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# Effect of Coating Materials on the Fatigue Behavior of Hip Implants: A Three-dimensional Finite Element Analysis

**Ayham Darwich [1,2], Hasan Nazha [2], Monzer Daoud [3]**

[1] Faculty of Biomedical Engineering, Al-Andalus University for Medical Sciences, Tartous, Syria, Email: a.darwich@au.edu.sy

[2] Faculty of Technical Engineering, University of Tartous, Tartous, Syria, Email: hasannazha@tartous-univ.edu.sy

[3] Department of Mechanical Engineering, École de Technologie Supérieure (ÉTS), Montreal, Canada, Email: monzerdaoud@hotmail.com

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Corresponding author: Hasan Nazha (hasannazha@tartous-univ.edu.sy)


**Abstract.** This study aims to validate, using finite element analysis (FEA), the design concept by comparing the fatigue behavior of hip implant stems coated with composite (carbon/PEEK) and polymeric (PEEK) coating materials corresponding to different human activities: standing up, normal walking and climbing stairs under dynamic loadings to find out which of all these models have a better performance in the prosthesis-bone systems. A 3D finite element models of hip implants, femur, coating layers with polymeric (PEEK) and composite (carbon/PEEK) coating materials are created for FEA. The cyclic loads are applied on the prosthesis head. Fatigue life durations are calculated based on the Goodman mean-stress fatigue theory. The fatigue safety factor for the coated implant is increased more than 12.73% at least compared to the uncoated implant. The carbon/PEEK composite material with 0, +45, -45, and 90 degrees fiber orientation (configuration I) has the highest fatigue life and fatigue safety factor. The numerical result show that the carbon/PEEK composite material (configuration I) seems to be a good solution to increase the values of fatigue safety factor of coating layers due to highest fatigue life and fatigue safety factor. It distributes the applied load and transfers it to the bone, reducing stress-shielding effects and prolong the bone-prosthesis system life span.

**Keywords**: Hip implants; Coatings; PEEK; Carbon/PEEK; Fatigue behavior; Finite element analysis.

## 1. Introduction

Total hip arthroplasty is considered as the most successful orthopedic procedures. Hip replacement is the most useful treatment option for rheumatoid arthritis of the hip joint that enables the patients to recover pain-free mobility [1, 2]. That is the reason why the hip replacement attracted the interest of many specialists during the last decades.

Hip implants are designed to last for twenty years at least; however, their life span might be decreased by several problems causing fatigue failure. The most important reasons are dislocations of the ball in the liner or bone cement not connecting to the hip stem [3, 4]. The other factors are differences in physical properties of the implant and the body, deterioration, design failure, biocompatibility and surgical procedures. If the shape or material of a stem implies high stresses in fixation areas, cracking in the short term or fatigue failure in the long term is quite probable to happen [5]. The forces applied to the prosthesis during different human activity produce dynamic stresses varying in time and may result in fatigue failure of an implant; hence, it is important to ensure that hip prostheses resist fatigue failure.

The design of hip implant prosthesis affects the osseointegration of implants [6]. Numerous methods are utilized to achieve osseointegration including implant surface treatments such as plasma spraying, acid etching, sand blasting, hydroxyapatite coating, and plasma treatment [7-11]. However, Hydroxyapatite and porous coatings are at present the most ordinarily utilized treatments [12]. Applying a coating layer intends to obtain the effective osseointegration with a vital bone-implant contact [13]. It likewise enhances the stress distribution on the femur head, which would decrease the failure occurrence of hip implants [14].

Modern composites seem to be promising for prosthesis applications on account of their high degree of biocompatibility with respect to strength and stiffness. The fiber orientation plays an important role in the mechanical properties of the composite materials, where the change in its orientation induces a change in tensile strength, shear and elastic modulus of the composites [15].

Some researches concentrated on the strength and stability of composite materials in hip replacement applications. Kaddick et al. [16] used finite-element analysis to investigate static failure loads and critical stresses of an anatomically shaped carbon fiber reinforced epoxy hip stems. They have reported that higher strains are produced inside the flexible implants compared with those inside stiffer devices at equal loads. They have reported also that more flexible implants demand superior fatigue properties to avoid stem fatigue fractures. Kayabasi and Ekici [17] studied, by finite element method, the effects of static, dynamic and fatigue behavior on three-dimensional shape optimization of titanium and cobalt-chromium alloy hip prosthesis with PMMA cement corresponding to normal walking condition. They found that stem designs predicted to be safe against failure under static loading, but failure could happen under dynamic repeated loadings.

Stolk et al. [18] developed a finite element algorithm to simulate damage accumulation in acrylic bone cement in a total hip arthroplasty (THA) reconstruction under dynamic loading conditions (normal walking), using an anisotropic continuum damage mechanics (CDM) approach. They found that debonded titanium alloy stems have lower lifetime than the bonded titanium alloy stems. Han et al. [19] studied the carbon/PEEK composite properties and their applications. It has been shown that the carbon/PEEK properties are very close to those of the human bones, especially density, strength and Young’s modulus. This is in agreement with what Fujihara et al. [20], reported in their review on using composite materials in orthopedic applications.

Returning to the concept of the fatigue behavior, Colombi [21] performed a fatigue analysis and a damage evaluation simulation with sensitivity analysis of acrylic cemented titanium alloy stems using a quasi-3D finite element model under normal walking conditions. Numerical results showed a significant fatigue sensitivity to variations of the cement Young's modulus and stems-cement friction coefficient and a moderate fatigue sensitivity to the stem Young's modulus. Therefore, hip stems fatigue behavior is a serious concern.

In literature, fatigue behavior has been analyzed for noncemented prosthesis, cemented prosthesis with hydroxyapatite (HA) material, cemented prosthesis with PMMA material and carbon fibre-reinforced epoxy prosthesis. To our knowledge, this is the first investigation that underlines the effect of hip implant stems coated with PEEK polymeric material and carbon/PEEK composite material on the fatigue behavior. Therefore, the aim of this study is to validate, using the 3D finite element method, the design concept by comparing the fatigue behavior of prosthesis component materials (hip implant stems + coating layers) corresponding to different human activities: normal walking, standing up and climbing stairs under dynamic loadings to find out the model that has a better performance in the bone-prosthesis system. The finite element (FE) analysis provides preliminary validation of the proposed hip implant design concept.

## 2. Materials and Methods

### 2.1. Finite element model

Computerized tomography (CT) scans were taken along the femur and exported in SolidWorks® software, where the in-plane resolution was 0.71 × 0.71 mm and slice thickness of 0.5 mm. The femur model was modified and the hip implants were also established using the same software with dimensions as shown in Fig. 1, where the neck angle are 120°.

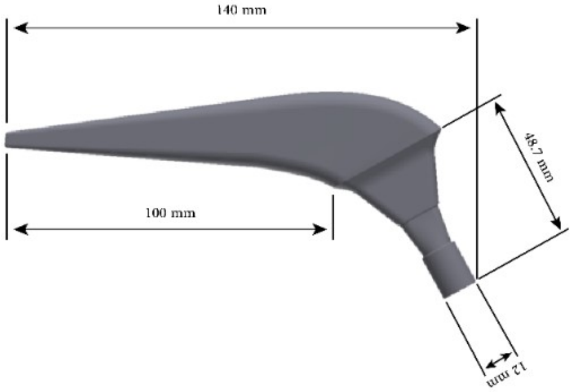


**Fig. 1.** Dimensions of hip implant stem used in this study.

The coated and uncoated implant models used in this study are shown in Fig. 2. All contacts interfaces between coating layer-implant stem, and bone-coating layer are defined as bonded [22]. The contact of bone implant interface (uncoated condition) is defined as frictional with a friction coefficient 0.2 [23].


**Fig. 2.** CAD models: (a) coated hip implant and (b) uncoated hip implant.

Figure 3 shows the coating layer assumed to be uniformly distributed along the surface of the implant stem, where 2 mm thick of coating layer is analyzed and compared to the uncoated implant. Models of the stem, the coating layer and the femur are exported to ANSYS and assembled into an individual finite element (FE) model. Fatigue calculations are based on the Goodman mean-stress fatigue theory. Equations (1) and (2) define the mean stress $\sigma_m$ and the alternating stress $\sigma_a$ magnitudes respectively as:

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \tag{1}$$

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2} \tag{2}$$

Equation (3) shows the relation between mean and alternation stress according to the modified Goodman theory as:

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_u} = \frac{1}{N_f} \tag{3}$$

where $S_e$ is the endurance limit and $S_u$ is the ultimate tensile strength of the material [24]. The fatigue safety factor, $N_f$, is given by:

$$N_f = \frac{1}{\dfrac{\sigma_a}{S_e} + \dfrac{\sigma_m}{S_u}} \tag{4}$$

Tetrahedron elements are used in the finite element analysis. The mesh is refined and accepted when the relative errors are less than 1%. The results of convergence analysis are shown in Figure 3.

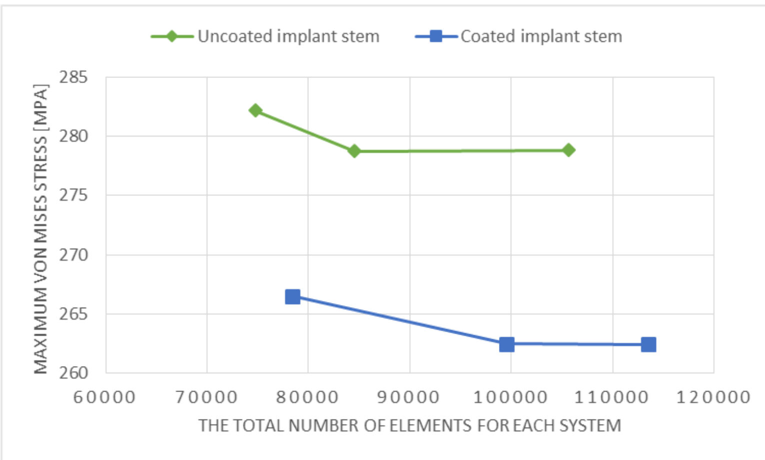


**Fig. 3.** Mesh sensitivity results in terms of the maximum von Mises stress.

### 2.2. Boundary conditions

The cyclic loads are applied on the prosthesis head, where a clinically proven implant with a ceramic head that articulated with a press-fit cup with cross-linked UHMWPE-Inlay is adjusted to measure the forces acting on the hip implant head. The electronics are coated by welding, where it is powered inductively by a coil around the hip joint and is provided with 6 strain gauges and a 9-channel amplifier with Telemetry. This system supplies the real-time observation of the 3-dimensional forces with an accuracy of 1–2% [25]. The bone is fixed at the distal end as shown in Fig. 4. Figure 5 shows the time history of the dynamic load cycle components for 1.2 (s) corresponding to different activities: normal walking, climbing stairs and standing up [25]. Table 1 shows the description of these activities. The description of the studied patient details in terms of his body weight, age and anatomical specification are listed in Table 2.

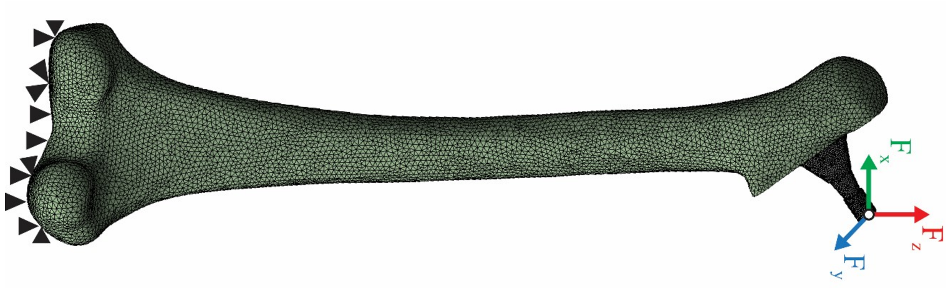


**Fig. 4.** Boundary conditions and mesh of model.

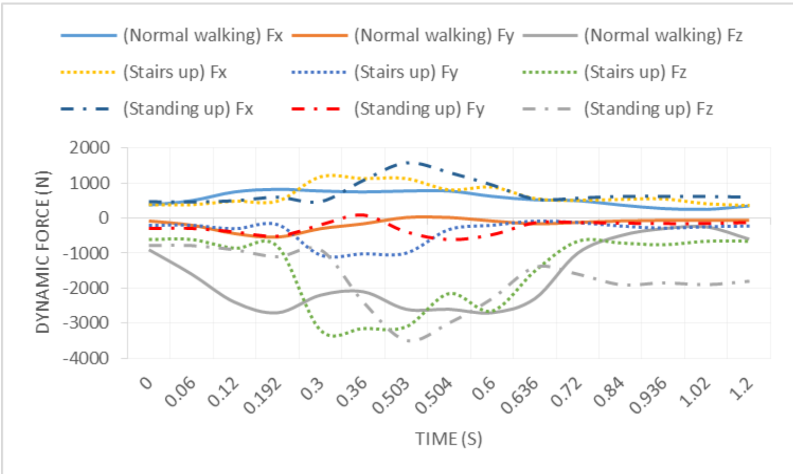


**Fig. 5.** Time history of load components on the prosthesis corresponding to different activities.

**Table 1.** Description of analyzed activities.

| Activity | Description |
|---|---|
| Normal walking | Level walking, speed = 1.0 –1.3 m/s; average = 1.1 m/s |
| Climbing stairs | Without use of handrail. Step height = 19.8 cm, width = 26.3 cm |
| Standing up | Without use of armrest. Seat height = 45 cm |

**Table 2.** Patients' personal data.

| Gender | Male |
|---|---|
| Body weight (kg) | 75 |
| Age (years) | 60 |
| Replaced joint | Right |

### 2.3. Material properties

The cancellous bone is assumed as a linear isotropic material while the cortical bone is modeled as a linear transverse isotropic material. To assign the material properties, elastic properties are inserted into ANSYS by selecting the type of engineering constants based on prior studies [14, 26, 27]. Table 3 shows a summary of the mechanical properties of materials used in the numerical analysis. Table 4 shows a summary of the mechanical properties of carbon/PEEK composite coating materials with two different fiber configurations as shown in Fig. 6 [28].

Equations (5-8) present the strength criteria of prosthesis components. $N_f$ in Equation (9) indicates the fatigue safety factor criteria for the prosthesis components.

$$\sigma_{stem} \leq (\sigma_{yield} = 800 \quad MPa) \tag{5}$$

$$\sigma_{PEEK} \leq (\sigma_{yield} = 102 \quad MPa) \tag{6}$$

$$\sigma_{Configuration \quad I} \leq (\sigma_{yield} = 627.5 \quad MPa) \tag{7}$$

$$\sigma_{Configuration \quad II} \leq (\sigma_{yield} = 327.4 \quad MPa) \tag{8}$$

$$N_f \geq 1 \tag{9}$$

**Table 3.** Mechanical properties of the bone, Ti alloy prosthesis, and PEEK coating material.

| Material | Plane | Elastic modulus $E$ [GPa] | Shear modulus $G$ [GPa] | Poisson's ratio $\nu$ |
|---|---|---|---|---|
| Cortical Bone | xx | 11.5 | – | – |
| | yy | 11.5 | – | – |
| | zz | 17 | – | – |
| | xy | – | 3.60 | 0.51 |
| | yz | – | 3.30 | 0.31 |
| | xz | – | 3.30 | 0.31 |
| Cancellous bone | – | 2.13 | – | 0.3 |
| Ti-6Al-4V | – | 114 | – | 0.33 |
| PEEK 150 XF | – | 3.7 | – | 0.4 |

**Table 4.** Mechanical properties of carbon/PEEK composites.

| Carbon/PEEK composites | Plane | Elastic modulus $E$ [GPa] | Shear modulus $G$ [GPa] | Poisson's ratio $\nu$ |
|---|---|---|---|---|
| Configuration I | xx | 4 | – | – |
| | yy | 9.8 | – | – |
| | zz | 9.8 | – | – |
| | xy | – | 3.5 | 0.3 |
| | yz | – | 3 | 0.3 |
| | xz | – | 3.5 | 0.3 |
| Configuration II | xx | 4.5 | – | – |
| | yy | 15.5 | – | – |
| | zz | 15.5 | – | – |
| | xy | – | 4 | 0.3 |
| | yz | – | 3.5 | 0.3 |
| | xz | – | 4 | 0.3 |

The alternating stress versus number of cycles (S-N curve) for different prosthesis component materials used in this study for fatigue calculations is given in the logarithmic scale in Fig. 7 [29-32]. After 1E10 cycles, if the stress levels are below a certain level (the endurance limit that shown as horizontal red lines), an infinite number of cycles can be applied without causing a failure. So all the stress levels that the implant is subjected to must be below the endurance limit to have infinite life.

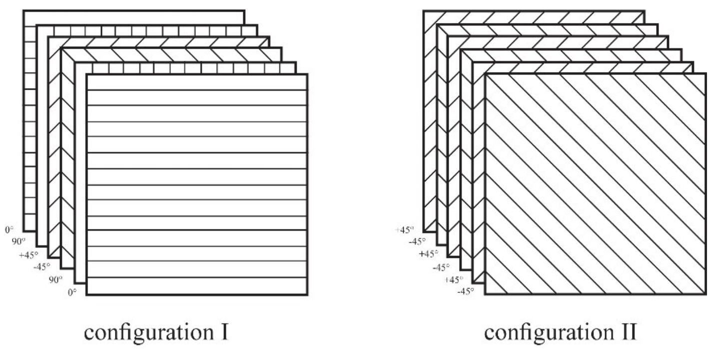


**Fig. 6.** Ply configurations for carbon/PEEK composites: (a) configuration I, (b) configuration II.

### 2.4. Methodology

Fatigue life, safety factor and stress values are determined for different prosthesis under different loading. The tested models are compared qualitatively and quantitatively, identifying the behavior of the coating materials. Dynamic stress and safety factor values pertaining to each material are used in order to assess the variability and correlation of the results independently of loading nature. One way ANOVA test between safety factor and stress values related to the different materials is performed, and a threshold ($p<0.05$) is used to indicate the significance of the results by using SPSS software. The Pearson correlation test is also performed between stress and safety factor values in dynamic case in order to evaluate the overall effect of the coating materials independently of the loading nature.

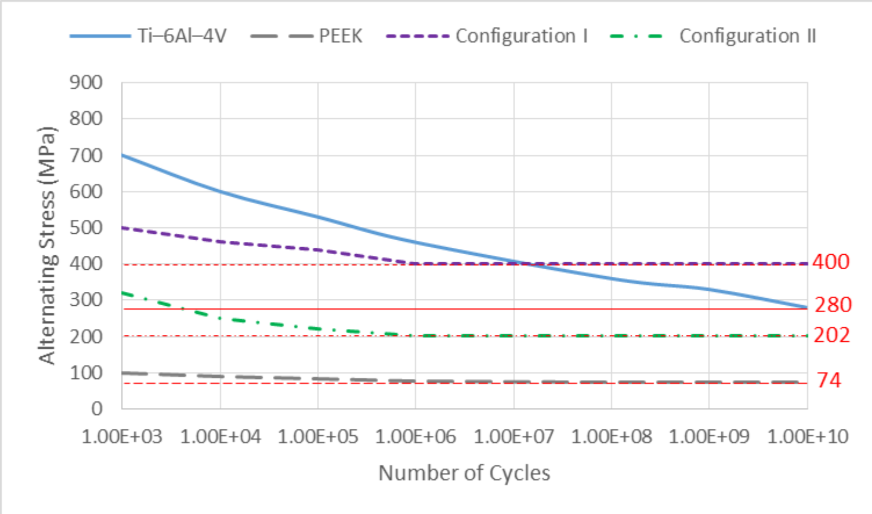


**Fig. 7.** S–N curves of different prosthesis component materials.

## 3. Results

Fatigue life and safety factors are the most important quantities to evaluate the durability of the prosthesis. Thus, all models with different coating materials are analyzed with the FEM by applying loads and boundary conditions corresponding to different activities. Fatigue life and safety factors of prosthesis are calculated based on the Goodman mean-stress fatigue theory.

From the numerical results, the maximum stress value (278.76 MPa) is obtained for uncoated stems in standing up condition, while the lowest value (78.74 MPa) is obtained in normal walking condition for coated stems. All maximum stress values generated in different stems are lower than yielding stress of stem material mentioned in Equation 5.

To investigate the coating material that has the best performance as a coating layer, the finite element analysis of maximum stress generated in coating layers is used, and the results are listed in Table 5. It can be observed that configuration I coating layer is more stressed than others in the different conditions, which means that load transfer are higher than others. All maximum stress values generated in different coating materials are much lower than the yielding stresses given in Equations (5-8), which means prosthesis with different component materials are safe whatever the activity: standing up, normal walking, or climbing stairs.

**Table 5.** Maximum von Mises stresses (in MPa) of the coating materials with various conditions.

| Activity | PEEK | Configuration I | Configuration II |
|---|---|---|---|
| Normal walking | 8.72 | 25.39 | 16.91 |
| Climbing stairs | 15.39 | 41.78 | 29.79 |
| Standing up | 16.20 | 40.54 | 30.09 |

Numerical fatigue life results show that different prosthesis components (hip implants + coating layers) are safe under various conditions as shown in Fig. 8, since stress values obtained after 1E10 cycles are lower than the conventional endurance limit of different prosthesis components (Figure 5). Among analyzed hip implant stems, the most risky is uncoated hip implant stem, especially under dynamic standing up condition, where the value of induced stress (278.76 MPa) is close to the conventional endurance limit (280 MPa). The safest coating layer among all coating materials is these fabricated of carbon/PEEK composite (configuration I), where the value of induced stress is too far from the conventional endurance limit whatever the activity: normal walking, climbing stairs or standing up.

In Equations 3 and 4, $N_f$ indicates the safety factor for fatigue life, where stresses obtained from finite element analysis are used in fatigue safety factor calculations. All fatigue analyzes are performed according to infinite life criteria (i.e. N=1E10 cycles). Safety factor distributions for hip implant stems with different coating materials under dynamic loadings are shown in Fig. 9, while minimum safety factors for coating materials based on infinite life criteria are given in Tables 6 corresponding to different human activities: standing up, normal walking and climbing stairs under dynamic loadings.

The numerical results of fatigue safety factor obtained for different hip implant stems show that 2 mm coating layer of PEEK or carbon/PEEK coating material have almost the same influence in increasing the safety factor for hip implant stems in comparison with uncoated one. Critical safety factor values are usually observed in the neck for all prosthesis under various conditions as shown in Fig. 9. For the coated models, fatigue safety factor is increased more than 12.73% at least compared to the uncoated model. It could also be observed that minimum safety factor is obtained with standing up activity for the coated and uncoated models, while the maximum safety factor corresponds to normal walking especially for coated models.

To investigate which coating material has the best performance as a stem coating layer in the bone-prosthesis system, the FE analysis of fatigue safety factors of coating layers is used, and the results have been tabulated in Table 6. It is observed that carbon/PEEK composite coating layer (configuration I) has the highest fatigue safety factor. This means that configuration I seems to present the best performance.

Figures 10 and 11 show the comparison of stress and fatigue safety factor values for different coating materials averaged across dynamic case. Pearson correlation test shows also a statistically significant correlation between stress and fatigue safety factor in dynamic conditions ($p < 0.05$). Variance tests show significant differences between the values of different coating materials. In comparison of carbon/PEEK configuration I mean stress value versus other coating materials, it could be noticed that the mean stress value is higher than others, where the value of configuration I (35.9 MPa) is high compared to configuration II (25.6 MPa) and compared to PEEK (13.43 MPa).

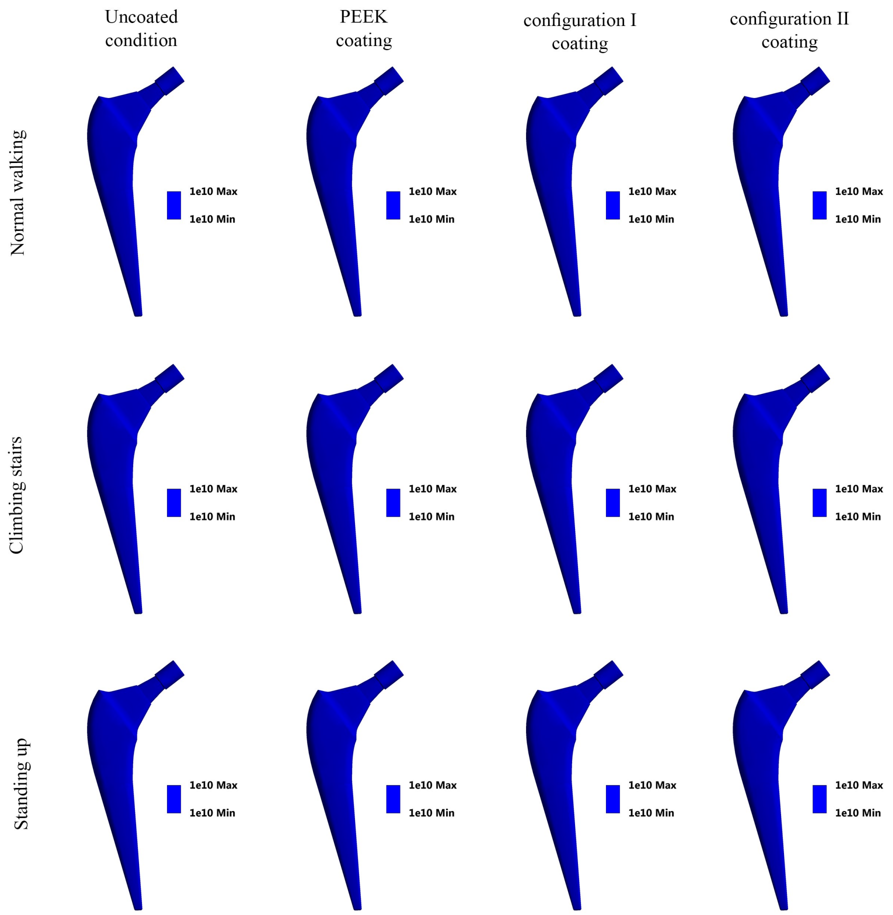


**Fig. 8.** Fatigue lives for hip implants with different coating materials under dynamic loadings after 1E10 cycles.

**Table 6.** Minimum safety factor of different coating materials with various conditions.

| Activity | PEEK | Configuration I | Configuration II |
|---|---|---|---|
| Normal walking | 8.48 | 15 | 11.97 |
| Climbing stairs | 4.81 | 9.57 | 6.80 |
| Standing up | 4.57 | 9.87 | 6.73 |

In comparison of carbon/PEEK configuration I mean fatigue safety factor versus other coating materials (Figure 11), it could be observed that mean fatigue safety factor value is higher than others, where the value of configuration I (11.48) is enormous compared to PEEK (5.95) and compared to configuration II (8.5). This increment in fatigue safety factor of coating layer confirms that carbon/PEEK configuration I is recommended to enhance the safety and the durability of the bone-prosthesis system.

## 4. Discussion

The limited lifespan of the total hip replacement is highly considered by the surgeons and prosthetists because of the complications of the revision surgeries [33, 34]. Therefore, researchers make an effort to increase the lifespan of the total hip replacement by improving surgery methods and designs [35].

Fatigue safety factor and fatigue life of the prosthesis play a significant role in the stability of the total hip replacement. Important aspects influencing the life and safety of the THR rely upon the suitable biocompatible materials utilized for the prosthesis where the choice of material is important to provide adequate resistance against failure. Therefore, prosthetists attempt to enhance the prosthesis properties by utilizing new materials in the prosthesis design to increase safety factor and fatigue life.

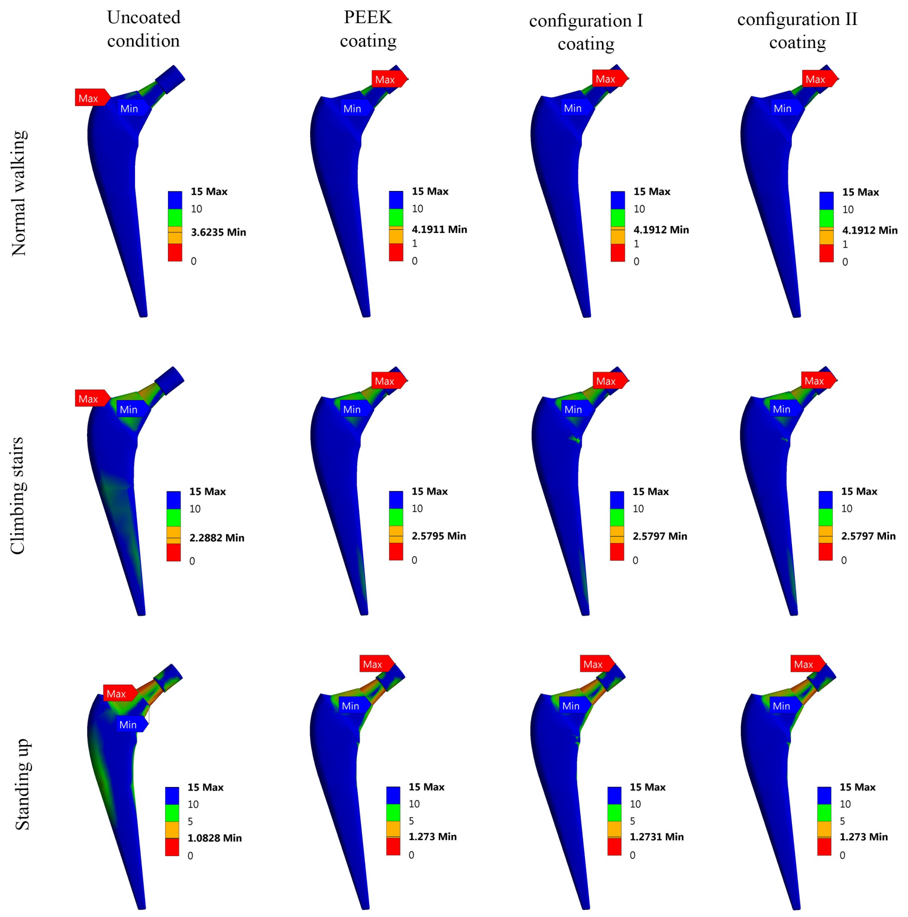


**Fig. 9.** Safety factor distributions for hip implants with different coating materials under dynamic loadings.

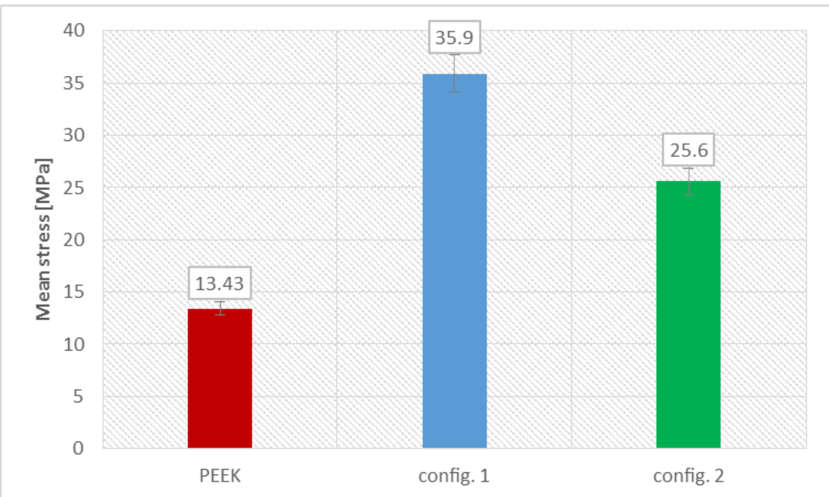


**Fig. 10.** Mean stress values of different coating materials under dynamic conditions.

In previous studies, researchers have employed finite element analysis in conjunction with metallic prosthesis to introduce new design and obtain strong and durable prosthesis [14, 17, 22, 33, 36-38]. However, their works were limited to traditional coated/uncoated metallic hip implant stems or cementless hip prosthesis coated with functionally graded materials that subjected to normal walking condition.

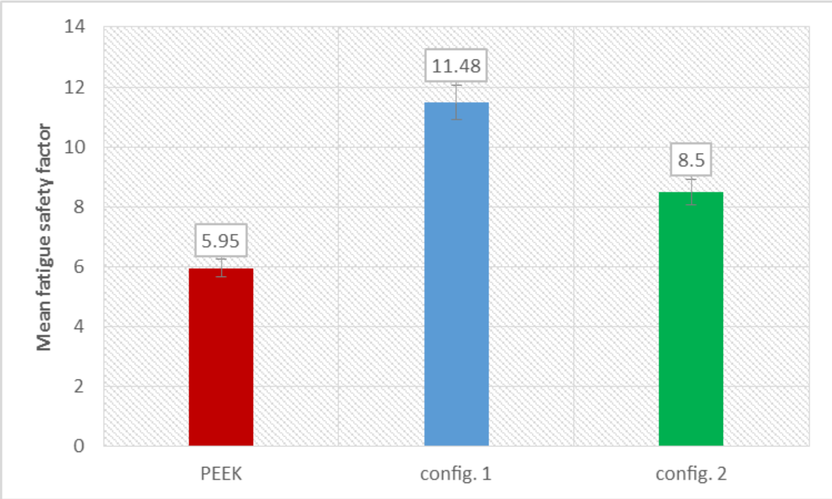


**Fig. 11.** Mean safety factor values of different coating materials under dynamic conditions.

The goal of the present study is to validate the design concept by comparing the fatigue behavior of prosthesis component materials (hip implant stems + coating layers) corresponding to different human activities: standing up, normal walking and climbing stairs under dynamic loadings to find out which of all these models have a better performance in the bone-prosthesis systems. The suggested approach would open the possibility to enhance fatigue behavior without the need to develop another implant geometry. As a result, any available implant could be treated by choosing an appropriate coating process.

Numerical results show a reduction of 4.6% at least in generated stress for the coated implant stems compared with uncoated one. The reduction of generated stress achieve by the increment in load transmitted to the bone via coating layer, which reducing stress-shielding effect. Table 5 show an increment of 25.77%, 20.2% and 28.7% at least in transmitted stress for configuration I coating layer under standing up, normal walking and climbing stairs condition respectively compared with other coating materials. This result is achieved by its ability to distribute the stresses throughout the bone-prosthesis system.

In comparison between the obtained results and fatigue curves for coated and uncoated stem models, it can be observed that the most riskiness prosthesis is uncoated hip implant stem, especially under dynamic standing up condition where the value of induced stress is close to the conventional endurance limit. While the coated hip implant stems is safer than uncoated one due to farness of induced stress values to the conventional endurance limit. It can be also observed that the safest coating layer among all of coating materials is carbon/PEEK composite (configuration I), where the value of induced stress is too far from the conventional endurance limit.

As previously mentioned, two different composite fiber configurations are used to address the fatigue behavior of carbon/PEEK composite coated prosthesis. The fiber plies in the configuration I are orientated multidirectional with fiber orientations of 0, +45, -45, and 90 degrees, while the fiber plies in configuration II are orientated multidirectional and alternated with fiber orientations of -45 and +45 degrees. The results show that the highest value of fatigue safety factor is obtained with coated implant stems under dynamic loadings. The use of configuration I coating material increases the values of fatigue safety factor of coating layers whatever the activity: normal walking, climbing stairs or standing up. These predictions imply that the possible failure will not occur due to a higher level of safety for hip implant stems coated with carbon/PEEK composite (configuration I).

It is known that the fiber orientation plays a very important role in the mechanical behavior of the composite materials. In the configuration I, as the fibers orientated with 0, +45, -45, and 90 degrees, the distribution of the applied load is the best due to this orientation of fibers that achieves the homogenous mechanical behavior in the system. This material enables to distribute the applied load and transfer it to the bone, that can influence mineral bone loss due to stress-shielding, minimizing stress-shielding effect, and thus it will be safer and more durable compared to the other models.

No earlier studies have examined the fatigue behavior of the present hip implant stems coated with carbon/ PEEK composite and PEEK polymeric coating materials. However, comparison of current results to prior studies on primary hip prosthesis may be instructive.

Enab [39], Fouda [40] and Hedia [41] showed that composite coatings led to reduce the stress in coated hip implant stems, and thus enhance its durability because of improved load transfer to the bone and reduced stress-shielding effect, which is in agreement with the presented results in this study. Brockett et al. [35] showed that the wear of carbon/PEEK against metallic counterface was less than PEEK when it studied to investigate the wear performance of PEEK and carbon/PEEK materials under a range of conditions as possible materials for total joint replacement (TJR). Thus, carbon/PEEK composites have the best performance as possible materials for TJR compared to PEEK polymeric material. This result is in agreement with the presented results in this study where it confirms that carbon/PEEK have a better performance than PEEK coating material.

From the results of this study, it could be observed that uncoated hip implant stems are not good and led to bad performance. On the contrary, the coated hip implant stems show a good performance, especially the configuration I coating material that seems to be a good solution to increase the fatigue safety factor of coating layers, and to improve load transfer to the bone that reduce stress-shielding effects and prolong the bone-prosthesis system life span. It seems to be a good solution to prevent aseptic loosening and improve the stability of the prostheses because of decreasing in the mismatch between the stiffness of the coated hip implant stem with the bone.

This study has some limitations that should be considered, the porous surface should be regarded as the proposed design concept depends on press-fit type implants. Bone apposition and resorption were neglected. However, continuous bone remodeling over the lifespan of the implant will alter the implant-bone biomechanics.

Further research is required to refine the suggested design concept, and to develop a proper coating process. In terms of manufacturing, processes, and carbon/PEEK composite formulations require investigation for the hip implant application via both in-vitro and in-vivo conditions.

## 5. Conclusion

This study investigated, using FEA, the fatigue behavior of prosthesis component materials (hip implant stems + coating layers) corresponding to different human activities: normal walking, standing up and climbing stairs under dynamic loadings to find out the model that has a better performance in the bone-prosthesis system. For all implants, modeling of standing up activity led to the worst implant fatigue behavior. It has been found that the implant coating layer made with PEEK or a composite of carbon/PEEK led to increase the implant fatigue safety factor under dynamic loadings. The carbon/PEEK composite material with 0, +45, -45, and 90 degrees fiber orientation (configuration I) was the best solution to increase the values of the fatigue safety factor of coating layers due to the highest fatigue life and fatigue safety factor. It distributed the applied load and transferred it to the bone. This will reduce stress-shielding problems and increases the lifetime of the bone-prosthesis system.

## Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

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## ORCID iD

Ayham Darwich https://orcid.org/0000-0002-2027-7950
Hasan Nazha https://orcid.org/0000-0003-1531-1824
Monzer Daoud https://orcid.org/0000-0003-0556-1360