The Effect of Dynamic Loading from Routine Activities on Mechanical Behavior of the Total Hip Arthroplasty

Mohamed Mokhtar Bouziane, Smail Benbarek, Essadek Mohamed Houari Tabeti, Bel Abbes Bachir Bouiadjra, Noureddine Benseddiq, Boualem Serier and Abdelmohsen Albedah

Abstract Dynamic loads from routine activities applied to the stem create dynamic stresses varying in time and resulting in the fatigue failure of the prosthesis components. Therefore, a finite element model can be used to predict mechanical failure. The purpose of this study was to develop a three-dimensional model of the cemented hip femoral prosthesis and to carry out finite element analysis to evaluate stress distributions in the bone, the cement and the implant compounds under dynamic loads from different human activities. Linear elastic

M. M. Bouziane (✉)
Department of Mechanical Engineering, University Mustapha Stambouli of Masacra, Mascara, Algeria
e-mail: agk_bouziane@yahoo.fr

M. M. Bouziane · S. Benbarek · B. A. B. Bouiadjra · B. Serier
LMPM, Department of Mechanical Engineering, University of Sidi Bel Abbes, Ben M'hidi, BP 89, 22000 Sidi Bel Abbes, Algeria
e-mail: sma_benbarek@yahoo.fr

B. A. B. Bouiadjra
e-mail: bachirbou@yahoo.fr

B. Serier
e-mail: boualems@yahoo.fr

A. Albedah
Mechanical Engineering Department, College of Engineering, King Saud University, Riyadh, Saudi Arabia
e-mail: albedah@ksu.edu.sa

N. Benseddiq
Laboratoire de Mécanique de Lille, IUT-A, 2 rue de la Recherche, 59653 Villeneuve d'Ascq Cedex, France
e-mail: noureddine.benseddiq@univ-lille1.fr

E. M. H. Tabeti
Department of Orthopedic Surgery, University of Sidi Bel Abbes, Ben M'hidi, 22000 Sidi Bel Abbes, Algeria
e-mail: chu-sba@sante.dz

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analysis is adapted; von Mises stress, normal stress and shear stress are the values that are of concern. Results show that the stresses distribution in the femoral arthroplasty components depends on the human activity. The analysis also showed that the stresses are high in the proximal and distal parts of the cement mantle.

Keywords Femoral prosthesis · Finite element method · Cement · Dynamic · Stress

1 Introduction

Total hip replacement (THR) is a very successful surgical technique that has become a well established procedure in current orthopedics. Patients with degenerative hip joint diseases, persistent to thigh pain and fractures of the femoral neck, can effectively be treated with an artificial hip joint reconstruction. Generally, THR leads to immediate pain relief and increased freedom of movement in the hip joint. Patients experience a substantial improvement in the quality of life, and need les support to carry out their daily activities [1]. The finite element method (FEM) is an advanced simulation technique that has been used in orthopedic biomechanics since 1972 [2]. It is an important tool used in the design and analysis of total joint replacements and other orthopedic devices [3]. Contact forces in the hip joint must be known for tests on strength, fixation, wear and friction of implants, for optimizing their design and materials by computer simulation and for giving guidelines to patients and physiotherapists as to which activities should be avoided after a replacement. The movement in the hip joint has to be known when implant wear is tested or the load directions relative to the pelvis are calculated from the forces acting at the femur [4]. The negative effects of stress singularities are also found in an FEA simulation that was derived in an earlier study [5] for the purpose of preclinical testing of cemented total hip replacement (THR) implants against the damage accumulation failure scenario. This failure scenario is often considered to be the most dominant failure scenario for the femoral component of a cemented THR reconstruction [6, 7]. Cemented hip arthroplasties are subjected to cyclic loads, which sometimes lead to the mechanical failure of components of the implant system, with the subsequent long-term failure of the whole fixation. There are usually recognized four vulnerable regions: the cement-stem interface, the bulk cement, the cement-bone interface and bone [8–10]. Higher peak stresses lead to earlier crack formation. The peak tensile stresses are usually found around sharp corners or edges in the reconstruction, and as such, crack formation is first observed at these locations [11]. The loading methods used to determine the stresses in the prosthesis design can, also,

Fig. 1 Osteal femur stem

give quite different information [12]. Forces applied to the implant due to human activity generate dynamic stresses varying in time and resulting in the fatigue failure of the implant material. Therefore, it is important to ensure the hip prostheses against static, dynamic and fatigue failure [13]. Since 1979, the Ceraver-Osteal model of cemented total hip arthroplasty (Fig. 1) with a titanium femoral stem [14] has been used. This study aims to take account of the patient activity (walking, up stairs, down stairs, standing up and sitting down) when designing a total hip replacement. In this regard the stress field in the artificial hip components (prostheses, cement mantle, and bone) is analyzed dynamically. The simulations have been conducted to investigate the effect of dynamic loading from routine activities patterns on the stress-based criteria to assess implant longevity. Two quantitative measures are calculated: stress distribution and peak stress. It has been shown that each measure may lead to differing conclusions.

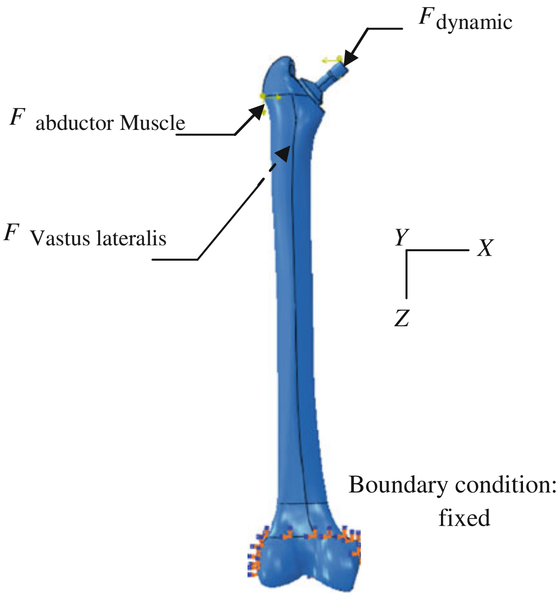


Fig. 2 Applied forces on the bone-cement–prosthesis assembly

2 Materials and Methods

2.1 Model Designs

For a three-dimensional solid model of the total hip replacement (THR), there are four major components that have to be modelled: cortical bone, cancellous bone, femoral stem and bone cement. The complete models were assembled using SolidWorks. The three-dimensional solid model assembly of femur, bone-cement and implant was transferred to Abaqus Workbench by the direct interface. Abaqus Workbench automatically recognizes the contacts existing between each part and establishes the contact conditions for corresponding contact surfaces. In this work, the Ceraver-Osteal model of the cemented total hip arthroplasty is designed (Fig. 2).

2.2 Material Properties

The material properties adopted were specified in terms of Young's modulus and Poisson's ratio for the implants and all associated components (Table 1). All materials were assumed to exhibit linear, homogeneous elastic behavior [15].

Table 1 The artificial hip components material properties [15]

Materials	Young's modulus E (MPa)	Poisson's ratio ν	Density (kg/m^3)
Cortical bone	15,500	0.28	1,990
Concelleous bone	389	0.3	500
Stem (Ti-6Al4 V)	110,000	0.3	4,430
Ciment PMMA	2,700	0.35	1,200

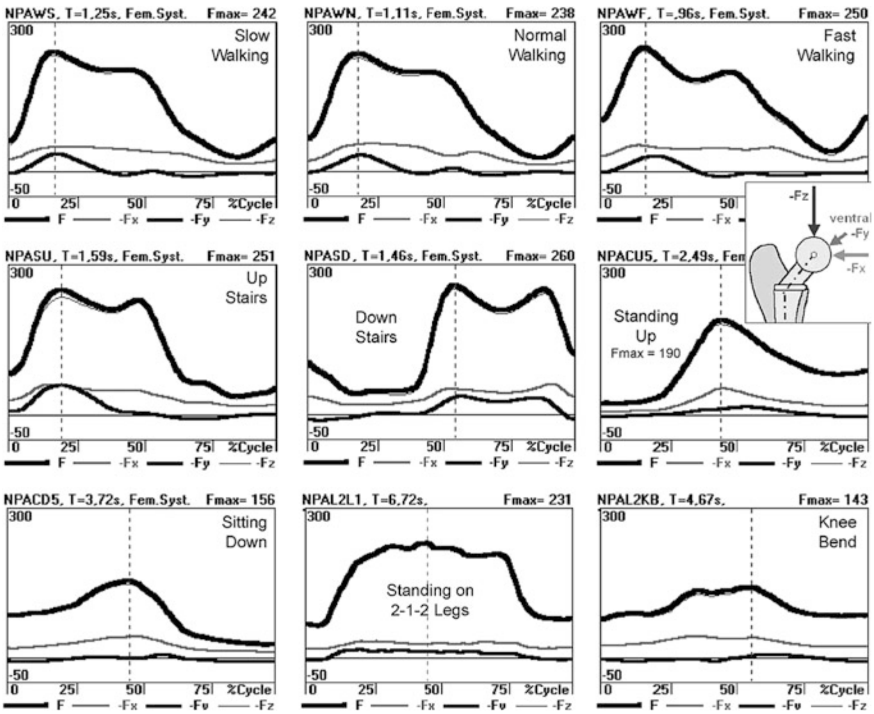


Fig. 3 Contact force F of typical patient NPA during nine activities. Contact force F and its components $-F_x$; $-F_y$; $-F_z$: F and $-F_z$ are nearly identical. The scale range is −50–300 % BW

2.3 Loading and Boundary Conditions

The contact forces F of the typical patient and their components are charted in Fig. 3 for the nine investigated activities [16]. In this study, the dynamic loads from five activities (walking, up stairs, down stairs, standing up and sitting down) were chosen from the hip contact forces, these loads for a person of 70 kg are illustrated in Fig. 4. The boundary condition was applied by fixing the distal epiphysis, which is the distal end of the femur that is connected to the knee [17]. The coordinate system used to represent the direction of the forces components is

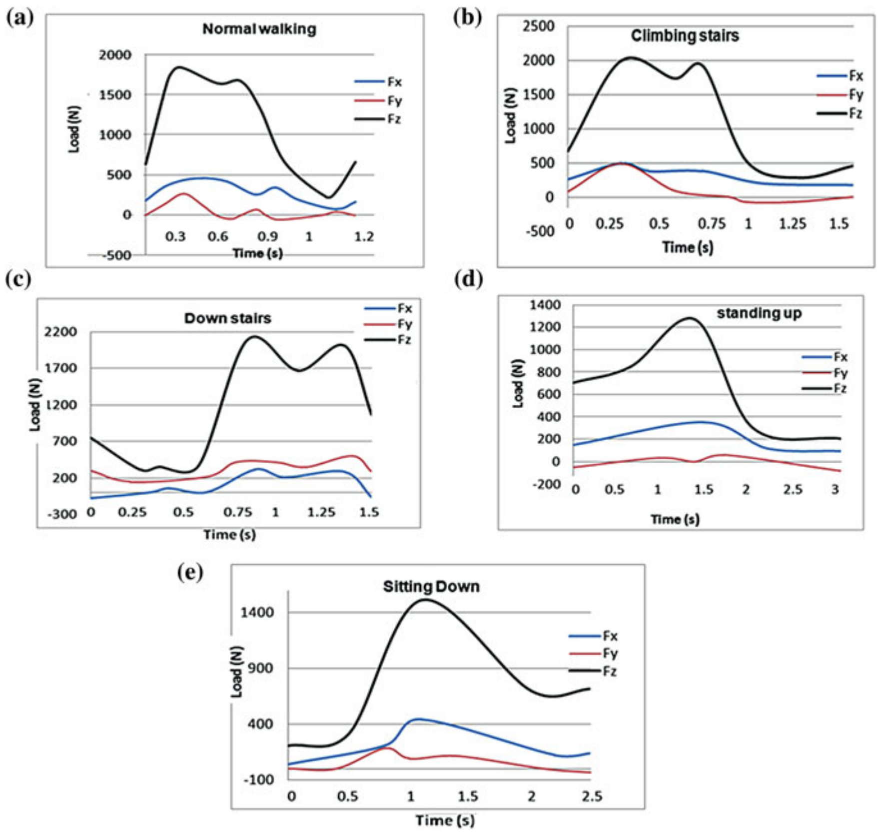


Fig. 4 The variation of forces applied on the prosthesis during five activities (**a** walking, **b** climbing up stairs, **c** down stairs, **d** standing up and **e** sitting down) for BW = 70 kg

shown Fig. 2. The femur is primarily loaded in bending [18]. The cement–bone and cement-stem interfaces were assumed rigidly fixed.

2.4 Model and Mesh

Finite element analysis (FEA) is a widely used research tool in biomechanics. A well-known problem in this type of analysis is the presence of singular points in the FEA model, causing the predicted peak stresses in particular to be dependent on the level of mesh refinement (Fig. 5). A method to reduce the mesh dependence would be of great value [11]. The model in this study is discretized by using tetrahedral elements. This is because the geometry of the femur is irregular. Tetrahedral elements are better to be suited and adjusted to curved boundaries

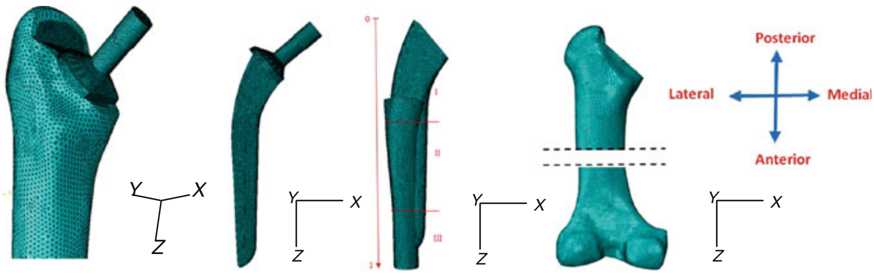


Fig. 5 Finite element meshes of hip prosthesis components: cemented hip stem, Osteal stem, cement and femur bone (from *left* to *right*) *I* Proximal part, *II* Median part and *III* Distal part

compared to others elements. Discretizing by using tetrahedral elements with four nodes makes the meshing becomes easier. The complete osteal model (stem, bone cement and femur) has in total 1,223,410 elements.

3 Result and Discussion

Hip contact forces based on gait analysis data were previously calculated using simplified muscle models and various optimization methods [19–26]. Most studies were restricted to walking or stair climbing. Typically the calculations delivered higher hip joint forces than those measured by other groups. Only Brand et al. (1994) compared calculated and measured data which were obtained, however, at different times [25]. The obtained gait data was used as an input for a musculoskeletal model to calculate muscle forces [27]. The measured hip contact forces served to check the validity of calculated results.

For walking and stair climbing measured and calculated contact forces agreed fairly well. Their model can therefore be used to investigate clinical problems like muscle deficiencies or operative procedures. Morlock et al. (2001) measured the activity levels of 31 patients with hip implants during day-long sessions [28]. The combination of average activity numbers with the typical hip contact forces and joint movements presented here can serve to test the strength, fixation stability and wear properties of hip implants more realistically than today. Adding the muscle forces of Heller et al. (2001) will make the test conditions for hip implants, femur and pelvis even more realistic [27]. Physiological loading conditions are mandatory if bone remodelling or implant subsidence is investigated [29].

Mechanical integrity can only be maintained if the overall stress is kept below some threshold over time [30]. Another practical problem is that the influence of cement porosity may dominate the effect of the stress [31]. These stresses may occur as tensile, compressive, shear, or a stress combination known as equivalent von Mises stresses. This last one depends on the entire stress field and are widely used as an indicator of the possibility of damage occurrence [32]. During normal

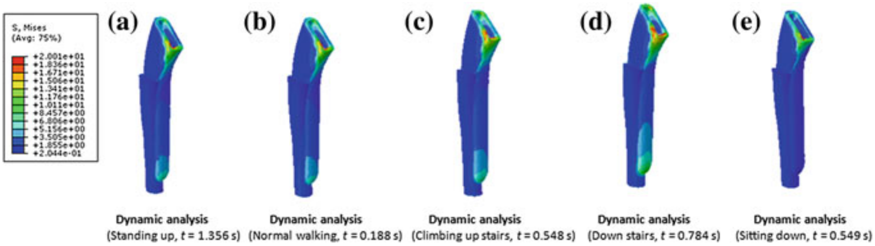


Fig. 6 von Mises stress distribution on the cement under dynamic loading from five activities: **a** Standing up (time = 1.356 s), **b** Normal walking (time = 0.188 s), **c** Climbing up stairs (time = 0.548 s), **d** Down stairs (time = 0.784 s) and **e** Sitting down (time = 1.549 s)

use, the joints experience cyclic stresses, which cause fatigue crack initiation and growth in the cement layer, leading to loss of structural integrity and eventual loosening of the implant [33].

In this study, we calculate the von Mises stresses distribution, in the components of the prosthesis (bone cement, stem and bone), for five cases of the dynamic loading (walking, up stairs, down stairs, standing up and sitting down). In addition, it is necessary to analyse the normal and shear stress distributions along the different regions of the cement mantle of the prostheses.

3.1 von Mises Stresses

Combined dynamic load was examined to determine on a phenomenological level what occurs when the hip prosthesis system is subjected to these specific loads. The stress analysis executed by Abaqus provided results that enabled the tracing of the von Mises stress field in the shape of color-coded bands. Each color band represents a particular range of stress value, which is given in Mega Pascals. Maximum stresses that occur in the cement, stem and bone under different dynamic loading conditions are shown in Figs. 6, 7, 8, 9, 10 and 11.

3.1.1 Cement Bone

By observing Figs. 6 and 7, it is found that, for all cases of the dynamic loading, the von Mises stress is still predicted to be high at proximal and distal regions, whereas the minimum stress is always found to be at the medial of the cement. Compared to the stresses, generally the stresses in the cement of the dynamic loading from the down stairs activity are higher (the maximum stress is in the order of 20 MPa for time = 0.784 s), while the stresses in the cement of the dynamic load from the sitting down activity are lower (the maximum stress is in the order of 15 MPa for time = 0.784 s). As for the results of THR with Osteal hip prosthesis, it is found

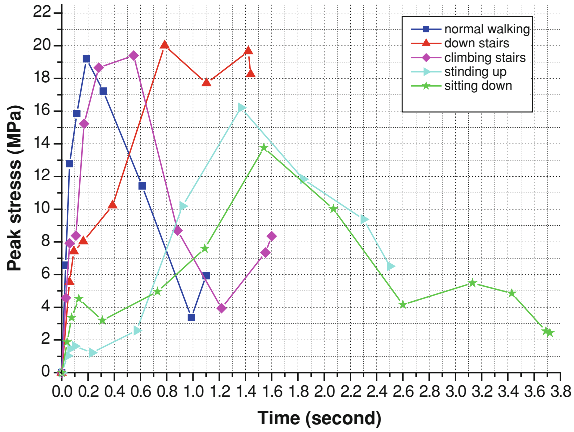


Fig. 7 Maximum von Mises stress in the cement mantle during five activities: *Standing up* (time = 1.356 s), *Normal walking* (time = 0.188 s), *Climbing up stairs* (time = 0.548 s), *Down stairs* (time = 0.784 s) and *Sitting down* (time = 1.549 s)

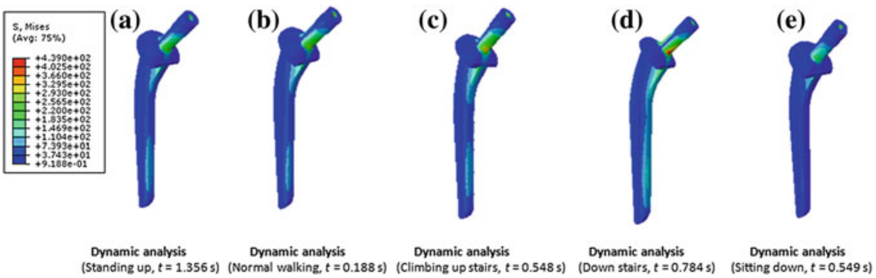
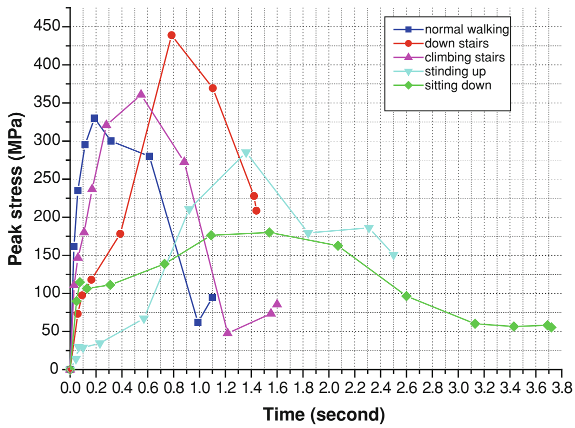


Fig. 8 von Mises stress distribution on the implant under dynamic loading from five activities: **a** Standing up (time = 1.356 s), **b** Normal walking (time = 0.188 s), **c** Climbing up stairs (time = 0.548 s), **c** Down stairs (time = 0.784 s) and **d** Sitting down (time = 1.549 s)

Fig. 9 Maximum von Mises stress in the implant during five activities: *Standing up* (time = 1.356 s), *Normal walking* (time = 0.188 s), *Climbing up stairs* (time = 0.548 s), *Down stairs* (time = 0.784 s) and *Sitting down* (time = 1.549 s)



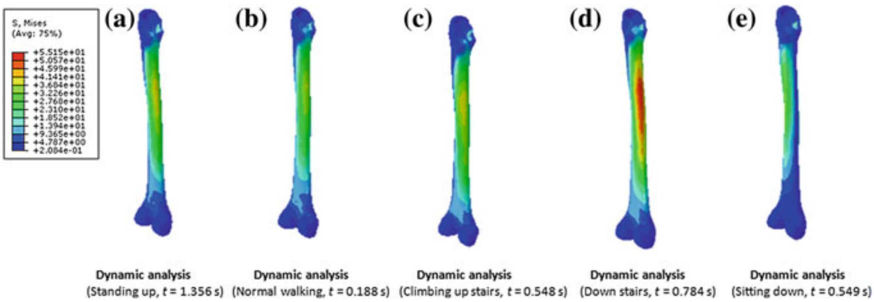
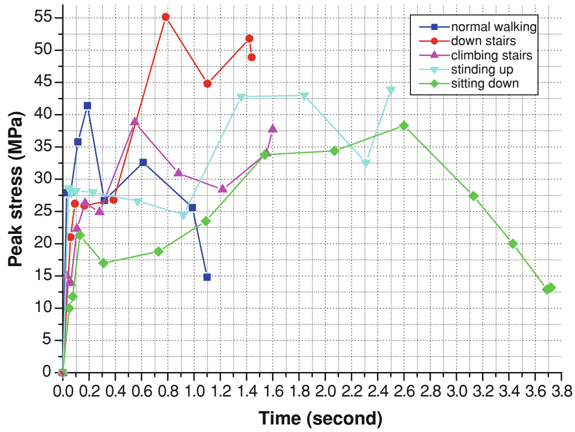


Fig. 10 von Mises stress distribution on the bone under dynamic loading from five activities: **a** Standing up (time = 1.356 s), **b** Normal walking (time = 0.188 s), **c** Climbing up stairs (time = 0.548 s), **d** Down stairs (time = 0.784 s) and **e** Sitting down (time = 1.549 s)

Fig. 11 Maximum von Mises stress in the bone during five activities: *Standing up* (time = 1.356 s), *Normal walking* (time = 0.188 s), *Climbing up stairs* (time = 0.548 s), *Down stairs* (time = 0.784 s) and *Sitting down* (time = 1.549 s)



that the bone cement does affect the stress distribution in the femur. Bone cement is made of polymer that has a relatively low Young's modulus, which is 2 GPa and it has a bad resistance to tensile loading (tensile strength = 25 MPa, compressive strength = 80 MPa and the shearing strength = 40 MPa) [34]. In other words, it is less stiff. Hence, when the hip prosthesis is loaded, it will transfer some of the load to the cortical through bone cement. Consequently, the stresses on the femur at that corresponding region are slightly higher. Although the difference is not much, the result is sufficient to tell us the effect of bone cement to the stresses on the femur.

3.1.2 Implant

Figures 8 and 9 show the von Mises stress distributions within the implant for five cases of the dynamic loading (walking, up stairs, down stairs, standing up and sitting down). Comparing the stress distributions on the hip prostheses, it can be observed that the stress concentration will be always at the neck area. Again, this is reasonable since there is cross section transitions at the neck are and it should always exhibit high stresses there. The higher stress is found in the prosthesis that occurred under dynamic loading from down stairs activity. The maximum stress is below 439 MPa for time = 0.784 s. If it is compared to the yield strength of Ti–6Al–4 V (880 MPa), there is still a safety factor of more than 2. Therefore, this result is still in the acceptable range. Whereas the lower stress is found in the prosthesis that occurred under dynamic loading from sitting down activity, the maximum stress is predicted to be 180 MPa for time = 0.784 s.

3.1.3 Bone

The von Mises stress distributions within the femur bone for five cases of the dynamic loading (walking, up stairs, down stairs, standing up and sitting down) is shown in Figs. 10 and 11. It is found that the stress is still predicted to be high at medial and proximal regions, whereas the minimum stress is always found to be at the distal end of the femur. Compared to the stresses, generally the stresses in the cortical bone of the dynamic loading from the down stairs activity are higher (the maximum stress is the order of 55 MPa for time = 0.784 s), while the stresses in the cement of the dynamic loading from the sitting down activity are lower (the maximum stress is the order of 33 MPa for time = 0.784 s). In biomechanical term, one say that a portion of the femur is being stress shielded. In long terms, it will cause bone sorption or bone loss. If this happens, the implant will have high possibility to loss and revision surgery is needed. The revision surgery will be more complicated than the primary surgery.

3.2 Axial Stresses

Irrespective of the method of analysis being used, maintaining the mechanical integrity is not a matter of reducing the peak stress in, e.g. the cement mantle or on the cement/bone and cement/prosthesis interfaces, although this criterion can be used to optimize a stem profile [35].

It is necessary to analyze the normal and shear stress distributions in the different regions of the cement mantle at the cement/bone and cement/prosthesis interfaces, because it is considered as the weakest component in the assembly of total hip arthoplasty. In this study we have chosen to analyze the stress distributions in the cement which was subjected to a dynamic load due to down stairs activity.

The variation of the normal stress according to *x*-direction (σ_x) along the cement/bone and cement/stem interfaces in the different regions (posterior, anterior, medial and lateral) of the cement mantle is shown in Fig. 12. Under combined dynamic load due to down stairs activity, the highest stresses of the cement were observed around the implant neck. The maximum tensile stress exists in the

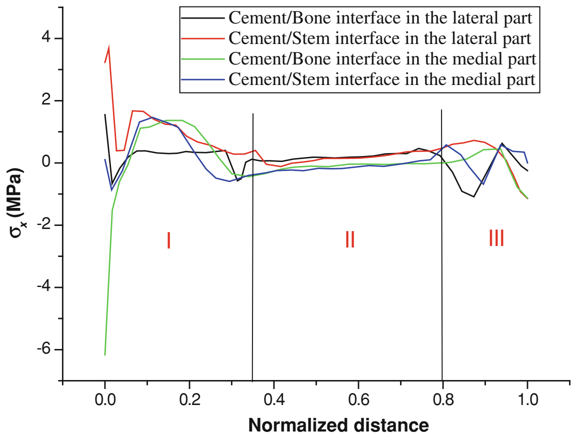


Fig. 12 Variation of the normal stress according to *x*-direction (σ_x) along the cement/bone and cement/stem interfaces in the different sides (lateral and medial) of the cement mantle for the static and dynamic analysis (down stairs, time = 0.784 s) *I* Proximal part, *II* Median part and *III* Distal part

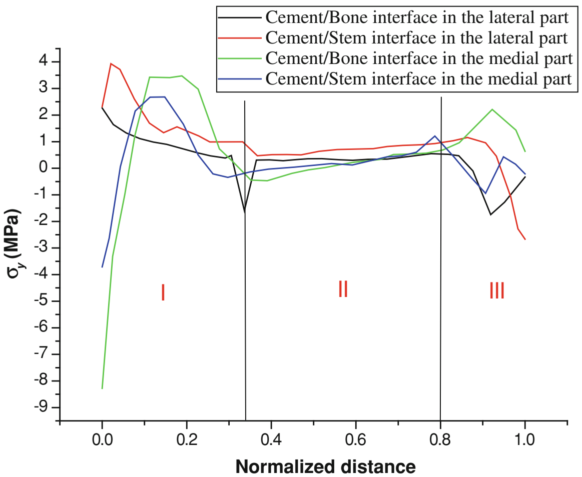


Fig. 13 Variation of the normal stress according to *y*-direction (σ_y) along the cement/bone and cement/stem interfaces in the different sides (lateral and medial) of the cement mantle for the static and dynamic analysis (down stairs, time = 0.784 s) *I* Proximal part, *II* Median part and *III* Distal part

posterior side at cement/stem interface with a value of 4 MPa and the maximum compressive stress exists in the anterior side at cement/stem interface with a value of 6 MPa. So, this result shows the major interaction effect between the dynamic loading and the implant neck shape.

Figure 13 shows the variation of the normal stress according to y-direction (σ_y) along the cement/bone and cement/stem interfaces in the different regions (posterior, anterior, medial and lateral). Comparing the stress distributions on the hip prostheses, it can be observed that the stress concentration will be always at the neck area. Again, this is reasonable since there is cross section transition at the neck area and it should always exhibit high stress values. The maximum tensile stress is localized in the posterior side at the cement/stem interface with a value of 4 MPa.

Fig. 14 Variation of the shear stress (τ_{xy}) along the cement/bone and cement/stem interfaces in the different sides (lateral and medial) of the cement mantle for the static and dynamic analysis (down stairs, time = 0.784 s). *I* Proximal part, *II* Median part and *III* Distal part

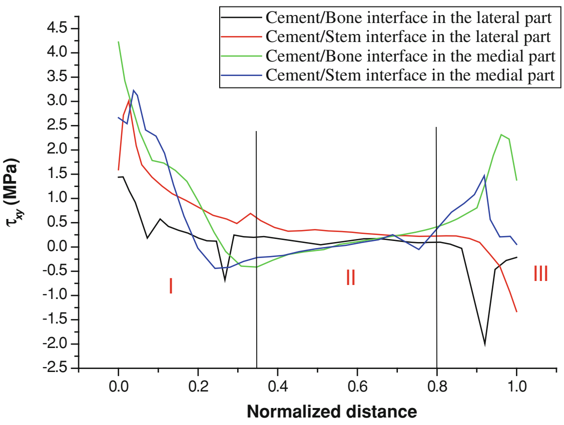


Figure 14 shows the variation of the shear stress (τ_{xy}) along the cement/bone and cement/stem interfaces in the different regions (posterior, anterior, medial and lateral).

When the prosthesis is being loaded, it will carry the entire applied load. Then, the load is transferred down along the prosthesis. When the load is transferred to the regions of the hip prosthesis, the load sharing will occur. This is due to the shear stress developed between the contact surfaces. The highest stress is observed in the anterior side at cement/stem with a value of 4 MPa.

4 Conclusion

For nearly all hip prosthesis systems, the major objective is long-term fixation of implants to bone. To achieve this goal, designers of implant systems must confront biomaterial and biomechanical problems, including in vivo forces on implants, load transmission to the interface, and interfacial tissue response. A three-dimensional finite element analysis is constructed to investigate the effect of combined dynamic load on the stress distribution in hip prosthesis. The loading methods used to determine the stresses in the prosthesis design can, also, give quite different information, and could lead to different conclusions. To be close to the reality, the dynamic load simulation is the only way to represent the effect of the patient activity on the prosthesis durability and design. This is important if finite element models are to achieve their potential as pre-clinical testing tools [36].

This study was carried out with the aim of analysing the effect of dynamic loading from routine activities on mechanical behavior of the total hip arthroplasty. The obtained results lead to the following conclusion:

- Compared to the stresses in the different components of the total hip arthoplasty, the stresses due to dynamic loading from the down stairs activity are higher, while the stresses due to dynamic loading from the sitting down activity are lower.
- In the cement mantle the critical region is still predicted to be at the neck region of the hip total arthoplasty. The critical stress is much lower than the yield strength. Hence, the design of the prosthesis is believed to be safe for use.

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