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Stress analysis of the canine cementless total hip prosthesis

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by

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GENERAL INTRODUCTION

Cemented total hip replacement is a method of treatment for canine hip disease.[1,2,3,4] As in man the cemented total hip has shown good results but is not without complications.[1,5] Some have suggested boney ingrowth for skeletal fixation may produce fewer complications than fixation with bone cement. This boney ingrowth or, biological fixation, would avoid the toxicity, heat necrosis, and shrinking seen with cement fixation.[6] Proponents of the cemtentless hip also believe that it may provide better long term fixation than possible with cemented models.[5] In man over half of the estimated 120,000 total hip replacements performed a year in North America are the cementless type.[5]

For biological fixation to occur there must be initial stability, contact over ingrowth areas, a uniform stress transfer, and a return of the femoral head position.[7] If these requirements are not met there can be problems that may have clinical consequences. Stress transfer is especially important in the cementless hip. If too little stress is transferred to the proximal femur reabsorption of bone may result.[5] In vitro strain analysis in man has shown that stress shielding does occur with the cementless prosthesis.[8,9]

Before cementless implantation can be recommended in the dog studies evaluating the stress transfer to the proximal femur must be carried out. Since the anatomy of the dog and human are different the results from human studies cannot be directly applied to the dog. A method of strain analysis that has been used for the proximal femur is the photoelastic measurement technique.[9,10,11] This technique has advantages of full field or quantitative point by point analysis without the directional constraints of strain gauges.[12]

The purpose of this study is to evaluate the stress induced in the proximal canine femur by the cementless femoral implant using photoelastic measurement techniques. The first question that must be answered is can the photoelastic technique be used for the analysis of strains in the dog femur and if so, what is the normal strain distribution for the intact femur. Since dog femurs are smaller and have more acute angles than human bone it may be difficult to accurately contour the plastic to the bone. Once the normal strain distribution of the intact femur is established the change in strains associated with implantation can be determined by comparison of pre and postimplantation values.

Explanation of Thesis Format

This thesis is prepared in the alternate format. The first section in this thesis will address the use of the photoelastic technique in the measurement of normal strain distribution of the canine femur. The second section will evaluate the strains induced by the femoral component of a canine cementless total hip replacement as compared to the strains present in the intact bone. Both sections will be written in a form that is acceptable for publication in Veterinary Surgery. Each section will begin with an abstract. An introduction, materials and methods, results and discussion will follow each abstract. A summary and discussion for the thesis will follow the second section. The primary author was principal investigator for both papers.

SECTION I. STRAIN ANALYSIS OF THE CANINE FEMUR BY PHOTOELASTIC TECHNIQUES

ABSTRACT

The principal objective of this study was to determine the feasibility of using the photoelastic method of analysis to define the strain distribution in the proximal canine femur. Photoelastic sheets were made and successfully contoured to 8 femurs from cadavers weighing 25-30 kg. Although the surface contour of the bones were varied, there were no problems with application of the coating. All bones were loaded to approximately 2 times body weight (55 kg.) without permanent deformation of the coating. Quantitative analysis of the strain distributions for the cranial, caudal, medial and lateral aspects were performed using a reflection polariscope and digital compensator. The cranial, caudal, and lateral aspects of the bone demonstrated the lowest strains proximally with strains increasing distally. The medial aspect had the highest strain magnitudes proximally with strains decreasing distally. The photoelastic technique of measurement provided a successful means to evaluate the strain distribution of the intact proximal canine femur.

INTRODUCTION

Stress and strain analysis of the femur can provide a better understanding of the biomechanics of bone. This information can also be used to understand and improve the design of orthopedic implants and prosthesis. Strain gauge analysis[1], photoelastic modeling[2], and finite element analysis[3] are methods which have been used for the evaluation of the stress distribution in the proximal femur. These methods have limitations which include directional and positional constraints, assumptions of homogeneity and sensitivity.[4] One method that does not have these constraints is the photoelastic coating technique.[5] This technique has been used in the field of engineering in the past and according to Measurements Group, Inc. is now being used in biomechanical evaluations of the femur, pelvis, skull, and cornea. Implants including artificial heart valves, dental implants, and prosthesis for the elbow, knee, and hip are being evaluated by photoelastic techniques as well.

Advantages of photoelastic analysis over traditional methods of strain analysis include; full field topographic evaluation of strain and strain gradients, point-by-point quantitative analysis, static or dynamic application, no limitation of directional placement as seen with strain gauges, and the ability to coat irregular surfaces.[5,6,7] Studies in human bone have proven the validity of this method as compared to strain gauge analysis.[5] The purpose of this study is to determine if the photoelastic method of analysis can be used on dog bones since they are smaller and have sharper bends and ridges as compared to human bones, and to determine the normal strain distribution for each face of the femur when loaded. This information will provide the ground work for future analysis with the photoelastic technique for the canine.

MATERIALS AND METHODS

Eight radiographically normal femurs were obtained from skeletally mature cadavers weighing between 25-30 kg. The bones were wrapped in saline soaked cloth and frozen at -15 degrees Celsius until they were thawed at room temperature at the time of study. All tissues and periosteum were removed from the bones. The distal femur was potted in a methylmethacrylate base at an angle of 20 degrees from vertical in the cranial to caudal plane, and 10 degrees from the vertical in the medial to lateral plane to simulate an ambulatory stance. All bones were prepared for photoelastic stress analysis according to previous reports.[4,5,6,7] This technique involves four steps: 1) sealing the bone with a bonding cement, 2) casting and contouring the photoelastic plastic to the femur, 3) bonding the plastic coat to the femur, and 4) measuring the strain when load is applied to the femur. This process will be briefly reviewed.

Sealing

Bones were sealed to prevent moisture and fat from accumulating on the surface of the bone during subsequent bonding procedures. This was accomplished by applying a thin layer of PC-1† adhesive to the bone and allowing 12 hours to dry. After drying was

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† Measurements Group, Raleigh, NC

complete fine sandpaper was used to remove excess adhesive. This left adhesive to seal the bone pores.

Casting

Casting and contouring are used for the application of photoelastic coating to irregular shaped objects. After the bone was cleaned with acetone to remove particulate matter, a sheet of photoelastic epoxy resin PL-1†† was made according to directions.[6] The sheet was contoured to the medial and caudal surfaces of the bone. After a 24 hour polymerization period the hardened plastic coating was carefully removed. A second sheet was prepared in the same manner and contoured to the cranial and lateral surfaces of the bone leaving a one millimeter gap between the contoured sheets. All sheets were 3 millimeters thick and started at the lesser trochanter and extended 10 cm. distally.

Bonding

After cleaning the femur with acetone the contoured photoelastic sheets were bonded to the femur with a thin layer of PC-1 adhesive as directed.[6] Care was taken to avoid air pocket formation between the plastic and bone. The adhesive was allowed 12 hours to polymerize.

Measurement

Ten points for data collection were located at one centimeter intervals on the cranial, medial, caudal, and lateral faces with the

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†† Measurements Group, Raleigh, NC

first point at the level of the lesser trochanter. A load of 55 kg. was applied to the femoral head using a dead weight system. Measurements were recorded using a reflection polariscope with a digital compensator¥.

Photoelastic measurement is based on strain sensitive plastic experiencing the same surface strains as the material that is underneath it. As a load is applied the index of refraction of the plastic changes. If circularly polarized light is passed through the loaded plastic and viewed through a quarterwave plate and polarizer of a reflection polariscope colored fringes are seen. A digital compensator can be used to quantitatively measure the colored fringes, isochromatics, at a given point. The number obtained, N, is directly proportional to the differences in principal strains experienced by the test material at that point. It is possible to convert fringe units to units of microstrain by knowing the thickness and the sensitivity of the plastic coating, as well as the wave length of light. Since the purpose of this paper was to determine the relative distribution of strains rather than their absolute magnitudes, all readings were reported in fringe compensator units for simplicity. The direction of the principal strains are obtained when the quarter wave plates are optically removed from the polariscope creating linearly polarized light

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¥ Measurements Group, Raleigh, NC

instead of circularly polarized light. The resulting isoclinic fringe pattern is used to obtain the principal strain direction.

The means and standard deviations of strains for the cranial, caudal, medial, and lateral faces of the 8 femurs were determined to give the normal strain distribution for each face of the femur.

RESULTS

Photoelastic sheets were made for eight canine bones. Minimum difficulty was experienced contouring the sheets to the bones although they were considerably smaller and had more acute angles than human femurs. An accurate contour of the bone was achieved for all 8 bones. All bones were loaded to approximately twice body weight (55 kg.) without any signs of damage or permanent deformation to the photoelastic coating.

The results for each point were averaged for all 8 bones. A line passing through the mean for each point was used to obtain the strain fringe order distribution for the medial, lateral, cranial and caudal faces of the femur and is shown in Figure 1. The number N (compensator units) is directly proportional to the differences in principal strains experienced by the bone at that point. The slope of the fringe order distribution was calculated for each side to evaluate the strain gradient present from the proximal to distal aspect of the bone. There were variations between bones in the magnitudes of strains measured but the trends seen from proximal to the distal were similar.

The slopes for the cranial, caudal, and lateral faces of the femurs were all positive. Slopes for the cranial, and caudal faces were 6.3 and 8.5 N/cm. This indicates that the strains were the lowest proximally and increased distally. The slope for the lateral face was 1.9 N/cm which indicates that the stain gradient from proximal to distal was not as great as seen in the cranial and caudal sides.

The slope for the medial aspect was -2.7. This indicates that the proximal region experienced more strain than the distal aspect of the medial face. The areas of highest strains were the most distal sites on the cranial and caudal faces.

Average strain distribution for cranial, caudal, medial and lateral sides of the femur.

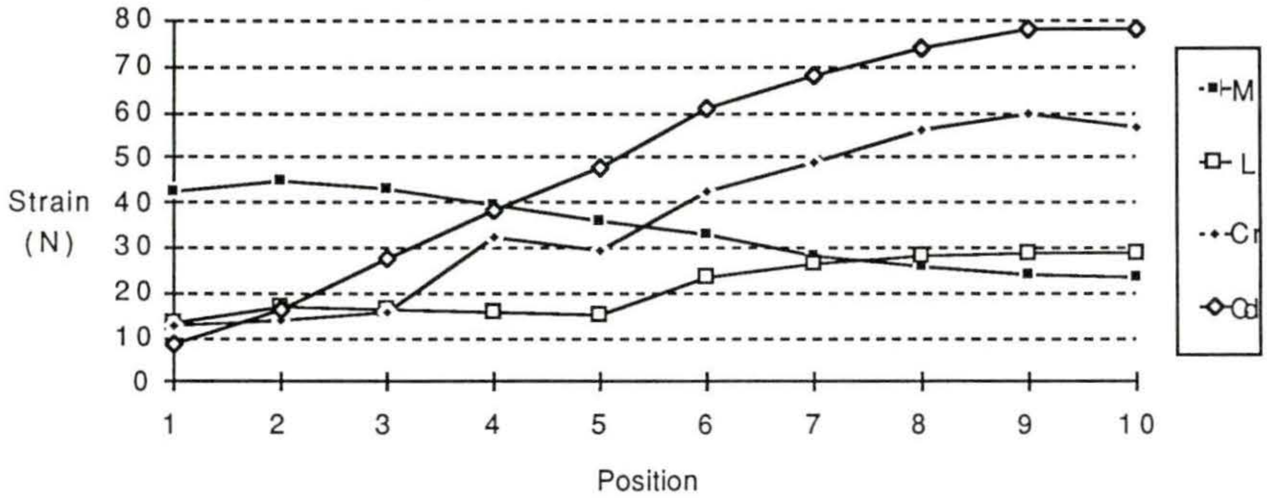

Figure 1. Average strain distribution of the canine femur. Strain is reported in fringe compensator units (N). Position 1=most proximal, position 10=most distal. M=medial, L=lateral, Cr=cranial, Cd=caudal.

DISCUSSION

Photoelastic coating techniques have been reported to offer advantages over traditional methods of strain evaluation. This method allows for full field analysis of the coated area, as well as point-by-point quantitative analysis, with static or dynamic applications. There are also no limitations associated with directional placement as with strain gauges.[7] This technique has been successfully used for the analysis of human bone.[7] Although the canine femur was smaller and had more acute angles it was possible to create an accurate contour of the bone with the photoelastic coating. There was no residual deformation in the coating after loads of twice body weight were applied.

The strain distribution for each of the 8 bones were similar, however, there were differences in magnitudes between individual bones. This could be due to the different sizes of the bones and variations in their geometries.

Means for each point on the cranial, caudal, medial, and lateral faces were obtained for the 8 bones. Slopes were then determined to give the strain distribution present for each face of the bone. The sign of the slopes gave an indication of the strain gradient from the proximal to the distal ends of the bone. A positive slope indicated that the strains were the smallest proximally and increased distally. This was the case on the cranial, caudal, and lateral faces of the bone. This is opposite from that found in strain analysis of the human femur.[1]

The medial aspect had a negative slope which indicated the greatest strains were proximally and decreased distally. This is similar to that found in the human femur where the greatest strain is found at the calcar region.[1,4]

The strain gradients, as indicated by the magnitudes of the slopes, were greatest on the cranial, and caudal surfaces. The magnitudes of the strains were the greatest distally on the cranial and caudal aspects. This was different from that reported in the human femur in which the medial and lateral surfaces had higher strains than the anterior and posterior aspects.[5] This may be due to the curvature of the canine femur in the cranial, caudal plane which creates a moment arm when a load is applied to the femoral head. The greater the curvature distally, the larger the distance from the point of loading. This results in a longer moment arm and a larger strain on the distal cranial and caudal aspects.

We conclude that the photoelastic technique can be applied to the canine femur. Photoelastic techniques demonstrated that the loaded intact femur transfers more strain distally than proximally for the cranial, caudal, and lateral aspects. Conversely, the medial aspect of the bone experiences the greatest strain proximally with decreasing magnitudes distally. All data were recorded during static loading and there was no accounting for the effects of the individual muscle tension present on the femur.

The photoelastic method provided a useful tool for the evaluation of overall strain distribution as well as a quantitative method for analysis. Information regarding the use of the photoelastic technique and the strain pattern for the loaded intact canine femur provides preliminary data for further biomechanical evaluation of the canine femur and its implants.

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SECTION II. STRAIN ANALYSIS OF THE CANINE CEMENTLESS TOTAL HIP PROSTHESIS

ABSTRACT

Cementless hip implantation has been used in human medicine as an alternative to cemented methods. Invitro strain studies have shown that the cementless implant can cause stress shielding in the femur of man. The purpose of this study was to determine the effect of cementless implantation on the strain distribution in the proximal femur in the dog. The strain pattern for 4 radiographically normal bones was determined for 36 kg (80 lbs.) and 55 kg (120 lbs.) loads using the photoelastic technique of measurement. The bones were then implanted with cementless femoral implants and strain measurements compared before and after implantation. Strains increased post implantation for all faces (cranial, caudal, medial and lateral) at the 55 kg and 36 kg load except 2 points on the medial aspect at the 36 kg load. Although most points showed an increase in strains, only the cranial aspect had a statistically significant increase. The cementless implant used in this study did not stress protect the femur. Whether the increase in strains would be detrimental could not be determined at this time.

INTRODUCTION

Hip dysplasia is a multifactorial developmental abnormality of the canine hip joint.[1] This condition manifest itself radiographically as a shallowness of the acetabulum with joint incongruity that will result in various degrees of coxofemoral subluxation. As the dog gets older, remodeling and degenerative joint disease become evident.[2] This degenerative condition causes pain and alters locomotor function.

One treatment for disabling hip dysplasia in the canine is total hip replacement.[3,4,5,6] Other indications for total hip replacement include; osteoarthritis unrelated to hip dysplasia, nonreducible chronic coxofemoral luxations, failed excision arthroplasties, severely comminuted femoral head fractures, avascular necrosis of the femoral head, nonunion of a femoral neck fracture and acetabular malunion.[3] Cemented canine total hip replacement has provided satisfactory performance in the past and subsequent reports have provided even lower complication rates. [3,4,5]

An alternative method for total hip arthroplasty is the cementless total hip replacement. This system depends on boney ingrowth into a porous coating for skeletal fixation of the prosthesis rather than cement fixation.[7, 8] Rational for choosing cementless fixation in humans is based on belief that it provides better long-term fixation and that it will provide potential for revision surgeries for failed hip replacement.[7, 9] Other advantages of a noncemented system is that it avoids toxicity, heat necrosis, shrinking, and aging that has been associated with bone cement.[10]

Whether a cementless or cemented prosthesis is used, one of the most important functions of the femoral stem is the transfer of load from the prosthesis to the bone.[11] If there is too little stress transferred, or stress shielding, the bone may reabsorb[7,9,12] which may result in poor long term implant performance. This is especially true in the cementless implant where initial stability, contact over ingrowth surfaces, uniformity of stress transfer, and restoration of the femoral head position are required for boney ingrowth.[13]

Methods which have been used for evaluation of stress transfer in the proximal femur include: finite element analysis[11], strain gauge analysis[14], and analysis by photoelastic models.[15] Limitations of these techniques include assumptions of homogeneity, and sensitivity, as well as directional and positional constraints.[16] These limitations are not a problem with a photoelastic coating technique as described by Jones and Hungerford.[17] The photoelastic coating technique allows a full field evaluation of stress patterns as well as quantitative data of selected points.[18]

The purpose of this study is to compare strains in the intact loaded proximal femur to strains after cementless total hip replacement by using the photoelastic measurement technique. Each femur served as its own control and stresses are comparative rather than absolute. The information gained maybe helpful in predicting the initial stress transfer post implantation which could affect boney ingrowth and remodeling that are essential for skeletal fixation. Further studies are necessary for evaluation of stresses after boney ingrowth has occurred.

MATERIALS AND METHODS

Four radiographically normal femurs were obtained from skeletally mature cadavers weighing between 25-30 kg. The bones were frozen in saline soaked cloth at -15 degrees Celsius and thawed at room temperature at the time of study. All tissues and periosteum were removed from the bones. The distal femur was mounted in methylmethacrylate at an angle of 20 degrees from vertical in the cranial to caudal plane, and 10 degrees from vertical in the medial to lateral plane to simulate an ambulatory stance. All bones were prepared for photoelastic stress analysis according to previous reports.[16,17] This technique involves four steps: 1) sealing the bone with a bonding cement, 2) casting and contouring the photoelastic plastic t1o the femur, 3) bonding the plastic coat to the femur, and 4) measuring the strain when load is applied to the femur. This process is briefly reviewed.

Sealing

Bones were sealed to prevent moisture and fat from accumulating on the surface of the bone during subsequent bonding procedures. This was accomplished by applying a thin layer of PC-1† adhesive to the bone and allowing 12 hrs. to dry. After drying was complete fine sandpaper was used to remove excess adhesive.

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† Measurements Group, Raleigh, NC

Casting

Casting and contouring are used for application of photoelastic coating to irregular shaped objects. This technique provides one of the advantages of the photoelastic process in that analysis can occur despite ridges or depressions in the tested material. After the bone was cleaned with acetone to remove particulate matter, a sheet of photoelastic epoxy resin PL-1†† was made according to directions.[18] The sheet was contoured to the medial and caudal surfaces of the bone. After a 24 hr. polymerization period the hardened plastic coating was carefully removed. A second sheet was prepared in the same manner and contoured to the cranial and lateral surfaces of the bone leaving a one mm. gap between the contoured sheets. All sheets were 3 mm. thick.

Bonding

After cleaning the femur with acetone the contoured photoelastic sheets were bonded to the femur with a thin layer of PC-1 adhesive as directed.[18] Care was taken to avoid air pocket formation between the plastic and bone. The adhesive was allowed 12 hrs. to polymerize.

Measurement

Although the photoelastic technique allows for full field analysis, point readings were obtained for all femurs. Ten data points were located at one centimeter intervals on the cranial,

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†† Measurements Group, Raleigh, NC

medial, caudal, and lateral faces with the first point at the level of the lesser trochanter. Intact bones were loaded to 36 kg. (80 lbs.) and 55 kg. (120 lbs.) with a dead weight system and readings were recorded. Loads and measurements were repeated after implantation of the prosthesis. The measurements taken before and after implantation were compared by analysis of variance. The differences between the implanted and intact values were considered significant when $P < 0.05$.

Photoelastic measurement is based on strain sensitive plastic experiencing the same surface strains as the material that is underneath it. As a load is applied the index of refraction of the plastic changes. If circularly polarized light is passed through the loaded plastic and viewed through a quarterwave plate and polarizer of a reflection polariscope, colored fringes are seen. A digital compensator¥ can be used to quantitatively measure the colored fringes, isochromatics, at a given point. The number obtained, N, is directly proportional to the differences in principal strains experienced by the test material at that point. The direction of the principal strains are obtained when the quarter wave plates are optically removed from the polariscope creating linearly polarized light instead of circularly polarized light. The resulting isoclinic fringe pattern is used to obtain the principal strain direction.

¥ Measurements Group, Raleigh, NC

It is possible to convert fringe units to units of microstrain by knowing the thickness and the sensitivity of the plastic coating, as well as the wave length of light. Since the purpose of this paper was to determine the relative distribution of strains rather than their absolute magnitudes, readings are reported in fringe units for simplicity.

Cementless Implantation

Each femur was radiographed with radiopaque markers to determine the amount of image magnification present. Acetate templates^ and radiographs were used for preoperative evaluation of the size of the femoral implant required^^.

Surgical implantation consisted of femoral head and neck resection followed by hand reaming of the femoral canal with the appropriate sized broach^^^. The corresponding implant was then inserted into the prepared femoral shaft. Implantation of the prosthesis was performed by the same surgeon. The same sized femoral neck length was used for each implant for consistency.

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^ Techmedica, Camarillo, CA

^^ Techmedica, Camarillo, CA

^^^ Techmedica, Camarillo, CA

RESULTS

The results for each point were averaged for the intact and implanted data for the 36 kg and the 55 kg loads separately. The average strain distributions for the medial, lateral, cranial, and caudal faces of the intact and implanted femurs for the 36 kg load are illustrated in Figures 1-4.

The strains in the implanted bones for the cranial, caudal and lateral aspects demonstrated an increase from the proximal to the distal aspects of the bones. The implanted medial aspect had the greatest strains proximally and decreased distally. These were the same trends found in the loaded intact bones. The post implantation pattern did demonstrate a slight increase proximally, followed by a transient decrease in strains at points 4 and 5 laterally, 3 cranially, and 2 caudally that the intact femoral strain patterns did not show.

All data points on the cranial, caudal and lateral aspects exhibited higher strains after implantation at both 36 kg and 55 kg loads. Each point on the medial aspect also had higher strains postimplantation except points 6 and 7 at the 36 kg load. The magnitude of difference between intact and implanted strain values was statistically significant for the cranial face ($p<.007$). Statistical significance could not be demonstrated in the strain differences after cementless prosthetic implantation for the medial ($p<.385$), lateral ($p<.0664$), or caudal ($p<.0588$) aspects with $P< 0.05$.

Intact versus implanted strains for the medial aspect with a 36 kg load.

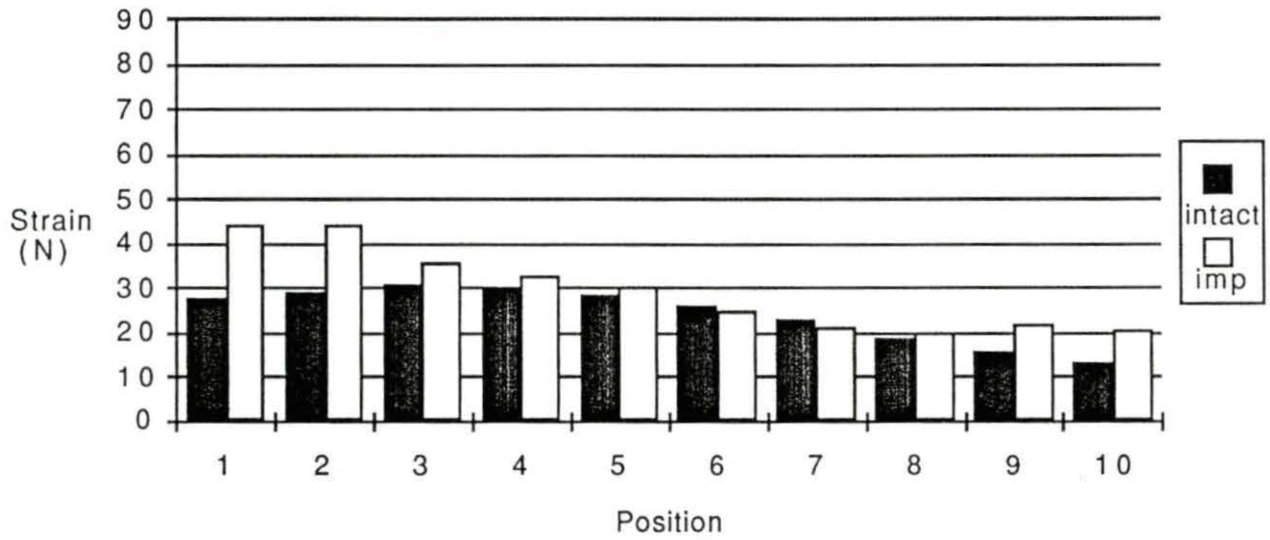

Figure 1. Intact (black) versus implanted (white) strains for the medial aspect for the 36 kg load. N= fringe compensator units.

Intact versus implanted strains for the lateral aspect with a 36 kg load.

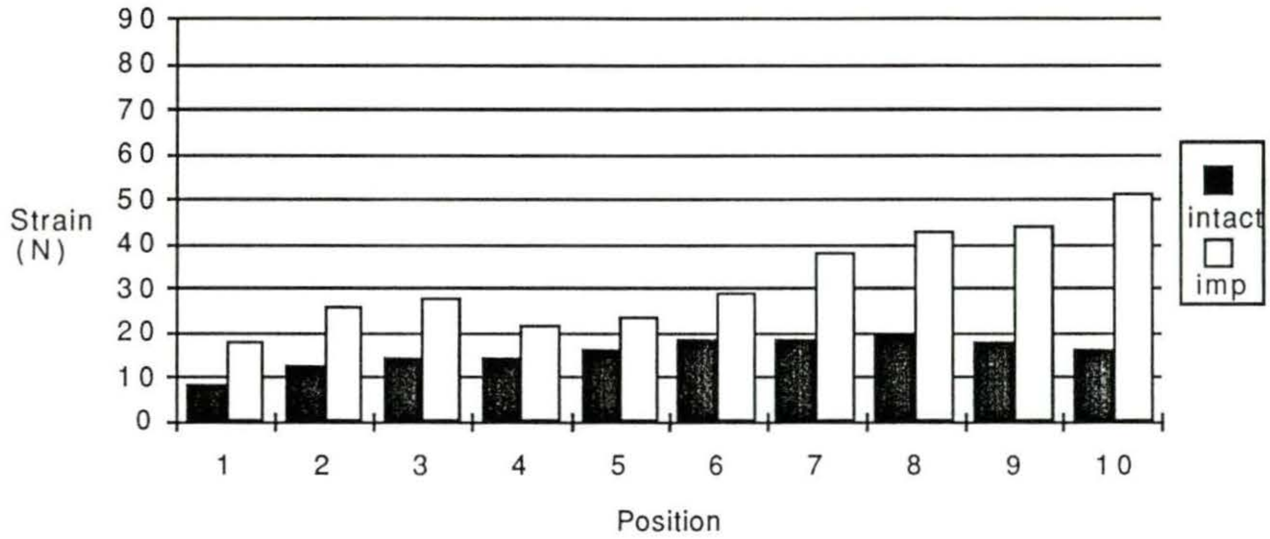

Figure 2. Intact (black) versus implanted (white) strains for the lateral aspect for the 36 kg load. N= fringe compensator units.

Intact versus implanted strains for the cranial aspect with a 36 kg load.

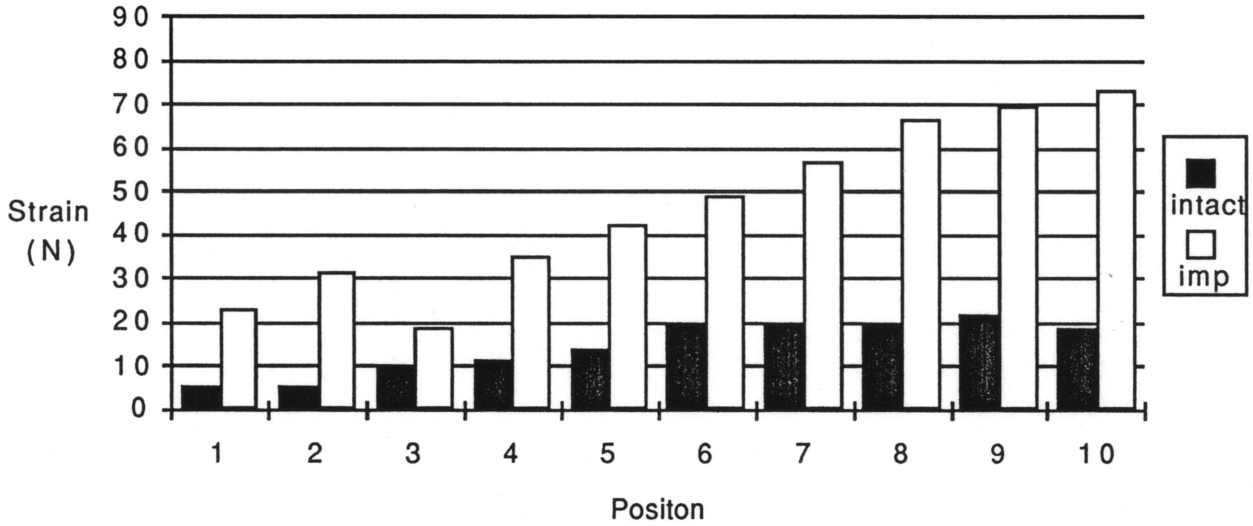

Figure 3. Intact (black) versus implanted (white) strains for the cranial aspect for the 36 kg load. N= fringe compensator units.

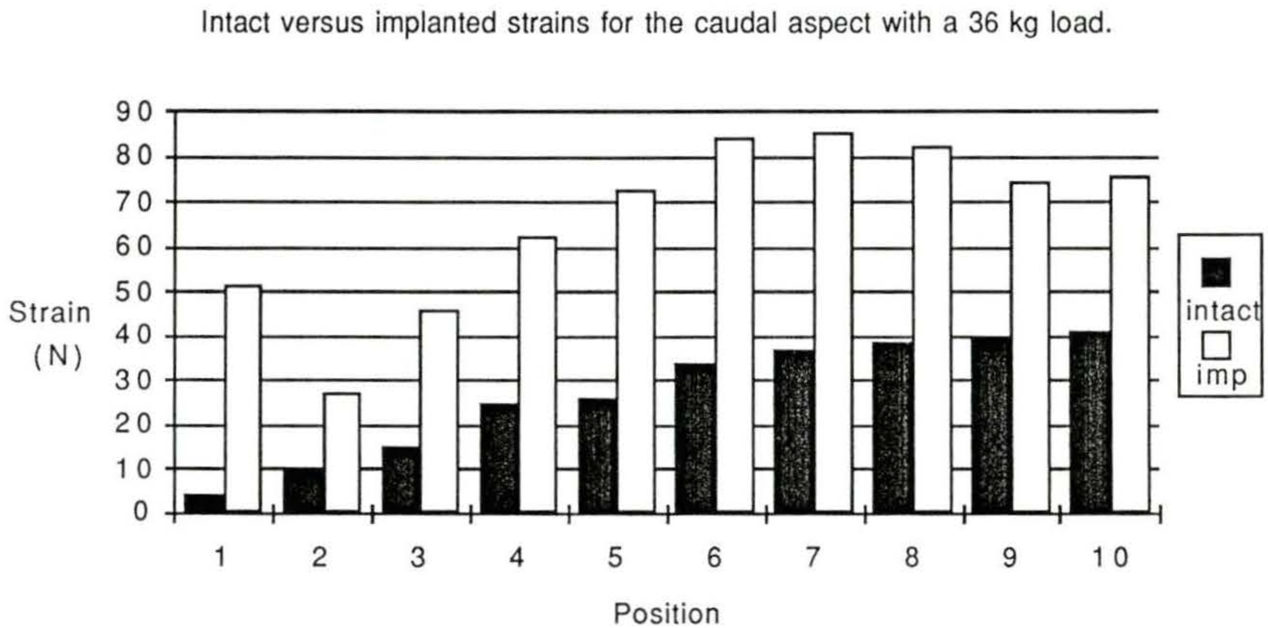

Figure 4. Intact (black) versus implanted (white) strains for the caudal aspect for the 36 kg load. N= fringe compensator units.

DISCUSSION

Cemented total hip replacement has proven to be effective treatment for dogs with hip disease. Current reports show good results several years postimplantation in the dog.[4] Although cemented hip prosthesis in the dog and man have shown good results, complications do occur. Some have looked to cementless implantation to avoid some of these problems.[7,19]

One way to predict performance of a total hip replacement system is by determining the amount of stress transfer from the prosthesis to the femur. If a pathologic amount of stress is transferred, the bone may reabsorb resulting in poor long term performance of the implant.[7,9,12] This study compared the post implantation stress transfer of a canine cementless total hip prosthesis to that of the intact bone by means of photoelastic analysis. Previous studies in man have found that cementless femoral hip replacements stress shield the femur.[7,9,11,19] In this study post implantation strain patterns showed similar trends to those in the intact bones. Although most strains after implantation were higher than the intact values, statistical differences could not be shown for the medial ($p<.385$), lateral ($p<.0664$), or caudal ($p<.0588$) aspects of the bones at loads of 36 or 55 kgs. The inablity to show statistically significant differences in changes in the lateral and posterior aspects may be due to the limited number of samples in this study or the wide range of values present. The cranial aspect did show a statistically significant increase in strain after implantation at both loads. This may be a result of the cranial bowing of the canine femur creating a stress riser distally at the cranial tip of the prosthesis.

The proximal elevation and transient decrease found on the cranial, caudal, and lateral aspects may be due to initial strain transfer where the implant contacted the bone. This would require cross sectional analysis at the levels of increased strains to determine the fit and fill of the medullary canal by the prosthesis for conformation.

We conclude that the cementless femoral implant used in this study does not stress shield the femur. There was a statistical difference in strain on the cranial aspect after implantation. Whether the amount of increase in strain would be detrimental to boney ingrowth is not known at this time. As boney ingrowth and remodeling occurs, stresses transferred to the femoral cortex will probably be altered and will necessitate further study.

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SUMMARY AND DISCUSSION

Eight canine femurs were successfully coated and measured by photoelastic techniques while loaded to 36 kg (80 lbs.) and 55 kg (120 lbs.). The normal strain distribution of the intact femur revealed that the strains were smallest proximally and increased distally in the cranial, caudal, and lateral aspects of the femur. The medial aspect showed the opposite pattern of strains with the highest strains proximally with strains decreasing as the distal aspect of the bone is approached.

Four bones were then implanted with the femoral component of a cementless total hip replacement. Strains were measured and compared with the intact values. All measurements for all aspects showed an increase in strains except two points on the medial aspect at the 36 kg load. Although strains increased, only the cranial aspect was statistically significant.

Unlike the human femur, dog femurs in this study did not display stress shielding when implanted with the femoral component of a cementless total hip replacement. Instead, almost all measurements showed an increase in strains. Further studies will be necessary to determine if the strain levels present in the implanted bones would be detrimental.

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