn-and-3% Fe	896	240	9.13	10 --30	0.865	0.745	0.665
8	**Co_Cr-alloys (cast-able-Co-Cr-Mo)**	Cobalt-balancing, 27-30% Chromium, 2.5% Molybdenum, 0.75% _Ni, 5-7% Fe, 0.36% Carbon &_ maximum_1% Mn-and-Silicon	655	240	8.3	10 -30	0.865	0.745	0.665
9	**Ti_alloys (pure Titanium)**	0.3%_Fe, 0.08%_ Carbon,0.13%_O2, 0.07%_N2	550	100	4.5	54	0.59	0.955	0.745
10	**Ti_alloys(6Al-Ti-4V)**	Titanium-balancing, 5.5-6.5% Aluminum, 3.5-4.5% V,0.25% Fe & 0.08%_C	985	112	4.43	12	0.665	0.955	0.745

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Table 2. Normalized Data for the femoral-component (FC)

Material Number	TS (Mpa)	EM (Gpa)	Density (g/cc)	Elongation (%)	WR	CR	Osseointegration
1	1	0.2	0.711938663	0.222222	1	0.696335	0.523560209
2	0.80645	0.0625	0.470974808	0.222222	1	0.892617	1
3	0.846774	0.45833333	0.495071193	0.23148	0.696335	0.696335	0.780104712
4	0.725806	0.46875	0.495071193	0.185185185	0.696335	0.696335	0.780104712
5	0.416935483	0.83333	0.876232201	0.740740741	0.617801	1	0.617801047
6	0.69516129	0.8333	0.876232201	0.222222	0.780105	1	0.617801047
7	0.72258	1	1	0.37037037	0.905759	0.892617	0.696335078
8	0.528225806	1	0.909090909	0.37037037	0.905759	0.892617	0.696335078
9	0.443548	0.4166666	0.492880613	1	0.617801	0.696335	0.780104712
10	0.794354838	0.46666666	0.485213581	0.222222	0.696335	0.696335	0.780104712

Only corrosion resistance (CR) considered as low obligatory property. Here are the normalized values.

Stage 3

Graphical illustration is one of most important stages. At this stage a graph is constructed by making the number of anchor points equal to the number of properties as well as their path represents their relative importance on each other and indicate their direction. As shown in the figure below.

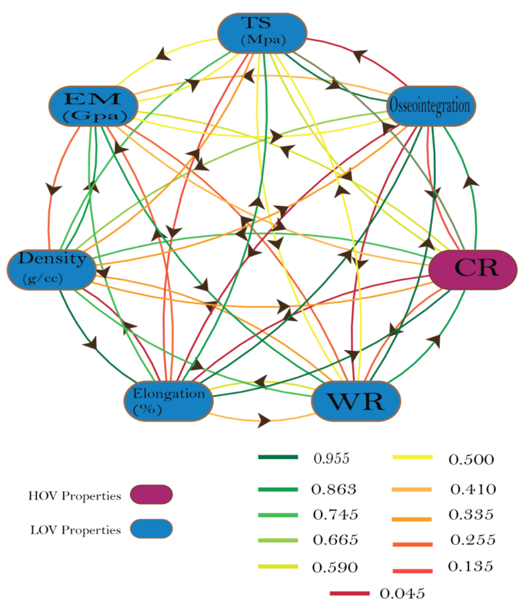

Figure 3. Graphical Illustration for femoral-component(FC)

Stage 4

Develop a material selection matrix for femoral-component(FC) selection property function. This is a NxN square matrix having diagonal elements Rp and off diagonal elements r_{pq} relative importance. Matrix constructed for femoral-component(FC) is given below

Stage 5

Femoral-component (FC) selection properties function for the matrix and substitute the values of R_p and r_{pq} from step 1 and 2. Then evaluation for the suitability index starts which indicate the best material for femoral-component (FC).

Final Stage

In the last stage final decision will be taken by considering practical applications and experience. All possible limitations which can be faced by the user including management, availability, economic, political and environmental limitations etc. should be considered. However any type of compromise should be in the favor of higher ranked material.

5. Result Analysis

There are main three reasons on the basis of which any of biomaterial or any other material can be analyze, which are mechanical properties (Wear Resistance, Tensile

Table 3. Matrix representation of femoral-component(FC)

Properties	TS (Mpa)	EM (Gpa)	Density (g/cc)	Elongation (%)	WR	CR	Osseointegration
TS (Mpa)	**R1**	0.458904996	0.711480576	0.157084	0.453022	0.586972	0.97879599
EM (Gpa)	0.541095004	**R2**	0.175992805	0.740687	0.825205	0.422786	0.55075545
Density (g/cc)	0.288519424	0.824007195	**R3**	0.928984	0.73852	0.276162	0.354540174
Elongation (%)	0.842915681	0.25931314	0.071016208	**R4**	0.39153	0.9708	0.93817
WR	0.546978214	0.174795	0.261479681	0.60847	**R5**	0.78421	0.981036
CR	0.413028266	0.5772145	0.723838009	0.0292	0.21579	**R6**	0.875204
Osseointegration	0.02120401	0.44924455	0.645459826	0.06183	0.018964	0.124796	**R7**

Table 4. Suitability Index for the femoral-component (FC)

Material Number	Material name	Detailed Material Composition	suitability index value	Ranking
1	**Ni_Ti shape-memory-alloy**	Titanium 43.835-45.0%,Nickle 55.0-56.0%, Hydrogen≤ 6 0.0050%,Carbon ≤ 6 0.050%,Oxyegen≤ 6 0.050%, iron≤ 6 0.050%, other≤ 6 0.010%	41.7415	7th
2	**Porous-Ni_Ti-shape-memory-alloy**	Titanium, 16%-porosity-Nickle-49.0	44.518	5th
3	**6Al-Ti-7Nb-(protasul-100 hot_forged)**		41.0224	8th
4	**6Al-Ti-7Nb (IMI_367_ wrought)**	Titanium balancing, 5.50-6.50% Aluminum, 60.080% Nb, 60.050%Carbon, 60.0090% Hydrogen, 60.25% Nitrogen,60.20% Oxygen,60.50%Ta	39.0831	10th
5	**stainless_steel_L316 (annealed)**	Fe-balancing,17-20% Molybdenum, 0.03-0.08% Cromium,10-14% Ni, 2-4% Carbon,2% Mn and 0.75% Silicon	49.505	3rd
6	**stainless_steel_L316_(cold-worked)**		48.5273	4th
7	**Co_Cr-alloys (wrought-Co-Ni-Cr-Mo)**	Cobalt-balancing, 19-21% Chromium, 9-11% Nickel, 14.6-16% W, 0.13% Molybdenum, 0.05-0.15% Carbon, 0.48% Silicon & maximum-2%-Mn-and-3% Fe	**56.644**	**1st**
8	**Co_Cr-alloys (cast-able-Co-Cr-Mo)**	Cobalt-balancing, 27-30% Chromium, 2.5% Molybdenum, 0.75% _Ni, 5-7% Fe, 0.36% Carbon &_ maximum_1% Mn-and-Silicon	52.2292	2nd
9	**Ti_alloys (pure Titanium)**	0.3%_Fe, 0.08%_Carbon,0.13%_O2, 0.07%_N2	43.7334	6th
10	**Ti_alloys(6Al-Ti-4V)**	Titanium-balancing, 5.5-6.5% Aluminum, 3.5-4.5% V,0.25% Fe & 0.08%_C	40.2823	9th

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Strength…etc.) chemical properties (Corrosion resistance) and biocompatibility with bones as well as with tissues. According to ranking results cobalt alloys (Co-Cr-Mo) are on the high rank whereas Titanium based alloys comes on 2nd number. Although titanium alloys are used rare than Co-Cr-Mo alloys just because of their less wear resistance.[21] cobalt alloys which are based on Co-Cr-Mo system are used widely for femoral-component(FC) for TKR as well as THR (total hip replacement) due to its mechanical properties, good wear resistance, corrosion resistance and biocompatibility [22-25].

5.1 Sensitivity Analysis

This is a method which is used to validate the MADM method. Basic reason to use this analysis is to analyze the variations of properties which affect the ranking. It will increase the effectiveness of material selections outcomes. The present work deals GTMA to select a material for femoral-component (FC) of TKR. In this section will investigate flexibility, efficiency and consistency of ranked material by normalizing with new method in GTMA

Sum based linear normalization is as follows

Table 5. Normalized data for sensitivity analysis

Material Number	TS (Mpa)	EM (Gpa)	Density (g/cc)	Elongation (%)	WR	CR	Osseointegration
1	0.143269786	0.034845735	0.104501607	0.078947368	0.126323	11.19463	0.07199424
2	0.11554015	0.010889292	0.069131832	0.078947368	0.126323	8.732984	0.137508999
3	0.121317157	0.079854809	0.07266881	0.082236884	0.087963	11.19463	0.107271418
4	0.103986135	0.081669691	0.07266881	0.065789473	0.087963	11.19463	0.107271418
5	0.059734257	0.145190562	0.128617363	0.263157894	0.078042	12.54135	0.084953203
6	0.099595609	0.145190562	0.128617363	0.078947368	0.098545	12.54135	0.084953203
7	0.103523974	0.174228675	0.146784565	0.131578947	0.114418	8.732984	0.095752339
8	0.075678798	0.174228675	0.133440514	0.131578947	0.114418	8.732984	0.095752339
9	0.063547082	0.072595281	0.072347266	0.355263157	0.078042	11.19463	0.107271418
10	0.113807047	0.081306715	0.071221864	0.078947368	0.087963	11.19463	0.107271418

Table 6. Comparison of Ranking in GTMA data

Material Number	Material name	GTMA	Modified GTMA
1	**Ni_Ti shape-memory-alloy**	41.7415	66.4053
2	**Porous-Ni_Ti-shape-memory-alloy**	44.518	54.8321
3	**6Al-Ti-7Nb-(protasul-100 hot_forged)**	41.0224	66.2351
4	**6Al-Ti-7Nb (IMI_367_ wrought)**	39.0831	65.5357
5	**stainless_steel_L316 (annealed)**	49.505	76.6503
6	**stainless_steel_L316_(cold-worked)**	48.5273	73.7897
7	**Co_Cr-alloys (wrought-Co-Ni-Cr-Mo)**	56.644	57.9048
8	**Co_Cr-alloys (cast-able-Co-Cr-Mo)**	52.2292	57.2048
9	**Ti_alloys (pure Titanium)**	43.7334	70.394
10	**Ti_alloys(6Al-Ti-4V)**	40.2823	66.0071

For HOV Properties: $N_{pq} = \frac{r_{pq}}{\sum r_{pq}}$

For LOV Properties: $N_{pq} = \frac{1/r_{pq}}{\sum 1/r_{pq}}$

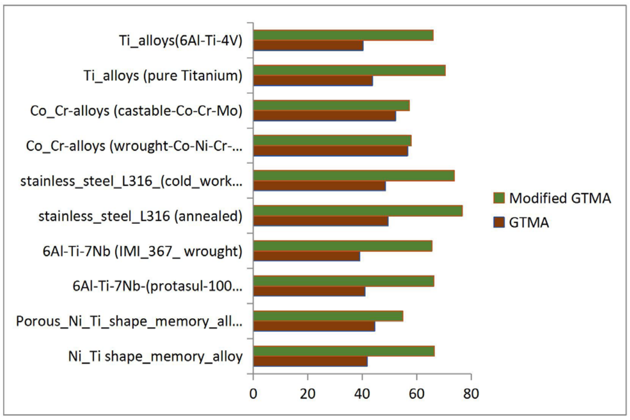

Figure 4. Correlation of Ranks between GTMA and modified GTMA

6. Conclusions

It is a general method which depends upon graphical illustration as well as matrix approach which helps to select a suitable material for femoral-component (FC) when a number of choices are available. In this method generally considered different properties and their correlation and then find out the suitability index and rank of the materials. It is useful for any type of quantitative and qualitative materials respectively and offers more objectives.

In further research the other parts of knee prosthesis can be optimized such as tibial try. By keeping in mind different requirements and target values for the different applications there should be different properties considered according to the problem. This paper is very help full for the researchers as well as the persons working in medical implantations.

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