ORIGINAL ARTICLE

The role of the calcar femorale in stress distribution in the proximal femur

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Objective: To investigate the role of the calcar femorale in stress distribution in the proximal femur.

Methods: Twenty-five specimens of proximal femurs were fixed to simulate single-limb stance. Strain gauges were applied to record the strain under different loads. Strain values of 27 selected sites in the proximal femur were recorded and analyzed at the level of 100 N, 200 N, 300 N, 400 N, 500 N, 600 N and 700 N, respectively before and after disruption of the calcar femorale.

Results: When a normal load was being borne, strain values measured in the posterior and medial aspects of the proximal femur were greater than those measured in the anterior and lateral aspects, no matter whether the calcar femorale was disrupted or not. However after disruption of the calcar femorale, strain values in the posterior and medial aspects of the proximal femur increased significantly, whereas those of the anterior and lateral aspects decreased significantly.

Conclusion: The calcar femorale redistributes stress in the proximal femur by decreasing the load in the posterior and medial aspects and increasing the load in the anterior and lateral aspects.

Key words: Calcar femorale; Femoral fractures; Stress, mechanical

Introduction

The calcar femorale is located at the posteromedial conjunction of the femoral neck and shaft, and runs along the posterointernal margin of the femoral neck from the diaphysis towards the femoral head¹. The calcar femorale was originally described by Merkel as early as 1874², named by Harty in 1957³ and its anatomic properties described in detail by Griffin in 1982⁴. Garden wrote a detailed account of both the structure and function of the proximal femur⁵. The calcar femorale, lying deep to the lesser trochanter, is a vertical plate composed of multilayer compact bone with a typical thickness of less than 1 mm.

The calcar femorale can bear compression load and redistributes stress or load from the femoral head to the proximal femur. The calcar femorale also contributes to the

strength of the femoral neck. Bigelow described the calcar femorale as 'the true neck of the femur'. As part of a truss system, it can transform bending moment and torsional moment. It plays an important role in the proximal femoral loading system and is highly significant in the treatment of proximal femoral fracture⁶. Gao *et al.* hold the opinion that the load on the femoral head can be distributed evenly to the medial cortex of the proximal femur due to a truss system⁷. Oh and Harris used gauges to measure the stress of the cortex container of the upper femur⁸. Their study showed that after insertion of a femoral component, the pattern of strain in the proximal part of the femur is reversed compared with that of an intact femur, in that the maximum strain occurs around the tip of the prosthesis rather than at the calcar femorale. The disruption causes a redistribution of stress in the proximal femur. However, how the forces transfer inside the proximal femur, and the exact role of the calcar femorale, is still unknown. This is what will be discussed in this report.

In the current study, the role of the calcar femorale in stress distribution was explored by comparing strain data acquired by strain gauges before and after disruption of the calcar femorale.

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Materials and methods

Specimens and instruments

This study included 25 cadaver femurs from male subjects with a mean age of 44 years (range, 23 to 57 years). The specimens were verified to be without obvious osteoporosis and other bone diseases by a SIEMENS Somatom sensation 64 CT scan (Munich, Germany). The instruments applied in the study include a CSS-44020 experimental biomechanics machine (Changchun, China), a WS3811 digital strain gauge (Beijing, China) and BX120-4AA strain gauges (Taizhou, China).

Methods

Specimens were fixed to simulate a single-limb stance and strain gauges adhered to 27 selected sites in the proximal femur. The 27 sites were as follows (Fig. 1): 1) the center of the lateral aspect of the femoral neck; 2) the center of the posterior aspect of the femoral neck; 3) the center of the medial aspect of the femoral neck; 4) the center of the anterior aspect of the femoral neck; 5) the lateral aspect of the proximal femoral neck; 6) the posterior aspect of the proximal femoral neck; 7) the medial aspect of the proximal femoral neck; 8) the anterior aspect of the proximal femoral neck; 9) the lateral aspect of the base of the femoral neck; 10) the posterior aspect of the base of the femoral neck; 11) the medial aspect of the base of the femoral neck; 12) the anterior aspect of the base of the femoral neck; 13) the anterolateral aspect of the greater trochanteric tip; 14) the posterolateral aspect of the greater trochanteric tip; 15) the proximal 1/3 of the intertrochanteric crest; 16) the distal 1/3 of the intertrochanteric crest; 17) the juncture of the lesser trochanteric base and the intertrochanteric crest; 18) the posterior aspect of the lesser trochanteric tip; 19) 1 cm below the distal end of the intertrochanteric line; 20) 1 cm below the distal 1/3 of the intertrochanteric line; 21) 1 cm below the proximal 1/3 of the intertrochanteric line; 22) 1 cm below the proximal end of the intertro-

chanteric line; 23) 3 cm perpendicularly distal to the base of the lesser trochanter; 24–27) the circum was divided equally into five parts at the level of site 23 and sites 24, 25, 26, and 27 located clockwise from site 23. The sites located on the lateral aspects of the proximal femur included 1, 5, 9, 13, 14, and 27. The sites located on the posterior aspects of the proximal femur included 2, 6, 10, 15, 16, 17, 18, and 23. The sites located on the medial aspects of the proximal femur included 3, 7, 11, and 24. The sites located on the anterior aspects of the proximal femur included 4, 8, 12, 19, 20, 21, 22, 25, 26. The strain gauges were connected to a WS3811 digital strain gauge (Beijing Bopu, Beijing, China). In this experiment, a CSS-44020 experimental biomechanics machine was used to provide load. Specimens were compressed at the rate of 5 N/S to 705 N. At the levels of 100 N, 200 N, 300 N, 400 N, 500 N, 600 N and 700 N, strain values were recorded by the strain gauges.

Preliminary experiments

Five proximal femurs were selected and the cortex disrupted at the tip of the lesser trochanter and the cancellous bone close to it excluding the calcar femorale. The aforementioned tests were repeated and strain values recorded. Each femur served as its own control. The loading tests were repeated six times both before and after disruption of the calcar femorale.

Secondary experiments

Twenty proximal femurs were selected. The tests mentioned above were repeated on the intact proximal femurs and the strain values recorded. A 1.5 mm Kirschner wire was used to disrupt the calcar femorale at the tip of the lesser trochanter, the disruption being verified by CT scanning (Fig. 2). After disruption of the calcar femorale, the tests were repeated and the strain values recorded. Each femur served as its own control. The loading tests

Figure 1. A, B and C show 21 of the selected 27 sites, to which the strain gauges were adhered.

Figure 2. CT scan, horizontal section, verifying disruption of the calcar femorale by a 1.5 mm Kirschner wire.

were repeated six times both before and after disruption of the calcar femorale.

Statistical analysis

Statistical analyses were performed using SAS 8.0 (SAS Institute, Cary, North Carolina, USA). All values were expressed as mean $\pm$ standard deviation (SD) for continuous variables. Comparisons between two groups were made by a two-tailed Student's *t*-test for continuous variables. Differences were regarded as statistically significant when $P < 0.05$.

Results

During the preliminary experiment, strain values became larger with increasing load in the proximal femur. There was no statistical significance between the two groups in strain values pre- and post-disruption of the cortex and its adjacent cancellous bone.

During the ensuing experiment, the relationship of strain value and load before and after disruption of the calcar femorale was analyzed. The results revealed elastic deformation of the proximal femur within the load range of up to 700 N. The strain values from the posterior and medial aspects of the proximal femur were larger than those from the anterior and lateral aspects, no matter whether the calcar femorale was disrupted or not (Tables 1–3). At the levels of 300 N, 500 N, and 700 N loads, 81 groups of data were selected and 72 groups of data show significant differences ($P < 0.05$) when comparisons were made between the data recorded pre- and post-disruption of the calcar femorale. The sites from which the strain values after disruption of the calcar femorale were greater than those with an intact calcar femorale included 2, 3, 6, 11, 16, 17, 18, 21, 22, 24 and 26, which are mainly distributed on the posterior and medial aspects of the proximal femur (Tables 4–6). The sites from

which the strain values after disruption of the calcar femorale were smaller than those with an intact calcar femorale included: 1, 4, 5, 7, 8, 9, 10, 12, 13, 15, 19, 20, 23, 25 and 27, which are mainly distributed on the anterior and lateral aspects of the proximal femur. Site 14 was not included in either group.

Discussion

The calcar femorale is an important component of the internal proximal femur. With the exception of age, few factors affect its density and rigidity. Li and Aspden found no difference between different groups of patients with osteoporosis and osteoarthritis in the density or rigidity of the calcar femorale¹. The material properties of the calcar femorale were found to be similar to those of the diaphyseal cortex in an elderly group^{9,10}. This makes it capable of conducting load from the trabecular bone of the femoral head to the femoral shaft. Li and Aspden's modeling, using finite element analysis, suggested that the cortex in the inferior medial aspect of the femoral neck carries most of the load, increasing from about 30% in the subcapital region to about 96% at the base of the femoral neck¹¹. Using finite element analysis, Wang *et al.* verified that the compression trabeculae and the calcar femorale above the entotrochanter bear the major part of the load¹². Our study arrived at the same conclusion with the use of strain gauges. The data acquired in the current study has confirmed that the load transferred along the posterior and medial proximal femur is larger than that transferred along the anterior and lateral aspects, whether the calcar femorale has been disrupted or not.

In the current study, specimens were fixed simulating single-limb stance, where the proximal femur simultaneously bears bending and torque moment. The femur grows to adapt to these mechanical requirements. The calcar femorale and three beams of bone trabeculae, comprising compression, tension and oblique trabeculae, constitute the loading system-truss system. The calcar femorale plays a special role in the truss system due to its flexural shape, and the fact that its attachment points are from posterior to anterior on the inside of the femur. Gao *et al.* hold the opinion that the load on the femoral head can distribute to the cortex of the medial aspect of the proximal femur evenly because of the truss system⁷. However, this is in conflict with our results, which demonstrate that the strain values are different at each site, even on the medial aspect of the femur the load did not distribute uniformly over the selected sites. Strain values from the posterior and medial sites were larger than those from the anterior and lateral sites. This reveals that the

Table 1 Strain values of sites 1–9 under a load of 700 N ($\bar{x} \pm s$, $\mu\epsilon$)

	1	2	3	4	5	6	7	8	9
Before disruption	455.50 $\pm$ 162.23	212.75 $\pm$ 235.17	732.2 $\pm$ 407.20	445.40 $\pm$ 171.61	261.00 $\pm$ 151.50	67.90 $\pm$ 63.89	961.30 $\pm$ 336.57	249.75 $\pm$ 189.07	296.25 $\pm$ 168.72
After disruption	363.6 $\pm$ 230.85	368.4 $\pm$ 188.26	945.20 $\pm$ 291.31	248.50 $\pm$ 167.34	136.20 $\pm$ 78.36	306.85 $\pm$ 221.85	567.55 $\pm$ 338.44	174.95 $\pm$ 136.44	236.95 $\pm$ 78.43

Table 2 Strain values of sites 10–18 under a load of 700 N ($\bar{x} \pm s$, $\mu\epsilon$)

	10	11	12	13	14	15	16	17	18
Before disruption	239.60 $\pm$ 64.51	609.00 $\pm$ 148.74	318.55 $\pm$ 126.92	93.10 $\pm$ 130.40	42.75 $\pm$ 26.66	112.00 $\pm$ 45.78	104.35 $\pm$ 74.80	64.60 $\pm$ 39.66	61.85 $\pm$ 40.44
After disruption	142.25 $\pm$ 113.22	816.80 $\pm$ 219.63	174.00 $\pm$ 138.60	26.25 $\pm$ 27.61	35.80 $\pm$ 112.38	59.85 $\pm$ 37.16	162.15 $\pm$ 75.34	210.10 $\pm$ 113.97	211.55 $\pm$ 114.78

Table 3 Strain values of sites 19–27 under a load of 700 N ($\bar{x} \pm s$, $\mu\epsilon$)

Site	19	20	21	22	23	24	25	26	27
Before disruption	527.00 $\pm$ 134.81	247.65 $\pm$ 90.64	147.55 $\pm$ 79.01	73.95 $\pm$ 66.40	146.29 $\pm$ 96.24	412.60 $\pm$ 219.36	355.85 $\pm$ 101.78	226.9 $\pm$ 133.41	327.45 $\pm$ 143.69
After disruption	439.70 $\pm$ 231.07	170.05 $\pm$ 81.47	323.75 $\pm$ 113.22	162.25 $\pm$ 99.18	113.10 $\pm$ 153.06	519.10 $\pm$ 217.06	276.80 $\pm$ 139.34	112.75 $\pm$ 98.78	218.45 $\pm$ 92.50

Table 4 Comparison of strain values of sites 1–9 between pre- and post-disruption of the calcar femorale

Load	1	2	3	4	5	6	7	8	9
300 N	N	↑	N	↓	N	N	↓	↓	↓
500 N	↓	↑	↑	↓	↓	↑	↓	↓	↓
700 N	↓	↑	↑	↓	↓	↑	↓	↓	↓

↓, statistically significant decrease in value after disruption of the calcar femorale; ↑, statistically significant increase in value after disruption of the calcar femorale; N, no statistically significant difference between pre- and post- disruption of the calcar femorale.

posterior and medial aspects of the proximal femur conduct most of the load from the femoral head, but not uniformly.

Before disruption of the calcar femorale, the load is transferred from the femoral head downwards to the femoral compact and cancellous bone which contains the calcar femorale. After disruption of the calcar femorale, the load once transferred by the calcar femorale is transferred by the femoral cortex. The disruption of the truss system leads to disruption of the mechanical conduction system, resulting in decreased efficiency in transforming bending and torque moment, and affecting the stress pattern in the proximal femur. It can be concluded that load transferred along the cortex of the proximal femur

Table 5 Comparison of strain values of sites 10–18 between pre- and post-disruption of the calcar femorale

Load	10	11	12	13	14	15	16	17	18
300 N	↓	↑	↓	↓	↑	N	↑	↑	↑
500 N	↓	↑	↓	↓	N	↓	↑	↑	↑
700 N	↓	↑	↓	↓	↓	↓	↑	↑	↑

↓, statistically significant decrease in value after disruption of the calcar femorale; ↑, statistically significant increase in value after disruption of the calcar femorale; N, no statistically significant difference between pre- and post- disruption of the calcar femorale.

Table 6 Comparison of strain values of sites 19–27 between pre- and post-disruption of the calcar femorale

Load	19	20	21	22	23	24	25	26	27
300 N	↓	↓	↑	↑	N	↑	↓	N	↓
500 N	↓	↓	↑	↑	↑	↑	↓	N	↓
700 N	↓	↓	↑	↑	↑	↑	↓	↑	↓

↓, statistically significant decrease in value after disruption of the calcar femorale; ↑, statistically significant increase in value after disruption of the calcar femorale; N, no statistically significant difference between pre- and post- disruption of the calcar femorale.

redistributes after disruption of the calcar femorale. The load conducted by the posterior and medial proximal femur becomes greater and the load in the anterior and lateral part becomes smaller compared with that of the intact femur, which means that an intact calcar femorale can reduce the load in the posterior and medial proximal femur and increase the load in the anterior and lateral part. In other words, the calcar femorale can prevent the posterior and medial proximal femur from suffering overload. Therefore, further consideration should be given to fractures involving the calcar femorale.

The calcar femorale is often involved in proximal femoral fracture. If the calcar femorale is broken by, or adjoining, a proximal femoral fracture, the fracture can be considered unstable. To manage such fractures, it is critical to achieve anatomic reduction and fixation of the calcar femorale. Apel *et al.* carried out mechanical tests in Evan's fracture with bigger or smaller posterior medial fracture masses¹³. In his opinion, fixation of the posterior medial fracture mass, especially the calcar femorale, is critical to the mechanical stability of intertrochanteric fracture. An intact calcar femorale is helpful in maintaining the stability of the internal fixators. Wang *et al.* placed fixators coincident to compression trabeculae and close to the calcar femorale during surgical treatment of femoral neck fracture and reported good outcomes¹². Levi *et al.* certified that the region with the greatest bone density as shown by CT scan was highly correlated with the reported best fixator location¹⁴. When surgery is performed on femoral fractures with intact calcar femorales, we should place the internal fixator close to the calcar femorale, thus not only making good use of firm support from the calcar femorale but also barely disrupting stress distribution and load conduction in the proximal femur.

Conclusion

When bearing a normal load, strain values in the posterior and medial proximal femur are larger than those of the anterior and lateral femur. The calcar femorale can bear compression load and affects load conduction and stress pattern by decreasing the load in the posterior and medial femur and increasing the load in the anterior and lateral femur.

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