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Effects of Total Hip Arthroplasty on Stress Adaptation and Bone Remodeling in Lower Limbs

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Stress adaptation in femoral bone is an important indicator to predict bone behavior and remodeling after arthroplasty, computationally. Presence of prosthesis stem in the affected limb has created mismatching materials in the femoral shaft which alters the load distribution. The changes are not only reflected on the operated limb but also to the non-operated limb as well. In this study, biomechanical evaluations of the lower limbs were established using the finite element method. Bone adaptation was predicted computationally for both limbs on the resulting principal stress and bone mineral density to predict the stress shielding and bone remodeling phenomenon. Computed tomography (CT-based) images of a 79-years old female patient with hip osteoarthritis were used in developing the three dimensional inhomogeneous lower limb model. Then, the affected hip joint was cut off and replaced with total hip artroplasty (THA) which consists of acetabular cup, liner, femoral ball and prosthesis stem. A distributed load of 60kg was applied in the cross sectional region of lumbar vertebra and totally fixed at the distal end of the limbs to present a quiet standing position. Results showed that the stress adaptation was predicted at both the operated and non-operated limb in THA model. The proximal region of the operated limb indicated the highest stress changes which lead to bone resorption while the distal region had a possibility of bone thickening. Findings of bone remodeling analysis also estimated high changes of bone mineral density in the operating limb over 5 years.

Keywords: lower limbs, total hip arthroplasty, stress adaptation, bone remodeling, finite element analysis

1. Introduction

Stress shielding and bone remodeling effects are significant issues in enhancing the stability and long term performance of total hip arthroplasty (THA). Stress shielding occurred at the femoral bone with the presence of prosthesis stem. The bone was shielded and experienced lesser load as the stiffer implant dominated the majority of the weight transfer[1)]. Although the current development of prosthesis has demonstrated long term fixation, some problems are still to be expected, which can encourage bone resorption and aseptic loosening[2)]. Alteration of stress distribution in limbs will somehow contribute to the bone remodeling after arthroplasty. As a living element, bone is remodeled constantly on the basis of the mechanical environment, but the presence of artificial materials will alter the process[3)]. Prediction of bone remodeling after arthroplasty has been more challenging till nowadays, especially in projecting the resorption and thickening behavior. Changes of mineral density in bones are believed to encourage the understanding of the bone remodeling process[4)].

In addition, adaptation of stress variation and bone mineral density in the lower limbs are believed to modify the gait pattern of patients at the initial stage. Gait imbalance and instability have been detected in THA patients during recovery. Generally, gait is adapted to ease the pain of the diseased limb, but consequently, it may also contributes to the risk of falls and subsequent injury. Unfortunately, the gait of the THA patient is modified at both the operated and non-operated limbs[5,6)]. Thus, the evaluation and prediction of stress adaptation in both limbs may contribute to the understanding of bone behavior after arthroplasty.

In the biomechanical point of view, changes of stress distribution and bone quality due to bone remodeling contribute to gait adaptation. Issues of imbalanced weight distribution between both limbs and stress shielding phenomenon were ~~parts~~ of the consequences. To the authors' knowledge, no study was conducted to investigate the effects of hip arthroplasty on both limbs for THA cases. Most of the related studies depended on rehabilitation and gait analysis[5-7].

The purpose of this study was to predict the changes of stress variation and bone remodeling in the lower limbs after THA using computational analysis. Inhomogeneous 3D-model of lower limbs was developed using computer tomography (CT) images to consider hip osteoarthritis (OA) and THA cases. A load case of quiet standing position was considered to evaluate the stress distribution in both limbs.

2. Finite Element Model

2.1 Development of lower limbs model

3D computational model of a pair of lower limbs was constructed from CT images of a 79-year old female patient with hip osteoarthritis (OA). The images were collected from Kyushu University Hospital, Japan. A finite element model was then developed from the 3D-model. Distribution of bone mineral density (BMD) was estimated using the gray values of Hounsfield unit (HU) in the image[8]. Distribution patterns of young modulus and yield strength were then calculated by correlating the mechanical proeprties with the BMD[8]. It was assumed that each of finite elements was homogeneous with one modulus. This modeling was processed using commercial biomedical software, Mechanical Finder v6.1. The distribution of young modulus in the model is shown in Fig.1. Higher values of young modulus at the outer part of the femoral bone indicated cortical bone with high stiffness, while the inner part was known as cancellous bone with porous structures. Hip cartilages were considered on both the left and right joints with a low elastic modulus. The bonds between cartilage, acetabulum and femoral head, sacrum and ilium were assumed to be rigidly connected.

2.2 Development of THA model

In developing a 3D model of the lower limbs with hip prosthesis, the femoral head of the left femur was cut and inserted with a prosthesis stem. Meanwhile, the acetabular cup and bearing were aligned properly to the acetabulum to demonstrate a ball and socket joint. A ceramic-on-ceramic type of implant was used in this analysis. The material properties of hip cartilage and prosthesis are described in Table 1. The matrials were assumed to be linear elastic and homogeneous. Interfacial connection between implant and bone was considered as perfectly bonded.

2.3 Loading & boundary conditions

A load case of quiet standing was considered in this analysis. The posture in the foot side-by-side position is known to contribute to the structural and functional equivalent of the lower limbs[9,10]. A distributed load of a 60kg patients' body weight was applied in the cross section of the lumbar vertebrae and fixed at the distal end of the femoral shafts, as shown in Fig.2.

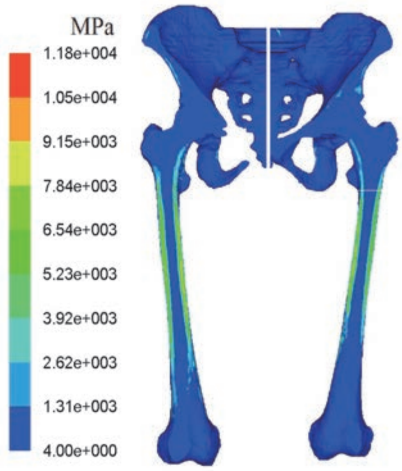

Fig. 1. Distribution of young modulus in lower limbs model with hip osteoarthritis.

Table 2. Description of material properties for hip arthroplasty.

Model	Material	Elastic Modulus (GPa)	Poisson ratio
Acetabular cup	Ti-Alloy	114	0.34
Bearing liner	Alumina	370	0.23
Femoral ball	Alumina	370	0.23
Prosthesis stem	Ti -Alloy	114	0.34
Hip cartilage	Cartilage	0.004	0.4

Fig. 2. Loading and boundary conditions in lower limbs model with hip osteoarthritis.

3. Results & Discussion

3.1 Stress adaptation in operated and non-operated limbs

THA patients were at risk of developing other joint diseases if the biomechanical function of lower limb did not return to normal[5]. The problem was projected not only in the operated limb, but also in the non-operated limb. Unfortunately, most researches had ignored the contribution and adaptation in non-operated limb[11,12] either in rehabilitation or biomechanical studies.

Stress distribution in the operated (right) and non-operated (left) limbs are illustrated in Fig.3(a) at anterior view. Proximal and distal regions of the limb were identified to experience most changes in stress variation. The number of elements at the respective regions were selected to calculate the peak value of the maximum principal stress. In the THA model, the stress magnitude was predicted to be lower in the proximal and middle shaft regions of the limb. The peak stress value was reduced from 27.33 MPa in hip OA model to 10.07 MPa (THA model) which presents 63.15 % of the change as shown in Fig.3(b). This phenomenon is known as stress shielding problem and is expected to lead to bone resorption. Furthermore, the bone is expected to become weaker[13] in the respective region. The higher modulus material of the prosthesis stem rather than the surrounding bone tissues contribute to such biomechanical behavior. More load was transferred to the stiffer material stem and concurrently reduced the stress on the surrounding bone. In the areas of reduced load, the skeleton conserves as much bone tissue as is required to uphold the lower load level[14]. Generally, the skeleton in the unloaded areas is weaker and at a higher risk of fracture under an unpredicted high force.

The distal region of the THA limb indicates dissimilar findings. The peak magnitude of stress was found to be higher when compared to the hip OA limb with increments up to 43.24 % (from 23.39 to 33.50 MPa). The possibility of bone thickening at a particular region after a period of time was expected. This incident potentially happens as the major load that was previously dominated by the prosthesis was transferred to the bone. The higher magnitude was found to start at the distal end of the prosthesis.

Stress distributions in the right limb before and after THA are shown in Fig.4. Although the stress variation was not as high as the operated limb, the findings suggested that the presence of the implant modified the stress pattern. The amendment of weight distribution might contribute to the findings. Similar stress patterns were observed in both limbs, but in different magnitudes. The comparison in Fig. 4 (b) signified that the proximal region experienced a 15.70% reduction while the distal region experienced a reduction of 3.34%. The whole limb was expected to experience reduced stress after arthroplasty. The minimum changes of stress along the limb suggested that it may contribute to gait imbalance at the initial stage. In correlation with rehabilitation studies, the non-operated limb also experienced gait adaptation, although not as much in the operated limb[11].

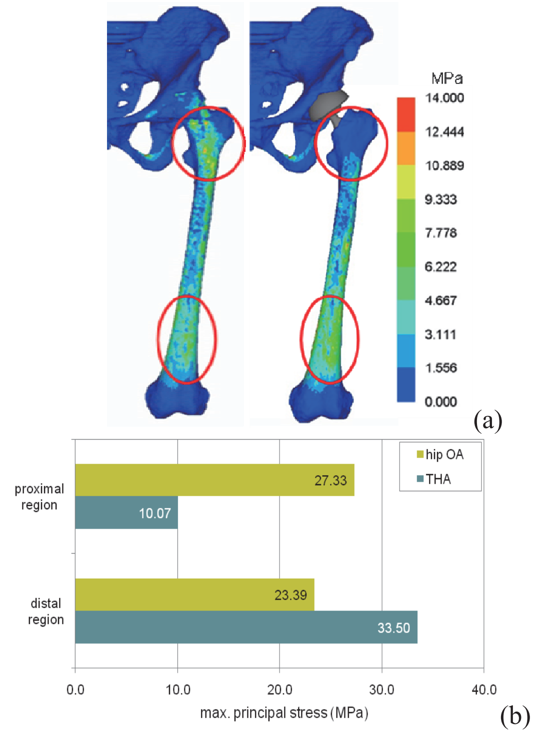

Fig. 3. (a) Changes of stress variation in the left limb with hip OA and THA (b) Highest magnitude of principal stress in the left limb at the proximal and distal regions.

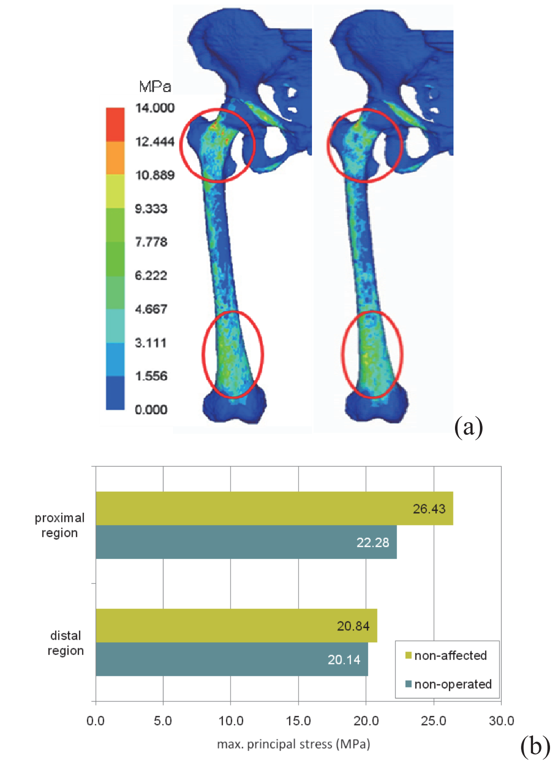

Fig. 4. (a) Stress distribution in the right femur before (left) and after (right) THA (b) Highest magnitude of principal stress in the right limb at the proximal and distal regions.

3.2 Prediction of bone remodeling in the lower limbs with THA over 5 years

Projection of bone remodeling in lower limbs after several years was discussed on the resulting bone mineral density (BMD). The process of bone remodeling was predicted by the adaptive changes in bone density life equations which were developed by Gesso[15,16]. The remodeling analysis was computationally conducted using the implemented sub - program in commercial biomedical software, Mechanical Finder v6.1.

Alteration of bone mineral density in the lower limb with THA over 5 years is illustrated in Fig. 5. The cross sectional view of the femoral shafts suggested that the bone density was reduced at the proximal and middle region throughout the years at both limbs. While, the distal region of the shafts indicated an increment of BMD. This finding correlates to the gain in the principal stress after THA. The changes were predicted to be high between year 0 and year 1, especially at the hip joint where the load was transferred from the pelvic to the femoral shafts. From year 1 onwards, the changes were mostly dominant at the femoral shafts and minimal

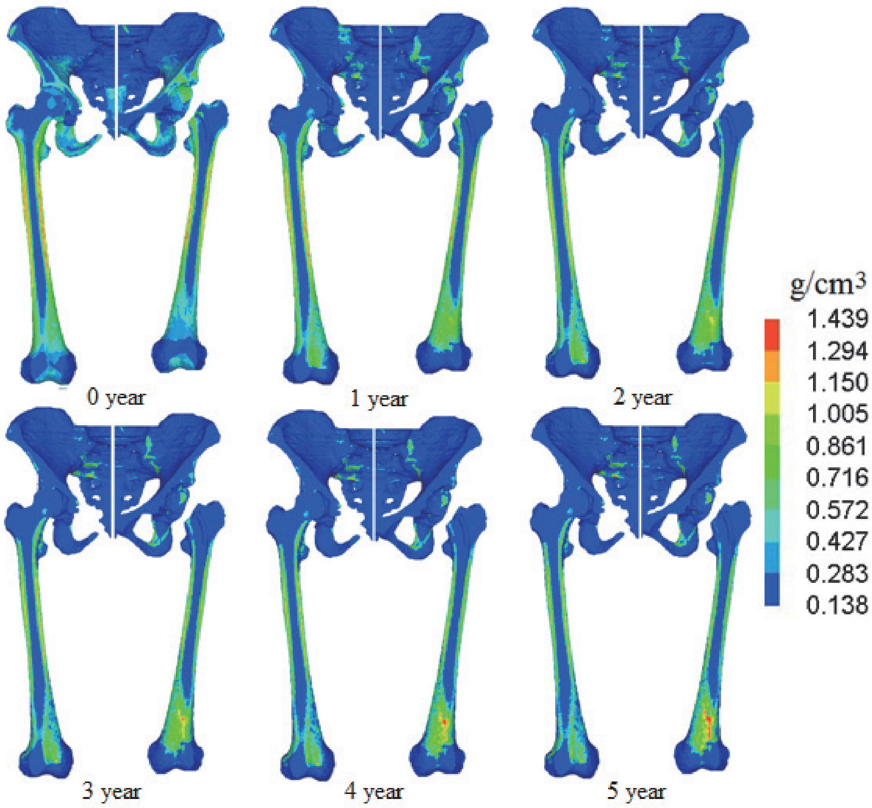

Fig. 5. Changes of bone mineral density (BMD) distribution in the lower limbs with THA after 5 years at the cross-sectional anterior view.

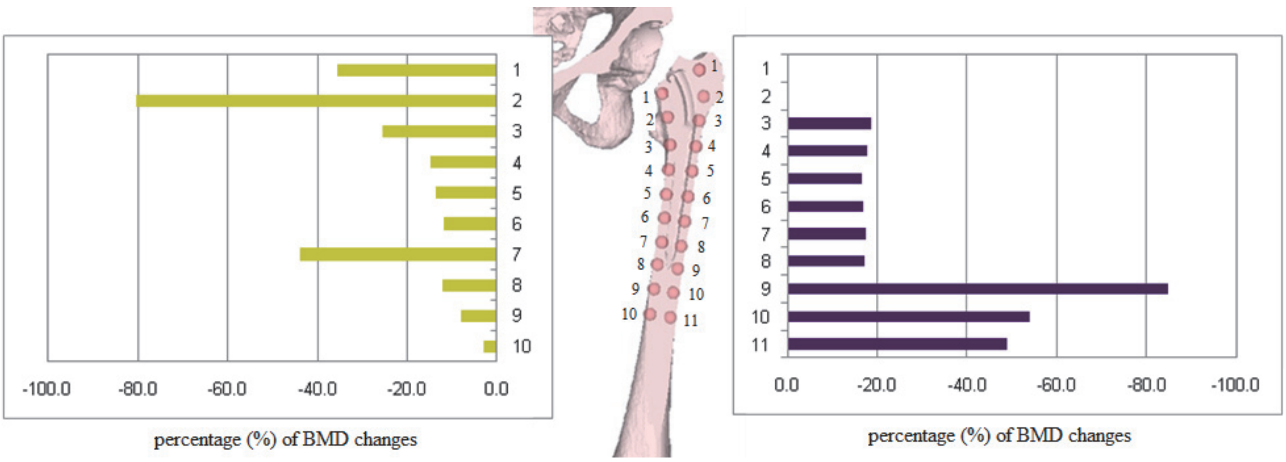

Fig. 6. Prediction of the possibility of bone loss in operated limb after 5 years at the medial (left) and lateral (right) aspects.

elsewhere. Similar clinical findings were reported by Venesmaa et al.[17] where the bone loss, acute at the initial phase while further losses was minimal in relation to the normal ageing bone. The operated limb indicated more changes as compared to the non-operated limb. Prediction of early bone loss was principally a consequence of stress shielding and bone disuse atrophy[17,18]. The findings recommended that the remodeling process of bone resorption and thickening problems may become worse after a period of time. Besides, the possibility of changes in bone mass and architecture was also projected as the bone will modify itself to adapt the new biomechanical environment[19]. All of these possibilities are believed to contribute to the instability and imbalance gait of the THA patients.

Critical adaptation was expected to occur in the operated limb. Fig. 6 shows the percentage of BMD change around the prosthesis stem. Several points were selected at the lateral and medial aspects to calculate the percentage of bone density change over 5 years and to further estimate the bone loss. Although the bone loss is not favorable to adaptive bone remodeling, consideration of changes in BMD values was sufficient to be taken as a baseline to assess bone loss after surgery[20]. In medial aspects, bone loss was predicted to be high in point 1, 2 and 7 (up to 80%). The result was expected as a high stress was concentrated in the respective region due to the bending effects of the prosthesis stem. The higher bone loss was also reported in Gruen zone 7 by Venesmaa et al.[17] which was presented as point 1 and 2 in this study. The respective areas were potentially becoming the weakest part and most probable location for failure to start. The bone loss was minimum in the middle and distal region of the femoral shaft. Different patterns was predicted in lateral aspects. No bone loss was predicted to occur in point 1 and 2 which are referring to the greater trochanter region of femur. An average of 19% of bone loss was estimated along the prosthesis stem, but it increases exponentially from the distal tip of the stem. The highest value predicted in the region was parallel to that reported by Herrera et al.[20]. The bending effects from the prosthesis shaft were assumed to influence the higher percentage.

Computational prediction conducted in this study showed overestimate difference (percentage of change) as compared to clinical findings[17,20]. However, the findings are sufficient to predict the bone remodeling behavior and regions in femoral shaft after arthroplasty. The weakness was contributed by the limitations in the present study. Contribution of associated muscles was not considered in the analysis. Gait stability was primarily supported by muscles in hip joints for proper balancing and adjustment. Different physiological loading can be considered to demonstrate the correlations between the computational findings and gait performance.

4. Conclusion

Development of a 3D inhomogeneous model of lower limbs had appropriately contributed to predict body weight distribution in the lower limbs. Predictions of stress adaptation and bone remodeling were properly defined on the resulting principal stress and bone mineral density for hip OA and THA models. Reduction of stress in THA limbs as compared to hip OA limbs explained the resorption phenomenon. Higher stress adaptation and bone loss were predicted in the operated limb due to the presence of prosthesis stem. The proximal and distal region of the femoral shafts indicated higher stress adaptation. Bone loss was predicted to be high at the proximal medial and distal lateral of the operated limb due to the bending effects of prosthesis stem.

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References

1) B. Van Rietbergen, R. Huiskes, H. Weinans, D.R. Sumner, T.M. Turner and J.O. Galante, *J. Biomech.,* **26**, 369 (1993).

2) C. Boyle and I.Y. Kim, *J. Biomech.,* **44**, 1722 (2011).

3) L. Gracia, E. Ibarz, J. Cegoñino, A. Lobo-Escolar, S. Gabarre, S. Puértolas, E. López, J. Mateo and A. Herrera, in *Finite Element Analysis - From Biomedical Applications to Industrial*, ed. by D. Moratal, InTech, Crotia, p. 217 (2012).

4) Y. Hayaishi, H. Miki, T. Nishii, T. Hananouchi, H. Yoshikawa and N. Sugano, *J. Arthroplasty,* **22**, 1208 (2007).

5) G. Holnapy, A. Iiiyes and R. M. Kiss, *J. Electromyogr. Kinesiol.,* **23**, 966 (2013).

6) D. Bennet, L. Ogonda, D. Ellitt, L. Humphreys, M. Lawlor and D. Beverland, *J. Arthroplasty*, **22**, 490 (2007).

7) R.M. Kiss, *J. Electromyogr. Kinesiol.,* **20**, 1044 (2010).

8) J.H. Keyak, H.B. Skinner and J.A. Fleming, *J. Orthop. Res.*, **19**, 539 (2001).

9) Z. Wang and K.M. Newell, *Exp. Brain Res.*, **222**, 333 (2012).

10) G. Recnik, V. Kralj-Iglic, A. Iglic, V. Antolic, S. Kramberger and R. Vengust, *Clin. Biomech.*, **22**, 1119 (2007).

11) M.L. Beaulieu, M. Lamontagne and P.E. Beaule, *Gait Posture*, **32**, 269 (2010).

12) K.C. Foucher, D.E. Hurwitz and M.A. Wimmer, *J. Biomech.*, **40**, 3432 (2007).

13) C. J. Sychterz and C. A. Engh, *Clin. Orthop. Relat. Res.*, **322**, 285 (1996).

14) I.R. Reid, *Bone*, **31**, 547 (2002).

15) H. Gesso, *Jpn. J. Clin. Biomech.*, **16**, 213 (1995).

16) H. Gesso, *Jpn. J. Clin. Biomech.*, **18**, 33 (1997).

17) P.K. Venesmaa, H.P.J. Krojer, J.S. Jurvelin, H.J.A. Miettinen, O.T. Suomalainen and E.M. Alhava, *Acta Orthop. Scand.*, **74**, 31 (2003).

18) R. Huiskes, *Clin. Orthrop. Res.*, **261**, 27 (1990).

19) H. Gong, L. Kong, R. Zhang, J. Fang and M. Zhao, *J. Bionic Eng.*, **10**, 350 (2013).

20) A. Herrera, S. Rebollo, E. Ibarz, J. Mateo, S. Gabarre and L. Gracia, *J. Arthroplasty*, **29**, 90 (2014).