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PHOTOELASTIC ANALYSIS OF THE PROXIMAL FEMUR IN DEVIATIONS OF THE MECHANICAL AXIS OF THE LOWER LIMB

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Abstract. *The purpose of this research was to assess the effects of pathological deviations in different levels of the lower limbs in the distribution of stress in the proximal femur region using photoelasticity. Geometric models of the femurs and tibias were obtained from frontal panoramic X-rays. The X-rays selected were those showing a normal axis and the following pathological deviations: coxa vara, femur varum, geno valgum due to deviation at the extremity of the femur, geno varum due to deviation at the proximal tibia extremity, varum ankle, valgum ankle and varus of the tibial diaphysis. Sixteen photoelastic models were made for all of the experimental groups. In general, an 8N compressive force was applied to the top of the femoral head through a semi-dome acrylic mould, which represented the acetabulum. The results showed that the stress was generally higher in the calcar region than in the trochanteric region, followed by the third distal of the femur head. This study allowed for the development of better criteria for the correction of angular deviations and helped identify the deviations that are most harmful to the mechanical axis in terms of the effects on the bone and the articular effort of the lower limbs.*

Keywords: *alignment, deviations, inferior limbs, mechanical axis, photoelasticity, stress.*

1. INTRODUCTION

Disorders of the anatomical and mechanical axis of the lower limbs are important because they influence the performance and efficiency of locomotion and, in years to come, may cause arthrosis in the hip, knee and ankle (Moreland, Bassett and Hanker, 1987; Bagren, Blaha and Freeman, 1983; Cooke and Scudamore, 2003; Felson *et al.*, 2004).

Due to the anatomical role of the lower limbs in weight bearing, unnatural angulations can cause significant modifications in the stress distributions experienced by the bones and articulations. According to Wolff's classical law, the internal form and structure of bones reflect the mechanical loading experience and the distribution of the applied stress. Consequently, regions that receive more stress become more resistant (*i.e.*, they develop higher bone density), while those subjected to lower mechanical requirements suffer osteopenia due to their lack of use. Importantly, the local distribution of stress is directly influenced by the angular relations between the bone segments. The various angular deviations in the hip, knee and ankle articulations are well known (Tang, Zhu and Chiu, 2000; Berger *et al*., 1998; Powers, Maffuccia and Hampton, 1995). However, the implications of the resulting deviations in stress on segments distant from the articulation have not been studied. Nevertheless, prior studies indicate that they may be important. While studying the performance of a knee prosthesis in the presence of a deformity in the ankle, it was observed that the index of loosening of the prosthesis was higher when there was poor alignment of the ankle (Kuster and Stachowiak, 2002; Kilgus, 2002; Whiteside, 1999; Hsu *et al*., 1990; Font-Rodriguez, Scuderi and Insall, 1997).

The lower limb alignment in the frontal plane is defined by the bone morphology (normal or pathological) and by the mechanical axis that represents the direction of functional stress loading. In panoramic X-rays of the lower limbs, this axis is traced by a line that goes from the centre of the femoral head down to the centre of the ankle. In normal cases, it passes up to 9.0 mm medially to the ankle (Paley *et al*., 1994). However, angular deviations alter this relation.

The purpose of this research was to assess the implications of angular deviations on the distribution of stress in the proximal femur using plane transmission photoelasticity. Deviations of both the proximal femur and the distal regions of the lower limb were studied by applying a compressive load to produce internal stress. The levels and distributions of stress along the bones and articulations were then determined qualitatively and quantitatively because changes in alignment cause redistributions of this stress.

2. MATERIALS AND METHODS

2.1 Selection of the deformity cases

The research was performed using images obtained from front panoramic X-rays of the lower limbs bones (femur and tibia) of individuals presenting alterations in the mechanical axis of the femur that were caused by deviations in the proximal region of the femur, the central region of the femur (*i.e.*, diaphysis), the knee, the central region of the tibia and the ankle. These individuals were treated in the Pediatric Orthopaedic Sector of the Clinics Hospital of the Faculty of Medicine of Ribeirão Preto, University of São Paulo.

2.2 Inclusion and exclusion criteria

Panoramic X-rays of individuals showing isolated deviations in the alignment of the lower limbs in the frontal plane were included in the research. Subjects whose X-rays did not show technical quality were excluded. Additional exclusion criteria were the presence of grotesque deviations affecting more than one plane and the presence of more than one deviation in a single bone. The X-rays selected were those showing a normal axis and the following pathological deviations: coxa vara, femur varum, geno valgum due to deviation at the extremity of the femur, geno varum due to deviation at the proximal tibia extremity, varum ankle, valgum ankle and varus of the tibial diaphysis. A Free and Clarified Consent Term was used, read and signed individually by all of the patients who were selected for the research (139.074).

(2)

2.3 Analysis of the X-Rays

The parametres used to trace the mechanical and anatomic axis were in accordance with the orientations of Paley *et al*., 1994. The values of the mechanical axis and of the cervical-diaphisary angles (124-136°) and tibia articular distal lateral were presented in Table 1.

2.4 Geometric Model

Geometric models of the femurs and tibias were obtained from frontal panoramic X-rays. These X-rays were scanned in high resolution, maintaining the real dimensions of the femurs and tibias. The images were imported into Auto CAD®, and contours of the bones were generated using the Spline function (Figure 1).

Table 1. Values for the mechanical axis and the cervical-diaphisary angles, and tibia articular distal lateral of the X-rays used**.**

Proximal femur (KPa)								
Regions	**Coxa Vara**	**Femur Varum**	**Geno Valgum**	**Geno Varum**	**Valgum ankle**	**Varum ankle**	**Tibia Vara**	**Without deviations**
Trochanteric	2,54	12,81	9,68	11,24	8,14	9,48	3,96	9,5
t-Ward	16,06	27,38	12,20	13,52	9,13	17,93	12,01	7,24
Tension band	10,76	28,32	15,82	17,54	17,60	19,06	8,83	11,47
Calcar	30,79	34,26	34,17	22,08	27,73	27,08	21,38	18,98
Proximal third	14,38	18,39	13,40	11,50	14,62	19,31	9,29	8,48
Medial third	19,36	16,67	22,49	13,49	19,91	17,58	8,21	16,56
Distal third	17,53	11,89	18,95	8,58	22,75	9,31	6,21	11,44

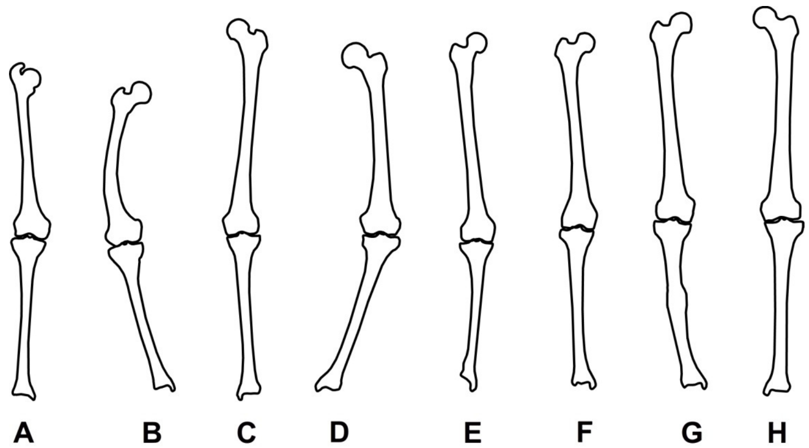

Figure 1. Geometric models obtained from the X-rays used in this research. A- Coxa vara, B- Femur varum (deformity in the diaphysis), C- Geno valgum due to deviation at the extremity of the femur, D- Geno varum due to deviation at the proximal tibia extremity, E- Valgum ankle, F- Varum ankle, G- Tibial diaphysis varum and H- Femur and tibia without pathological axis deviations

2.5 Photoelastic Model

Using the geometric models, acrylic moulds of the femurs and the tibias were made using a special water jet cutting method. This method allowed for the strict standardisation of the experimental technique and photoelasticity measurements. To obtain the photoelastic models, four photoelastic moulds in acrylic were used, two of which were used for the femurs and two used for the tibias. Silicon rubber (Master®) was cast into the photoelastic mould, creating a plaque of silicon that was put inside the mould. The acrylic moulds of the femur or tibia that had been made before were positioned on top of this plaque. Silicon mixture and catalysing agent were then cast into the photoelastic mould, allowing for reproduction of the femur and tibia acrylic moulds with a good surface finish.

Inside the acrylic moulds, the proximal and distal regions of the femurs and tibias were filled with a photoelastic epoxy resin and catalysing agent (Polipox®). The bodies or diaphyses of these structures were made of acrylic. The limits of the proximal and distal articular segments (hip, knee and ankle) were defined by Heim's epiphysis square, which has sides that are the same length as the widest part of the epiphysis (Slongo et al., 2007).

Sixteen photoelastic models were made for all of the experimental groups, where eight were femurs and eight were tibias. All of the models were 15.00 mm thick. The photoelastic resin used has an optical constant of 0.2 N/mm fringe, Young's Modulus of 4.51 MPa and Poisson's Ratio of 0.4 v. The photoelastic analysis was performed on a transmission polariscope. In general, an 8N compressive force was applied to the top of the femoral head through a semi-dome acrylic mould, which represented the acetabulum. The acetabulum mould was positioned in an anatomical manner above the femoral head. An intra-articular silicon rubber mould was interposed to uniformly fill the space between the acetabulum and the femur mould and to biomechanically simulate the articular cartilage. The acetabulum was represented in an anatomical form in two planes for each type of deviation of the mechanical axes of the femur and the tibia.

During compressive loading, the models (acetabulum – femur – tibia) were positioned to achieve an inclination of 17° of frontal plane valgum in relation to the vertical axis. This experimental setup is in accordance with the principles of Pauwells (Pauwells, 1980). The internal stress was analysed in the proximal regions of the femur and evaluated both qualitatively and quantitatively (KPa).

The shear stress was calculated in a standardised form, with points localised at 5.0-mm increments over the entire length of the photoelastic model. Thus, the number of points varied according to the geometry of each femur. Regardless of the type of deviation, the proximal femur was divided into the following regions: trochanteric, Ward's triangle (t-Ward), tension band, calcar, proximal third, medial third and distal third (Figure 2).

The shear stress values were obtained using a process similar to what has been used for the vertical polariscope and applying Tardy's compensation method (Hirokawa, Yamamoto and Kawada, 2001).

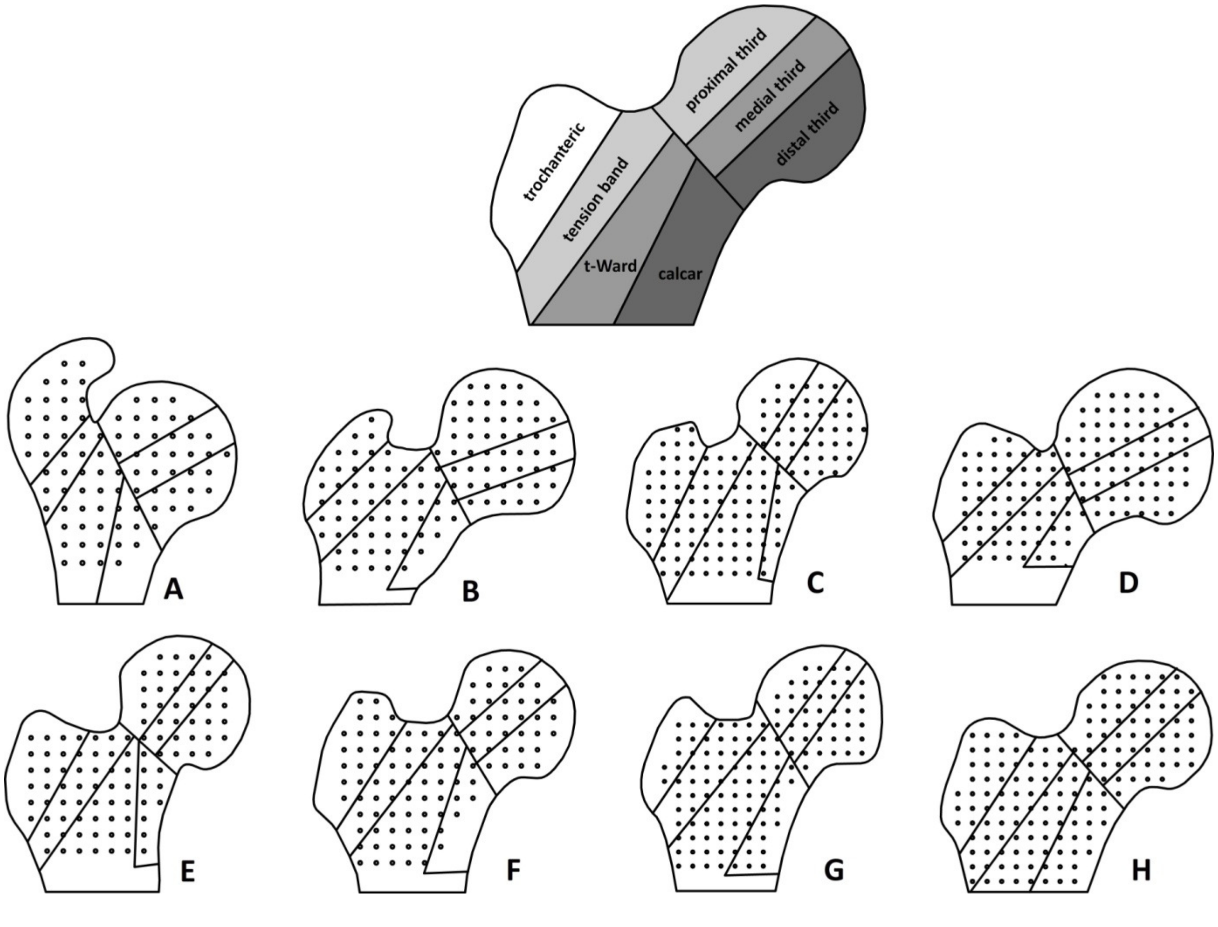

Figure 2. Schematic drawings of the points analysed in the proximal regions for the following deviations: A- Coxa vara, B- Femur varum (deformity in the diaphysis), C- Geno valgum due to deviation at the extremity of the femur, D- Geno varum due to deviation at the proximal tibia extremity, E- Valgum ankle, F- Varum ankle, G- Tibial diaphysis varum, H- Femur and tibia without pathological axis deviation

3. RESULTS

Qualitative analysis of the stresses in the proximal femur was carried out on the photoelastic models corresponding to the eight deviations mentioned earlier.

Regardless of the type of deviation, the initial location of the fringe order and the highest concentration of stress were in the calcar region of the proximal femur. In the coxa vara, geno valgum deviations and in femurs and tibias without pathological axis deviations, the fringe order also began in the medial third region of the femoral head. In genus varum, due to deviation in the proximal tibia extremity and femoral varum, the fringe order also began in the tension band. In the tibial diaphysis varum, valgum ankle and varum ankle, the fringe order also began in the regions of Ward's triangle (t-Ward), the distal third of the femoral head and the proximal third of the femoral head, respectively. In most of the deviations analysed, the region experiencing the lowest stress concentration was the trochanteric region, followed by the distal third of the femoral head (Figure 3).

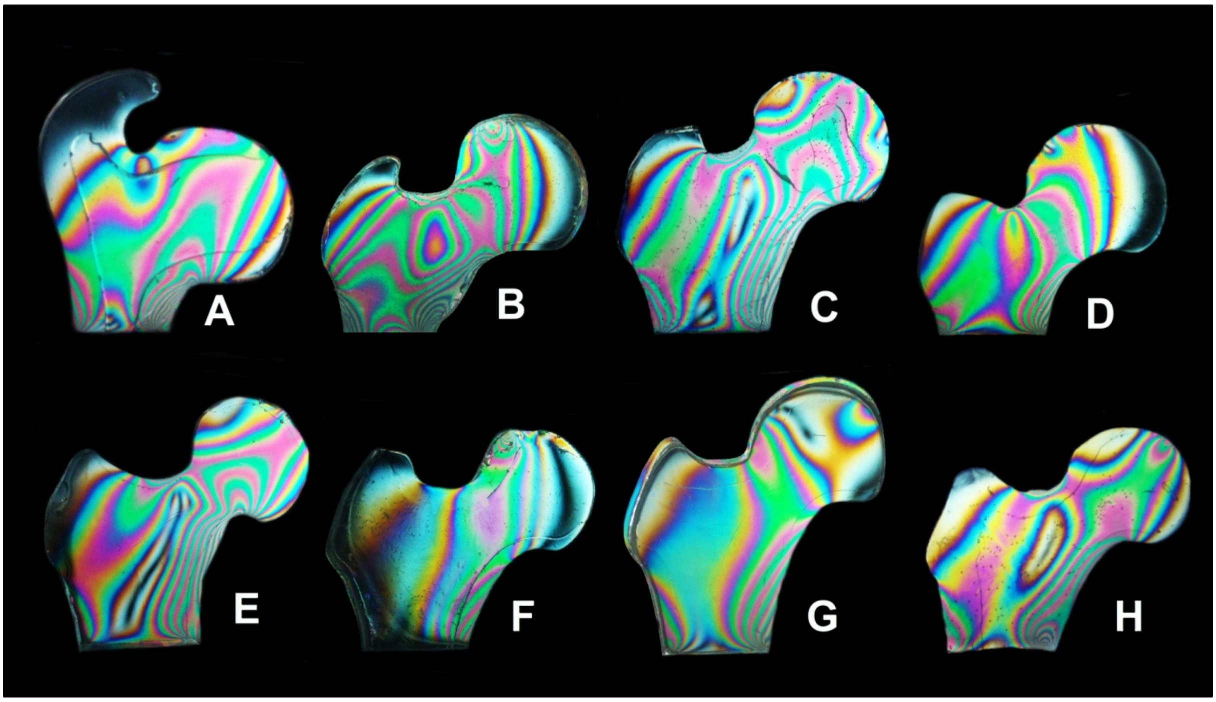

Figure 3. Standard orders of the isochromatic fringes obtained during the analysis of the deviations: A- Coxa vara, B- Femur varum (deformity in the diaphysis), C- Geno valgum due to deviation at the extremity of the femur, D- Geno varum due to deviation at the proximal tibia extremity, E- Valgum ankle, F- Varum ankle, G- Tibial diaphysis varum, H- Femur and tibia without pathological axis deviations

The results obtained are in accordance with the models, the proposed conditions of fixation and the geometry of long bones. For conditions of different fixations, there may be different results. Thus, as the compressive strength increases, stress increases.

For the quantitative analysis, Tardy's compensation method was used to determine the shearing stress (τ). The general behaviour of the photoelastic models was analysed in the proximal femur for each type of deviation. To visualise this behaviour, a graph showing the average shear stress for each of the seven regions of the proximal femur (*i.e.*, trochanteric, t-Ward, tension band, calcar, proximal third, medial third and distal third) was prepared (Fig. 4).

Analysis concerning the general behaviour of the photoelastic models was carried out in the proximal femur, in each type of deviation. In order to visualize this behaviour, graphs were prepared representing the average values of the shearing stress with localized points in accordance with the seven regions (trochanteric, t-Ward, tension band, calcar and proximal third, medial and distal) (Figure 4).

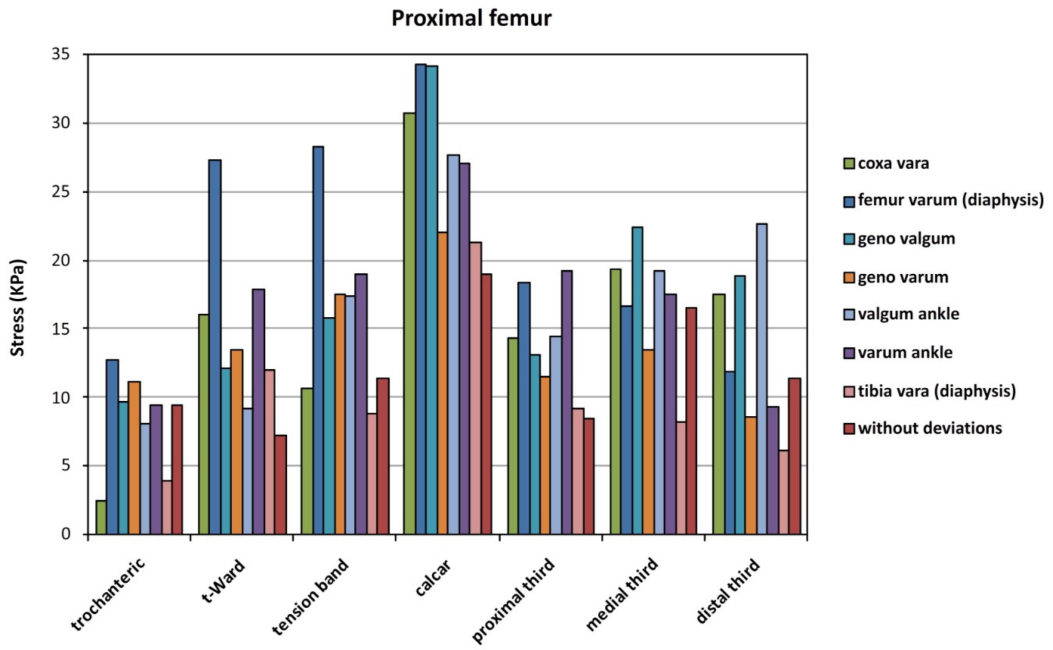

Figure 4. Average values of the shearing stress obtained during the analysis of the proximal femur

In the femur and tibia without pathological deviations, the shear stress was highest in the calcar region, followed by the medial third and ultimately dissipating to the tension band, the distal third and the trochanteric regions. The regions with the lowest concentrations of stress were the t-Ward, followed by the proximal third.

For the case of angular deviation of coxa vara, we observed that the shear stress on the proximal femur was highest in the calcar region, followed by the medial third, and dissipated to the distal third, t-Ward and the proximal third. The regions with lowest concentrations of stress were in the trochanteric region, followed by the tension band. The trochanteric region showed low fringe orders, indicating that the application of the load had less influence in this region.

In the varus deviation of the tibia diaphysis, the stress was highest in the calcar region, followed by the t-Ward. Internal stress dissipated posteriorly to the proximal third, the tension band and the medial third regions. The trochanteric and distal third regions showed the lowest values of average shear stress.

In the geno valgum deviation of the femur, the shear stress was highest in the calcar region and in the medial third, and then dissipated to the distal third, the tension band and the proximal third. The regions of lowest stress were the trochanteric and t-Ward regions.

In the angular deviation of geno varum at the proximal extremity of the tibia, the stress was highest in the calcar region, followed by the tension band. With the increase of the the applied compressive load, the internal stress dissipated to the t-Ward, the medial third and the proximal third regions. The region with the lowest concentration of stress was the distal third, followed by the trochanteric.

In the valgum ankle deviation, the stress was most concentrated in the calcar region, followed by the distal third. The stress dissipated into the medial third, the tension band and the proximal third regions. The concentration of stress was lowest in the trochanteric region, followed by the t-Ward region.

In the varum ankle deviation, the stress was highest in the calcar region, followed by the proximal third. The stress then dissipated through the tension band, the t-Ward and the medial third regions. The region with the lowest concentration of stress was the distal third, followed by the trochanteric region.

Finally, in the femur varum deviation (deformity in the diaphysis), the stress was highest in the calcar region, followed by the tension band. The internal stress dissipated posteriorly to the t-Ward, proximal third and medial third regions. The distal third showed the lowest average shear stress, followed by the trochanteric region.

4. DISCUSSION

Although the concepts of anatomical and mechanical deviation of the lower limbs are not new in orthopaedics, the subject has taken on higher interest due to the studies of Paley (2003), concerning the correction of deviations. Interest has also been raised by the increasing use of articular prostheses, which are becoming increasingly personalised and must be in harmony with the local stress.

Previous studies have concentrated primarily on the effects of deviations in the articulations that are closest to the deviation. Consequently, little is known about the effects of deviations, both combined and simple, on the articulations. The present study addresses an important knowledge gap by clarifying how the anomalous stress resulting from deviations is distributed along the bone and through the proximal and distal articulations. Importantly, we observed that deviations of the mechanical axis of the lower limbs cause important changes in the distribution of stress not only in the nearest articulation but also in articulations that are more distant. This information is useful for understanding which deformities are more harmful. It may also be valuable for studying the use of prostheses in deformed bones because the redistribution of stress may have important implications for complications such as prosthesis wear and loosening.

Alignment of the lower limb is characterised by the angle of the proximal femur, the knee and ankle angles and by deviations in the central part of the femur (Goker and Block, 2007; Hunt *et al*., 2006; Sailer *et al*., 2005; Specogna *et al*., 2007). Anatomical alignment has important implications for the mechanical axis because prolonged deviations of the mechanical axis lead to articular dysfunction. Subsequent wear and tear leads to pain and can restrict movement. In advanced cases, this damage is treated by articular substitution with a prosthesis. While it is important that the deviation be corrected before or during arthroplasty to prevent future complications, surgeons currently focus on correcting the deviation of the articulation that is being repaired. Our results preliminarily showed that alignment deviations, even in another bone or in another region, significantly alter the stress distribution in the whole lower limb. This stress redistribution may be important for explaining the mechanisms of prosthesis failure (*e.g.*, loosening, fracture) (Specogna *et al*., 2007; Guilak, 2011; Sharma *et al*., 2010; Duggal *et al*., 2014; Sharma *et al*., 2001; Cicuttini *et al*., 2004; Cooke *et al*., 1997; Tetsworth and Paley, 1994; McKellop, Llinas and Sarmiento, 1994).

We specifically observed that the deformities of geno varum due to deviation of the proximal extremity of the tibia and femur varum led to increase in the concentration of the stress on the femoral calcar. This result was most likely due to the increased intensity of the compressive force. Shear stress also increased in the region of the tension band, most likely due to an increase in the stress forces.

In the varum ankle, there appeared to be a tendency toward abduction of the proximal femur extremity. As a result, the inclination of the neck in relation to the force vector passing from the acetabulum to the centre of the femoral head is increased. The trochanteric region showed a decrease in the concentration of force, most likely due to the medial detachment of the forces.

In the valgum ankle, there was a tendency of adduction of the proximal femur extremity. This adduction aligns the axis of the femoral neck with the force transmission vector going from the acetabulum to the centre of the femoral head. Thus, even though the concentration of compressive calcar forces is increased, there is most likely an alteration in the standard force of the tension band due to the occurrence of compressive forces instead of stress forces.

We consider our results preliminary because some stress alterations are difficult to explain (*e.g.*, the influence of the ankle deviation in the proximal femur). Future work will assess the effects of alterations of the deviations in the various articulations. In addition, the technique of the finite element analysis will be used, which may help better explain the stress distribution results.

5. CONCLUSION

Using photoelasticity, it was possible to observe that local deviations of the femur in the hip, or even at a distance, significantly influence the distribution of stress in the proximal femur. In the angular deviations analysed, the calcar femoral region was the most critical. In contrast, the trochanteric region showed lower average values of shear stress in most of the deviations.

6. ACKNOWLEDGEMENTS

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