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Bone Mineral Density and Stress Distribution in Human Patella

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요 약 : 본 연구에서는 슬개골의 골밀도와 Von Mises응력의 분포를 조사하였다. 18개 슬개골의 골밀도는 컴퓨터 단층촬영과 영상분석 소프트웨어를 사용하여 결정하였다. 슬개골의 골밀도는 위치에 따라 변화됨을 발견하였다. 골밀도값은 상외측부(上外側部)에서 가장 크고 아래쪽 혹은 내쪽으로 갈수록 감소하였다. 이 분포는 슬개골 안에서 소주(小柱)의 조직과 일치됨을 보였다. 각 슬개골에서 2차원 유한요소법을 실행한 결과 슬개골의 최대 Von Mises응력은 비관절 표면 위에 있는 피질외피에 따라 발생하였다. 소주(小柱)의 최대 Von Mises응력은 슬개골의 후방 부에 존재했다. 이 발견들은 생체내에 유한요소 연구에 대한 잠재적 가능성을 증명하였다. 따라서 이러한 연구들은 주문형, 환자특성에 맞는 슬개골 인공보철물들의 개발을 유도할 수 있게 한다.

Abstract : This study examined the distribution of bone mineral density (BMD) and the von Mises stress in the patella. The BMD of eighteen patellae were determined by using quantitative computed tomography and imaging analysis software. It was found that the BMD of the patella varied with location. BMD values were largest at the superior and lateral regions and decreased inferiorly and medially. This distribution appeared to correspond to the organization of trabeculae within the patella. A two-dimensional finite element analysis was performed on each patella. It was also found that the maximum von Mises stress in the patella occurred along the cortical shell on the non-articular surface. The trabecular von Mises stress existed in the posterior region of the patella. These findings demonstrated the potential for finite element studies in vivo. Further, such studies may lead to the development of custom-made, patient-specific patella prostheses.

Key words : Bone mineral density, Total knee arthroplasty, Stress, Patella prosthesis, Finite element

INTRODUCTION

The patella plays an important role in total knee arthroplasty (TKA) [1-6]. TKA has been successful in the management of advanced arthritic conditions of the knee. During TKA, the knee joint consisting of the proximal tibia and the distal femur is resurfaced with implant prostheses. The patella may have its articular surface removed and replaced with a "button-like" plastic prosthesis. Patella resurfacing is primarily dependent on the severity of the arthritis that exists at the patello-femoral joint [2]. Patella resurfacing has been a controversial topic. Numerous complications have arisen due to patellar resurfacing. These complications include prosthesis loosening, post-operative fracture of the patella, implant component fracture, and prosthesis instability [1,5,7]. Scott et al. [8] studied post-operative fractures of the patella associated with resurfacing and discussed some guidelines in order to minimize fracture potential. They found that a minimal amount of articular surface should be removed while the peripheral cortex of both the medial and lateral facets should be preserved. Josefchak *et al.* [9] determined bearing resistance of the cancellous bone in the patella. They attempted to evaluate the optimal location of the fixation pegs in a patellar prosthesis. However, there was no consistent pattern in the patella to justify a pre-determined location for fixation pegs.

The purpose of the current investigation was to determine distribution of BMD and, on the basis of this information, further present stress distribution using finite element (FE) analysis in the human patella. The distribution of BMD may play an important role

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Fig. 1. Images of Ct scan of patellae for BMD measurements

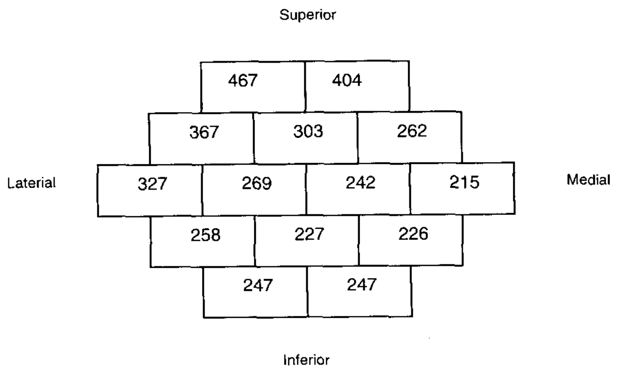

Fig. 2. Average BMD (mg/cm^3) values at each location for eighteen patellae examined

in the design of patellar prostheses including the placement of patellar prosthesis fixation pegs or the location of the prosthesis on the resurfaced patella. Current designs and techniques do not take advantage of higher BMD in some regions of the patella. The von Mises stress distribution within the patella is a valuable piece of information prior to TKA. The ability to predict the location of high stress regions within the patella would give the designer the advanced knowledge of how the patella distributes stresses. This may have an effect on the location of the prosthesis on the patella and in the overall prosthesis design.

MATERIALS AND METHODS

Eighteen human patellae were harvested from eighteen unembalmed cadavers (10 females and 8 males) obtained within three days of death, with a mean age of 74 (SD 9.3) years. These patellae were scanned using a Computed Tomography (CT) system (General Electric 9800). The patellae were aligned in a two row by nine column arrangement, with the anterior sides facing upward and the superior portions entering the scanner first. Transverse CT images were taken at 120 kVp, 120 mA, with 1.5 mm slices at intervals of 3 mm, and a field of view of 14 cm. The images were transferred to a computer (Sun Sparc Station 10), and analyzed using CT imaging software (C-Med Virtual Visions, Cupertino, CA).

Each patella produced between 12 and 14 CT slices. Figure 1 shows transverse images of CT scan. Raw CT numbers for each patella were obtained and recorded on a gird. The grid consisted of fourteen regions as shown in Figure 2. CT numbers were converted to BMD values by using a calibration phantom containing regions of known BMD [10].

The average von Mises stress within the eighteen patellae at a specific loading case was determined by the finite element method (Ansys 5.1 on a Sun Sparc 10 Station). The von Mises stress is based on distortion energy in a body and can be presented in terms of the three principal stresses (s_1, s_2, s_3) [11] :

$$\textit{von Mises stress}=$$

$$0.5\sqrt{(s_1-s_2)^2+(s_2-s_3)^2+(s_3-s_1)^2}$$

Two-dimensional patellar FE model was created by digitizing the midsagittal cross-section of each patella (Sigma Scan digitizer) to provide the patella's outer

Table 1. Computational results of finite element analysis at different mesh sizes using linear and quadratic elements

Element Type	Size of Mesh(Elements)	Maximum stress(psi)
Linear Elements	115	675
	243	810
	339	950
	512	1085
Quadratic Elements	115	765
	243	930
	339	1015
	512	1050

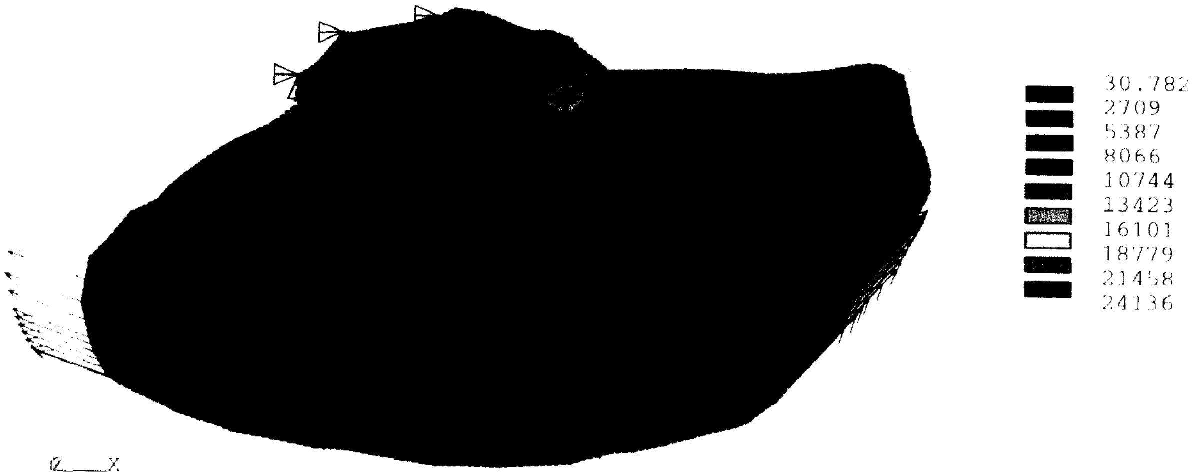

Fig. 3. Contour plot of the von Mises stress (psi) in a typical patella. The elements, forces, and constraints are also shown

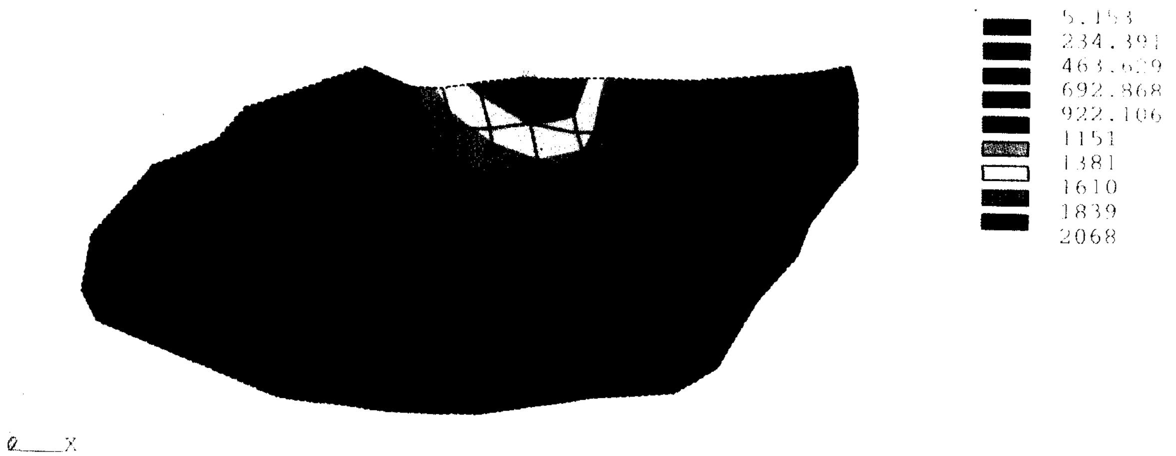

Fig. 4. Contour plot of the von Mises stress (psi) distribution within the trabecular region of a sample patella

boundary and inner boundary for the cortical shell. Although three-dimensional measurements are needed to represent the true geometry of a bone, two-dimensional FE analysis often provides a reasonable approximation, depending on the situation [12]. In order to represent isotropic, inhomogeneous material properties of the patellar FE model, elastic modulus values at five regions were found by converting average BMD values in their respective areas by the method described in the previous study [13]. Using the knowledge that CT numbers are linearly related to apparent density [14], and utilizing an equation relating apparent density and strain rate to Young's modulus :

$$E=3950\left(\frac{d\varepsilon}{dt}\right)^{0.06}\rho_{app}^{3}$$

where $\frac{d\varepsilon}{dt}$ is the strain rate and ρ_{app} is the apparent density, the elastic modulus can be determined. This relationship is valid over many different strain rates (0.001 to 10 sec^{-1}). A strain rate of 0.001 was used in this study to represent the strain rate of gait.

The articular surface of the patella was constrained in the anterior-posterior (AP) direction. To prevent any rigid body motion, and to mathematically be able to solve the problem, zero-displacement constraints in the superior-inferior (SI) direction were necessary. The midsagittal cross-section was placed in the x-y plane so the coronal plane was parallel with x-z plane of the reference axis. The quadriceps force was then taken to be 605 lbs acting at 48° (to the superior-inferior plane (horizontal axis), toward the anterior portion of the patella in a counterclockwise direction [12]. The patellar ligament force was taken to be 431 lbs acting at 160° (to the same horizontal [12]. A mesh was then generated. Plane strain quadratic elements were chosen. Solutions were generated using eight different mesh sizes in order to find an optimum mesh size for determining the von Mises stress within the patella while conserving computer time. Table 1 summarizes the results of the preliminary study to determine an optimal mesh size. There was the smallest change in maximum stress from the 512 to 339 element case (3.4%) at the same node as seen in Figure 3. Thus, the quadratic elements with a mesh size of 339 was used in this study.The first four analyses utilized linear interpolating elements while the final four utilized quadratic interpolating elements. In each set of four tests, the mesh size was varied in order to determine whether an optimal mesh existed. The mesh density decided upon consisted of 339 quadratic elements. In order to include the patello-femoral joint force, which was absent from the mesh size analysis, a 0.05 inch thick layer of cartilage was added to the patella. This additional material added 116 elements to the overall model, for a total of 454 elements. An elastic modulus of 7000 psi was used for the cartilage [12]. The anterior side of the cartilage was attached to the patella, while the posterior side was constrained from displacements in the x and y directions (no displacement in the respective directions).

RESULTS

BMD ranged from 48 mg/cm^3 in the least dense specimen to 667 mg/cm^3 in the most dense specimen. BMD values for each region were averaged and shown in Figure 2. In the mediolateral direction, it was found that the average BMD values were greatest at the lateral region and decrease medially. Average BMD values were larger at the superior region (maximum 467 mg/cm^3) than at the inferior region (minimum 247 mg/cm3, $p<0.006$). Additionally, average BMD values located at the lateral region (327 mg/cm^3) were larger than the values located at the medial region (215 mg/cm^3, $p<0.05$).

A contour plot in a typical specimen of the von Mises stress is shown in Figure 3. There exists two regions of high stress areas. The first exists along the non-articular surface in the cortical region. These stresses range in value from 14000-16000 psi. A second region exists just anterior to the articular cartilage. Values in this region range from 20000-23000 psi. Contour plot in the same sample specimen of the trabecular von Mises stress is shown in Figure 4. This plot demonstrates that maximum trabecular von Mises stress exists in the posterior region of the patella and is as high as 2200 psi.

DISCUSSION

The results of this study revealed that BMD values varied through the patella. In the superior region, BMD values were found to be largest, while decreasing inferiorly. In addition, the lateral portion of the patella contained larger BMD values than the medial portion. The regions of highly organized vertical trabecular orientation observed by Raux et al. [15] corresponded to the regions of maximum trabecular BMD values found in the current study. Regions of highly organized mediolateral trabecular structures produced larger BMD values than regions of disorganized trabeculae, however not to the extent of the vertical trabecular structures. Regions of mixed orientation, or no predominant orientation was found to exhibit low BMD values. The results of this investigation suggest that in the patella, regions of singly oriented trabecular bone may produce larger BMD values than trabecular bone which has mixed or random orientation.

The optimal mesh study demonstrated that 339 quadratic interpolating elements would best suit the patella model for this problem, since the maximum stress increased only 3.4% when the number of elements were increased. The linear elements, particularly the triangular elements, formed a mesh that was too stiff in bending according to the software. This error arises when the linear element's aspect ratio is too high, which results in incorrect or inaccurate solutions [16]. High aspect ratios have less significant error when higher order elements are used. Therefore, to avoid this problem, quadratic interpolating elements were used.

The finite element analysis showed that the highest values of von Mises stress occurred in the cortical shell. Two separate regions of high stress concentration existed in the patella. The first exists along the non-articular face of the patella. These stresses are the result of tensile forces applied by the patellar ligament and the quadriceps tendon. These results are consistent with those of Hayes *et al.* [12]. A second region of stress concentration is shown to exist just anterior to the articular cartilage. Stresses in this region can be attributed to the force exerted by the patellar ligament force, the quadriceps force, and the patello-femoral joint force acting in tendon with each other. These three forces act to bend the patella in this region. The magnitude of this stress however, is misleading. It is believed that the value of the stress may be over-exaggerated due to the abrupt change in material properties in this region. Another possibility for inaccurate stress values is the coarseness of the mesh in that region. Yet another factor that contributed to inaccurate stress values is the zero-displacement constraints on the articular cartilage. These constraints create "infinite" stresses to occur at the particular nodal point during any finite element analysis. Therefore, stress values in these regions tend to be inflated.

In the trabecular region, maximum von Mises stress existed in the posterior region of the patella. The magnitudes of the maximum von Mises stress may be distorted, due to the over-exaggerated von Mises stress existing in the cortical bone in the same region. The magnitudes of the stress in the trabecular region are significantly lower than in the cortical region. This indicates that the cortical shell is acting as the main structural component at this bony site. The results found in the trabecular region of this study is not consistent with those found by Hayes *et al.* [12]. The disagreement in stress results between the current investigation and that of Hayes *et al.* [12] may be attributable to the following differences. First, the current study modeled the articulating cartilage as a linear, isotropic, and elastic material, while Hayes *et al.* [12] utilized linear elastic springs to model articular cartilage. Secondly, plots of trabecular von Mises stress in the current study were obtained by excluding cortical bone in the output plot and concentrating on the trabecular region. This added resolution to the trabecular region and allowed for a more detailed analysis of stress within the region. Plots which displayed the cortical bone region could not have produced any significant results due to the difference in orders of magnitude between stresses in the cortical region and the trabecular region. Thus, the stress results of the cortical region have been left off in order to clearly visualize the trabecular region's stress distribution. Hayes *et al.* [12] did not do this, thus it is difficult to accurately determine regions of maximum trabecular stress. Finally, Hayes *et al.* [12] used a FE model containing 168 isoparametric, plane-strain quadrilateral elements, while the current study used over 400 quadratic element.

Knowledge of the distribution of BMD and stresses within the patella could help to reconsider the current design of the patella prostheses used in TKA. Using the information found in the assessment of the patella, improvements can be made in the location of fixation screws, prosthesis shape and material properties. The shape of the resurfaced patella can also be affected. Currently, patellae are resurfaced by making a flat cut parallel to the coronal plane. Rand [5] suggests resurfacing the patella by making an inset patella prosthesis, leaving a peripheral rim of cortical bone for added support. Results of the finite element analysis demonstrated that the cortical shell of the patella is responsible for absorbing the majority of the stress on the patella. This technique suggested by Rand [5] may improve the results of TKA.

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