Computer assisted analysis of the locus of the dynamic loading axis on the knee

+*Kawakami H; *Sugano N; *Yonenobu K; *Ochi T; *Yoshikawa H; **Hattori A; **Suzuki N
+*Department of Orthopedic Surgery, Osaka University Medical School, Japan
**Jikei University School of Medicine, Department for High Dimensional Medical Imaging, Tokyo, Japan

Introduction
Precise estimation of the loading axis of the lower limb on the knee joint is important for patients with knee osteoarthritis (OA). Anteroposterior (A-P) long-standing radiographs have been used for assessment of the loading axis. However, on radiographs, the loading axis reflects a static mechanical environment of the knee. Hurwitz et al. [1] reported the importance of evaluating dynamic loading of the knee joint for understanding the disease process and treatment of OA knees. They also evaluated the moment around the knee by gait analysis. However, there has been no report demonstrating the locus of the dynamic loading axis during gait.

Materials and methods
This system uses skeletal structure data, motion capture data, and force plate data. Six reflective markers for infrared-light were attached to characteristic positions on the lower limb, and CT images were obtained from the proximal end of the femur to the distal end of the tibia. Then, 3-D skeletal models of the femur, tibia and reflective markers were reconstructed from CT images (Analyze PC 3.0). Motion capture data and force plate data during gait were acquired with the VICOM system (Oxford Metrics Ltd). Using positional relationships between bones and markers (3 points for femur and 3 points for tibia), movement of skeletal structures was calculated by matching markers from CT data with markers from motion capture data. Thus, the relative motion of the femur and tibia during gait was visualized on a computer display. To visualize the locus of the dynamic loading axis on the knee joint surface, the loading axis was defined as a straight line through the center of the femoral head and the gravity center of the distal tibia joint surface. The axis was defined as the set of points across the plane of the proximal tibia joint surface and the loading axis. We examined 10 normal knees of 5 female volunteers (mean age, 75 years) who had no complaints in their knees and no history of knee disorders and 22 knees of 16 patients with medial OA of the varus knee (7 male and 9 female with mean age of 60 years). Informed consent was obtained from all of the subjects.

To examine the accuracy of this system, positions of skin markers relative to bones during knee flexion with weight bearing were evaluated using open MRI (SIGNA SP 0.5T, GE Medical Systems). Six healthy female volunteers (mean age, 21 years) participated in the evaluation of accuracy. Six reflective markers were attached to each volunteer’s lower limb. To examine the bone structure and the relative positions of the reflective markers, MR images (SIGNA Horizon LX HiSpeed 1.5T,GE Medical System) in supine position and open MR images in standing position were obtained. The 3-D models, in supine position, of full limb, and CT images obtained from the proximal end of the femur to the distal end of the tibia were reconstructed from MRI data. The 3-D bone structures and markers around the knee, at flexion angles of 0, 15, 30 and 45 degrees with weight bearing, were reconstructed from open MRI data. The bone structures derived from the open MR images and the 3-D models derived from MR images were matched using a 3-D surface registration algorithm (ICP algorithm). At each knee flexion angle, we obtained the relative position between the full-length femur and full-length tibia; this relative position was designated the gold standard group. Next, relative position between the femur and tibia was obtained by matching marker positions between MR images and open MR images; this relative position was designated the marker measurements group. In both groups, at each knee flexion angle, we calculated points of the loading axis on the proximal tibia joint surface. Measurement error was defined as differences in point locations between the gold standard group and marker measurements group.

Results
This system shows time sequential images of skeletal structures of the lower limb during gait, the locus of the loading axis on the proximal tibia joint surface during gait, and the force plate data. We can select characteristic points of the stance phase during gait from force plate data, and compare each point of the loading axis on the knee joint between subjects.

In the stance phase of gait, each subject showed a characteristic locus. However, the locus of the normal volunteers tended to pass through the central and medial area of the knee joint surface, and the locus of patients with medial OA tended to pass through the medial and posterior area of the medial joint edge of the knee (Fig.1). Mean lateral movement from heel contact to loading response peak was 23.0 ± 10% of the medial joint in the normal knee and 30.2 ± 17% in varus knee with medial OA.

Measurements errors of this system were as follows. In the lateral direction on the proximal tibia joint surface, the mean value of measurement error (ratio of the cross point of the loading axis on the knee joint to joint width) was 2.3 ± 1.4% (mean ± SD) of medial compartment joint width (MCJW) at 0 degrees, 1.9 ± 1.1% of MCJW at 15 degrees, 1.6 ± 1.0% of MCJW at 30 degrees, and 6.0 ± 4.7% of MCJW at 45 degrees. In the A-P direction on the proximal tibia joint surface, the mean value of measurement error was 9.0 ± 6.4% of the anterior half of A-P joint width (APJW) at 0 degrees, 10.7 ± 7.3% of APJW at 15 degrees, 19.0 ± 9.7% of APJW at 30 degrees, and 25.1 ± 8.5% of APJW at 45 degrees.

Discussion and conclusions
We developed a new system to visualize the locus of the dynamic loading axis on the knee joint surface. Using this system, the locus of dynamic loading axis during gait on the proximal tibia joint surface can be analyzed, including movement in the A-P direction on the knee joint surface. The loci on the knee joint passed through the central and medial area of the knee joint for normal knees, and passed through the medial and posterior area of the medial joint edge for varus knee with medial OA.

At knee flexion angles of 0, 15 and 30 degrees, the mean measurement error of this system was within 2.3% of medial joint compartment width in the lateral direction on the knee joint surface, and within 19% of the anterior half of A-P joint width in the A-P direction on the knee joint surface. In a previous study, during gait, the flexion angle of the knee was limited to within 30 degrees in the stance phase, except for the end of the stance phase [2]. Thus, it may be useful to compare the characteristic locus of the dynamic loading axis on the proximal tibia joint surface during gait.

References

Fig.1 Locus of dynamic loading axis on the right proximal tibia joint
(a) Normal knee (b) Varus knee with medial OA

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