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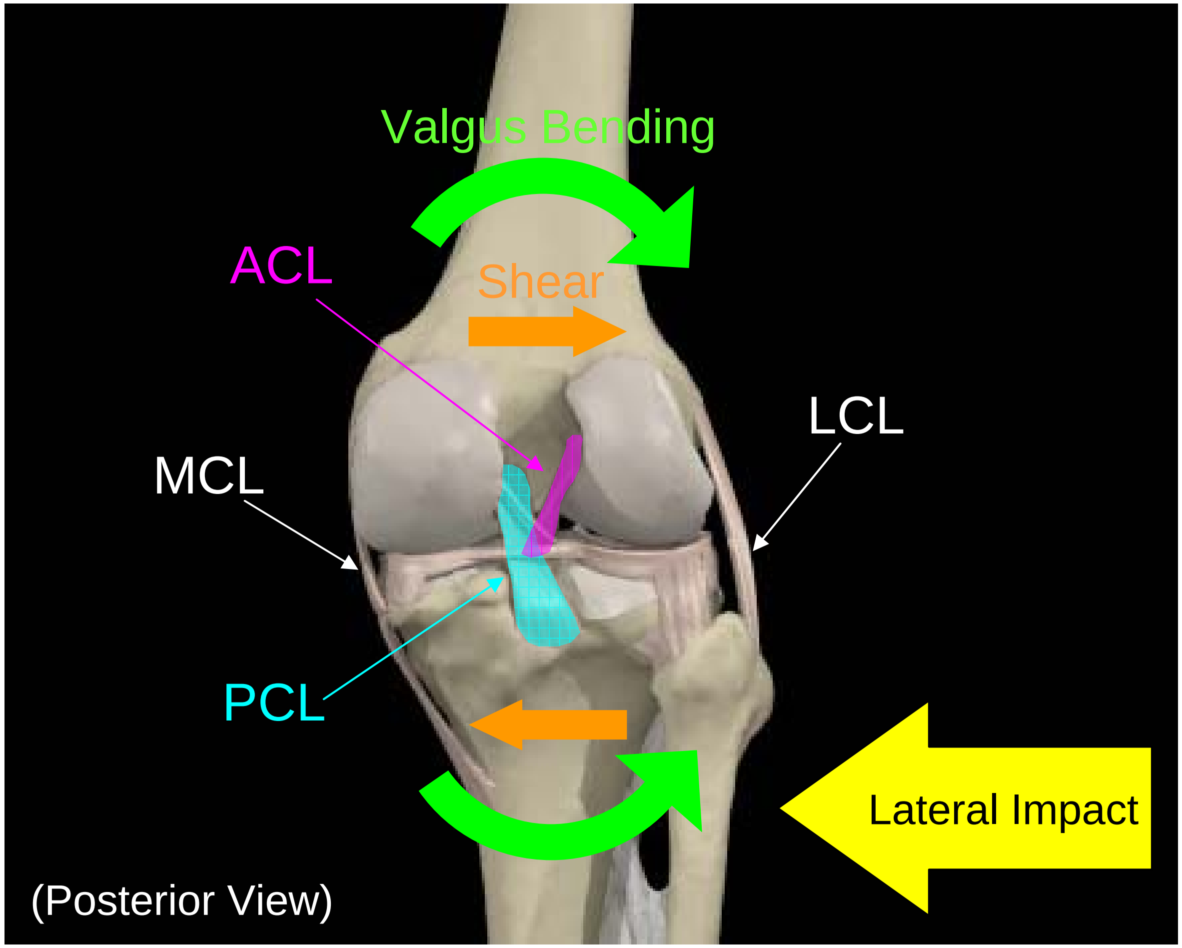
Informal document No. **GRSP-46-11**
(46th GRSP, 8-11 December 2009
agenda item 4(a))

Consideration on ACL/PCL Failure Evaluation

December 2009

Geneva

Anatomy



- In shear of a struck-side knee due to lateral impact, ACL is in tension and PCL is in compression
- ACL should fail first due to shear loading

Accident Analysis

Teresinski et al. (2001)

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Forensic Science International 124 (2001) 74–82

Forensic Science International

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Knee joint injuries as a reconstructive factors in car-to-pedestrian accidents

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Received 23 April 2001; accepted 26 July 2001

Abstract

Knee joint injuries were found in 214 out of 357 fatal pedestrian victims of traffic accidents (60%). The cross-sections of tibial and femoral epiphyses revealed bone bruises (due to compression and avulsion) and the percentage of victims with knee

Reference: Teresinski et al., *Knee joint injuries as a reconstructive factors in car-to-pedestrian accidents*, Forensic Science International, 124 74-82 (2001)

Accident Analysis

Teresinski et al. (2001)

extremely important in legal assessment of the driver's responsibility for causing the accident.[2]

2. Material and methods

The knee joints were examined in the earlier described way [10] in 357 fatal pedestrian victims of car accidents (Table 1). In each case, the postmortem examinations additionally included routine preparation of the soft tissues of the back and limbs evaluation of the pelvis [12] and character of fractures of the diaphyses of the lower limbs [13]. In the majority of the cases the examinations assessed also the ankle joints [14,15] and the structures of neck ligaments and muscles [16]. The cross-sections of the epiphyses of the knee bones (Fig. 1) were performed in 249 victims (Table 1).

The injuries found were classified on the basis of their mechanism (avulsive or compressive) according to the rules presented in Figs. 4–6 [9,10,12,17]. An important element of this classification was to determine the mechanism of bone bruises and broken off fragments. The bone bruises which occurred in the mechanism of condyle compression (Fig. 2)

and collateral ligaments) or beneath the intercondylar eminence (in the cases of cruciate ligament avulsion) and the broken off bone fragments which sometimes accompanied them involved only the adjacent attachments of the ligament structures (Fig. 4G and H). On the basis of these findings the so-called Segond's fractures[3] [18] due to avulsive mechanisms (Figs. 3B and 5G) were differentiated from the condylar fractures due to compressive mechanisms (Fig. 6D).

In the fractures of the head of fibula, it was necessary to differentiate the effects of avulsive mechanisms (Fig. 4H) from those of direct trauma (multifragmental fractures) and the cases of "high", pronation–rotation malleolar fractures of the shins (Maisonneuve's type) which are always accompanied by disruption of the interosseous membrane along the epiphyses of tibia and fibula [12,14].

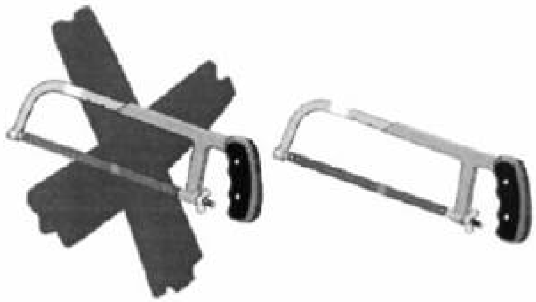
On the basis of the character of injuries,[4] the mechanism of joint damage was determined according to the rules presented in Figs. 7–10. Beside the mechanisms of knee injuries due to valgus and varus flexion, hyperextension and posterior dislocation of the proximal tibial epiphysis (anterior → posterior, A-P) in relation to the femoral condyles[5] (Fig. 10A) which were already known, a new mechanism[6] of anterior dislocation of the proximal tibial

- 357 fatal pedestrian victims of car accidents were examined
- Among those, dissection of the knee was performed in 249 victims

Reference: Teresinski et al., *Knee joint injuries as a reconstructive factors in car-to-pedestrian accidents*, Forensic Science International, 124 74-82 (2001)

Accident Analysis
Teresinski et al. (2001)

Table 1
Frequencies of knee injuries before and after cutting through the tibial and femoral epiphyses (additionally, the frequency of isolated injuries to the anterior cruciate ligament was included)



	Impact side					Run over only	Total
	From front	From rear	From lateral	From medial	Not determined		
Number of victims	24	87	165		37	44	357
Percentage (%) of victims with knee injuries (visible before the cross-sections were performed)	79	51	81		32	11	60
Number of victims with the cross-sections of the knee epiphyses	18	47	139		25	20	249
Percentage (%) of victims with knee injuries	89	72	94		64	15	80
Number of isolated injuries to the anterior cruciate ligament	1	13	2	2	0	2	20

- 165 pedestrian victims were subjected to lateral / medial impacts
- 165*0.94=155 victims sustained knee injuries
- Only 4/155*100=2.6% of those sustained isolated ACL failure (2 cases for each of lateral and medial impacts)

Reference: Teresinski et al., *Knee joint injuries as a reconstructive factors in car-to-pedestrian accidents*, Forensic Science International, 124 74-82 (2001)

Accident Analysis

Teresinski et al. (2001)

In the upright hits, a strong statistically significant correlation was found between the side of impact and the mechanism of knee injuries ($\chi^2 = 400.9$, d.f. $= 9$, $P = 0.00000$, Pearson's C coefficient of contingency $= 0.79$,[10] Cramer's V coefficient $= 0.75$). The knee joints were damaged mainly due to valgus flexion in the lateral impacts and varus flexion in the medial ones. In the front hits the injuries were caused by hyperextension (or A-P dislocation) while in the back ones by the P-A dislocation mechanism (Fig. 10B). The highest correlation was found for hyperextension, valgus and varus flexion mechanisms ($\chi^2 = 163.6$–173.2, d.f. $= 3$, $P = 0.00000$, $V = 0.83$–0.85) and slightly lower (but also extremely significant) for the P-A dislocation mechanism ($\chi^2 = 55.8$, d.f. $= 3$, $P = 0.00000$, $V = 0.48$).

In the remaining cases, the knee injuries were most

shins) or high-above-knee impacts (e.g. the proximal thigh or hip girdle) the direction of pathological dislocation of the articular structures may be reversed compared to the assumed one and only then the so-called "reversed lower complexes" (Figs. 11A, 12A, 13A) and "reversed upper complexes" (Figs. 11D, 12D, 13D) may occur.

Thus, in the cases in which the impact side can be determined (e.g. on the basis of the soft tissue injuries) the knee injuries may be the basis[14] for deducing about the type of vehicle involved (depending on the mechanisms found — the mechanism theoretically assumed for impacts by passenger cars or the "reversed" complex one).

Beside the cases in which the "expected" or "reversed" mechanism was observed, there were also some knee injuries in the victims with valgus or varus flexion instead of expected hyperextension or dislocation in the sagittal plane.

- Strong correlation between the side of impact and knee injury mechanism
- Knee joints were damaged mainly due to valgus flexion in lateral impacts (highest correlation)

Reference: Teresinski et al., *Knee joint injuries as a reconstructive factors in car-to-pedestrian accidents*, Forensic Science International, 124 74-82 (2001)

Accident Analysis

Teresinski et al. (2001)

Table 2

The mechanism of knee injuries (determined on the basis of damage to ligamentous and bony structures and bone bruises in the region of knee bone epiphyses) in relation to the impact side

	Impact side				Total (*n*)
	From front	From rear	From lateral	From medial	
Number of the knee joints injured	32	48	113	95	288
Characteristic injury complexes (%)	94	69	82	87	239
Mechanism (%)					
Hyperextension or posterior dislocation	**70**	26	2	2	42
Anterior tibial dislocation	6	**72**	11	11	18
Valgus flexion	0	3.5	**93**	3.5	88
Varus flexion	0	6	9	**85**	91

- 93% of knee injuries in lateral impact involves valgus bending mechanism

Reference: Teresinski et al., *Knee joint injuries as a reconstructive factors in car-to-pedestrian accidents*, Forensic Science International, 124 74-82 (2001)

Accident Analysis
Teresinski et al. (2001)

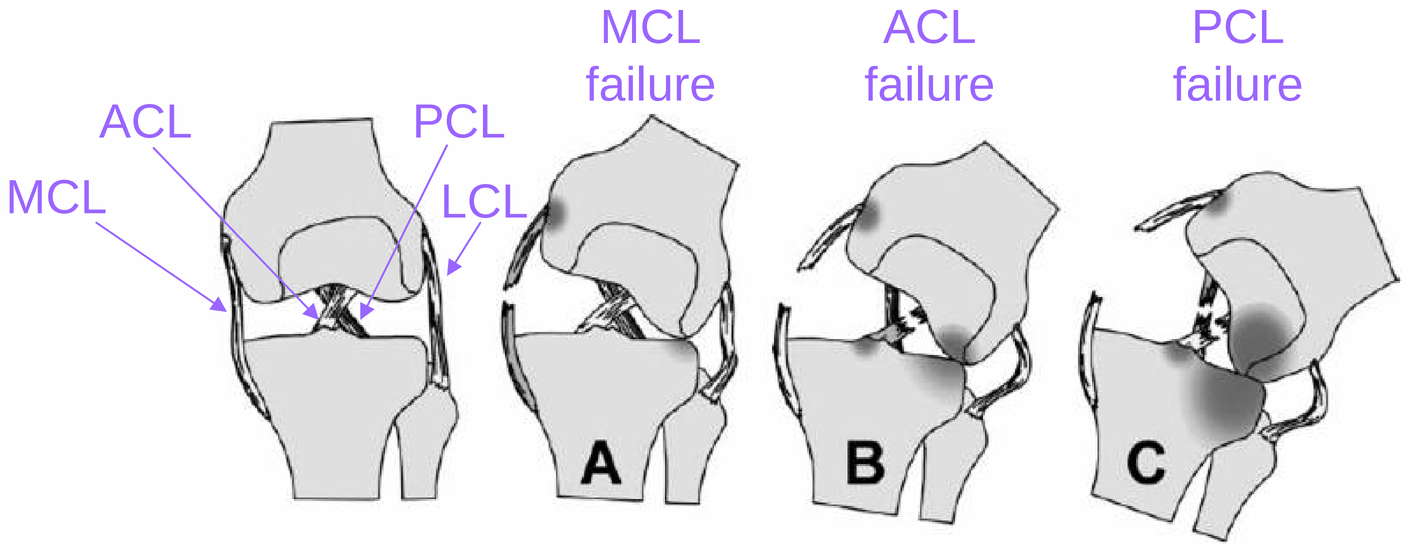


Fig. 8. Stages of the left knee injury (frontal view) in the mechanism of valgus flexion. (A) Avulsion of the medial collateral ligament; (B) avulsion of the anterior cruciate ligament; (C) avulsion of the posterior cruciate ligament. A → C increasing compression of the lateral tibial and femoral condyles.

- Sequence of ligament failure in valgus bending
  (A) MCL failure (B) ACL failure (C) PCL failure
- In valgus bending, MCL fails first, followed by ACL and PCL

Reference: Teresinski et al., *Knee joint injuries as a reconstructive factors in car-to-pedestrian accidents*, Forensic Science International, 124 74-82 (2001)

Experimental Study-1

Bhalla et al. (2003)

EVALUATION OF THE RESPONSE OF MECHANICAL PEDESTRIAN KNEE JOINT IMPACTORS IN BENDING AND SHEAR LOADING

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Paper Number 429

ABSTRACT

The knee joint is especially susceptible to injury in the pedestrian impact loading environment. However, the mechanical response, injury mechanisms and injury thresholds for lateral impact loading of the knee joint remain poorly understood. This paper reviews real world crash data and PMHS tests and identifies knee joint injuries commonly seen in pedestrian crashes. This is compared with results from knee joint shearing and bending tests reported in the biomechanics literature. It is shown that lateral knee joint shearing is unlikely to occur in real world pedestrian crashes.

sophisticated material representations. Unfortunately, in the absence of experimental studies, validating these models has been difficult and finite element models of the knee joint have so far found limited applications in the design and development of vehicles for pedestrian safety.

Most current computational models and knee joint test devices have been validated by comparing with knee shear and bending tests performed by Kajzer et al. (1990,1993,1997,1999). The knee joint tolerance levels reported have been used to propose acceptance levels for sub-system impactor tests (EEVC, 1998) for

Reference: Bhalla et al., *Evaluation of the Response of Mechanical Pedestrian Knee Joint Impactors in Bending and Shear Loading*, 18th ESV Conference, Paper #429 (2003)

Experimental Study-1

Bhalla et al. (2003)

4-point Valgus Bending

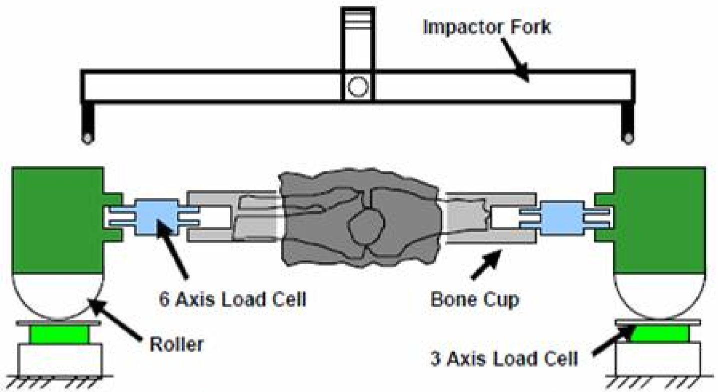

Figure 2. Schematic of the four-point knee bend test set up used in the UVA knee tests (Kerrigan et al. 2003).

Shear

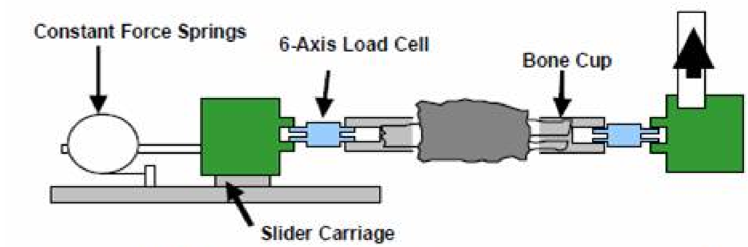

Figure 3. Schematic of the shear test set up used in the UVA knee tests (Kerrigan et al. 2003). Constant force springs are used to apply a compressive axial force on the knee joint.

Table 1: Factors derived for scaling test results

Spec	Test	Age (yrs)	Sex (M/F)	Height (in)	λ_L	λ_{mass}	λ_{Lequiv}
124R	Bend	58	F	5'9"	1.00	1.31	1.07
167L	Bend	66	M	5'10"	1.01	0.81	0.95
135L	Bend	63	M	5'8"	0.98	0.93	0.98
121L	Shear	40	M	5'	0.87	0.82	0.92
167R	Shear	66	M	5'10"	0.87	0.82	0.92
169R	Shear	62	M	5'7"	1.01	0.81	0.95

Notes: λ_x = (x in test subject) / (x in target anthropometry)

- 3 tests in valgus 4-point bending, 3 tests in shear, both using isolated knee joints

Reference: Bhalla et al., *Evaluation of the Response of Mechanical Pedestrian Knee Joint Impactors in Bending and Shear Loading*, 18th ESV Conference, Paper #429 (2003)

Experimental Study-1

Bhalla et al. (2003)

In the knee joint bending tests, the rotation of the supports was directly measured using angular velocity sensors, which provide an accurate measurement of knee bending angle. In the shear tests, applied shear displacement was measured using displacement transducers. However the results reported for actuator displacement are expected to be higher than the applied knee shear displacement because there was bending in the fixtures of the test set up (Kerrigan et al., 2003). Since the tests were imaged using high-speed digital cameras, the motion of the cups was obtained from video analysis. Thus, shear displacement results after compensating for bending are shown in this paper.

As suggested by Irwin et al. (2002), results should be appropriately scaled in order to account for the varying anthropometry of the subjects tested. Using a methodology of dimensional analysis similar to the one proposed by Irwin et al. (2002), scaling factors for force, λ_{force}, momentum, λ_{moment}, and displacement λ_{disp} are easily related to an equivalent length scaling factor λ_{Lequiv}:

- $\lambda_{force} = (\lambda_{Lequiv})^2$
- $\lambda_{moment} = (\lambda_{Lequiv})^3$
- $\lambda_{disp} = \lambda_{Lequiv}$

An equivalent length scaling factor, λ_{Lequiv}, can be derived by accounting for both mass and height of the subject as $\lambda_{Lequiv} = (\lambda_{mass} \cdot \lambda_L)^{1/4}$ by recognizing that $\lambda_{mass} \sim \lambda_L^3$. Scaling factors were derived by using the weight, 164.1lb, and height, 69.29", of the H-model (Finite Element Human Model, Takahashi et al., 2000) as a reference. It should be noted that these numbers are close to that for a 50th % Male (169.8lb, 69.8", based on Cheng et al., 1994). Table 1 shows the derived scaling factors and the scaled results are shown in Figures 4 and 5.

- Shear displacement results were compensated for bending of test fixtures
- Results were geometrically scaled

Reference: Bhalla et al., *Evaluation of the Response of Mechanical Pedestrian Knee Joint Impactors in Bending and Shear Loading*, 18th ESV Conference, Paper #429 (2003)

Experimental Study-1

Bhalla et al. (2003)

Three shear tests were performed, one (Test 0.2RR) of which was subject to repeated testing and thus the force-displacement data should not be used for quantitative analysis (figure 5). An initial inertial spike is not seen in the shear tests data shown in figure 6 because the loads reported are from the femoral side knee load cell which moves little during the test. Figure 6(b) shows the most common injury mechanism (partial ACL tear and osteo-chondral fracture). In one of the two tests, Test 2.2, where the applied shear displacement was larger, this injury mechanism was accompanied by damage to both menisci and the ACL tear was complete. The osteo-chondral fracture observed in all the shear tests results from the tibial spine gouging/plowing into the femoral condyles. Thus, it is clear that the applied shearing force is resisted by both, bone-bone contact within the knee joint and the ACL. The importance of bone-bone contact in resisting shear displacements in pedestrian impact is unclear since real world pedestrian crash data currently reported in the biomechanics literature does not suggest that such an injury mechanism is common. It is likely that osteo-chondral fractures were observed in these tests because the shearing displacement was applied in the presence of axial force corresponding to full body weight. Future testing should investigate the role of this compressive joint load in order to mimic real world

In comparison with bending tests, the relative timing of knee damage in shear tests is difficult to evaluate. The knee shear forces are seen to have a steadily increasing trend with shear displacement. Since tibial-spine gouging/plowing is likely an ongoing process, a drop in forces is likely due to ACL damage. Thus, it is hypothesized that the early peak in shear forces (at 12.7 mm of shear displacement, 693N shear force) in Test 2.2 is due to ACL failure. Similarly, ACL failure in Test 2.1 occurs at a shear force of 1839N and a shear displacement of 17.8 mm.

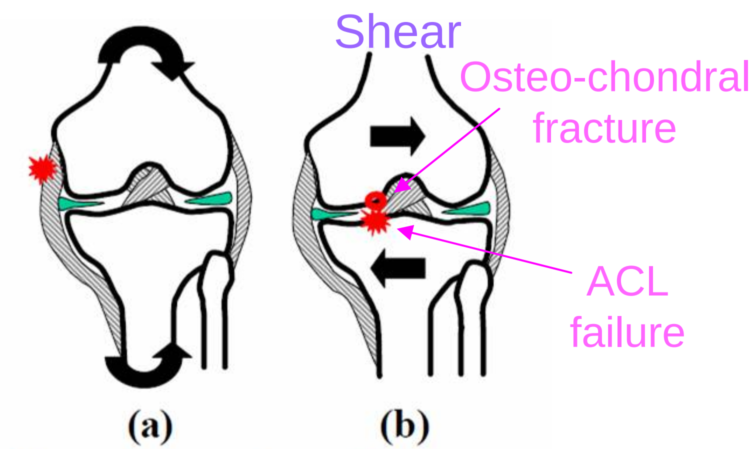

Figure 6. Damage mechanism in knee bending, (a), and knee shear, (b), loading.

- 1/3 test was a repeated test and should not be used
- Uncommon osteo-chondral fracture was involved in both of remaining 2 tests
- Estimated shear displacement at ACL failure
  17.8 mm for test 2.1, 12.7 mm for test 2.2 (only 2 data available)

Reference: Bhalla et al., *Evaluation of the Response of Mechanical Pedestrian Knee Joint Impactors in Bending and Shear Loading*, 18th ESV Conference, Paper #429 (2003)

ISO/TC22/SC12/WG6 N 713 Draft

ISO/TC22/SC12/WG6 N 713

METHOD OF CONSTRUCTION FOR INJURY RISK CURVES ISO TC22/SC12/WG6

CONTENT

1 Introduction 2
1.1 Development of risk curves 2
1.2 Rationale for handling of data 3
2 Definitions 3
2.1 Censoring (Censored Observations) 4
2.2 Single and Multiple Censoring 4
2.3 Left and Right Censoring 4
2.4 Confidence Interval 4
2.5 What are variables 5
2.6 Outliers 5
2.7 Loss Function 6
2.8 Maximum Likelihood Loss Function 6
2.9 Maximum Likelihood Method 7
2.10 Link Function and Distribution Function 7

ISO/TC22/SC12/WG6 N 713 Draft

1.2 Rationale for handling of data

The numerical process described above would require some form of data reduction or organization to achieve the best estimate with the least error. The most common approach to such data reduction is to create "intervals of values" of the variable (parameter) being considered for the risk analysis, and make a frequency tally of the observations within each interval. The key issue is to decide on "how many intervals" the data range should be divided, which is intern will decide the "size" of the interval.

Although there is no hard and fast rule as to how many intervals to use, a consensus has developed in the research community that anywhere from ten to twenty intervals, depending on the type, breadth and depth of the data can usually generate a satisfactory representation of the distribution of data.

Two more issues need to be taken into consideration with regard to the above approach. First, how many observations would be ideally considered for each interval, and second, where to begin the lowest value interval. It is clear from any statistical treatment that the best number of observations for any numerical treatment is between three and five, accordingly data that can be fit into twenty intervals of five observations each (for a total of 100) will generate satisfactory representation of the estimated function. In contrast, ten intervals with one observation each (total of ten), will produce a representation that is not recommended by the scenario described above. Any amount of data observations that are less than 100 and greater than 10 will produce some results that depend on a number of issues such as availability of data within each interval, the function distribution thought, the critical path of any concentration of data and data density within the range of observation.

A final consideration in developing an interval scheme is the selection of the lowest value interval. The importance of such selection stems from the fact that the final distribution is highly affected by the personal judgment used in the selection of such an interval.

To summarize. It is clear from the above discussion that

- Large data sample (n>100) agreement exists in research community.
- Small data samples (n<10) little statistics can be done and therefore, more data is needed to perform the analysis.
- Intermediate data samples (10<n<100) there is no consensus on the ISO/TC22/SC12/WG6 N 682

Sample size n < 10 :
More data is needed
to perform the analysis

Experimental Study-2

Bose et al. (2004)

2004-01-1608

Response of the Knee Joint to the Pedestrian Impact Loading Environment

Bose, D., Bhalla, K., Rooij, L., Millington, S., Studley, A., and Crandall, J.
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ABSTRACT

Isolated knee joints from Post Mortem Human Subjects (PMHS) were tested in dynamic lateral-medial valgus loading that replicated a vehicle-pedestrian impact at 40 km/h. Eight specimens were tested in 4-point bending (pure bending) and eight specimens were tested in 3-point bending in configurations chosen to apply varying proportions of moment and shear at the knee joint. The medial collateral ligament (MCL) was the only major load

(Takahashi et al., 2001, Konosu et al., 2001, Bhalla et al., 2003). Unfortunately, there is little data available from experimental studies for model and test device validation. Much of the current understanding of the response of the human knee joint in the pedestrian impact environment is based on quasi-static bending and shearing tests reported by Ramet et al. (1995) and from a series of studies by Kajzer and colleagues (1990, 1993, 1997, 1999), which reported results from low speed (20 km/h), and high speed (40 km/h) impacts to

Reference: Bose et al., *Response of the Knee Joint to the Pedestrian Impact Loading Environment*, SAE World Congress, Paper #2004-01-1608 (2004)

Experimental Study-2

Bose et al. (2004)

TEST METHODOLOGY

SPECIMEN PREPARATION

Sixteen human lower leg specimens were obtained from medical cadavers in accordance with ethical guidelines and research protocol approved by the Human Usage Review Panel, National Highway Traffic and Safety Administration, and a University of Virginia institutional review board. Prior to testing, all specimens were screened for HIV and hepatitis, and X-rays were checked for signs of pre-existing bone and joint pathology. The subjects were all male and had an average age of 67.8 years, average weight of 83.3 kg, and average height of 1.76 m. Anthropometric details of the subjects are reported in Table 1.

The harvested limbs were frozen (–20°C) and stored until 24 hours prior to testing. They were then removed from the freezer and allowed to thaw at room temperature. Once thawed the tibia and fibula were sectioned by cutting parallel to a transverse plane approximately 5 cm

Table 1: Anthropometric details of the specimens

	Specimen #	Age (years)	height (m)	weight (kg)	Sex
1	2002-FRM-159	66	1.665	65.9	Male
2	2001-FRM-141	65	1.778	78.2	Male
3	51000944-004	69	1.7	81.8	Male
4	2002-FRM-179	78	1.78	65	Male
5	2003-FRM-187	54	1.778	112.7	Male
6	2001-FRM-152	70	1.78	79.5	Male
7	2002-FRM-178	73	1.81	80.7	Male
8	2003-FRM-188	71	1.72	85	Male
9	2003-FRM-201	51	1.78	86.6	Male
10	2003-FRM-202	90	1.77	74.8	Male
	Average	**68.7**	**1.7561**	**81.02**	

- 16 knee specimens taken from 10 cadavers (all males)
- Average height of the cadavers almost exactly represent that of 50th %ile male

Reference: Bose et al., *Response of the Knee Joint to the Pedestrian Impact Loading Environment*, SAE World Congress, Paper #2004-01-1608 (2004)

Experimental Study-2

Bose et al. (2004)

- Kerrigan et al. (2003) = Bhalla et al. (2003): UVa knee tests
- 3 shear tests on isolated knee joints

Kerrigan et al. (2003) also reported results from three shear tests on isolated knee joints. In these tests the femoral end was held while the tibia was sheared laterally. A compressive axial force equivalent to full body weight was superimposed on the knee joint. Post-test necropsy of the specimens showed that, in every case, damage to the ACL was the only relevant ligamentous injury. In addition, all the tests showed osteo-chondral defects produced by the tibial spine gouging/plowing into the femoral condyles. Such osteo-chondral defects have never been reported in real world pedestrian crashes or in staged collisions using cadavers. In addition, ACL injuries rarely occur as isolated ligamentous injuries. Thus, it was hypothesized that the pure shear loading of the knee in the presence of compressive loads produced in these tests was an extreme loading environment that does not occur in real-world pedestrian impacts. Instead it is likely that shearing is always accompanied by knee bending. Since the relative proportion of bending and shear occurring in a pedestrian-vehicle impact depends on the location of the bumper relative to the knee joint, combined loading tests of the knee joint should study the effect of varying moment-shear ratios. Thus, in the current study, 3-point bend tests were performed without a compressive axial load and the location of the knee joint relative to the supports was varied to induce varying proportions of bending moment and shear at the knee joint.

- In all tests, isolated ACL damage occurred along with unrealistic osteo-chondral defects
- Isolated ACL injuries rarely occur

- Hypothesis: knee shear is always accompanied by knee bending
- Bose et al. (2003) performed 3-point bending tests with various locations of the knee joint relative to the supports to vary proportions of bending moment and shear at the knee joint

Reference: Bose et al., *Response of the Knee Joint to the Pedestrian Impact Loading Environment*, SAE World Congress, Paper #2004-01-1608 (2004)

Experimental Study-2

Bose et al. (2004)

4-point Valgus Bending (Pure Bending)

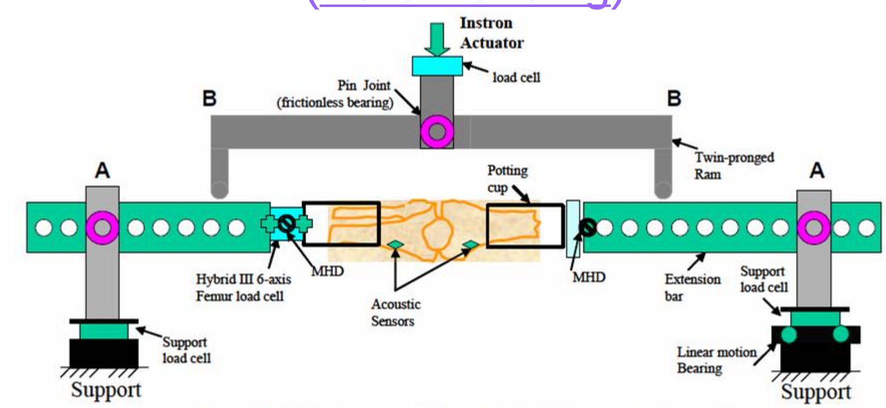

Figure 1: Test schematic for the four-point bending (pure bending) test.

Table 2 a: Test matrix for all 4-point pure bending tests

Test #	Specimen	Aspect	Confg.
Bend 1	51000944-004	Right	4 Point
Bend 2	2002-FRM-159	Right	4 point
Bend 3	2001-FRM-141	Left	4 point
Bend 4	2002-FRM-179	Right	4 point
Bend 5	2002-FRM-179	Left	4 point
Bend 6	2001-FRM-141	Right	4 point
Bend 7	2003-FRM-187	Left	4 point
Bend 8	2001-FRM-152	Left	4 point

3-point Valgus Bending (Combined Bending/Shear)

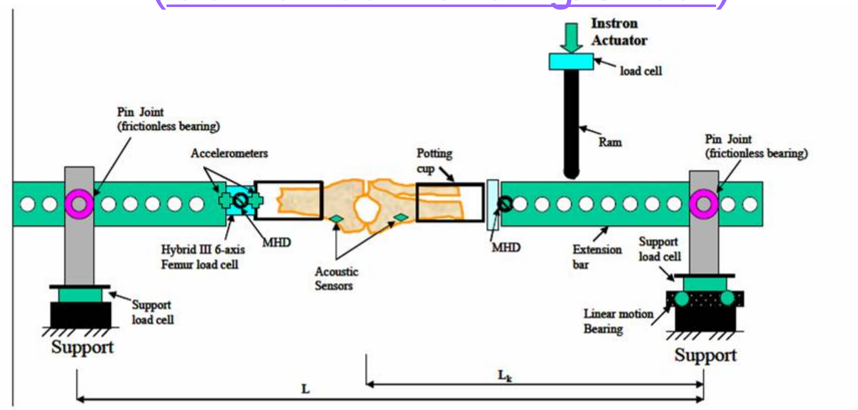

Figure 3: Test schematic for the three-point bending (combined bend-shear loading) test.

Table 2 b: Test matrix for all combined loading tests

Test #	Specimen	Aspect	Test Confg.	M/V Ratio
Comb 1	2002-FRM-178	Right	3 point	4.2
Comb 2	2003-FRM-188	Left	3 point	4.44
Comb 3	2003-FRM-187	Right	3 point	4.09
Comb 4	2003-FRM-201	Right	3 point	2.73
Comb 5	2003-FRM-202	Left	3 point	3.12
Comb 6	2003-FRM-202	Right	3 point	2.92
Comb 7	2003-FRM-201	Left	3 point	1.88
Comb 8	2001-FRM-152	Right	3 point	1.95

- 8 tests were performed in each of 4-point and 3-point valgus bending configurations

Reference: Bose et al., *Response of the Knee Joint to the Pedestrian Impact Loading Environment*, SAE World Congress, Paper #2004-01-1608 (2004)

Experimental Study-2

Bose et al. (2004)

3-point Valgus Bending
(Combined Bending/Shear)

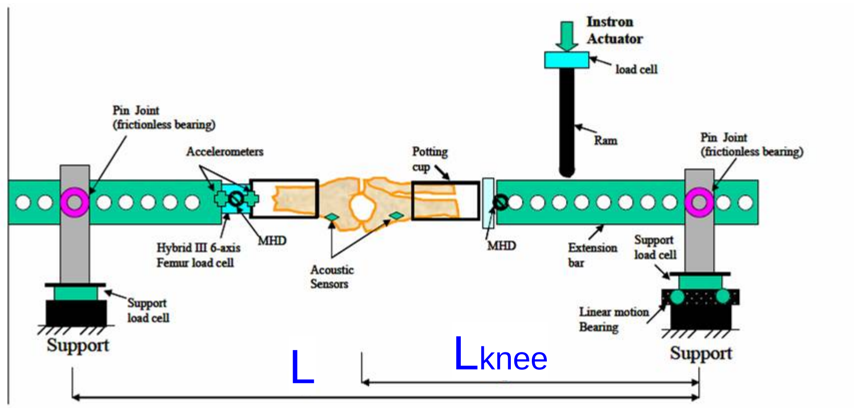

Figure 3: Test schematic for the three-point bending (combined bend-shear loading) test.

The test configuration in the 3-point bend tests (Figure 3) was identical to that used in the 4-point bend tests, with the exception that a single-prong ram was used. In order to obtain varying proportions of bending moment and shear, the distance between the two supports and the knees was systematically varied. In order to produce lateral-medial shear, the specimen was installed so that the impactor pressed down on the lateral side of the distal part of the specimen. If idealized 3-point bending of a simply supported beam is assumed, the ratio of bending moment, M_{knee}, to the shear force, V_{knee}, at the knee joint is given by:

$$\boxed{\frac{M_{knee}}{V_{knee}} = L - L_{knee}} \quad \ldots \quad [1]$$

Table 2 b: Test matrix for all combined loading tests

Test #	Specimen	Aspect	Test Confg.	M/V Ratio (*10)
Comb 1	2002-FRM-178	Right	3 point	4.2
Comb 2	2003-FRM-188	Left	3 point	4.44
Comb 3	2003-FRM-187	Right	3 point	4.09
Comb 4	2003-FRM-201	Right	3 point	2.73
Comb 5	2003-FRM-202	Left	3 point	3.12
Comb 6	2003-FRM-202	Right	3 point	2.92
Comb 7	2003-FRM-201	Left	3 point	1.88
Comb 8	2001-FRM-152	Right	3 point	1.95

- Moment / Shear Force (M/V) = L - L_{knee}
- M/V Ratio varied between 0.188 and 0.444 to represent different proportions of knee bending moment and shear force

Reference: Bose et al., *Response of the Knee Joint to the Pedestrian Impact Loading Environment*, SAE World Congress, Paper #2004-01-1608 (2004)

Experimental Study-2

Bose et al. (2004)

Results: Injury

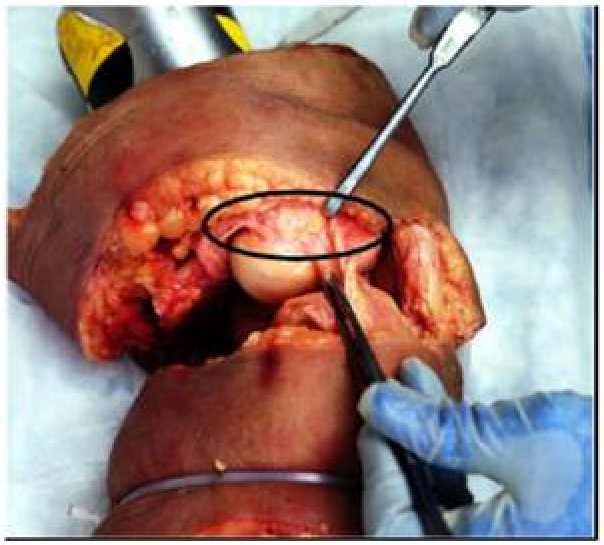

Figure 22: The characteristic MCL avulsion injury observed after many tests.

Table 3: Injuries observed in each tested specimen

Test #	Specimen #	Aspect	Test	ACL	PCL	MCL	LCL
Bend 1	51000944-004	Right	4 pt	v	v	P	v
Bend 2	2002-FRM-159	Right	4 pt	v	v	P	v
Bend 3	2001-FRM-141	Left	4 pt	v	v	P	v
Bend 4	2002-FRM-179	Right	4 pt	v	v	P	v
Bend 5	2002-FRM-179	Left	4 pt	v	v	C	v
Bend 6	2001-FRM-141	Right	4 pt	v	v	P	v
Bend 7	2003-FRM-187	Left	4 pt	v	v	v	v
Bend 8	2001-FRM-152	Left	4 pt	v	v	P	v
Comb 1	2002-FRM-178	Right	3 pt	v	v	v	v
Comb 2	2003-FRM-188	Left	3 pt	v	v	C	v
Comb 3	2003-FRM-187	Right	3 pt	v	v	B	v
Comb 4	2003-FRM-201	Right	3 pt	v	v	C	v
Comb 5	2003-FRM-202	Left	3 pt	L	v	C	v
Comb 6	2003-FRM-202	Right	3 pt	v	v	P	v
Comb 7	2003-FRM-201	Left	3 pt	v	v	P	v
Comb 8	2001-FRM-152	Right	3 pt	v	v	P	v

4 pt: 4 point bending, 3pt: 3 point combined Loading
v : No injury, P: Partial avulsion, C: Complete avulsion
B: Bony Avulsion, L: Slight laxity

- In combined loading, MCL failed in 7/8 cases
- ACL failed in 1 case with MCL failure – no isolated ACL failure

Reference: Bose et al., *Response of the Knee Joint to the Pedestrian Impact Loading Environment*, SAE World Congress, Paper #2004-01-1608 (2004)

Summary

- Accident analysis (Teresinski et al. 2001)
  - Isolated ACL failure was observed in 2.6% of pedestrians (4/155) subjected to lateral / medial impacts and sustaining knee injuries
  - 93% of knee injuries in lateral impact involves valgus bending mechanism
  - In valgus bending, MCL fails first, followed by ACL, then PCL
- Experimental Study-1 (Bhalla et al. 2003)
  - 3 shear tests on isolated knee joints (pilot study)
  - One of them was a repeated test and should not be used for determining injury thresholds
  - ACL failed and unrealistic osteo-chondral fractures occurred in both of the remaining 2 tests
  - Estimated shear displacement at ACL failure for the 2 tests : 12.7 mm and 17.8 mm
  - ISO/TC22/SC12/WG6 N 713 draft suggests that at least 10 data are needed to perform analysis for injury risk curve development

Summary

- Experimental Study-2 (Bose et al. 2004)
  - 3-point bending tests using isolated knee joints with bending moment/shear force ratio varied based on the assumption that knee shear is always accompanied by knee bending
  - 7/8 knees sustained MCL failure
  - ACL failed in one case accompanied by MCL failure – no isolated ACL failure

Recommendation

- Isolated ACL failure is very rare in both real world accidents and experimental studies
- Only two data are available from the knee shear tests that resulted in unrealistic osteo-chondral fractures

- Considering very low frequency of isolated ACL failure and lack of sufficient human data, it would be appropriate to measure ACL elongation for monitoring purpose only, in preparation for future potential need for ACL failure evaluation
- More biomechanical data are required if ACL failure threshold needs to be determined