STRAIN-RATE DEPENDENCE OF MECHANICAL FAILURE PROPERTIES OF RABBIT MCL AND ACL

Sota Yamamoto(1), Akinori Saito(1), Masaki Kabayama(2), Satoshi Sugimoto(1)
Kei Nagasaka(1), Koji Mizuno(1), Eichi Tanaka(1)

(1)Department of Mechano-Informatics & Systems
Graduate School of Engineering
Nagoya University
Nagoya, Japan

(2) Products Planning Healthy Life Products Div., Home Appliances Company
Matsushita Electric Works, Ltd.
Hikone, Japan

INTRODUCTION

In car-to-pedestrian collisions and sports accidents, knee joint ligaments are frequently injured. Ligament injuries require a long time for healing and rehabilitation, and recovery of their original functions is difficult. Thus, reducing knee injuries is an important task for pedestrian protection. Recently, various studies of pedestrian injury prevention have used finite element analyses [1] or impact tests with mechanical models (legform impactor or pedestrian dummy [2]). However, there are few data on the mechanical properties of knee joint ligaments under such a high strain rate as is seen in car-to-pedestrian collisions [3-4]. Therefore, knowledge of the mechanical properties under impact conditions of the medial collateral ligament (MCL) and anterior cruciate ligament (ACL), which are frequently injured, are required for further discussion.

Against this background, the objective of this study was to evaluate the failure properties of MCL and ACL. To investigate the strain rate dependece of the failure properties of MCL, an axial tensile test of the mid substance and tibial insertion were conducted. Tensile tests for ACL were also performed using femur-ACL-tibia complexes to investigate their failure pattern.

MATERIALS AND METHOD

Female Japanese white rabbits (weight 3.0±0.35 kg, mean±S.D.) were used for the experiments. These rabbits were sacrificed by injecting an overdose of pentobarbital sodium. MCL or ACL was then removed with the distal femur and proximal tibia.

Tensile test of MCL substance

First, the cross sectional area of MCL was measured with a previously developed a measuring system using a laser width meter [5].

Then the tibial insertion of MCL was detached to avoid avulsion of the tibial insertion, and the distal end of MCL was fixed on a metal jig with cyanoacrylate cement. The femur was embedded in resin and fixed on another jig. A schematic diagram of the system is shown in Figure 1. This system can be operated in a low-speed range (0.01~10mm/sec) by an AC servomotor and in a high-speed range (10~300mm/sec) by a gas actuator [5]. The tensile speed was set at 0.01, 0.3, 10, 100 or 300 mm/sec. During the tensile test, the movement of markers put on the surface of the substance at 5 mm interval was recorded by a high-speed digital video camera (MEMRECAM fx-K3, NAC) to measure the strain. All of the tests were performed in physiological saline solution at 37 ˚C.

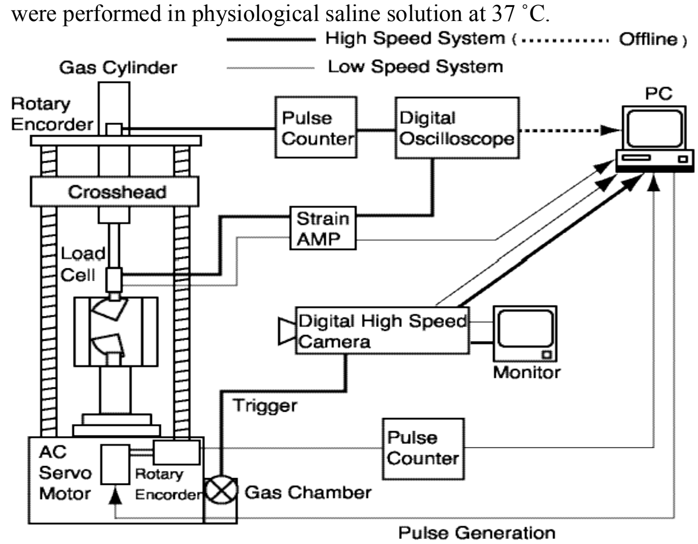

Figure 1. Schematic diagram of tensile test system

Tensile test for tibial insertion of MCL

The femoral insertion of a specimen was detached for the tensile test of the tibial insertion of MCL and the proximal end of MCL was fixed on a metal jig with cyanoacrylate cement. The tibia was embedded in resin and fixed on another jig. The test was performed by the same apparatus as that for the test of the MCL substance and the tensile speed was also set at 0.01, 0.3, 10, 100 or 300 mm/sec.

Tensile test of ACL

First, the lateral condyle was removed to measure the cross sectional area, using the same method as for MCL.

The tensile test was performed with a femur-ACL-tibia complex. The tibia and femur were embedded in resin and fixed on metal jigs, respectively. To measure strain, we put two marks on the frontal areas of both condyles. The test was performed with the same apparatus as that for the tests of the MCL substance and tibial insertion. The tensile speed was set at 200 mm/sec.

RESULTS AND DISCUSSION

The stress-strain curves of the MCL substance are shown in Figure 2. With tensile speeds of 0.01, 0.3 and 10 mm/s, the stress-strain curves showed the type of nonlinear relation typically seen for biological soft tissue. With higher tensile speed conditions, however, the stress-strain curves were almost linear.

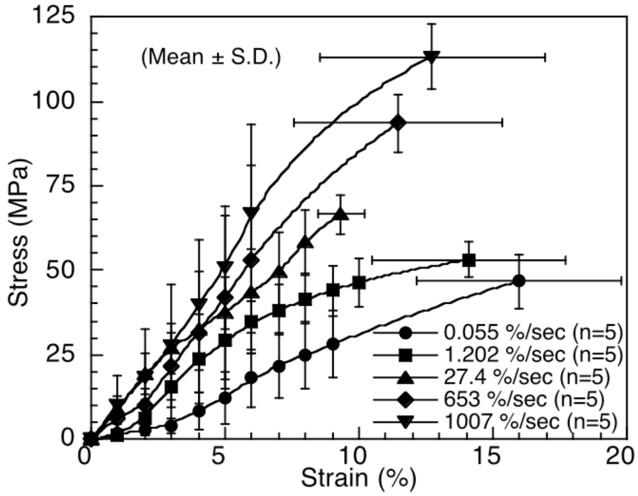

Figure 2. Stress-strain curve of MCL substance

The correlation between the tensile speed and failure load was statistically significant ($P < 0.05$, one-way ANOVA), but there was no significant relation between the tensile speed and failure strain or tangent modulus in the range of between 2 and 6 % strain in the MCL substance ($P > 0.05$). The comparison between the failure loads of the MCL substance and tibial insertions in each tensile speed condition is shown in Figure 3. The failure load of the tibial insertion also showed significant strain-rate dependence ($P < 0.05$, one-way ANOVA).

The failure load of the MCL substance was larger than that of the MCL tibial insertion under every tensile speed condition. A schematic drawing of a typical failure pattern of the ACL in tensile tests is shown in Figure 4. A typical case for the femur-MCL-tibia complex is also shown in the same figure as a reference. The failure pattern of the ACL was an avulsion fracture with a small piece of tibial condyle in all specimens, while that of the MCL was avulsion of the tibial insertion without fracture.

On the basis of the results discussed above, it is considered that the tibial insertions of the MCL and ACL are the sites most likely to sustain injury under axial tensile load. Because of the lack of sufficient data for ACL tensile strength, we did not perform a statistical analysis for strain-rate dependence of the failure properties ACL in this study. However, we did not the type of rupture of ACL the substance that is frequently seen in real accidents. Therefore, the failure mode may depend on loading direction. Other mechanical tests in different loading modes, for example a medial-lateral shearing test or an anterior drawer test, are thus needed.

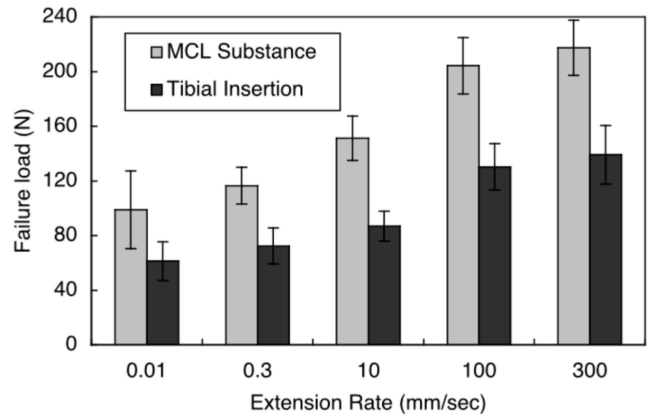

Figure 3. Strain-rate dependency of failure load of tibial insertion and mid substance of MCL

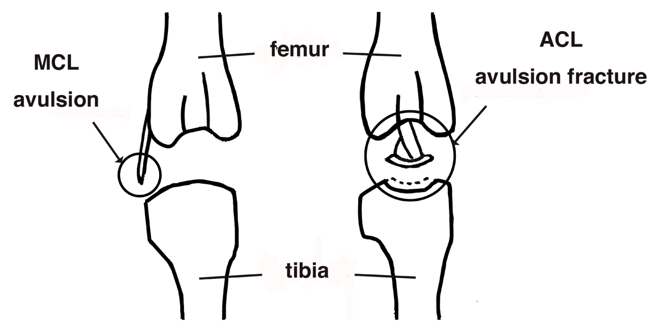

Figure 4. A schematic drawing of typical failure patterns of MCL and ACL

CONCLUSION

We performed the tensile tests of rabbit MCL and ACL at various tensile speeds and evaluated the failure properties of MCL and ACL. With the MCL substance, the failure stress showed a significant strain-rate dependence, but the failure strain and tangent modules were independent of strain rate. It was found that tibial insertion has the highest possibility for injury in both MCL and ACL. The difference between the failure properties of the MCL and ACL will be discussed quantitatively in the next study.

REFERENCE

1. Takahashi, Y. and Kikuchi, Y., 2001, "Biofidelity of Test Devices and Validity of Injury Criteria for Evaluating Knee Injuries to Pedestrians" ESV Paper No. 373.
2. Matsui, Y., 2001, "Biofidelity of TRL Legform Impactor and Injury Tolerance of the Human Leg in Lateral Impact" Stapp Car Crash Journal, Vol. 45, pp. 495-510.
3. Danto, M. I. and Woo, S.L-Y., 1993, "The Mechanical Properties of Skeletally Mature Rabbit Anterior Cruciate Ligament and Patellar Tendon over a Range of Strain Rates, Journal of Orthopaedic Research, Vol. 11, pp. 58-67.
4. Yamamoto, N. and Hayashi K., 1998, "Mechanical properties of rabbit patellar tendon at high strain rate," Bio-Medical Materials and Engineering, Vol. 8, pp. 83-90.
5. Yamamoto, S., Kajzer, J., and Tanaka, E., 2000, "Development of High-Speed Tensile Test System for Ligaments and Skeletal Muscles," Human Biomechanics and Injury Prevention, J. Kajzer et al., eds., Springer-Verlag Tokyo, pp. 167-172.