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| 著者 | Terashima Shojiro, Ishii Yoshinori, Terajima Kazuhiro, Koga Yoshio |
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# In Vivo Three-Dimensional Kinematics of the Human Knee

Shojiro TERASHIMA*, Yoshinori ISHII**, Kazuhiro TERAJIMA***,
And Yoshio KOGA****

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Knee motion was measured with an instrumented spatial linkage (accuracy ; linear ± 500$\mu$m, angular ±0.5° ) fixed with intracortical Kirschner wires in five healthy male volunteers (five knees, judged clinically to be normal). This technique allows an accurate description of the relative angular and linear movements between tibia and femur without the effect of skin movement relative to the bone, and changing muscle volume. Motion of the tibia relative to the femur was described in terms of three clinically meaningful rotations and three translations between full extension and 60° flexion: (a) abduction and adduction: 3.4±1.2° , (b) internal and external rotation: 10.6±2.8° ; representing screw home motion, (c) anterior and posterior: 5.2±1.7 mm ; representing roll back phenomenon, (d) proximal and distal: 1.2±2.7 mm, (e) medial and lateral: 1.1±2.6 mm.

*Key words : Motion Analysis, In Vivo, Knee Kinematics, Three Dimensional*

## 1. INTRODUCTION

Measurement of relative motion between the tibia and femur in vivo usually is accomplished indirectly, by attaching transducers to the soft tissues surrounding the calf and thigh. Skin movement relative to bone and change in muscle volume can influence these measurements. Thus, the precision of three-dimensional measurement of tibiofemoral motion has been limited because of the error introduced by the nonstationary soft tissues in both commonly used methods of goniometric [8,9,13,14,22,24,25,29,32] and photogrammetric [1,2,3,4,12,18,26] techniques. In an in vitro study, it is difficult to reproduce proper tension to muscles and ligaments that regulate knee motion and geometry. Therefore, there is still considerable question as to what constitutes normal motion at the knee.

The purpose of this study is to provide an accurate description of the relative angular and linear movements between tibia and femur without the effect of soft tissues, for knee flexion and extension, by in vivo use of an instrumented spatial linkage fixed with intracortical Kirschner wires (K wires).

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*Department of Mechanical and Control Engineering, Research Associate
**Department of Orthoaedic Surgery, School of Medicine, Niigata Univ., Japan
***Department of Mechanical Engineering, Niigata Univ., Japan
****Niigata Kobari Hospital, Japan

## 2. MATERIALS AND METHODS

Five healthy male volunteers (five knees), with knees judged clinically to be normal, participated in this study. The subjects had a mean age of 26±1 years, mean height of 170±3 cm, and mean body weight of 63±3 kg. Before the experiment began, the subjects signed a consent form that included an explanation of the procedures, a description of the experimental protocol, and potential for complication such as infection, discomfort, pain, pin related failures. This procedure was performed with the same infection control procedures as standard during operative procedures in surgical suites. Two K wires (2.4 mm diameter) were inserted with an electric orthopaedic drill into cortices of the left femur and tibia of the five subjects. The pins penetrated the bones in a medial direction from lateral, parallel to each other. The pin insertion sites were anesthetized with injections of 1% mepivacaine into surrounding soft tissues and periosteum. Before insertion of the pins into the bones, 5 mm width transverse incisions were made through the skin and soft tissues to prevent these structures from applying forces to the wires.

Knee joint kinematics were measured with a 6 degree of freedom instrumented spatial linkage attached to the K wires. The instrumented spatial linkage is composed of seven metal pieces or links interconnected by six electrical hinges or potentiometers. The ends of the instrumented spatial linkage are fixed to the tibia and femur so that the instrumented spatial linkage spans the joint. The links and potentiometers freely change their relative positions and orientations as the knee moves. By knowing the geometry of the links, the electrical parameters which characterize the potentiometer, and voltages generated by the potentiometers as the knee moves, the position of one end of the instrumented spatial linkage can be computed relative to the other end (Fig 1).

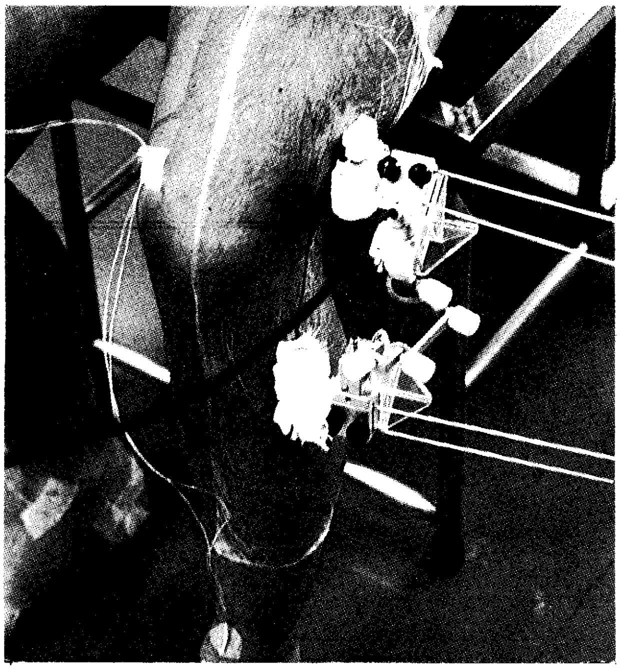

Figure 1: An instrumented spatial linkage fixed with intracortical Kirschner wires. Active knee motion between full extension and 60 ° flexion was analyzed while the subject was seated.

The linear accuracy of the instrumented spatial linkage was determined by placing the instrumented spatial linkage in known configurations on a milling machine, and comparing the known and predicted relative positions of the ends of the instrumented spatial linkage. The linear accuracy was determined to be ±500 μm, and the angular accuracy was ±0.5°.[31] Active knee motion between full extension and 60° flexion was analyzed while the subject was seated. (Sixty degrees flexion was chosen because it is thought to be the peak flexion angle in swing phase during normal gait and in the authors' gait analysis using the same instrumented spatial linkage[29]). Also, limiting motion to 60° flexion avoided any pain to subjects. Average kinematic patterns of the tibia with respect to the femur were obtained from three trials in each of five subjects.

Motion between the ends of the instrumented spatial linkage was related to the anatomy of the knee through the application of a biplanar radiographic technique with the knee in full extension, to accurately calculate the dimensions of the femur and tibia (Fuji Computed Radiographic System, Fuji Film Inc, Tokyo, Japan) (Fig 2). Using the radiographic images of the knee joint and the targets on the ends of the instrumented spatial linkage, anatomic rotation axis directions were determined, and a point from which tibial translations would be defined. The origin of the femur was defined as the center of both condyles, and the origin of the tibia was defined as the center of the tibia plateau.[28,30]

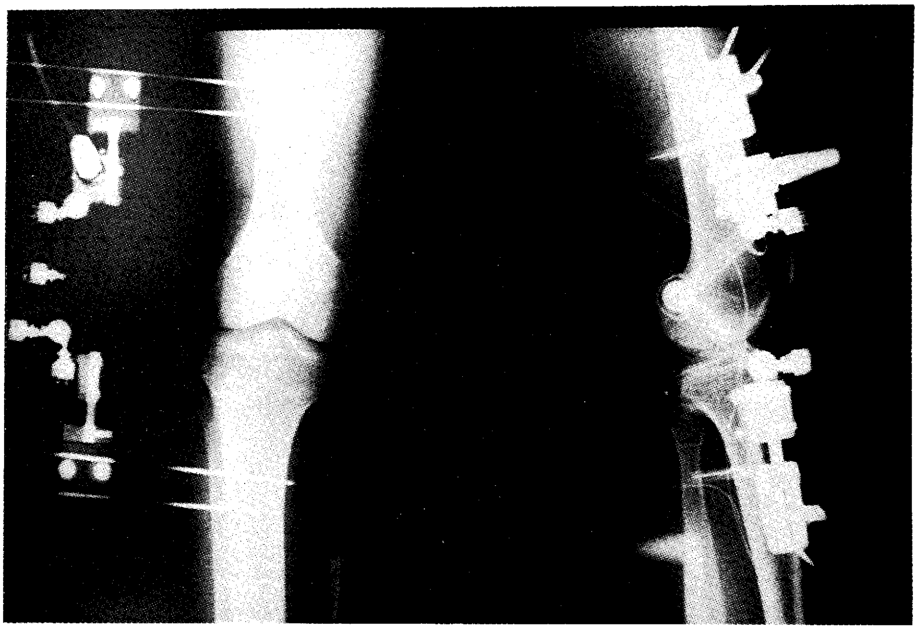

Figure 2: To transfer the instrumented spatial linkage's coordinate to the femur and tibia, biplanar X-rays were taken with the knee at full extension.

Motion of the tibia relative to the femur was described in terms of three clinically meaningful rotations (flexion and extension, internal and external rotation, abduction and adduction) and three translations (anterior and posterior, medial and lateral, proximal and distal). The calibration was performed on the system before and after each test and exhibited 0.5 ° in angular accuracy and 500μm in linear accuracy.

## 3. RESULTS

All subjects tolerated the protocol well. Knee kinematic data are shown in Figure 3. Motion of the tibia relative to the femur (average ±1 standard deviation) was described in terms of three clinically meaningful rotations and three translations between full extension and 60 ° flexion : (a) abduction and adduction: 3.4±1.2 ° , (b) internal and external rotation: 10.6±2.8 ° ; representing screw home motion, (c) anterior and posterior: 5.2±1.7 mm ; representing roll back phenomenon, (d) proximal and distal: 1.2±2.7 mm, (e) medial and lateral: 1.1±2.6 mm.

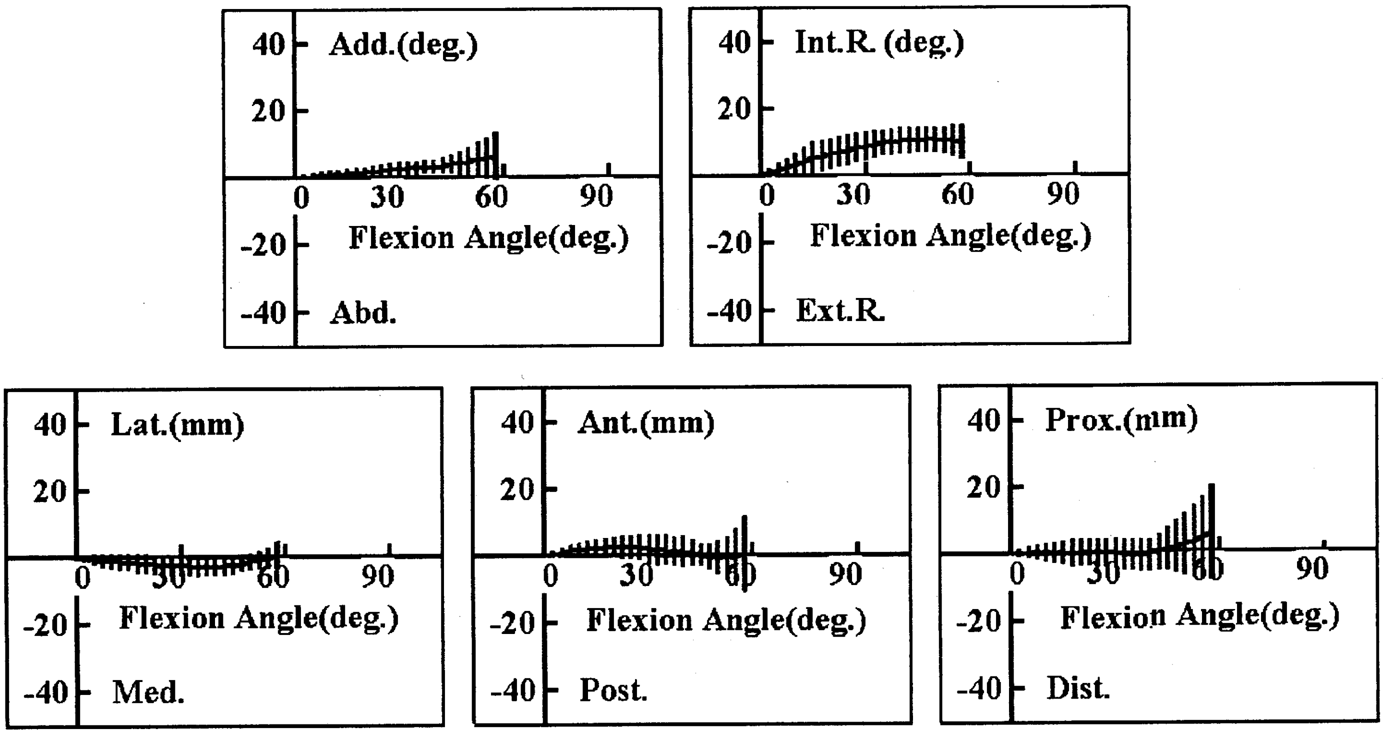

Figure 3: Average (Solid lines) and standard deviation (vertical bars) of angular and linear displacement of tibiofemoral joint between 60 ° flexion and extension at sitting position.

## 4. DISCUSSION

Although there have been many papers analyzing the kinematics and kinetics of the human knee, most have been cadaver studies that were controlled under artificial tension of muscles or ligaments. In these in vitro studies, various knee simulators were controlled by various mathematically derived inputs. [5,6,7,16,17,21,23,27,33,34] Therefore, those data had some limitations regarding how well they reflect knee motion in vivo. Even in vivo studies using noninvasive transducers fixed with straps or using skin markers, include errors caused by skin and soft tissue movement. Several in vivo methods have been used including the goniometric [8,9,13,14,22,24,25,29,32] and photogrammetric [1,2,3,4,12,18,26] methods. Thus, it is difficult to identify the more subtle movements of the knee joint, such as internal and external rotation and abduction and adduction. The knee motion is controlled by the function of the muscles in combination with geometric and ligamentous constraints. Consequently, there is still considerable question as to what constitutes normal motion at the knee in previous studies.

To overcome those issues, there have been studies in the literature that use invasive methods to precisely measure three-dimensional kinematics in the normal knee in vivo. In one study, knee motion was measured during gait by the photogrammetric method, using insertion of Steinmann traction pins into the femur and tibia, reported by Lafortune et al.[15] In other studies, after insertion of 0.8 mm tantalum balls into the tibia and femur, they were tracked using stereophotogrammetry with radiographs, as reported by Kärrholm et al[10,11] and Nilsson et al.[19,20] Although their amount of rotations and translations were not completely coincident with this present study because of different muscle condition during measurement ( one was knee motion during gait and the others were that of prone position), intersubjective difference, and use of different coordinate systems, most patterns were in agreement to the present study (Fig 4).

The authors' method of in vivo insertion of K wires into the femur and tibia of human subjects, as was done in this study, is also highly invasive, however, it has several advantages. It allowed the authors to obtain serial knee kinematics during active flexion and extension in a sitting position as contrasted with the quasistatic procedure using stereophotogrammetry with radiographs. If the electrogoniometers are applied to the cadaver in the same manner as this study, it will enable researchers to simulate normal knee kinematics in a cadaver study. Furthermore, because this system can be fixed to a patient's leg with straps, which are noninvasive and easy to apply in clinical use, the effect of movement of superimposed soft tissues may be accounted for, knowing the discrepancy between the two types of fixation.

This study provided an accurate description of knee kinematics in vivo without superimposed soft tissue motion. If the cadaver studies with knee simulator or testing device used these data as input, researchers might obtain much more physiologic and significant data than the present.

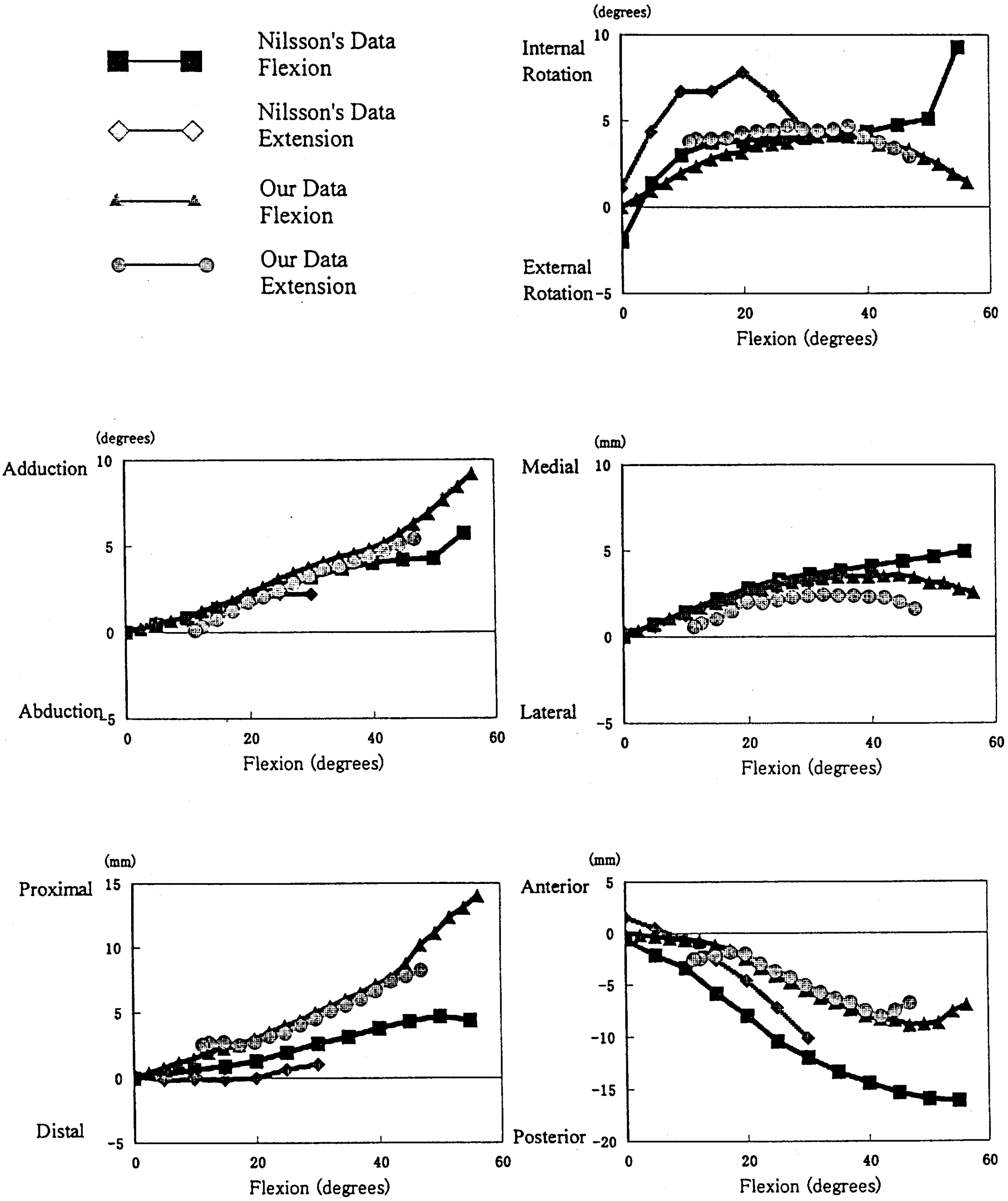

Figure 4: The data were translated by the coordinate system of Nilsson et al.[20] Most patterns were in agreement with those seen in the present study.

## 5. CONCLUSION

This study provided an accurate description of knee kinematics in vivo without superimposed soft tissue motion.

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