Mechanical Functions of the Three Bundles Consisting of the Human Anterior Cruciate Ligament: Application of a Robotic System to Joint Biomechanics Study

INTRODUCTION:
The current reconstruction technique of the anterior cruciate ligament (ACL) attempts to reproduce the anteromedial (AM) and posterolateral (PL) bundles of the ACL independently. This technique called double-bundle ACL reconstruction has been recently developed in which the three bundles of the ACL are individually reconstructed with tendon grafts although the detailed mechanical functions regarding the three bundles have not been quantitatively determined yet. Therefore, a 6-degree-of-freedom (DOF) robotic system, developed in our laboratory, was applied to the determination of the force sharing in the medial and lateral parts of the AM bundle, and PL bundle of the human ACL in response to externally applied anterior force and internal moment to the knee.

MATERIALS AND METHODS:
A 6-DOF robotic system consisting of a custom made 6-axis manipulator with a 6-DOF universal force/moment sensor (UFS) (Fig.1) was used. All the actuators attached to the axes of the manipulator were position control-based actuators. A LabView-based control program runs on a windows PC to control the displacement of, and force/momoment applied to the cadaveric knee joints with respect to the knee joint coordinate system. In the present study, the anterior-posterior force up to 120 N was applied to the human knee joint (n=5) while recording the 6-DOF motion and the force/moment of the knee. The ACL was divided into the AM and PL bundles followed by a previous study, and the AM bundle was subsequently divided into the medial part (A-AM bundle) and lateral part (P-AM bundle). The intact knee motion was reproduced to the knee after the A-AM bundle was transected, then reproduced again after the transection of the P-AM bundle, and finally after the transection of the PL bundle. Under the principle of superposition, the bundle forces in response to 100 N of anterior force were determined. Subsequently, the bundle forces in response to 5 Nm of internal moment were also determined through the experimental procedure similar to that for the above-mentioned anterior test.

RESULTS:
The average cross-sectional areas of the A-AM, P-AM, and PL bundles at mid-substance of the ACL were 11, 11, and 16 mm², respectively. The anterior-posterior laxity between 100 N of anterior-posterior forces varied between 6 and 9 mm at flexion angles from 0 to 90 degree. The laxity became more than double after the transection of the ACL. In response to 100 N of anterior force the PL bundle force was larger than other bundle forces at 0 degree of flexion (Figs.2). As the flexion angle was more than 30 degree the force in the A-AM bundle increased, but the force decreased as the flexion angle was more than 60 degree. The force in the P-AM bundle increased as flexion angle was more than 60 degree. In response to 5 Nm of internal moment at 0 degree of flexion, the bundle forces in the PL and A-AM bundles were larger than that in the P-AM bundle (Fig.2). The PL bundle force was decreased while those in the A-AM and P-AM bundles remained almost unchanged as flexion angle was 15 and 30 degree of flexion. When the flexion angle was more than 30 degree, the bundle forces became smaller in response to internal moment.

DISCUSSION:
The present study is the first one that quantitatively determined the mechanical functions of the three bundles of the human ACL. The joint loading tests have been successfully performed using the 6-DOF robotic system developed in our laboratory. As compared with a previous study performed by Sakane et al., the force in the AM bundle (A-AM+P-AM) was slightly larger, possibly because the cross-sectional area of the transected AM bundle (11+11 mm²) was larger than that of the PL bundle (16 mm²). The obtained results of the reciprocal function of the anterior stability of the knee joint at deep flexion angles and that the reconstruction of the P-AM bundle may be crucial for relatively active patients suffering from ACL injury.

REFERENCES:
3) Shino, et al., Operative Techniques in Orthopaedics, Vol. 15, pp. 130-134, 2005

ACKNOWLEDGMENT
The present study was financially supported in part by the Project-In-Aid for the Establishment of Strategic Research Centers (BERC, Kogakuin University) and Grant-In-Aid for Scientific Research (#20591766) both from the MEXT, Japan.