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ORIGINAL ARTICLE

EVALUATION OF A BONE REINFORCEMENT TECHNIQUE USING FINITE ELEMENT ANALYSIS

AVALIAÇÃO DE UMA TÉCNICA DE REFORÇO ÓSSEO COM O MÉTODO DE ELEMENTOS FINITOS

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ABSTRACT

Objectives: To compare the results of a simulated fall on the greater trochanter in the proximal portion of a synthetic femur before and after femoral reinforcement with tricalcium phosphate bone cement (TP) and polymethyl methacrylate (PMMA), using finite element analysis (FEA). Methods: Using two synthetic proximal femurs, a FEA simulating a fall on the greater trochanter was performed, using the Bi-directional Evolutionary Structural Optimization (BESO) program. For this analysis, the femurs were filled with TP and PMMA after perforations were created in the trochanteric region and neck. The results were compared with the strength values obtained from testing the control specimen, a synthetic bone without reinforcement. Results: FEA showed a value of 600 N prior to reinforcement. After cementing with PMMA, the load increased by 57.5% (945 N), and by 53% (920 N) after cementing with TP. Conclusion: Synthetic femurs gained resistance to fracture-causing forces in a simulated fall on the trochanter after bone reinforcement with PMMA and TP. ***Level of Evidence III; Experimental study.***

Keywords: Osteoporosis. Femoral fractures. Hip.

RESUMO

Objetivos: Avaliar, com o método de elementos finitos (EF), os resultados obtidos com a simulação de queda sobre o trocanter maior, usando a porção proximal de um fêmur sintético, com a finalidade de comparar os valores obtidos antes e após técnica de reforço femoral com cimento de fosfato tricálcico (FT) e polimetilmetacrilato (PMMA). Métodos: Utilizando dois fêmures proximais sintéticos, foi realizada a análise de elementos finitos, simulando queda sobre o trocanter maior com o programa Bi-directional Evolutionary Structural Optimization (BESO). Para essa análise, os fêmures foram preenchidos, após a realização de pertuitos na região trocantérica e no colo, com FT e PMMA e os resultados foram comparados com a força obtida na análise do corpo de prova controle, osso sintético sem preenchimento. Resultados: Comparando a análise de elementos finitos antes do reforço femoral, obteve-se o valor de 600 N. Depois da cimentação com PMMA, foi observado um aumento na carga máxima da ordem de 57,5% (945 N) e de 53% (920 N) com o FT. Conclusão: Os fêmures sintéticos ganharam resistência aos fatores causadores de fratura em queda simulada sobre o trocanter depois do reforço ósseo com PMMA e cimento de FT. ***Nível de Evidência III; Estudo experimental.***

Descritores: *Osteoporose. Fraturas do fêmur. Quadril.*

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INTRODUCTION

The World Health Organization (WHO) predicts that the incidence of osteoporotic fractures of the proximal femur will triple by 2050. In the population below 65 years of age, the incidence of femoral neck fractures is 2–4 cases per 10,000 people. However, this value increases in the population above 70 years of age to 28/10,000 in men and 64/10,000 in women. It is estimated that 6.3 million osteoporotic fractures will occur by 2050, three times the current number; half of these fractures will occur in Asia.[1] In the United States, the annual cost related to treatment of osteoporotic fractures is 20 billion dollars, and hip fractures account for 60% of this cost.[2] Between 1 and 1.5% of all hospital beds in Europe are occupied by patients with osteoporotic fractures.[3] Twenty-two million women and 5.5 million men in the European Union (EU) received a diagnosis of osteoporosis in 2010, and 3.5 million insufficiency fractures occurred that year, 610,000 in the hip.[3] The cost of treating these fractures was 37 billion euros, and is expected to increase by 25% by 2025.[3] The measures of care for patients with osteoporosis in the EU have demonstrated significant results, with multidisciplinary application techniques that can reduce the occurrence of new fractures by 80%. However, this

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percentage falls to 40% in preventing hip fractures.[3] The mortality of patients who experience a fracture of the proximal femur after surgical treatment is 30% in the first year; patients with these fractures have up to 30% greater risk of fracturing the contralateral femur over a 2-year period, and this value rises further over a 5-year period.[4] In the case of non-simultaneous fracture of the contralateral hip, mortality reaches 64% in men and 58% in women.[5] Several methods have been proposed to reduce the risk of proximal femur fracture in osteoporosis, such as adjustments to the home environment, use of hip protectors, multidisciplinary treatment, and use of medications. Many drugs of different classes have been suggested for this purpose, but even though many have shown satisfactory results in preventing fractures (approximately 50% reduction in new osteoporotic fractures and 40% reduction in hip fractures), they have undesirable characteristics such as adverse effects with long-term use, high cost, and contraindications.[6] The reduction rates are influenced by sex, and according to published studies, this rate is always observed in women but not always in men.[7]

Bone strengthening using polymethyl methacrylate (PMMA) and tricalcium phosphate (TP) bone cement has already been described in the literature, generally in cadaver models and mechanical tests simulating falls on the greater trochanter.

This study consequently describes the behavior of synthetic bone subjected to a femoroplasty technique, and presents the results simulating falls on the greater trochanter in synthetic bone using PMMA and TP bone cement.

METHODS

Since this study does not involve humans, ethics committee approval was not required. We used two synthetic proximal femurs (Sawbone 3rd generation, Pacific Research Laboratories, Vashon, WA, USA) with a cortical segment manufactured in 30 pcf solid polyurethane foam and the following properties provided by the manufacturer: Poisson ratio ~ 0.3, tensile modulus ~450 MPa, and yield strain of 0.7%. The spongy segment consisted of 5MPa open cell polyurethane foam with the following mechanical properties: Poisson ratio ~ 0.3, elasticity module ~5 MPa, and yield strain of 3%. The images of this model were obtained before (control model) and after cementing, using helical computed tomography (Toshiba Activion 16/BF, Toshiba Medical Systems, Tochigi, Japan) with the following acquisition parameters: X-ray voltage = 120 kVp; X-ray power = 250 BUT; collimation (slice thickness) = 1.0 mm; space between slices = 0.5 mm. Multiplanar reconstructions were performed after image acquisition, as well as volumetric reconstructions. A steel guide wire, cannulated drill bit, and electric drill were used to create three filling holes in the following positions:

Hole I - 25–50 mm from the apex of the greater trochanter using the 2.5 mm guide wire in the centrolateral aspect of the synthetic model. With the aid of fluoroscopy, the hole crossed two main points in a straight line: one in the upper anterior region of the middle third of the femoral neck, and another in the central portion of the femoral head. Once the correct positioning of the wire on the frontal and axial planes as described above was confirmed, a 5.00 mm cannulated drill bit was used to perforate the first tunnel. Next, the guide wire was removed and the wire was redirected (using fluoroscopy) through Hole I to create Hole II.

Hole II - positioned at an angle connecting two other main points: one in the posterior-inferior region of the medial third of the femoral neck, and another in the posterior inferior portion of the femoral head. Once the appropriate position was determined in the axial and front views using fluoroscopy, a 5.0 mm cannulated drill bit was used to create the second tunnel.

Hole III - The references for the third hole are the lateral hole, which was already created for the first and second tunnels, and the apex of the lesser trochanter (medial calcar femorale). After fluoroscopy was used to orient and confirm the position of the guide wire to reach these two points, a 5.0 mm cannulated drill bit was used to create the third hole. (Figures 1A and 1B)

Approximately 24ml of TP and PMMA were used separately to fill in the structures in the synthetic model. The cement was injected with a syringe through previously made holes.

To conduct the finite element analysis (FEA), images were obtained before and after femoral reinforcement using Bi-Directional Evolutionary Structural Optimization software (BESO), which has the ability to highlight points with lesser load resistance and add elements in areas of higher mechanical stress, using resistance to traction as a criterion and thus optimizing the areas where cement is applied. This in turn allows the determination of mechanical resistance in Newtons (N) before (Figure 2) and after (Figure 3) reinforcement. The conditions used in the simulations are similar to a fall on the greater trochanter. Increasing force was applied and evenly distributed across the surface nodes of the femoral head.

RESULTS

Analysis of the synthetic model prior to cementing showed that in the simulated fall, two areas had significant concentrations of stress: one in the upper anterior basicervical region and another in the posterior inferior area of the same region. (Figure 3)

The synthetic model endured a load of 600 N before cement (control model) after TP was applied this load rose to 920 N, an increase of 53%. When PMMA was used, the load reached 945N before collapse, an increase of 57.5% (Figure 4).

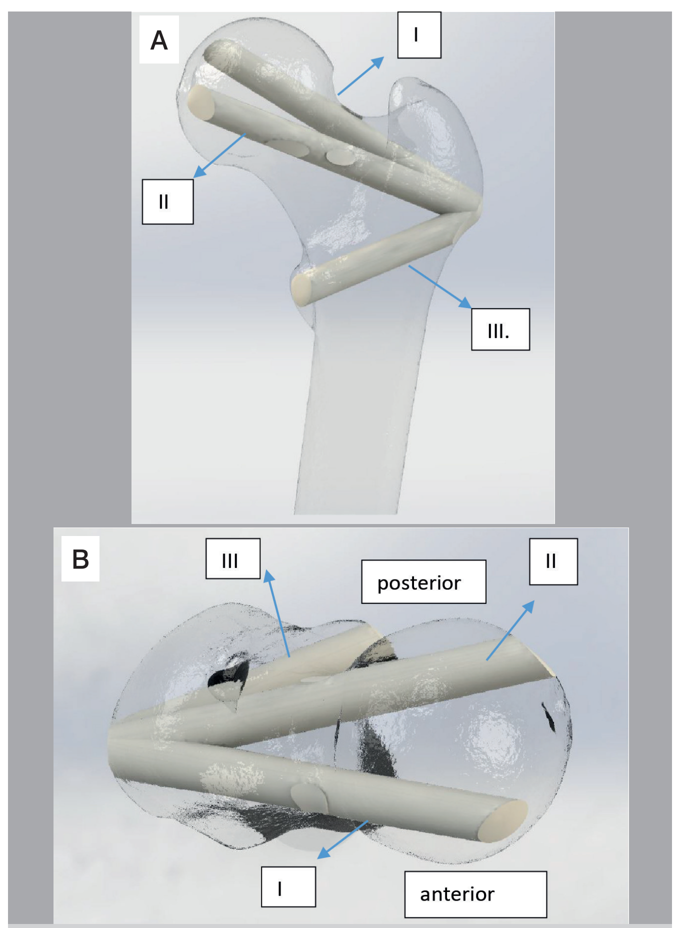

Figure 1. A) anterior view B) axial view, representation and positioning of tunnels I, II and III.

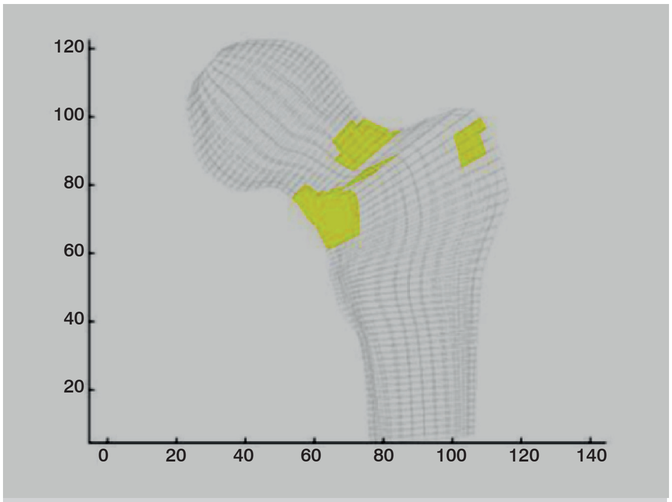

Figure 2. The areas in yellow represent the highest points of tension during FE analysis, in the position of falling on the large trochanter.

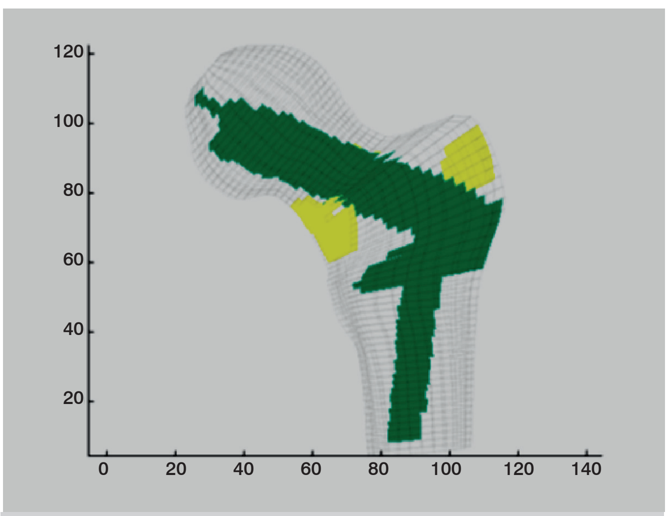

Figure 3. Synthetic model after filling the tunnels with PMMA, represented by green areas, during FE analysis.

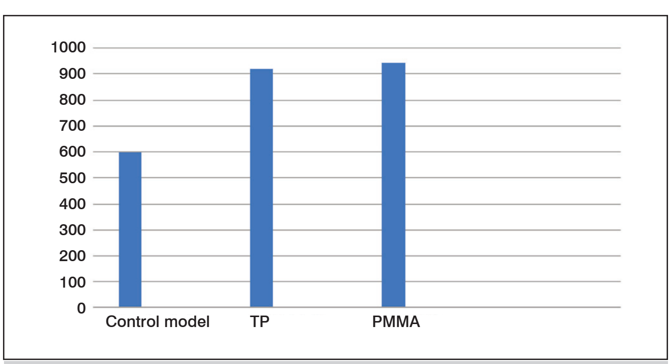

Figure 4. Strength (N) in FE analysis of synthetic models reinforced with PMMA, TP and control model (standard synthetic model, without perforations and without filling).

DISCUSSION

Reinforcement of the hip bone has already been described in the literature to prevent fractures in focal neoplasia, but its use in preventing osteoporotic fractures requires trials with good levels of evidence to validate results; this is because even though significant improvement has been seen in mechanical resistance, most articles which have been published are experimental studies.[8]

Other studies using PMMA for femoral reinforcement have shown up to 33% greater bone resistance to fracture, using volumes of cement ranging from 6 to 40 mL.[9-13] For TP the additional resistance values varied from 21 to 43%, but the volumes of cement used were not described.[14,15]

It should be noted that the results obtained in this study for increases in bone resistance correspond with previous works in the literature describing both synthetic bone models and cadaverous specimens. The absolute values are lower in cadaver bones, but the relative values are similar.[9]

Some considerations are important when comparing these results with other studies. First, this present study differs in its methodology by using synthetic bones for FEA, a new technique in this field of study.

Secondly, FEA was conducted before and after femoral reinforcement, which differs from the methodology in the lines of research used as references, which conducted in vitro stress tests in cadaver bones.

In terms of the evaluation technique, we used a protocol similar to that of Basafa et al.,[16] which was based on FEA to perform optimized and personalized femoroplasty for better results in increased bone strength. However, not all studies followed the same methodology, which complicates comparative analysis and makes it impossible to extrapolate the results.

There is no consensus on the ideal compound for femoroplasty in various studies. Some authors found superior results for PMMA, but did not address the advantages of calcium phosphate, namely its osteointegrative ability and security in terms of not inducing thermal necrosis.[15]

With regard to the cementing technique, the osteoconductive properties of TP immediately restore part of the lost bone mineral content. Furthermore, this compound facilitates the stabilization of fragile cell areas, theoretically increasing the bone matrix, and does not carry the theoretical risk of thermal necrosis caused by the polymerization of PMMA, an undesirable adverse effect in cases with low bone mineral density.[9,14]

Despite the varying methodologies and the lack of multicenter studies, femoroplasty seems to be a viable alternative for preventing fractures of the proximal femur.[17,18] The development of a standardized methodology would facilitate the progression of this technique and the evaluation of results in future studies. The use of substances with biological properties can theoretically provide even greater benefits for individuals with reduced bone mass.

CONCLUSION

We observed an increase in resistance to forces causing fracture in synthetic femur bones during simulated falls on the greater trochanter after the use of both PMMA and TP in a pre-defined cementing technique.

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