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Injury Tolerance of Knee Joint Subjected to Dynamic Three-Point Bending*

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Abstract

A knee joint injury is one of the most common injuries in car-pedestrian accidents. For the examination of the knee joint injury tolerance and the determination of the absolute range of knee joint injury criteria, we performed dynamic three-point bending tests on the porcine knee joint using the own drop impact test setup. During the test, an impactor (mass: 21 kg) was launched toward the lateral side of the specimen placed on a three-point bending support. The femoral epiphysis was completely fractured when the drop height was 700 mm. Multiple damages to the medial collateral ligament and other soft tissues such as the posterior cruciate ligament were observed when the drop height was 500 mm. Only the medial collateral ligament was damaged when the drop height was 300 mm. No injury was observed when the drop height was 100 mm. The calculation of the maximum bending moment acting at the knee joint showed that the injury criterion range was from 136 to 320 Nm. This range includes the values of injury criterion in previous studies on the human knee joint. Thus, there is hardly any difference between the injury criteria for the porcine and human knee joints.

Key words: Traffic Accident, Pedestrian, Injury Criterion, Knee Joint, Three-Point Bending Test, Medial Collateral Ligament

1. Introduction

According to some recent reports on traffic accidents in Japan, the number of injured persons has remained high while that of the dead has decreased. However, the number of injured persons has become less than one million in 2008 at last [(1)]. This decrease in the number of traffic accident deaths and injured persons was the result of the introduction of effective vehicle safety devices, revision of penalty for driving offences, and provision of effective emergency trauma care. Moreover, for a long time, a large number of studies have been carried out worldwide to elucidate the injury mechanism in humans during traffic accidents; these studies have also contributed to the decrease in the number of injured persons. These days, the structure of passenger cars is continuously undergoing changes; for example, the conventional gasoline engines are being replaced by hybrid engines. Further, it is expected that hybrid engines will be replaced with completely electric engines in the near future. Such a change will alter the mass, appearance, etc., of the cars, which may affect the injury patterns in traffic accidents. Therefore, studies focusing on the human injury mechanism in traffic accidents have to be carried out.

In the case of traffic accidents, although the number of injured persons is high when the vehicle is in motion, the severity of injury is high when a pedestrian is involved in a traffic

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accident. Several investigations on the injury mechanism in pedestrian accidents have been carried out in the field of impact biomechanics since a long time. Many studies, in particular, have focused on leg injuries, which are the most common injuries because the legs first come in contact with a car during a collision.

Previous studies related to pedestrian leg injuries showed that an increase in the impact velocity from 20 to 40 km/h leads to a transformation of the injury pattern [(2)(3)(4)]. In addition, several studies performed impact tests imitating actual accident conditions. For example, Snedeker et al. performed impact tests using PMHSs (post-mortem human subjects) to investigate the relationship between bone density and fracture risk in the pelvis and femur [(5)]. Bhalla et al. replicated the environment of pedestrian-vehicle collisions and studied the impact on limbs taken from PMHSs [(6)]. Kerrigan et al. carried out four-point bending tests and shear tests to review the bending and shear strength of human knee joints [(7)].

It is easy to visually determine the instant at which an injury occurs in simple tissues like bones, ligaments, etc. [(8)]. However, it is difficult to determine the instant of an injury in complex regions like the knee joint or regions whose appearance does not change with injury. Although the development of several methods such as acoustic emission or strain measurement has made it possible to predict the instant of an injury [(9)], it is impossible to identify it. Therefore, the injury criterion cannot be determined exactly. Hence, we suggested the determination of the injury criterion by gradual narrowing the range of injury criteria. The term leg injury refers to various injuries such as femur fracture, knee joint injury, etc. Although a femoral or tibial fracture and a knee joint injury are both serious injuries, it is more difficult to treat the latter from the clinical perspective because a knee joint involves hard and soft tissues. Hence, knee joint injuries should never be ignored.

The purpose of our study is to examine the knee joint injury tolerance and determine the range of injury criteria. We have conducted dynamic three-point bending tests in which bending moment was applied to the porcine knee joint using the own experimental setup and investigated the dynamic load response and injury pattern of the knee joint.

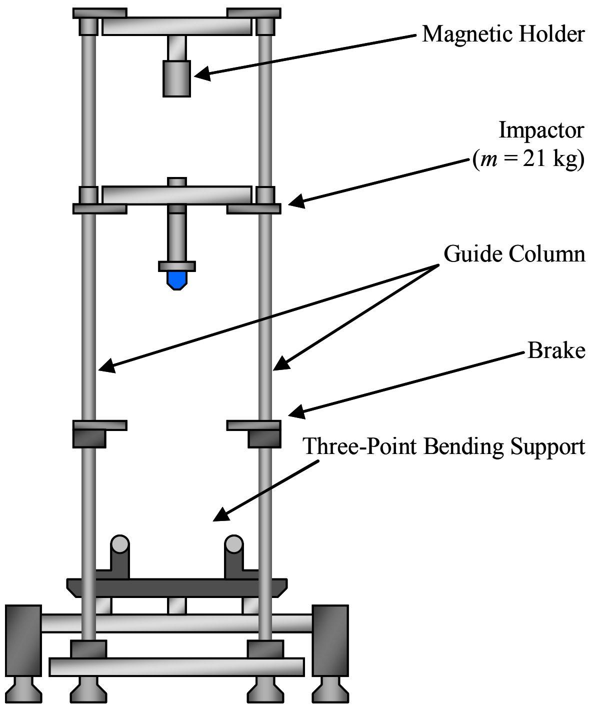


Fig. 1 Schematic diagram of experimental setup. A drop test system is adopted and the impactor is released smoothly by using a magnetic holder. A three-point bending support is placed directly below the impactor.

2. Materials and methods

2.1 Experimental setup

Figure 1 shows a schematic diagram of the experimental setup of a drop test system. The experimental setup can be divided into two major parts: the main body and the specimen base. The main body includes four guide columns, a magnetic holder, and an impactor. The impactor moves along the four guide columns with low friction due to linear bushes. The magnetic holder enables the smooth release of the impactor. The impactor includes a dynamic force sensor (Model M200C20, PCB PIEZOTRONICS, New York, U.S.A.) that measures the input impact load on the specimen. The displacement of the impactor is measured by using a laser displacement sensor (LB-1100, KEYENCE, Osaka, Japan). A plastic resin block (MC901, Nippon Polypenco Limited, Tokyo, Japan) located at the tip of the impactor prevents bone fractures due to stress concentration. The part of the plastic resin in contact with the specimen has a flat surface, and the total impactor mass is 21 kg. The specimen base placed directly below the main body includes a three-point bending support with adjustable span.

2.2 Specimen

The porcine hind leg was used as a substitute for the human lower extremity in our drop impact tests. Fresh knee joints removed from hogs (18 weeks old) that had been slaughtered for meat packing were used. After slaughter, knee joints were conserved in refrigerator at 0℃ for 2 days, and delivered to our laboratory. We conducted tests on the same days when specimens were delivered. The porcine knee joint comprises the femur, tibia, fibula, patella, and soft tissues that include four ligaments (ACL: anterior cruciate ligament, PCL: posterior cruciate ligament, MCL: medial collateral ligament, and LCL: lateral collateral ligament), two meniscuses (medial meniscus and lateral meniscus), and a patellar tendon. The lengths of porcine femur and tibia are 194.2 mm (S.D. 4.2) and 173.2 mm (S.D. 3.2) respectively. The proximal end of the femur and distal the end of the tibia were placed in metal boxes and fixed with a hard resin. A length of 90 mm of the femur and a length of 90 mm of the tibia and fibula from the knee joint level, i.e., a total length of 180 mm of the knee joint, were exposed. In this study, the muscle tissues covering the knee joint were removed to eliminate the possibility of energy absorption by soft tissues. Specimens were covered with towels containing a saline to prevent a drying during preparation.

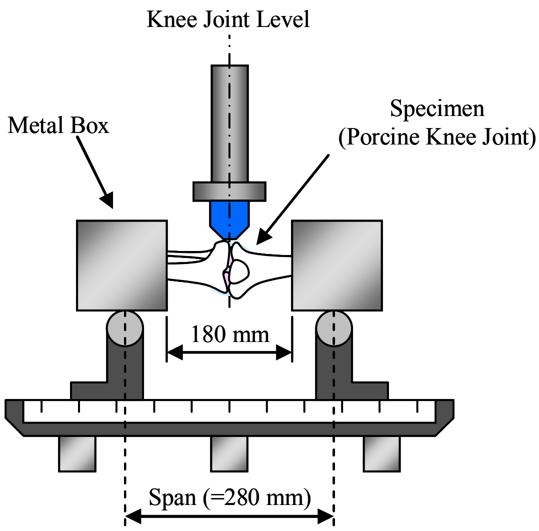


Fig. 2 Geometry of specimen. The knee joint of length 180 mm was exposed. The span length of the three-point bending support was fixed at 280 mm. The impactor was launched toward the lateral side of the specimen.

2.3 Experimental condition

The specimen was placed on the three-point bending support, with the lateral side of the specimen pointing upward. The impactor was launched toward the lateral side of the knee joint in order to simulate the collision between the bumper of a passenger car and the knee joint of a pedestrian crossing a road. The span length of the three-point bending support was fixed at 280 mm (Fig. 2). The impact velocity was adjusted by changing the drop height of the impactor; the impactor was released from four different heights above the specimen: 700, 500, 300, and 100 mm. The impactor was decelerated and stopped by the four brakes set in the guide columns after it compressed the knee joint 50 mm to prevent the impactor from striking the bottom. Two specimens were used for each drop height; thus, a total of eight specimens were used.

3. Results

Table 1 lists the impact velocities calculated from the potential energy at the drop heights and the impact velocities determined from the data measured by using the laser displacement sensor. The latter were determined from the gradient of the displacement-time curves just before the contact between the impactor and the specimen. The impact velocities calculated from the measured data were less than those calculated from the potential energy due to the effects of air resistance on the impactor and extremely low friction between the guide columns and the linear bushes. The impact velocity was defined as the measured impact velocity in this study.

Table 1 Relationship between drop height and impact velocity. The actual velocity is less than the theoretical velocity because of the air resistance effect.

Test Number	Drop Height [mm]	Theoretical Impact Velocity [m/s]	Measured Impact Velocity [m/s]
Test 1	700	3.71	3.46
Test 2			3.50
Test 3	500	3.13	2.97
Test 4			2.96
Test 5	300	2.43	2.30
Test 6			2.30
Test 7	100	1.40	1.28
Test 8			1.32

Anatomical observations of the knee joint were carried out after all drop impact tests to record the injury patterns. In this study, the injury is defined as the condition that the continuity of target tissues is destroyed completely or partially at macro level. The target tissues means a distal femur, proximal tibia, ACL, PCL, MCL, LCL, medial and lateral meniscus, and patellar tendon. Additionally, a visible lack of initial tensile force in target soft tissues is included as the injury. Figure 3 and Table 2 illustrate the injury patterns of the knee joint specimens observed after the drop impact tests. The knee joint injury patterns varied with the change in the impact velocities. When the drop height was 700 mm, the impact resulted in complete fracture of the femoral epiphysis (Fig. 4). Additionally, soft tissues were injured in one case (test 2). MCL injuries that include other ligament damages such as the avulsion fracture of the lower insertion of PCL, substance tear of PCL, and partial avulsion of upper insertion of PCL occurred when the drop height was 500 mm (Fig. 5). For the drop height of 300 mm, only the MCLs were damaged; either the avulsion of the upper insertion of the MCL or stretching of the MCL was observed (Fig. 6). No injury was observed in the knee joints when the impactor was dropped from the height of 100 mm.

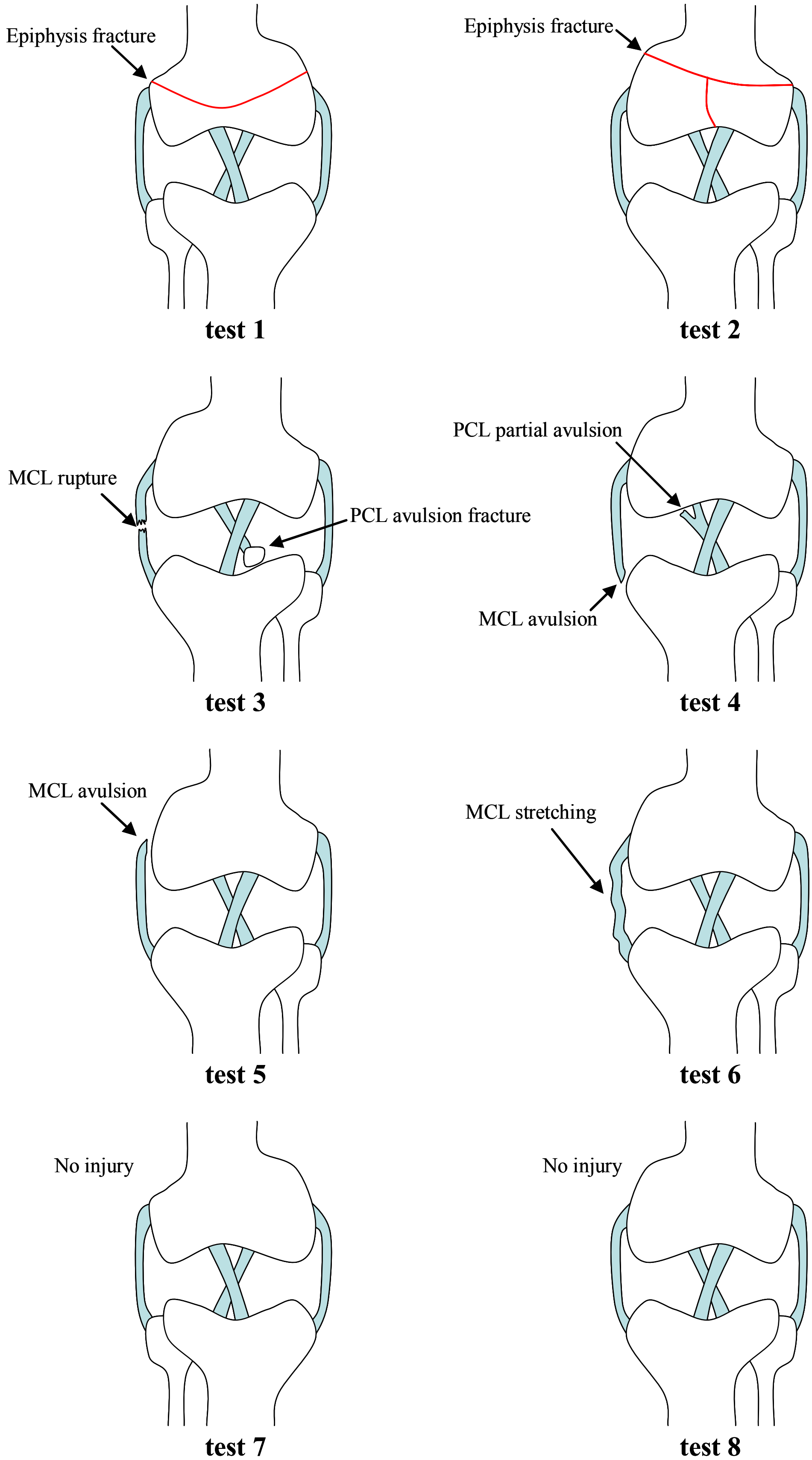
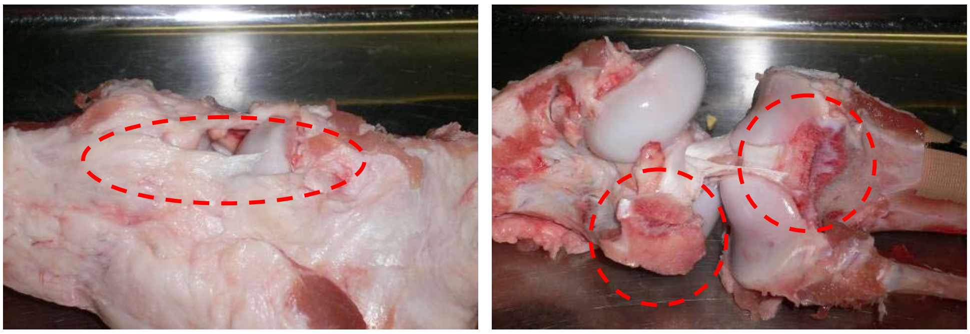


Fig. 3 Schematic injury description of specimens (front view of knee joint).

Table 2 Injury patterns of knee joint determined by anatomical observations after drop impact tests.

Test Number	Injury Pattern
Test 1	*Complete Fracture of Femoral Epiphysis*
Test 2	*Complete Fracture of Femoral Epiphysis, Tear of Upper Insertion of ACL, Tear of Insertion of Lateral Meniscus*
Test 3	*Rupture of MCL, Avulsion Fracture of Lower Insertion of PCL, Tear of PCL*
Test 4	*Avulsion of Lower Insertion of MCL, Partial Avulsion of Upper Insertion of PCL*
Test 5	*Avulsion of Upper Insertion of MCL*
Test 6	*Stretching of MCL*
Test 7	*No Injury*
Test 8	*No Injury*

Fig. 4 Injury pattern of knee joint for drop height of 700 mm (test 1). Femoral epiphysis is fractured and the continuity of the epiphysis was completely destroyed.



(a) Rupture of MCL (b) Avulsion fracture of PCL

Fig. 5 Injury pattern of knee joint for drop height of 500 mm (test3): (a) completely ruptured MCL and (b) fractured lower insertion of PCL.

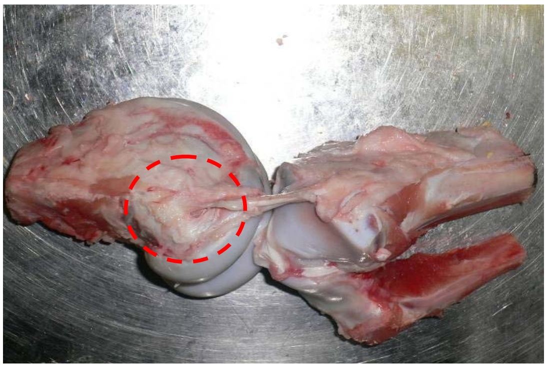


Fig. 6 Injury pattern of knee joint for drop height of 300 mm (test 5). The upper insertion of MCL is avulsed.

Figure 7 shows the load-displacement curves obtained from drop impact tests. These data were measured by the two sensors—the dynamic force sensor in the impactor and the laser displacement sensor. When the drop height was 700 or 500 mm, the impactor displacement data until the impactor contacted with brakes were used. When the drop height was 300 or 100 mm, the impact displacement data until the initial peaks were used. All curves showed more than two peaks regardless of the drop heights. The reason why the load responses do not draw equal curves irrespective of the same experimental conditions is effect of individual difference. While the contact region of the impactor was flat surface (100 mm×24 mm), lateral side of knee joints that consist of femoral condyle and fibular head were not flat. Moreover, the contact area between the impactor and the knee joint undergoes a lot of changes as the impactor compresses the knee joint. Therefore, dynamic loads go up and down in the process of one compression, and maximum peaks appear in different points. It seems that similar curves present when the changing patterns of contact area are similar, however, the method to measure the contact area is not established yet. The reason why the highest drop tests (tests 1 and 2) do not represent the highest load values is that the great impact energy is expended for occurrence of bone fracture.

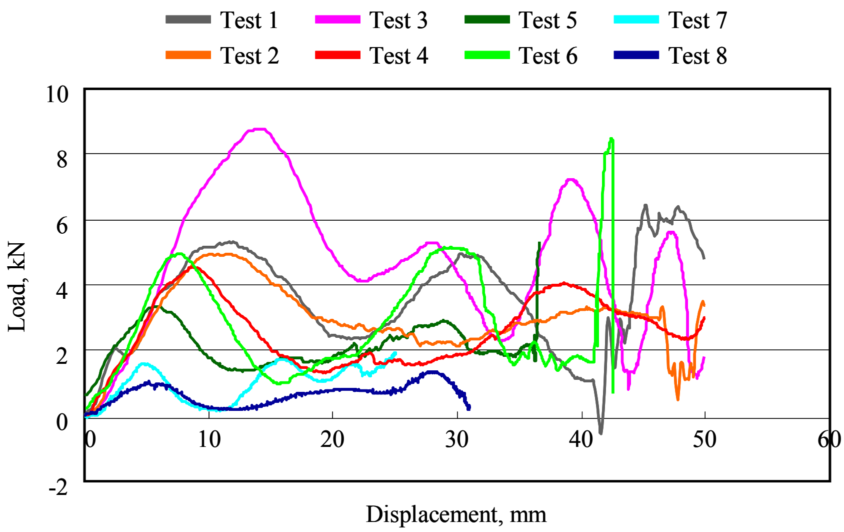


Fig. 7 Load-displacement curves obtained from drop impact tests.

4. Discussion

In previous studies, it was found that an increase in the impact velocity changes the knee joint injury pattern from ligament damage to bone fracture [(3)(4)]. The results of this study also showed that the injury pattern changes from only MCL damage to multiple soft tissue damage including MCL and finally to bone fracture as the impact velocity increases. The compressive displacements get longer as the drop heights are higher. Accordingly, the valgus bending angles of the knee joints also get lager, and MCL and other soft tissues suffer higher tensile force. Finally, injury degree became more serious. In the meantime, it is considered that occurrences of femoral epiphysis fracture depend on a growth cartilage plate in distal femur. The trabecular structure inside a distal femur is not continual because the growth cartilage plate divides it (Fig. 8). Therefore, it is estimated that the femoral epiphyses had fractured in the highest drop tests that knee joints were subjected to the highest impact force due to the growth cartilage plate that extremely weakens the toughness of trabecular bone in distal femur.

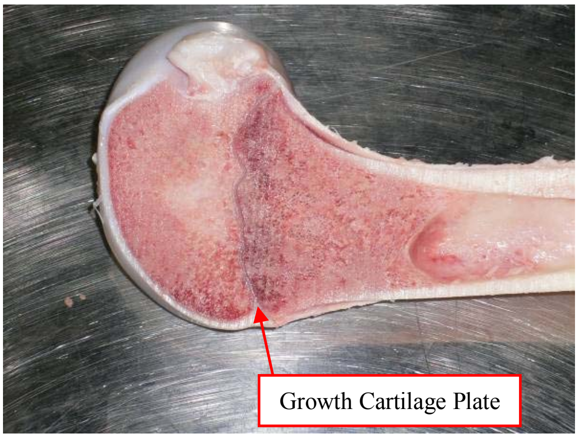


Fig. 8 Sagittal cross section of porcine distal femur. The growth cartilage plate divides trabecular bone.

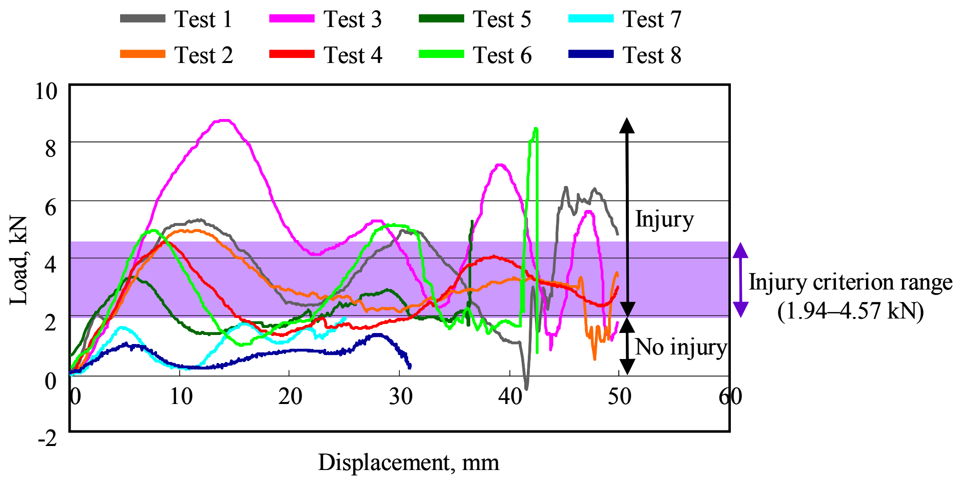


Fig. 9 Injury criterion range lapped over Fig. 7. The purple band illustrates the injury criterion range.

Although the points of injury occurrence in each test are not able to be identified in only Fig. 7, it is clear that the difference between tests 1 to 6 and tests 7 and 8 is boundary between injury occurrence and no injury. Specifically, the difference is fluctuation band of dynamic load. The injury criterion range was lapped over the load-displacement curves in Fig. 9. The dynamic loads obtained in tests 1 to 6, in which knee joint injuries were observed, were higher than those obtained in tests 7 and 8, in which no injuries were observed. Thus, the injury criterion range for the knee joint relative to the impact load is 1.94–4.57 kN.

In previous studies, the bending moment had been adopted as the injury criterion for the knee joint [(3)(4)(7)]. In our study, the injury criterion range relative to the maximum bending moment M_{max} was briefly calculated by using the span length L and impact load P, considering a simply supported beam to be subjected to a concentrated load (Eq. (1)).

$$M_{\max} = \frac{1}{4} LP \tag{1}$$

The calculation of the maximum bending moment showed that the injury criterion was in the range of 136–320 Nm. In addition, we attempted to compare the injury criteria obtained in this study with those of the human knee joint reported in previous studies (Table

3). While the length of human femur is 486 mm in reference [9], the length of porcine femur is 194.2 mm (S.D. 4.2). Thus, a bone length is different between human lower extremity and porcine hind leg. In this study, the effects of bone length difference are extremely low because the ends of femur and tibia were fixed in metal boxes. Although the experimental setups and conditions were different among these three studies, the objectives were the same, namely, to damage the knee joint by bending it [3][7]. We found that the range of injury criteria obtained in this study includes that obtained in previous studies. Thus, there is hardly any difference between the injury criteria for the porcine and human knee joints. However, the size of knee joints is also different; the width of porcine knee joint is 61.9 mm (S.D. 3.4), which is necessarily smaller than human knee joint. Although the scale effect of specimen is considerable when this study is compared with human data in more detail, these injury patterns correspond biomechanically. More specifically, the MCL is the tissue that is initially damaged by knee joint over-valgus, and the femoral epiphysis tends to fracture under high impact force because human distal femur also contains the growth cartilage plate. In this study, the knee joint injury criterion range could be determined, but not the criterion value. It is necessary for determining the criterion value to narrow down the range of injury criteria, which can be achieved by subdividing the drop height from 100 to 300 mm that includes the injury criterion into a smaller range.

Table 3 Injury criteria for knee joint obtained in present study and previous studies.

Study	Bending Moment [Nm]	Specimen	Experimental Method
Present Study	***136 ~ 320***	***Porcine Knee Joint***	***Three-Point Bending***
Kajzer [3]	***307 (S.D. = 147)***	***PMHS***	***Cantilever Bending***
Kerrigan [7]	***137 (S.D. = 5.5)***	***Human Knee Joint***	***Four-Point Bending***

5. Conclusions

In our study, dynamic three-point bending tests were performed on the porcine knee joint using a drop test system. Following are the conclusions of the study.

1. The knee joint injury pattern changes from only MCL damage to multiple soft tissue damage including MCL and to bone fracture as the impact velocity increases.
2. A bending moment of 136–320 Nm is the injury criterion for the porcine knee joint.

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