Identification of Flexural Modulus and Poisson's Ratio of Fresh Femoral Bone Based on a Finite Element Model

https://doi.org/10.3991/ijoe.v18i04.28939

Kriengkrai Nabudda[1], Jarupol Suriyawanakul[1](✉), Kiatfa Tangchaichit[1],
Nantiwat Pholdee[1], Weerachai Kosuwon[2], Taweechok Wisanuyotin[2],
Kamolsak Sukhonthamarn[2]
[1] Faculty of Engineering, Khon Kaen University, Khon Kaen, Thailand
[2] Faculty of Medicine, Khon Kaen University, Khon Kaen, Thailand
jarupol@kku.ac.th

Abstract—Finite element analysis (FEA) is increasingly applied to medicine because it could increase accuracy and rapid outcomes. However, there is a lack of the method to determine Young's modulus and Poisson's ratio for fresh femoral bone and the mathematical principle's optimization for calculating nonuniform configuration. This study aimed to investigate the surrogate model for the optimization method to determine Young's modulus and Poisson's ratio of the fresh femoral bone. Young's modulus and Poisson's ratio obtained 20 ranked pairs by the Latin hypercube sampling method. The values were calculated in the finite element for root mean square error (RMSE) and were then used for solutions by a quadratic function, radial basis function (RBF), and Kriging (KG). The lowest RMSE value was 0.1518 for the RBF method, with the young's modulus at 304.4756 and the Poisson's ratio at 0.3334. The current study identified the RBF technique to determine the properties of the femoral bone. Moreover, the RBF procedure might apply to other long bones because of the comparable non-uniform configuration.

Keywords—FEA, surrogate model, biomechanics test, fresh femoral bone, RBF, KG

1 Introduction

In advance, the ability to predict femoral bone surgeries will have good efficiency on the surgery, making accuracy and precision. To be able to make a prediction, that is necessary to know the properties of the fresh femoral bone and the treatment method, which can be finite element analysis (FEA) in advance to make the treatment more efficient. Therefore, the determination of the properties of the fresh femoral bone has needed to be able finite element analysis to make a model in prediction.

The finite element analysis is currently widely applied in medical practice to determine the optimum for orthopedic surgery [1], [2]. Previous studies identified Young's modulus for cortical bone from compression and cancellous bone from bending under machine testing [3], [4]. Deformation, including Young's modulus and Poisson's ratio, calculated from the natural fresh femoral bone, has a vital role for FEA. The configuration of bone is nonuniform, but the common input function in the testing machine is a uniform model. Thus, Young's modulus is an approximate value [5]. There is a lack of the method to determine Young's modulus and Poisson's ratio for fresh femoral bone and the mathematical principle's optimization for calculating nonuniform configuration. Latin hypercube sampling (LHS) is the most common procedure for designing computer experiments. Various studies presented that LHS had a simple and effective way to be accepted [6]. However, there were a variety of techniques such as quadratic polynomial function, radial basis function (RBF), and Kriging method (KG) were also introduced to computing the model [7], [8]. There is defined validity of the element size that is caused the lowest error to finite element analysis of the radius bone to determine the appropriate treatment method [9]. The X-ray method was used to determine the strength of the femoral bone validated by the finite element method that occurs as a result of the distribution of strain energy and the deformation on the femur [10], [11]. Femoral bone strength was analyzed by CT scan method, using finite element method to analyze a failure of the femoral using bone density obtained from the baseline quantitative CT scans [12] – [17]. Finite element analysis to find stress distribution for femoral bone was used to determine a failure of femoral bone and determine deformation when the load was applied on femoral and then define the stiffness for femoral fixation [18] – [22]. The biomechanics test of synthetic bone mechanically strengthens the proximal femur by the load to failure to determine stiffness and toughness [23], [24]. Biomechanics testing metacarpal bone 3-point bending and FEA were validated in experimental studies that a result in further reliable and simple FEA of biomechanical applications of different metacarpal bones [25]. The biomechanical test for femoral bone was validated with FEA to determine the deformation, the stress, and the stiffness that use to be an able prediction for surgical treatment of the femur [26] – [29]. The study optimization was analyzed gene expression data, the evolution algorithm was applied and combined with the advantages of crossover strategy [30], [31]. The finite element method was used to study thermal conditions for different filling gases that have been resolved [32].

This study aims to find the surrogate model for the optimization method to determine Young's modulus and Poisson's ratio property for a nonuniform femoral bone with the mathematical principle.

2 Materials and methods

2.1 Biomechanical testing

Determining a uniform geometry of fresh femoral bone, a cylindrical geometry from the BLUEHILL program of ElectroPuls E10000 machine approximates Young's modulus and Poisson's ratio. However, the analysis in nonuniform shapes must be calculated by engineering methods such as FEA and optimization. A previous study demonstrated the internal fixation for femoral bone with FEA to identify the best fixation model and validated with biomechanics testing for Young's modulus and Poisson's ratio property [5].

The femoral model was created from the Digital Imaging and Communications in Medicine (DICOM) format of computerized tomography (CT) scan of the fresh femoral cadaver, which was then exported to MIMICS (Materialise, Leuven, Belgium). The samples were then exported to SolidWorks software (SolidWorks Corp., MA, USA) and PowerShape (Autodesk Inc., San Rafael, California, USA) to create the femoral model with a long bone at 420 mm in length and a diameter of the midshaft at 25 mm. The configurations were exported to ANSYS workbench software (ANSYS Inc., Canonsburg, Pennsylvania, USA) for deformation analysis of fresh femoral bone property shown in Figure 1. The compression was performed with the INSTRON ElectroPuls E10000 machine (INSTRON Co., Ltd., High Wycombe, Bucks, UK) shown in Figure 2.

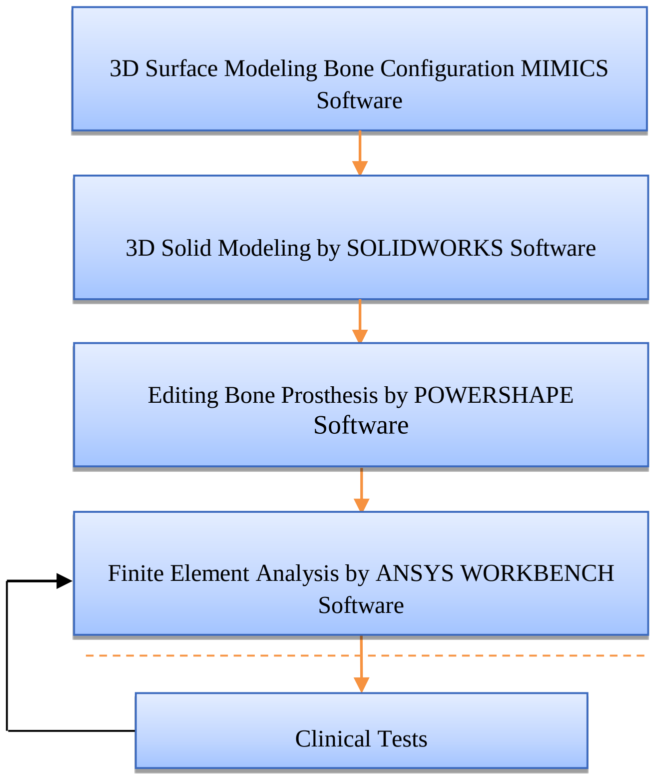

Fig. 1. The workflow for the validated biomechanics testing

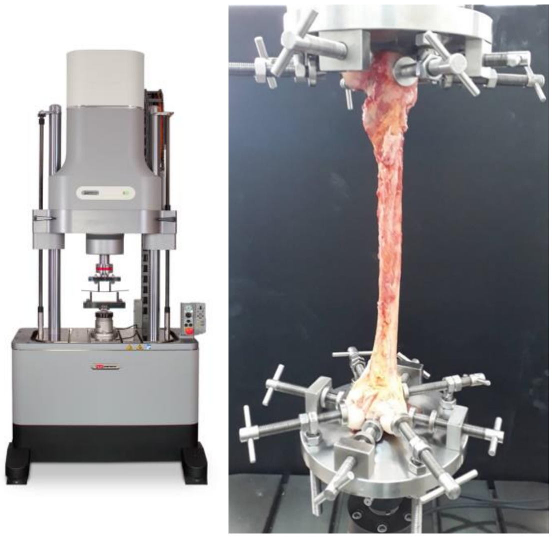

Fig. 2. Biomechanics set up the fresh femoral bone test

The vertical direction on the fresh-cadaveric femur (bone length at 420 mm and mid-shaft diameter at 25 mm) was conducted with a 50 N preload. The load was applied at the rate of 12.5 N/s to a maximum load of 1500 N and displacement at 3.26 mm under BLUEHILL program version 3 (INSTRON Co., Ltd., High Wycombe, Bucks, UK) shown in Figure 3.

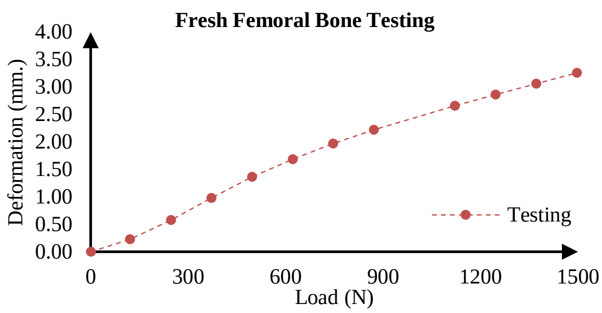

Fig. 3. The load and deformation for a fresh femoral bone test

2.2 Finite element analysis

The study was identified a mesh quality at 1 to 1.4 mm for FE models for the femoral bone with a reasonable accuracy comparable with our finding [9]. Therefore, the element sizes of femoral bone that were optimized for FEA should not exceed 4 mm for accuracy to determine due to deformation.

The boundary condition of FEA on fresh femoral bone was compression force on the axial direction for 1500 N in Figure 4a. Mesh method on the fresh femoral bone, with 4 mm in size, was generated for the hexahedral mesh methods. The FE was demonstrated nodes and elements at 164106 and 48023 for hexahedral in Figure 4b.

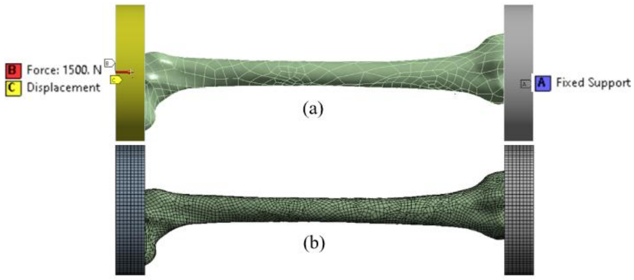

Fig. 4. FEA (a) geometry applied force acting on the femur, (b) hexahedral mesh method

The definite range of Young's modulus (250-450) and Poisson's ratio (0.1-0.4) were validated with biomechanics testing. The deformations were then compared to the root mean square error method (RMSE) from Latin hypercube sampling (LHS).

3 Results

The current study demonstrated that the element sizes of 1 to 4 mm exhibited a lower accuracy of deformation at 2.98 mm compared to the feature sizes of 5 to 6 mm and sizes 7 to 10, which showed a deformation at 2.97 mm and 2.92 mm, respectively.

Deformation for fresh femoral bone properties from biomechanics testing Young's modulus was 370.3 MPa, and Poisson's ratio was 0.3 on compress load at 1500 N from hexahedral mesh analysis shown in Figure 5.

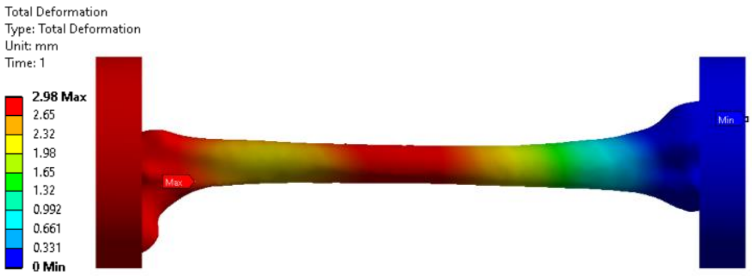

Fig. 5. The deformation at 2.98 mm for hexahedral elements with a size of 4 mm

Young's modulus and Poisson's ratio from LHS were demonstrated in Table 1, which determined the result of another surrogate model and compared RMSE. The quadratic function had the maximum deformation at 3.4271 mm under the boundary condition of Young's modulus and Poisson's ratio at 312.2370 MPa and 0.4000, respectively shown in Figure 6.

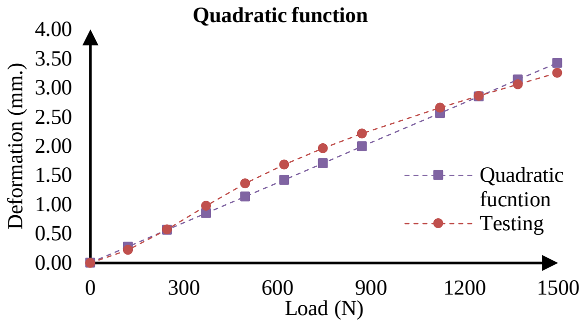

Fig. 6. Graph exhibited a comparison of biomechanics testing and quadratic polynomial

Radial basis function was exhibited the maximum deformation for 3.5260 mm under the boundary condition of Young's modulus and Poisson's ratio at 304.4756 MPa and 0.3334, respectively shown in Figure 7.

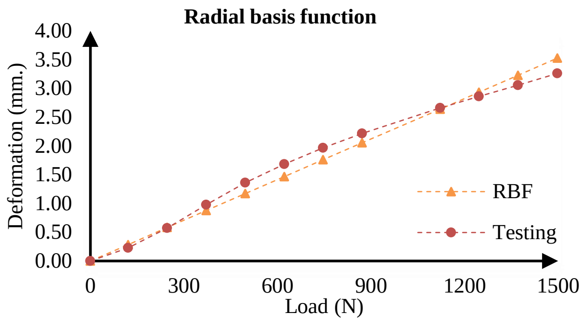

Fig. 7. Graph exhibited a comparison of biomechanics testing and radial basis function

Kriging had the maximum deformation at 3.4447 mm under the boundary condition of Young's modulus and Poisson's ratio at 311.5012 MPa and 0.3452, respectively shown in Figure 8.

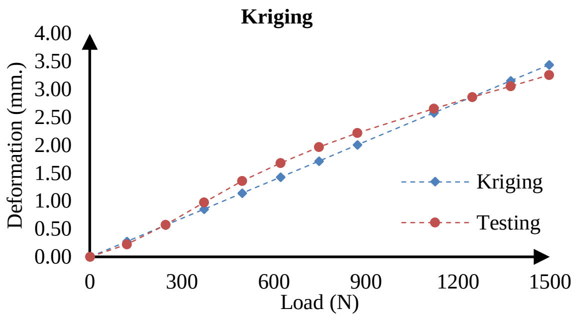

Fig. 8. Graph exhibited a comparison of biomechanics testing and Kriging

The comparisons among 3 methods of RMSE (the quadratic polynomial method, RBF method, and KG method) calculated RMSE was identified from the KG method at 0.1438 with Young's modulus and Poisson's ratio at 311.5012 MPa and 0.3452, respectively shown in Table 1.

Table 1. Latin hypercube sampling with 20-order pairs to determine the root mean square error in finite element analysis

Young's Modulus (MPa)	Poisson's Ratio	Validated RMSE
362.0000	0.2320	0.3401
334.1752	0.2770	0.2228
345.3917	0.1502	0.2654
405.0000	0.3662	0.5195
425.9057	0.3130	0.5889
373.3044	0.1099	0.3839
355.0000	0.3433	0.3167
447.8086	0.2581	0.6558
295.0000	0.1384	0.1774
386.8007	0.2905	0.4458
257.3031	0.3018	0.4216
393.2864	0.1654	0.4654
304.4756	0.3334	0.1518
263.2318	0.1825	0.3791
315.0000	0.1970	0.1576
275.0000	0.3775	0.2747
324.8165	0.3880	0.1924
417.8332	0.2123	0.5566
437.5808	0.1212	0.6192
286.6599	0.2402	0.2125

Simultaneously, minimum RMSE was presented in the RBF method at 0.1518 shown in Table 2.

Table 2. Optimization to determine Young's modulus and Poisson's ratio by surrogate model

Quadratic Polynomial			
Young's Modulus	Poisson's Ratio	Calculated RMSE*	Validated RMSE*
312.2370	0.4000	0.2313	0.1572
RBF**			
Young's Modulus	Poisson's Ratio	Calculated RMSE*	Validated RMSE*
304.4756	0.3334	0.1518	0.1518
KG***			
Young's Modulus	Poisson's Ratio	Calculated RMSE*	Validated RMSE*
311.5012	0.3452	0.1438	0.1547

* RMSE= root mean square error, ** RBF= radial basis function, *** KG=Kriging

4 Discussion

This study has no limitations. Firstly, we validated from a single fresh femoral bone which may be difficult to exhibit the universal femoral properties. Secondly, we used a method for evaluation, but we tried to select the most common and frequently used way to evaluate. In this work, three methods have been selected as the polynomial function method, RBF method, and KG method as shown in Figure 9. Comparative all methods, we were found that the lowest RMSE was the optimization method in this work.

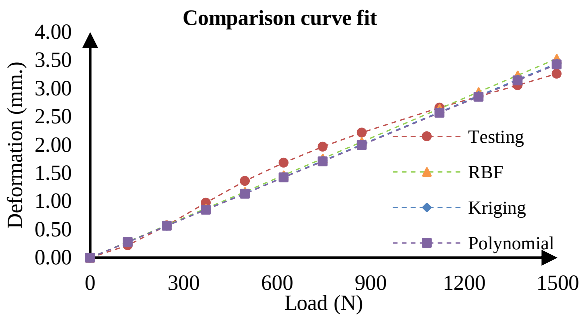

Fig. 9. Graph exhibited a comparison curve fit of biomechanics testing and optimization methods

The results obtained from this study can be used to define to property another bone such as the radius, the tibia, the clavicle, etc. If the calculation has accurate and precise for finite element analysis then the surgical have predictable in advance for selecting the appropriate surgery that is extremely valuable for treatment. In addition, this can also study the properties of materials that are nonuniform with finite element method by surrogate model.

5 Conclusion

In conclusion, FEA is applied to orthopedic surgery in various works since it could save time and costs before analyzing a natural bone setting. The complexity of human bones could make it difficult for calculation and analysis. The mathematic model, which has excellent accuracy, should be validated with biomechanical testing before application in a clinical setting. Surrogate models are the optimization method to determine the result of Young's modulus and Poisson's ratio.

Therefore, the model should introduce the accuracy and rapid application to analyze the fresh femoral bone's nonuniform. We conducted the FEA, optimization, and biomechanics testing to determine a resultant of Young's modulus and Poisson's ratio property. Moreover, the surrogate model should have a minimum RMSE to indicate the most proper method. From the current study, the KG method had the lowest approximate RMSE from the calculation.

However, the biomechanical testing demonstrated RBF was the lowest point. Although the KG method showed the calculated RMSE at 0.1438, which was less than other methods, RBF demonstrated the lowest RMSE from validated with biomechanical testing. Therefore, RBF should be the method for determining the deformation property after validation.

6 Acknowledge

Yuichi Kasai MD, Ph.D. proofreading in English.

7 Compliance with ethical standards

Ethics Committee in Human Research HE611524.

8 References

[1] M. T. Bahia, M. B. Hecke, and E. G. F. Mercuri (2019). "Image-based anatomical reconstruction and pharmaco-mediated bone remodeling model applied to a femur with subtrochanteric fracture: A subject-specific finite element study," Med Eng Phys, vol. 69, pp. 58-71. http://doi.org/10.1016/j.medengphy.2019.05.005

[2] E. Basafa, R. S. Armiger, M. D. Kutzer, S. M. Belkoff, S. C. Mears, and M. Armand. (2013). "Patient-specific finite element modeling for femoral bone augmentation," Med Eng Phys, vol. 35, no. 6, pp. 860-5. http://doi.org/10.1016/j.medengphy.2013.01.003

[3] M. Blondel, Y. Abidine, P. Assemat, S. Palierne, and P. Swider. (2020). "Identification of effective elastic modulus using modal analysis; application to canine cancellous bone," J Biomech, vol. 110, p. 109972. http://doi.org/10.1016/j.jbiomech.2020.109972

[4] G. Odin, C. Savoldelli, P. O. Bouchard, and Y. Tillier. (2010). "Determination of Young's modulus of mandibular bone using inverse analysis," Med Eng Phys, vol. 32, no. 6, pp. 630-7. http://doi.org/10.1016/j.jbiomech.2021.110315

[5] T. Wisanuyotin, W. Sirichativapee, P. Paholpak, W. Kosuwon, and Y. Kasai. (2020). "Optimal configuration of a dual locking plate for femoral allograft or recycled autograft bone fixation: A finite element and biomechanical analysis," Clin Biomech (Bristol, Avon), vol. 80, p. 105156. http://doi.org/10.1016/j.clinbiomech.2020.105156
[6] H. Ziaeipoor, M. Taylor, M. Pandy, and S. Martelli. (2019). "A novel training-free method for real-time prediction of femoral strain," J Biomech, vol. 86, pp. 110-116. http://doi.org/10.1016/j.jbiomech.2019.01.057
[7] W. Phukaokaew, S. Sleesongsom, N. Panagant, and S. Bureerat. (2019). "Synthesis of four-bar linkage motion generation using optimization algorithms," Advances in Computational Design, vol. 4, no. 197-210. http://doi.org/10.12989/acd.2019.4.3.197
[8] N. Pholdee, H. M. Baek, S. Bureerat, and Y.-T. Im. (2015). "Process optimization of a non-circular drawing sequence based on multi-surrogate assisted meta-heuristic algorithms," Journal of Mechanical Science and Technology, vol. 29, no. 8, pp. 3427-3436. http://doi.org/10.1007/s12206-015-0741-6
[9] S. P. Vaananen, L. Grassi, G. Flivik, J. S. Jurvelin, and H. Isaksson. (2015). "Generation of 3D shape, density, cortical thickness and finite element mesh of proximal femur from a DXA image," Med Image Anal, vol. 24, no. 1, pp. 125-134. http://doi.org/10.1016/j.media.2015.06.001
[10] D. O'Rourke, B. R. Beck, A. T. Harding, S. L. Watson, P. Pivonka, and S. Martelli. (2021). "Assessment of femoral neck strength and bone mineral density changes following exercise using 3D-DXA images," J Biomech, vol. 119, p. 110315. https://doi.org/10.1016/j.jbiomech.2021.110315
[11] D. Nolte and A. M. J. Bull. (2019). "Femur finite element model instantiation from partial anatomies using statistical shape and appearance models," Med Eng Phys, vol. 67, pp. 55-65. http://doi.org/10.1016/j.medengphy.2019.03.007
[12] F. Eggermont et al. (2020). "Patient-specific finite element computer models improve fracture risk assessments in cancer patients with femoral bone metastases compared to clinical guidelines," Bone, vol. 130, p. 115101. http://doi.org/10.1016/j.bone.2019.115101
[13] J. Li, P. Yin, L. Zhang, H. Chen, and P. Tang. (2019). "Medial anatomical buttress plate in treating displaced femoral neck fracture a finite element analysis," Injury, vol. 50, no. 11, pp. 1895-1900. http://doi.org/10.1016/j.injury.2019.08.024
[14] Y. Katz, G. Dahan, J. Sosna, I. Shelef, E. Cherniavsky, and Z. Yosibash. (2019). "Scanner influence on the mechanical response of QCT-based finite element analysis of long bones," J Biomech, vol. 86, pp. 149-159. http://doi.org/10.1016/j.jbiomech.2019.01.049
[15] J. V. Inacio, A. Malige, J. T. Schroeder, C. O. Nwachuku, and H. L. Dailey. (2019). "Mechanical characterization of bone quality in distal femur fractures using pre-operative computed tomography scans," Clin Biomech (Bristol, Avon), vol. 67, pp. 20-26. http://doi.org/10.1016/j.clinbiomech.2019.04.014
[16] C. Falcinelli, A. Di Martino, A. Gizzi, G. Vairo, and V. Denaro. (2019). "Mechanical behavior of metastatic femurs through patient-specific computational models accounting for bone-metastasis interaction," J Mech Behav Biomed Mater, vol. 93, pp. 9-22. http://doi.org/10.1016/j.jmbbm.2019.01.014
[17] M. Ramezanzadehkoldeh and B. H. Skallerud. (2017). "MicroCT-based finite element models as a tool for virtual testing of cortical bone," Med Eng Phys, vol. 46, pp. 12-20. http://doi.org/10.1016/j.medengphy.2017.04.011
[18] L. Tianye et al. (2019). "Finite element analysis of different internal fixation methods for the treatment of Pauwels type III femoral neck fracture," Biomed Pharmacother, vol. 112, p. 108658. http://doi.org/10.1016/j.biopha.2019.108658

[19] S. Jade, K. H. Tamvada, D. S. Strait, and I. R. Grosse. (2014). "Finite element analysis of a femur to deconstruct the paradox of bone curvature," J Theor Biol, vol. 341, pp. 53-63. http://doi.org/10.1016/j.jtbi.2013.09.012
[20] W. S. Enns-Bray, J. S. Owoc, K. K. Nishiyama, and S. K. Boyd. (2014). "Mapping anisotropy of the proximal femur for enhanced image based finite element analysis," J Biomech, vol. 47, no. 13, pp. 3272-8. http://doi.org/10.1016/j.jbiomech.2014.08.020
[21] I. A. Takacs, A. I. Botean, M. Hardau, and S. Chindris. (2015). "Displacement-stress Distribution in a Femoral Bone by Optical Methods," Procedia Technology, vol. 19, pp. 901-908. http://doi.org/10.1016/j.protcy.2015.02.129
[22] S. Abe, N. Narra, R. Nikander, J. Hyttinen, R. Kouhia, and H. Sievanen. (2018). "Impact loading history modulates hip fracture load and location: A finite element simulation study of the proximal femur in female athletes," J Biomech, vol. 76, pp. 136-143. http://doi.org/10.1016/j.jbiomech.2018.05.037
[23] S. A. Hockett, J. T. Sherrill, M. Self, S. C. Mears, C. L. Barnes, and E. M. Mannen. (2021). "Augmentation of core decompression with synthetic bone graft does not improve mechanical properties of the proximal femur," J Mech Behav Biomed Mater, vol. 115, p. 104263. http://doi.org/10.1016/j.jmbbm.2020.104263
[24] M. Marco, E. Giner, R. Larraínzar-Garijo, J. R. Caeiro, and M. H. Miguélez. (2018). "Modelling of femur fracture using finite element procedures," Engineering Fracture Mechanics, vol. 196, pp. 157-167. http://doi.org/10.1016/j.engfracmech.2018.04.024
[25] İ. K. Yılmazçoban. (2018). "Numerical Analysis of the Lamb Metacarpal Bone: Approximation of Bending Tests," Sakarya University Journal of Science, pp. 1-1. http://doi.org/10.16984/saufenbilder.333519
[26] Y. Katz, O. Lubovsky, and Z. Yosibash. (2018). "Patient-specific finite element analysis of femurs with cemented hip implants," Clin Biomech (Bristol, Avon), vol. 58, pp. 74-89. http://doi.org/10.1016/j.clinbiomech.2018.06.012
[27] I. T. Haider, J. Goldak, and H. Frei. (2018). "Femoral fracture load and fracture pattern is accurately predicted using a gradient-enhanced quasi-brittle finite element model," Med Eng Phys, vol. 55, pp. 1-8. http://doi.org/10.1016/j.medengphy.2018.02.008
[28] E. Dall'Ara, R. Eastell, M. Viceconti, D. Pahr, and L. Yang. (2016). "Experimental validation of DXA-based finite element models for prediction of femoral strength," J Mech Behav Biomed Mater, vol. 63, pp. 17-25. http://doi.org/10.1016/j.jmbbm.2016.06.004
[29] K. K. Nishiyama, S. Gilchrist, P. Guy, P. Cripton, and S. K. Boyd. (2013). "Proximal femur bone strength estimated by a computationally fast finite element analysis in a sideways fall configuration," J Biomech, vol. 46, no. 7, pp. 1231-6. http://doi.org/10.1016/j.jbiomech.2013.02.025
[30] M. Hamim, I. El Moudden, M. D Pant, H. Moutachaouik, and M. Hain. (2021). "A Hybrid Gene Selection Strategy Based on Fisher and Ant Colony Optimization Algorithm for Breast Cancer Classification," International Journal of Online and Biomedical Engineering (iJOE), vol. 17, no. 02. https://doi.org/10.3991/ijoe.v17i02.19889
[31] Q. Wan, M.-J. Weng, and S. Liu. (2019). "Optimization of Wireless Sensor Networks Based on Differential Evolution Algorithm," International Journal of Online and Biomedical Engineering (iJOE), vol. 15, no. 01. https://doi.org/10.3991/ijoe.v15i01.9786
[32] M. Maaspuro. (2021). "Novel Ideas for Thermal Management of Filament LED Light Bulbs" International Journal of Online and Biomedical Engineering (iJOE), vol. 17, no. 08. https://doi.org/10.3991/ijoe.v17i08.23695

9 Authors

Kriengkrai Nabudda studies in PHD program mechanical engineering at the Department of Mechanical Engineering, Faculty of Engineering, Khon Kaen University. The current research interests are Finite Element Analysis, Biomechanics, and Energy Conservation.

Jarupol Suriyawanakul is an Assistance Professor at the Department of Mechanical Engineering, Faculty of Engineering, Khon Kaen University, as a Lecturer. His current research interests include Artificial Intelligence, Computational Fluid Dynamics, Biomechanics, and Finite Element Analysis.

Kiatfa Tangchaichit is an Associate Professor at the Department of Mechanical Engineering, Faculty of Engineering, Khon Kaen University, as a Lecturer. His current research interests include Energy Conservation, Computational Fluid Dynamics, and Finite Element Analysis.

Nantiwat Pholdee is an Associate Professor at the Department of Mechanical Engineering, Faculty of Engineering, Khon Kaen University, as a Lecturer. His current research interests include Artificial Intelligence, Optimization, and Finite Element Analysis.

Weerachai Kosuwon is a Professor at the Department of Orthopaedic, Faculty of Medicine, Khon Kaen University. His current research interests include Hip & Knee Reconstruction, Biomechanics, and Finite Element Analysis.

Taweechok Wisanuyotin is an Associate Professor at the Department of Orthopaedic, Faculty of Medicine, Khon Kaen University, as a Lecturer. His current research interests include Orthopaedic Oncology, Biomechanics, and Finite Element Analysis.

Kamolsak Sukhonthamarn joined at Department of Orthopaedic, Faculty of Medicine, Khon Kaen University, as a Lecturer. His current research interests include Hip & Knee Reconstruction, Biomechanics, and Finite Element Analysis.

Article submitted 2021-12-17. Resubmitted 2022-01-18. Final acceptance 2022-01-19. Final version published as submitted by the authors.