Failure Mode of Depressive Osteochondral Fracture under Maximum Compressive Load: Studies of Normal, Osteoporotic, and Osteosclerotic Subchondral Bones

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Abstract :

Objective : **To determine the failure mode of depressive osteochondral fracture under the maximum compressive load.**

Design : **An experimental cadaveric study. A compressive load was applied through an indenter on a femoral condyle to create a depressive osteochondral fracture until the maximum load was reached.**

Background : **Most depressive osteochondral fractures occur without a gross articular cartilage injury because a large amount of load is reabsorbed by the surrounding tissues, especially the subchondral bone under the cartilage. We asked what the mode of depressive osteochondral fracture is. It might function as a load absorber from the articular cartilage.**

Methods : **Three groups of depressive osteochondral fractures were studied. Group 1 consisted of 12 pieces of middle third of normal median and lateral femoral condyles. Groups 2 and 3 consisted of 12 pieces of osteoporotic and osteosclerotic middle third of both femoral condyles. Using a universal testing machine, a depressive osteochondral fracture was created by applying a uniaxial compressive load through an indenter until the load rose to the maximum level. At that point, the load applied was stopped in order to minimize the extent of subchondral trabeculae fracture. Maximum load was recorded. Pressure and stiffness were calculated. The pattern of depressive fracture was studied histologically.**

Results : **The failure mode of depressive osteochondral fracture was such that the bone under the articular cartilage had a subchondral plate fracture, an interlacing of bone trabeculae under the plate, and a few fractures of the bone trabeculae. The interlacing of subchondral bone trabeculae was most evident in the normal bone as compared with the osteoporotic and osteosclerotic bones. The osteosclerotic bone failed at the highest load, while the osteoporotic bone failed at the lowest.**

Conclusion : **The subchondral plate fracture and the interlacing of subchondral bone trabeculae under the plate are the characteristics of the failure mode of depressive osteochondral fracture. This failure mode occurs before there is a discernible fracture of the subchondral bone trabeculae. The amount of load causing a fracture depends on the quality of the bone.**

Relevance : **The failure mode, especially the interlacing of subchondral bone trabeculae, might function as a load absorber from the articular cartilage. Therefore, the quality of subchondral bone is important for protection of the articular cartilage from compressive load injury.**

Key words : Compressive load, depressive osteochondral fracture, indenter, articular cartilage, interlacing, bone trabeculae, universal testing machine

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เรื่องย่อ : Failure Mode ของ Osteochondral Fracture ภายใต้แรงกดสูงสุดของ Normal, Osteoporotic และ Osteosclerotic Subchondral Bones

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Objective : หา failure mode ของ depressive osteochondral fracture ภายใต้แรงกดสูงสุด

Design : การศึกษาแบบทดลอง

Background : ส่วนใหญ่ depressive osteochondral fracture พบว่าไม่มีบาดเจ็บตัว articular cartilage เพราะว่าแรงกดส่วนใหญ่ถูกกระจายไปรอบ ๆ โดยเฉพาะกระจายลงสู่ subchondral bone ที่อยู่ใต้ cartilage การหา fracture mode ของ depressive osteochondral fracture อาจทำให้ทราบขบวนการกระจายแรงกดที่กระทำต่อ articular cartilage ไม่ให้เกิด injury

Method : ใช้กระดูกข้อเข่าส่วน middle third ของ median และ lateral femoral condyles มาศึกษา โดยแบ่งกลุ่มการศึกษา 3 กลุ่ม กลุ่มละ 12 ชิ้นงานทดลอง กลุ่ม 1 เป็นกลุ่มกระดูกปกติ กลุ่ม 2 เป็นกลุ่มกระดูก osteoporotic และกลุ่ม 3 เป็นกลุ่มกระดูก osteosclerotic ทุกกลุ่ม ทำให้เกิด depressive osteochondral fracture โดยให้แรงกดผ่าน indenter จาก universal testing machine จนกระทั่งได้แรงกดสูงสุด จากนั้นให้หยุดการกดทันที บันทึกผลแรงกดสูงสุดและนำมาคำนวณ pressure และ stiffness ศึกษารูปแบบของ depressive osteochondral fracture โดยการดูผลทาง histology

Results : Failure mode ของ depressive osteochodral fracture มีการหักของ subchondral plate กระดูกใต้ subchondral plate เกิดการเลื่อนซ้อนกันของ bone trabeculae และมีการหักของ trabeculae บ้าง โดยการเลื่อนนี้เกิดมากที่กระดูกปกติ เมื่อเปรียบเทียบกับกระดูก osteoporotic และ osteosclerotic ต้องใช้แรงมากสุดในกระดูก osteosclerotic และน้อยสุดในกระดูก osteoporotic

Conclusion : การหักของ subchondral plate และการเลื่อนเข้าหากันของ subchondral trabeculae ใต้ plate เป็นลักษณะ failure mode ของ depressive osteochondral fracture ซึ่งจะเกิดก่อนที่จะมีการหักของ subchondral bone trabeculae นอกจากนี้ปริมาณของแรงที่ทำให้เกิดการหักขึ้นอยู่กับคุณภาพของกระดูก

Relevance : Failure mode โดยเฉพาะการเลื่อนเข้าหากันของ subchondral bone trabeculae อาจทำหน้าที่เสมือน load absorber จาก articular cartilage ฉะนั้นคุณภาพของกระดูก subchondral จึงมีความสำคัญต่อการป้องกันการบาดเจ็บของ articular cartilage ต่อแรงกด

คำสำคัญ : แรงกด, compressive osteochondral fracture, indenter, กระดูกอ่อนผิวข้อ, การเลื่อนเข้าหากัน bone trabeculae, universal testing machine

INTRODUCTION

Most depressive osteochondral fractures involve the articular cartilage and metaphyseal bone. However, the articular cartilage of the fracture fragment shows no gross injury[1,2,3] because the excessive load on the articular cartilage is reabsorbed by the surrounding tissues through some mechanisms[3,4]. This study was carried out to investigate the failure mode of depressive osteochondral fracture under the maximum load. It may shed light on the load absorption mechanism that protects the articular cartilage from load injury.

MATERIALS AND METHODS

Three groups of depressive osteochondral fractures were studied. In group 1, 3 pairs of normal femoral condyles with no history of metabolic bone disease or tumor were obtained from 24, 26, and 31-year-old cadavers. A femoral condyle was osteotomized at medial and lateral condyles with a bone saw to obtain a specimen of the middle one-third of the femoral condyle including the articular cartilage. The specimen was 2x3 cm in size and 1 cm thick at the middle. Twelve pieces of specimens were prepared.

In group 2, 12 pieces of osteoporotic femoral condyles were obtained from 65 to 70-year-old female patients who had undergone a total knee arthroplasty procedure. In group 3, another 12 pieces of osteosclerotic femoral condyles were obtained in the same manner as those in group 2. The osteoporotic and osteosclerotic quality of the subchondral bone was confirmed by X-ray and histological section. The specimens in both groups (group 2 and 3) were cut into 2x3 cm size and 1 cm thick at the middle by a mini bone saw.

In group 1, each specimen was mounted on the universal testing machine (Shimadzu, Tokyo, Japan) with bone cement such that the articular surface faced upward against and perpendicular to a 6-mm round tip metal indenter (Figure 1). Each depressive osteochondral fracture was created at the middle of the specimen by a compressive load applied at the speed of 2 mm/min. until the maximum load was reached, i.e. when there was an abrupt change in the load-deformation curve. At that point, the load was immediately stopped.

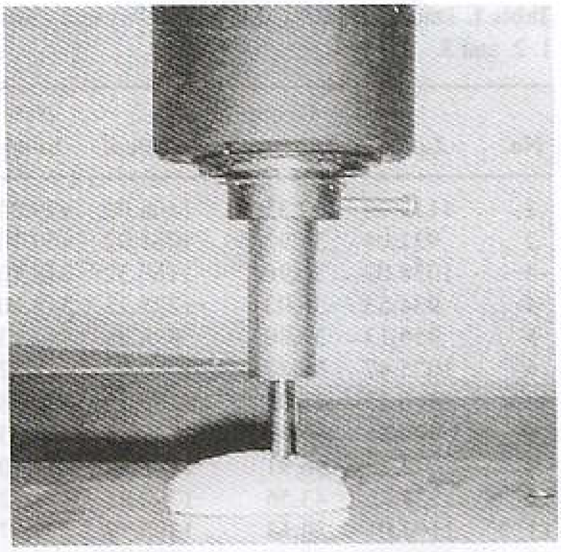

Figure 1. A depressive osteochondral fracture was created at a femoral condyle by applying a compressive load from a universal testing machine through a 6-mm diameter round tip metal indenter.

In group 2 and 3, depressive osteochondral fractures were created in the same manner as those in group 1.

The maximum load and depth of depression were recorded. Pressure and stiffness were calculated. The data were analyzed by the non-parametric Mann-Whitney test. Comparisons were made among group 1, 2, and 3. After the test, the specimens were fixed with 10% formalin solution and a histological study was carried out using a standard decalcified hematoxylin-eosin preparation technique. Care had been taken so that approximately 5 mm of the surrounding tissue next to the depressive fracture was well preserved for histological study.

RESULTS

The average maximum compressive load, pressure, and stiffness of the specimens in group 1 were 1025.69 N (SD 127.25), 36.25 MPa (SD 4.50), and 1173.68 N/mm (SD 164.84) respectively. The corresponding figures for group 2 were 353.34 N (SD 99.93), 13.38 MPa (SD 3.37), and 332.18 N/mm (SD 164.27) respectively, and those for group 3 were 1519.35 N (SD 419.25), 53.71 MPa (SD 14.82), and

Table 1. Data of load (N), pressure (MPa), and stiffness (N/mm) of depressive osteochondral fractures of groups 1, 2, and 3.

	Group 1			Group 2			Group 3		
No.	**Load**	**Pressure**	**Stiffness**	**Load**	**Pressure**	**Stiffness**	**Load**	**Pressure**	**Stiffness**
1	1113.28	39.35	1406.00	479.80	16.96	512.25	1743.62	61.63	1897.28
2	931.04	32.92	1081.92	460.10	16.30	265.29	1884.74	66.62	1447.79
3	1038.07	36.96	1160.32	348.10	12.30	398.57	1865.92	65.96	2252.73
4	934.53	33.03	1228.23	348.10	12.30	190.61	1081.92	38.24	1893.03
5	956.13	33.80	998.33	464.13	16.41	350.15	1960.00	69.28	3036.73
6	1025.47	36.25	1060.00	198.62	17.63	674.24	1762.43	62.30	2101.12
7	1216.17	43.01	1369.35	486.08	17.18	501.76	1445.70	51.10	1468.69
8	972.16	34.36	1139.45	307.33	10.86	173.66	2123.07	75.05	1176.00
9	1043.43	36.91	1102.82	131.60	11.09	192.37	1194.82	42.23	1395.52
10	1232.45	43.56	1290.98	341.82	12.08	303.11	1006.66	35.58	1113.28
11	1107.01	39.13	1395.52	275.97	9.75	298.72	903.17	31.93	1050.96
12	1038.02	36.69	1151.25	216.38	7.65	125.44	1260.17	44.56	1688.25
Average	1025.69	36.25	1173.68	353.34	13.38	332.18	1519.35	53.71	1635.12
SD	127.25	4.50	164.84	99.93	3.37	164.27	419.25	14.82	602.38

1635.12 N/mm (SD 602.38) respectively (Table 1). Statistical analysis showed that the load, pressure, and stiffness of the fractures in group 1, 2, and 3 were statistically different ($P < 0.05$). Group 2's load and stiffenss were the lowest with statistical significance ($P > 0.005$), while those of group 3 were the highest with statistical significance ($P < 0.005$). The histological study of group 1 showed a normal bone appearance. There was no articular cartilage injury of the depressive fragment observed under the light microscope. The fracture line extended vertically from the articular cartilage to the subchondral plate. The subchondral plate was also fractured. There were a few fractures of bone trabeculae just under the plate. Subchondral cancellous bone under the depressive fragment showed that the bone trabeculae slid into one another in an interlacing fashion (Figure 2). Histological study of group 2 and 3 showed osteoporotic and osteosclerotic appearances respectively. Depressive fractures occurred at the level of the subchondral plate plus a few fractures of bone trabeculae just under the plate as in group 1. There was a lesser amount of subchondral bone trabeculae in group 2 that correlated with the radiographic appearance as osteoporosis. The sliding and interlacing phenomena of bone trabeculae under the depressive subchondral plate were not clearly demonstrated as in those in group 1 (Figure 3). In group 3, there was a large amount of thick bone trabeculae that correleated with radiographic appearance as osteosclerosis. The sliding and interlacing phenomena of bone trabeculae under the depressive subchondral plate were not as clear as those in group 1, including a few fractures of sclerotic bone trabeculae (Figure 4). The failure mode of depressive osteochondral fracture of normal, osteoporotic, and osteoporotic bones under the maximum compressive load is the fracture of subchondral plate and the sliding into one another in an interlacing fashion of bone trabeculae with a few fractures of bone trabeculae just under the plate.

DISCUSSION

The ultimate strength under compressive load of the articular cartilage is 10 MPa[3]. The depressive osteochondral fracture was created in this experiment at a pressure of more than 10 MPa but there was no articular cartilage injury observed at the level of the light microscope. The absence of

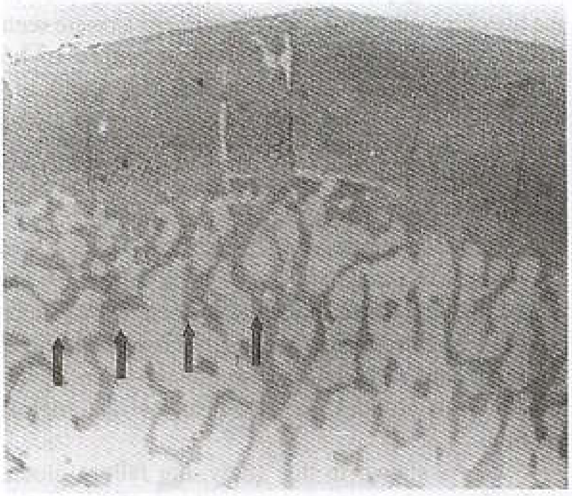

Figure 2. Histological section of group 1 (x10) showed a depressive osteochondral fracture. There was a subchondral plate fracture and a sliding and interlacing of bone trabeculae under the depressive plate with a few fractures of subchondral bone trabeculae just under the plate.

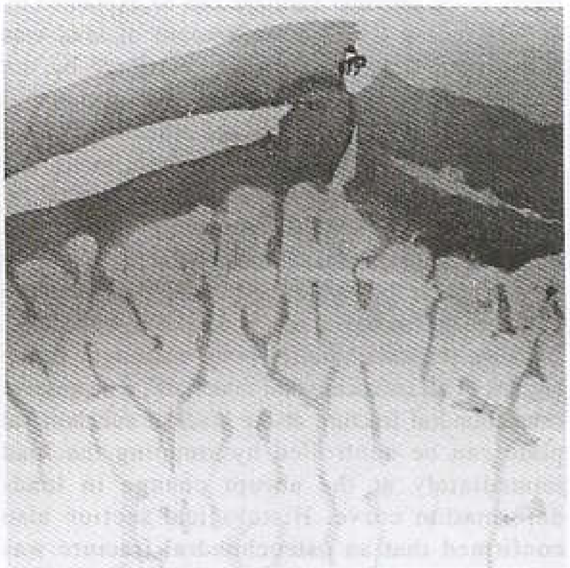

Figure 3. Histological section of group 2 (x10) showed the same appearance as that of group 1. There was an osteoporosis of subchondral bone. The sliding and interlacing of bone trabeculae under the depressive subchondral plate was not clearly demonstrated as it was in group 1. However, there were a few bone trabeculae fractures just under the depressive plate.

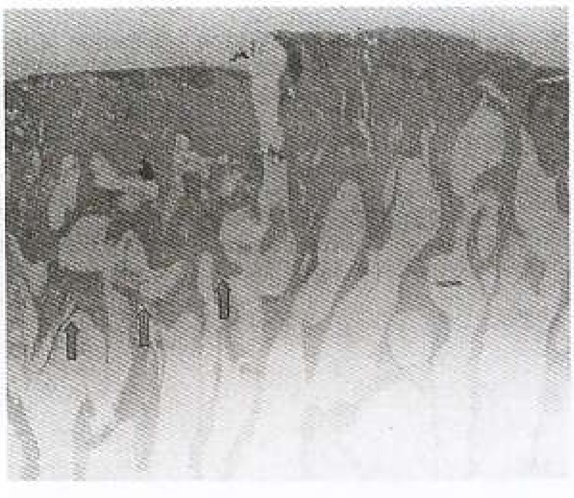

Figure 4. Histological section of group 3 (x10) showed that there was a sclerosis of subchondral plate and bone trabeculae. The sliding and interlacing of bone trabeculae with a few fractures of bone trabeculae just under the depressive subchondral plate was demonstrated but not as clearly as that in group 1.

injury to the articular cartilage can be explained by understanding that a large amount of load was reabsorbed from the articular cartilage by the surrounding tissue, especially by the subchondral bone[3,4,5,6], so that the load on the articular cartilage was less than 10 MPa. In this experiment, the depressive osteochondral fracture was created by applying a load which was immediately stopped when the load reached the maximum in order to create only the fracture at the level of subchondral plate and to minimize the fracture of subchondral bone trabeculae. Because the subchondral plate's strength is the highest of all osteochondral materials[3], a depressive osteochondral fracture at the level of subchondral plate can be controlled by stopping the load immediately at the abrupt change in load-deformation curve. Histological section also confirmed that an osteochondral fracture was produced at the level of subchondral plate with a few fractures of bone trabeculae just under the plate. There was no distinct fracture of subchondral bone trabeculae.

In the experiment of group 2, which used osteoporotic subchondral bones, a depressive osteochondral fracture was created under the lowest load with the lowest stiffness. Because there was a depletion of the bone trabeculae in osteoporotic bone, the subchondral cancellous bone was less efficient in reabsorbing the load from the articular cartilage into the subchondral bone[3]. The sliding and interlacing phenomena were not clearly seen in the histological section of the specimens as were seen in those in group 1. The load appeared to be concentrated on the articular cartilage and the subchondral plate producing the fracture[3,4,6] at the lowest load and stiffness.

In contrast, the creation of depressive fractures in group 3's specimens required the highest load with the highest stiffness[3,4,6]. Because the specimen had a large amount of thick sclerotic bone trabeculae with little space in between, it was more difficult for the sliding and interlacing phenomena to occur and it was less pronounced than in the specimen in group 1, as shown in the histological section.

As shown in this study, the failure mode, under the maximum compressive load, of depressive osteochondral fracture is the subchondral plate fracture, including the sliding and interlacing phenomena of the subchondral bone trabeculae before there is a distinct subchondral bone trabeculae fracture. This failure mode may function as a load absorber from articular cartilage. Therefore, any intervention that improves the quality of subchondral bone will also improve the tolerance of the articular cartilage to compressive injury. Perhaps more attention should be paid to improving the quality of subchondral bone in osteoarthritis patient.

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