Variations of the 'grand-piano sign' during total knee replacement

A COMPUTER-SIMULATION STUDY

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The appearance of the 'grand-piano sign' on the anterior resected surface of the femur has been considered to be a marker for correct femoral rotational alignment during total knee replacement. Our study was undertaken to assess quantitatively the morphological patterns on the resected surface after anterior femoral resection with various angles of external rotation, using a computer-simulation technique. A total of 50 right distal femora with varus osteoarthritis in 50 Korean patients were scanned using computerised tomography. Computer image software was used to simulate the anterior femoral cut, which was applied at an external rotation of 0°, 3° and 6° relative to the posterior condylar axis, and parallel to the surgical and clinical epicondylar axes in each case. The morphological patterns on the resected surface were quantified and classified as the 'grand-piano sign', 'the boot sign' and the 'butterfly sign'. The surgeon can use the analogy of these quantified sign patterns to ensure that a correct rotational alignment has been obtained intra-operatively.

Rotational malalignment of the femoral component in total knee replacement (TKR) affects mediolateral stability during flexion and patellar tracking.¹⁻³ External rotation of the component is recommended to improve patellar tracking and the overall stability, and to decrease polyethylene wear on the patellar component, thereby reducing anterior knee pain after a TKR.^{3,4}

Several methods have been proposed to determine the correct rotational alignment of the femoral component during the operation, including the use of the epicondylar axis,⁵ the application of external rotation of 3° based on the posterior condylar axis,⁶ the use of the anteroposterior (AP) trochlear line (Whiteside's line)⁷ and the adjustment of external rotation of the component to create a symmetrical flexion gap after balancing of the collateral ligaments.⁸ However, the formation of osteophytes, destruction of the posterior condylar surface, difficulty in locating the epicondyles and an error of assessment by the surgeon may lead to an inappropriate femoral resection and malalignment of the femoral component. Currently, instruments which can assess whether the anterior and posterior femoral resections have been done correctly are not available.

Insall⁹ was the first to describe the appearance of the 'grand-piano sign' on the anterior

resection surface of the femur as a marker for anterior femoral resection with external rotation. We believe that if the morphology of the resected surface was to be quantified specifically the information obtained may provide a visual tool for surgeons to identify errors of rotation.

Our aim therefore was to assess quantitatively the morphological variations which appear on the anterior resection surface of the femur with varying angles of external rotation using a computer-simulation technique.

Patients and Methods

A total of 50 Korean patients with 50 osteoarthritic knees with varus deformity scheduled for a TKR were included in the study. All the patients had standardised full-length weight-bearing AP radiographs pre-operatively. The mean mechanical angle was 8.8° varus (0° to 20°); 32 had less than 10° of varus, 14 had 11° to 15° of varus and four 15° to 20° of varus. Patients with osteophytes on the posterior femoral condyle which affected measurements, rheumatoid arthritis or other bone disorders such as tumours or infections were excluded. We obtained clinical approval. There were 14 men with a mean age of 62.6 years (43 to 84) and 36 women with a mean age of 67.3 years (44 to 95). Their overall mean age was 65.9 years (43 to 95).

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Fig. 1

A CT scan showing the transverse view of the distal femoral condyles (SEA, surgical epicondylar axis; CEA, clinical epicondylar axis; PCA, posterior condylar axis; and APA, anteroposterior axis).

Computed tomography (CT). All the patients had a pre-operative CT scan of their right distal femur (Siemens Ltd., Erlangen, Germany) in a high-resolution mode using the 512 x 512 pixel matrix. The scan parameters included slices of 1 mm thickness and spacing from 200 mm proximally down to the knee. The patients were supine with the involved limb taped to the scanner platform in the extended position during scanning. Using AP and lateral scout views, the direction of the scan was aligned perpendicular to the

longitudinal axis of the femur. A total of 201 consecutive slices for each patient was obtained and imported into special medical imaging software (Rapidia; Infinite Co., Seoul, Korea) to create three-dimensional (3D) reconstruction models. Bone was extracted from the soft tissues on the CT by density thresholding (Window width 1700 Hounsfield units (HU), level 300 HU). In addition, the computer software was used to draw lines or points on the scans, to measure the angles between lines and to simulate the anterior bone cuts of the TKR, which were set at various angles in the axial plane.

Measurements and simulations. Transverse sections through the most prominent part of the femoral condyles were used for measurement and for setting the rotational angles of the simulated resection surface in the axial plane. The clinical epicondylar axis was defined as a line connecting the most prominent points of the medial and lateral epicondyles; whereas the surgical epicondylar axis was defined as a line connecting the most prominent point of the lateral epicondyle and the deepest point of the sulcus on the medial epicondyle (Fig. 1).⁵ The AP axis was defined as a line connecting the deepest part of the patellar groove anteriorly and the centre of the intercondylar notch posteriorly. The posterior condylar axis was defined as a line connecting the posterior aspects of the femoral condyles (Fig. 1).¹ The angle of the posterior condylar axis relative to the surgical and clinical epicondylar axes was measured and expressed as the 'posterior condylar angle' and the 'posterior condyle-clinical epicondylar angle', respectively.

At the start of the simulation procedure, one sagittal section through the most prominent surface of the anterior cortex of the distal femur was selected from the CT images. The simulated anterior femoral resection plane was placed

Fig. 2

A 3D model and 2D CT image in a window of image software during a simulation procedure showing the longitudinal axis of the femur (LAF) which is a line through the midline of the distal femur. The cutting plane (CP yellow) was flexed 3° relative to the LAF in the sagittal view. The green point is the rotation point of the cutting plane.

Fig. 3

The morphology of the resected surface of the femur is quantified in a CT scan (A, the most proximal point of the anterior bone cut on the medial condyle; B, the most proximal point of the anterior bone cut on the lateral condyle; C, the most distal point on the anterior bone cut on the lateral condyle; D, the most distal point on the anterior bone cut on the medial condyle; E, the intersection of A to C-D; F, the intersection of B to C-D).

on the most prominent surface of the anterior cortex, and was then flexed to create 3° of flexion relative to the midline of the distal femur to avoid the possibility of notching and undersection (Fig. 2). This was done to achieve a situation which was consistent with current TKR instrumentation, e.g. PFC Sigma (Depuy, Warsaw, Indiana) in that there is 3°

of flexion built in between the anterior cutting plane and the intramedullary guide placed at the longitudinal axis of the femur. In the axial plane, the anterior femoral resections were simulated under five different conditions for each case. Specifically, the simulated resection plane was rotated to produce an external rotation angle of 0° , 3° and 6° relative to the posterior condylar axis, and parallel to the surgical and clinical epicondylar axis, respectively. The rotational centre of the cutting plane was determined on the AP axis (Fig. 2). The varying types of morphology obtained on the anterior resected surface of the femur were then classified. The vertical distance (A-E) between the most proximal point (A) of the anterior bone cut on the medial condyle and the line (C-D) connecting two most distal points (C and D) of anterior bone cut on both the lateral and medial condyles was measured. Another vertical distance (B-F) was measured between the most proximal point (B) of the anterior bone cut on the lateral condyle and the line (C-D) (Fig. 3). The ratio of A-E to B-F (A-E:B-F) was calculated for each simulated resection. The intra-observer reproducibility assessed by one observer (W-QC) for repeated angular measures from single acquisitions as measured by the coefficient of variation was 5.6% for the posterior condylar angle relative to the surgical epicondylar axis, and 5.2% for the posterior condylar angle relative to the clinical epicondylar axis. The coefficient of variation as a measure of intra-observer reproducibility for the ratio of A-E:B-F was 4.9%.

Fig. 4a

Fig. 4b

Similar cutting surface morphologies produced by a) the simulating bone cut and b) the actual bone cut in a cadaver distal femur.

Table I. Comparison of the morphological measurements from the simulated and real bone cuts

Specimens	Simulated cuts*			Real cuts		
	A-E (mm)	B-F (mm)	A-E:B-F	A-E (mm)	B-F (mm)	A-E:B-F
1	26.10	41.40	0.63	26.45	45.41	0.58
2	25.04	39.59	0.63	24.56	40.11	0.61
3	31.65	48.05	0.66	30.65	50.82	0.60
4	33.25	49.2	0.68	33.95	47.51	0.71
5	33.58	51.41	0.65	32.92	50.74	0.64

* A-E, the vertical distance between the most proximal point (A) of the anterior bone cut on the medial condyle and the line (C-D) connecting the two most distal points (C and D) of anterior bone cut on both the lateral and medial condyles; B-F, the vertical distance between the most proximal point (B) of the anterior bone cut on the lateral condyle and the C-D line; A-E:B-F, the ratio of A-E to B-F

The multipaired samples *t*-test was used to compare the difference in the ratio of A-E:B-F after the simulated anterior bone cuts with various angles in each case.

To validate the reliability of the computer-simulation technique, an additional test was performed to compare the results from simulating bone cuts with those from actual anterior bone cuts. Five right femora harvested from cadavers were scanned by CT at intervals of 1 mm. The procedures for image import, the simulating anterior bone cuts, and the morphological measurements were the same as those described above. In the axial plane, only 3° of external rotation relative to the posterior con-

dylar axis was applied to each simulated cut. Likewise, using a 3° rotational guide of the TKR instrument system (Scorpio; Stryker, Mahwah, New Jersey), actual bone cuts were made (Fig. 4). The quantitative indices of morphology, A-E and B-F, were measured by a digimatic caliper (Mitutoyo Co., Kanagawa, Japan). The paired samples *t*-test was used to compare the difference in morphological measurements between bone cuts under two different situations. No significant difference in A-E, B-F and A-E:B-F was found between the simulated and actual bone cuts (Table I), indicating that the CT image-based simulation technique was clinically relevant.

Fig. 5a

Fig. 5b

Fig. 5c

Fig. 5d

Fig. 5e

Morphological patterns obtained in a 3D model produced by anterior bone cuts with various rotational angles showing a) 0° relative to the posterior condylar angle (PCA); b) 3° of external rotation relative to the PCA; c) 6° of external rotation relative to the PCA; d) parallel to the surgical epicondylar angle and e) parallel to the clinical epicondylar angle (L, lateral; M, medial).

Table II. A-E:B-F ratio produced by anterior bone cuts with varying rotational angles and the peak range of A-E:B-F distributions

Anterior bone cuts	Mean A-E:B-F* (SD)	Peak range
0° relative to the posterior condylar axis	0.83 (0.13)	0.80 to 0.98
3° relative to the posterior condylar axis	0.69 (0.16)	0.61 to 0.69
6° relative to the posterior condylar axis	0.55 (0.10)	0.50 to 0.59
Parallel to the surgical epicondylar axis	0.66 (0.08)	0.65 to 0.74
Parallel to the clinical epicondylar axis	0.53 (0.09)	0.50 to 0.59

* A-E, the vertical distance between the most proximal point (A) of the anterior bone cut on the medial condyle and the line (C-D) connecting the two most distal points (C and D) of anterior bone cut on both the lateral and medial condyles; B-F, the vertical distance between the most proximal point (B) of the anterior bone cut on the lateral condyle and the C-D line; A-E:B-F, the ratio of A-E to B-F

Fig. 6

Statistical graph showing the differences in the A-E:B-F ratio of the sign produced by various anterior bone cuts (S-epi, Surgical epicondylar axis; C-epi clinical epicondylar axis; Ro, rotation).

Results

Of 50 medial sulci, 41 (82%) could be identified on the femoral condyle by CT. The mean values of the posterior condylar angle ($n = 41$) and the posterior condyle-clinical epicondylar angle ($n = 50$) were 3.26° (2.04° to 5.54°) and 6.87° (3.84° to 9.55°) of internal rotation, respectively. There was a significant difference between the two relative angles (paired Student's *t*-test, $p < 0.0001$, $n = 41$). The mean values were 3.08° (2.04° to 5.24°) and 7.13° (5.35° to 9.08°) for men, and 3.34° (2.05° to 5.54°) and 6.77° (3.84° to 9.55°) for women. The gender difference was not significant (unpaired Student's *t*-test, $p = 0.44$, $p = 0.41$). The morphology of the resected surface of the anterior femoral resections varied under different conditions (Fig. 5). The 'grand-piano sign' (Figs 5b and 5d) usually appeared on the resected surface when the anterior femoral resection was performed with 3° of external rotation relative to the posterior condylar axis or was parallel to the surgical epicondylar axis. The 'boot sign' (Figs 5c and 5e) was most often seen on the cutting surface when the bone cut was done with 6° of external rotation or was parallel to the clinical epicondylar axis. The 'butterfly sign' (Fig. 5a) emerged on the resected surface when the anterior femoral resection was done with 0° of external rotation relative to the posterior condylar axis. The mean of the values of the A-E:B-F ratio and the peak differences produced by anterior bone cuts with external rotation of 0° , 3° and 6° , and by anterior bone cuts parallel to the

surgical and clinical epicondylar axes are shown in Table II. There was no significant difference between the A-E:B-F ratio of morphology in anterior bone cuts between 3° of rotation and cuts parallel to the surgical epicondylar axis and none between anterior cuts of 6° of rotation and those parallel to the clinical epicondylar axis (Fig. 6).

Discussion

The concept of the grand-piano sign, is that an asymmetrical bone resection is produced on the resected surface of the medial and lateral aspects of the anterior distal femur when an external rotation angle is applied to the resection. This concept is further quantified by our simulation study.

The morphology of the resected surface varied according to the distribution of the values of the A-E:B-F ratio. Asymmetrical resections with an A-E:B-F ratio ranging from 0.65 to 0.69 and 0.50 to 0.55 were defined, respectively, as the typical grand-piano sign and the typical boot sign, whereas approximately symmetrical resections with an A-E:B-F range from 0.80 to 0.98 were defined as the typical butterfly sign. The simulation showed that the grand-piano sign was consistently produced by the anterior resection with 3° of external rotation relative to the posterior condylar axis or by resection parallel to the surgical epicondylar axis (Figs 5a and 5d), whereas the butterfly sign was produced by resection with 0° of external rotation relative to the posterior condylar axis (Fig. 5a). Most of the boot signs appeared in cases in which bone cuts were made with 6° of external rotation relative to the posterior condylar axis and cuts parallel to the clinical epicondylar axis (Figs 5c and 5e). Moreover, there was no significant difference in the A-E:B-F ratio between bone cuts with 3° of external rotation relative to the posterior condylar axis and those parallel to the surgical epicondylar axis. However, once the anterior bone cuts were made with external rotation of 0° , 3° and 6° relative to the posterior condylar axis, differences in the A-E:B-F ratios were statistically significant. These results suggest that bone cuts in range from 3.0° to 3.26° of external rotation relative to the posterior condylar axis will not significantly affect the morphological pattern of the resected surface, whereas those of 3° would lead to resected morphology with a significant difference in the A-E:B-F ratio. Overall, a trend towards a decrease in the A-E:B-F ratio of

the resected bone was seen after an increment in the external rotation angle for the anterior femoral resection (Fig. 6).

It is generally accepted that the femora epicondyles are important landmarks for appropriate rotational alignment of the femoral component in TKR.^{1,3,5} Biomechanical analysis also shows that the surgical transepicondylar axis is essentially parallel to the primary centre of rotation of the knee.^{5,10,11} In our computer-simulation test based on CT scans, when the anterior femoral resection is parallel to the surgical epicondylar axis, the morphological pattern of the resected bone is relatively constant and expressed by an A-E:B-F value with a smaller SD (0.08) than that produced by other conditions. Thus, the morphology of an asymmetrical bone resection on the two anterior condyles produced by a cut which is parallel to the surgical epicondylar axis is defined as the standard pattern, called the grand-piano sign. However, the practical usefulness of the axis is limited because the sulcus of the medial condyle is particularly difficult to palpate and locate. Even based on CT scans with an interval of 1 mm we found that 18% of the medial sulci on the femoral condyle still could not be identified. This has led to the use of the most prominent point of the epicondyle as a landmark for the medial epicondyle, namely the clinical epicondylar axis. Our results showed a significant difference between the posterior condylar angles relative to the surgical and clinical epicondylar axes. The anterior bonecut parallel to the clinical epicondylar axis means that the cutting plane is excessively externally rotated to the surgical epicondylar axis. At this point, an appearance of the boot sign indicates a reduction in the contact area between the anterior cut surface of the medial femoral condyle and the femoral component, which may lead to an overhang of the femoral component on the medial condyle.

When using the posterior condylar axis as a reference for femoral rotation, the anterior femoral cut with an angle of 0° relative to the posterior condylar axis means that the cutting plane is internally rotated to the surgical epicondylar axis, at least more than 3°. This situation would lead to the appearance of the butterfly sign with an A-E:B-F ratio close to 1.0 (Fig. 5a). This visual and simply measurable information provides the surgeon with an opportunity to check whether a proper anterior femoral resection has been made, thereby preventing a subsequent posterior condylar resection with malrotational alignment. An increased internal malrotation of the femoral component may result in maltracking of the patella and an asymmetrical flexion gap, whereas an increased external malrotation can cause patellar subluxation.

Although our study is a computer-simulated experiment, the conditions applied to the procedure are in keeping with those of a real TKR, including the use of bony landmarks as reference, the rotational angles in relation to the simulated bone cuts in both the sagittal and axial plane, the determination of the rotational centre of the resection plane and the principle of bone cutting without notching and under-resection. Moreover, morphological measurements of the

resected surface from the simulated and real bone cuts were comparable. Thus, the results obtained from the simulation are clinically relevant.

A limitation of our study is that only Korean patients with osteoarthritic knees with limited varus deformity were included because valgus knee deformity is relatively rare. Several anatomical studies^{12,13} have shown that valgus knees have a greater posterior condylar angle or posterior condyle-clinical epicondylar angle than varus knees and those with no deformity. Therefore the morphological information on the femoral resection which is presented may well apply to the varus knee with limited deformity, but not to the valgus knee or to the severely-deformed varus knee. Moreover, the data may be typical for knees of the Asian population but may not apply to Caucasians or other populations.

Our results should also be interpreted cautiously. Although several reports^{14,15} have suggested that there are racial differences in the 3D geometry of the femur, our results of angular measurements based on CT scans are consistent with those of other studies. In a study of 75 embalmed anatomical specimens, the mean posterior condylar angle was 3.5° (SD 0.3) in males and 0.4° (SD 1.2) in females.⁵ Another study using MRI found that the overall mean posterior condylar angle was 3.11° (SD 1.75) with no difference between male and female femora;¹⁶ whereas Arima et al¹ reported a posterior condylar angle of 4.4° (SD 2.9) using a visual and a radiological technique, and also recommended external rotation of 4° when using the posterior condylar line as a reference.

Based on the results of our study, we recommend the application of an external rotation angle of 3° to the anterior femoral resection in Korean patients with varus deformity when using the posterior condylar axis as a reference. Thus, the anterior femoral cuts would consistently produce a broader cut on the lateral condylar bone than on the medial condylar bone, the so-called grand-piano sign. We use the analogy of the butterfly sign with an A-E:B-F ratio close to 1°, the grand-piano sign for a ratio of 2:3 and the boot sign for that of 1:2 so that the surgeon can ensure intra-operatively that a correct rotational alignment for the femoral component has been used.

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References

1. Arima J, Whiteside LA, McCarthy DS, White SE. Femoral rotational alignment, based on the anteroposterior axis, in total knee arthroplasty in a valgus knee: a technical note. *J Bone Joint Surg [Am]* 1995;77-A:1331-4.
2. Akagi M, Matsusue Y, Mata T, et al. Effect of rotational alignment on patellar tracking in total knee arthroplasty. *Clin Orthop* 1999;366:155-63.
3. Anouchi YS, Whiteside LA, Kaiser AD, Milliano MT. The effects of axial rotational alignment of the femoral component on knee stability and patellar tracking in total knee arthroplasty demonstrated on autopsy specimens. *Clin Orthop* 1993;287:170-7.
4. Barrack RL, Schrader T, Bertot AJ, Wolfe MW, Myers L. Component rotation and anterior knee pain after total knee arthroplasty. *Clin Orthop* 2001;392:46-55.
5. Berger RA, Rubash HE, Seel MJ, Thompson WH, Crossett LS. Determining the rotational alignment of the femoral component in total knee arthroplasty using the epicondylar axis. *Clin Orthop* 1993;286:40-7.

6. **Laskin RS.** Flexion space configuration in total knee arthroplasty. *J Arthroplasty* 1995;10:657-60.
7. **Whiteside LA, Arima J.** The anteroposterior axis for femoral rotational alignment in valgus total knee arthroplasty. *Clin Orthop* 1995;321:168-72.
8. **Stiehl JB, Cherveney PM.** Femoral rotational alignment using the tibial shaft axis in total knee arthroplasty. *Clin Orthop* 1996;331:47-55.
9. **Insall JN.** Surgical techniques and instrumentation in total knee arthroplasty. In: Insall JN, Scott WN, eds. *Surgery of the knee*. Second ed. New York: Churchill Livingstone, 2001:743.
10. **Mantas J, Bloebaum R, Skedros JG, Hoffmann AA.** Implications of reference axes used for rotational alignment of the femoral component in primary and revision arthroplasty. *J Arthroplasty* 1992;7:531-5.
11. **Yoshioka Y, Siu D, Cooke D.** The anatomy and functionale axes of the femur. *J Bone Joint Surg [Am]* 1987;69-A:873-80.
12. **Griffin FM, Insall JN, Scuderi GR.** The posterior condylar angle in osteoarthritic knees. *J Arthroplasty* 1998;13:812-15.
13. **Matsuda S, Miura H, Nagamine R, et al.** Anatomical analysis of the femoral condyle in normal and osteoarthritic knees. *J Orthop Res* 2004;22:104-9.
14. **Tang WM, Zhu YH, Chiu KY.** Axial alignment of the lower extremity in Chinese adults. *J Bone Joint Surg [Am]* 2000;82-A:1603-8.
15. **Yip DK, Zhu YH, Chiu KY, Ng TP.** Distal rotational alignment of the Chinese femur and its relevance in total knee arthroplasty. *J Arthroplasty* 2004;19:613-19.
16. **Griffin FM, Math K, Scuderi GR, Insall JN, Poilvache PL.** Anatomy of the epicondyles of the distal femur: MRI analysis of the normal knees. *J Arthroplasty* 2000;15:354-9.