EXPERIMENTALLY PRODUCED TIBIAL PLATEAU FRACTURES

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ABSTRACT

Tibial plateau fractures are among the most severe lower limb injuries suffered in car crashes in terms of long-term impairment. Axial loading of a flexed, entrapped knee by an impact delivered to the plantar surface of the foot is a likely injury scenario for a number of lower limb injuries sustained in frontal crashes, including tibial plateau fractures. In order to determine the injury tolerance of the leg to axial loading, axial impact tests at injurious load levels were conducted using 20 above-knee cadaver leg specimens in which the ankle was neutrally positioned and the knee was constrained and flexed 90°. Injury to the foot/ankle complex was generated in 15 specimens, and tibial plateau fractures were generated in 5 of these specimens. All tibial plateau injuries were Schatzker VI type bicondylar fractures associated with severe comminution and disruption of the articular surface. However, the fact that tibial plateau fractures never occurred independently of foot and ankle injury suggests that an axial loading injury criterion based on the injury tolerance of the foot/ankle complex is sufficiently conservative to protect against tibial plateau fractures in this impact scenario.

Key Words: Biomechanics, Injury Criteria, Knees, Joints, Cadavers

DUE TO IMPROVEMENTS in belt and airbag restraint systems, the overall number of car crash fatalities in recent years has been significantly reduced, and as a consequence, lower extremity injuries have emerged as the most frequent non-minor injury resulting from frontal collisions (Crandall et al., 1996). Approximately 20% to 30% of all moderate to severe injuries sustained in automobile crashes are to the lower extremity (Morgan et al., 1991; Dischinger et al., 1994), making it the most commonly injured body region after the head (Pattimore et al., 1991). Though not life-threatening, lower extremity injuries are often the most severe injuries suffered in a crash (Pattimore et al., 1991), and may be the most common cause of long-term impairment and disability (States, 1986).

Epidemiological studies show that tibial plateau fractures comprise about 10% of all belowknee injuries sustained in car crashes (Taylor et al., 1997; Sherwood et al., 1999). Among the general population, Roberts (1968) reported that 26% of all tibial plateau fractures were sustained by occupants in car crashes, and an additional 13% were sustained by pedestrians hit by a car. These high-energy fractures carry a poor prognosis because they disrupt the articular cartilage in a weightbearing joint, which can lead to long-term complications such as infection, malunion, and osteoarthritis. In addition, associated injuries such as compartment syndrome, ligamentous disruption, and neurovascular injury make these fractures particularly devastating. Along with fractures of the calcaneus, talus, and tibia plafond, tibial plateau fractures are considered to be among the most severe below-knee injuries in terms of expected long-term impairment (Morris et al., 1997).

The most widely used classification scheme to describe tibial plateau fractures is the one proposed by Schatzker et al. (1979). The Schatzker classification includes six types of fractures (Figure 1a-f). Briefly, type I is a split fracture of the lateral tibial plateau without articular depression (Figure 1a), type II is a split depressed fracture of the lateral tibial plateau (Figure 1b), and type III is an isolated depression of the lateral plateau (Figure 1c). Type IV is a medial plateau fracture (Figure 1d), and type V is a bicondylar fracture of the tibial plateau (Figure 1e). The most severe injury in the

Schatzker classification is the type VI fracture, which is a bicondylar tibial plateau fracture characterized by articular disruption and dissociation of the metaphysis from the diaphysis (Figure 1f). The type VI fracture is almost invariably the result of severe high-velocity trauma, such as a car crash or a fall from a height (Schatzker et al., 1979).



Figure 1. The Schatzker classification scheme for tibial plateau fractures (adapted from Schatzker et al., 1979).

In order to develop countermeasures to reduce the incidence of tibial plateau fractures in car crashes, it is first necessary to determine the most common mechanism of injury for these fractures, and then to determine the tolerance of the tibiofemoral joint to this mode of loading. Several possible mechanisms for tibial plateau fractures have been proposed, including axial loading (Hirsch and Sullivan, 1965), varus/valgus bending (Kennedy and Bailey, 1968), and knee hyperextension (Nagel et al., 1976). In the case of a frontal car crash, most researchers agree that axial loading of a flexed, entrapped knee by an impact delivered to the plantar surface of the foot is a likely injury scenario (Nagel et al., 1976; Taylor et al., 1997; Banglmaier et al., 1999a) (Figure 2). Although Banglmaier et al. (1999a) suggested the possibility of tibial plateau fracture due to axial loading without knee entrapment, it seems unlikely that the rotational inertia of the upper leg alone could generate enough axial loading of the tibial plateau to cause injury. Klopp et al. (1997) and Funk et al. (2000) investigated that very injury mechanism by testing a combined total of 71 above-knee limbs in a position simulating typical driver geometry without knee entrapment. Foot and ankle fractures were documented in a total of 22 specimens, but no knee injuries were ever produced. Therefore, it seems likely that some degree of knee entrapment is necessary for tibial plateau fractures to occur as a result of axial loading of a flexed knee.

Although the incidence, severity, and mechanism of injury to the tibial plateau is similar to foot and ankle injuries such as calcaneus and pilon fractures, very little research conducted in the last 20 years has addressed the tibial plateau region. Early attempts to quantify the injury tolerance of the tibiofemoral joint produced widely divergent results. In 1965, Hirsch and Sullivan conducted quasistatic axial compression tests on 32 cadaver knees at varying flexion angles. They documented an average failure load of 800 kg (8 kN) for specimens tested at flexion angles between 0° and 20°. Kennedy and Bailey (1968) quasistatically tested 44 knees in a variety of loading modes, including varus/valgus bending, axial compression, and combinations of bending, compression, and internal/external rotation. Failure forces in axial compression averaged more than twice as high as Hirsch and Sullivan's results, and were often reported to be in excess of 8000 lb (35 kN).



Figure 2. Compressive loading of the tibial plateau due to knee entrapment.

In addition to the conflicting results, methodological considerations suggest that the studies by Hirsch and Sullivan (1965) and Kennedy and Bailey (1968) require further validation for automobile safety applications. First, both studies were performed at quasistatic load rates that are not representative of the high-velocity impacts seen in car crashes. The increase in axial failure force in dynamic versus quasistatic loading has been documented to be approximately 50% for the foot/ankle complex (Roberts et al., 1992), and may be similar for the tibiofemoral joint complex. In addition, both Hirsch and Sullivan (1965) and Kennedy and Bailey (1968) tested their specimens near full knee extension. This position is unrealistic when discussing car occupants, where knee flexion is typically 90° (Viano et al., 1978). The fact that both studies found that failure force decreased as the flexion angle of the knee increased emphasizes the need to test at 90° knee flexion for automotive applications. In spite of these methodological shortcomings, the Hirsch and Sullivan data are the basis of the 8 kN axial load in jury criterion component of the tibia index proposed by Mertz (1993).

More recently, Banglmaier et al. (1999ab) dynamically tested 12 matched pairs of isolated tibiofemoral joints. Tibia travel was constrained to purely axial translation. One aspect of each pair was repetitively impacted until gross fracture was observed, and the contralateral limb was subjected to a single impact. Average peak loads in the repetitive impact group were 8.0 ± 1.8 kN. Fractures of the femoral notch, femoral condyles, tibial plateau, and combinations of these were reported. In the single impact group, fracture was produced in four of the twelve specimens at an average peak load of 5.8 ± 1.8 kN. Each of these four specimens suffered a fracture of either the medial tibial plateau or lateral tibial plateau only.

Although the data of Banglmaier et al. provide excellent information about the dynamic in jury tolerance of the tibiofemoral joint, further study is warranted for two reasons. First, the loading mode in their experiments was not physiological. Because isolated joints were used, the contribution of the fibula and surrounding soft tissue was neglected. Also, the motion of the tibia was constrained to pure axial translation, which prevented the tibial plateau from sliding anteriorly with respect to the femoral condyles, as would occur in an intact knee. Second, because injuries to the foot/ankle complex may occur by the same axial loading mechanism as tibial plateau fractures, it is necessary to perform experiments on entire lower extremities to determine the "weakest link," and thereby calculate the most conservative injury criterion for the entire lower leg (Banglmaier et al., 1999a). The aim of this study was to investigate the load response of the below-knee complex as it sustained clinically relevant injuries when subjected to axial impact loading characteristic of a car crash.

MATERIALS AND METHODS

TEST APPARATUS – Dynamic impact tests were conducted on 20 above-knee cadaver limbs in order to investigate lower leg injury due to axial loading. A test apparatus was constructed to deliver dynamic axial impact loads to the plantar surface of the foot of a cadaver specimen via a compound pendulum. The pendulum struck a padded transfer piston which directed the impact to pure horizontal translation of up to 16 cm. The leg specimens were placed horizontally in the test rig with the ankle in a neutral orientation and the knee constrained in an adjustable block (Figure 3). 5-axis load cells at the footplate and knee block recorded loads and moments during the impact event. Two plies of 3/8" (9.5 mm) foam padding were placed between the foot and the footplate, and 1" (25.4 mm) foam padding was placed around the knee for load distribution. The femur was tied back to a uniaxial load bolt to prevent flexion of the knee during impact. The knee block position was adjusted longitudinally to compress the instrumented leg until it was axially preloaded to half of the specimen's body weight immediately prior to impact.



Figure 3. Test apparatus. A pendulum (not shown) strikes the transfer piston, causing longitudinal footplate intrusion and axial compression of the leg specimen.

SPECIMEN PREPARATION – 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 an 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. Approximately half of the specimens tested were fresh or fresh frozen, and half were embalmed with an in-house mixture that has been shown not to significantly alter tissue properties (Crandall, 1994). Frozen specimens were allowed to thaw at room temperature for at least 24 hours prior to testing. All specimens were sectioned above the knee to preserve the functional anatomy of the knee joint and leg musculature. Specimens were instrumented with an implanted tibia load cell. A mounting jig was used to ensure that the length, rotation, and alignment of the tibia shaft were preserved while an approximately 9 cm portion of the tibia diaphysis was removed and an in situ 5-axis tibia load cell was installed in its place (Funk et al., 2000). Using a two-part epoxy mixture with sand added, the proximal and distal bone ends of the tibia shaft were potted in bone cups to which the load cell was attached.

TEST PROTOCOL – The approach taken in this study was to input a high level of impact energy (~ 800 J) so that injury would be produced in every test. The effective mass of the pendulum was 33 kg and the impact velocity was 7 m/s for all tests. The full 16 cm of footplate intrusion was allowed for the first ten tests. However, in six of these tests, mid-shaft tibia fractures occurred at the interface between the bone and the potting material, all of which were deemed artifactual. For the next ten tests, the level of footplate intrusion was limited to 6 cm with all other test conditions held constant.

DATA ACQUISITION AND ANALYSIS – All electronic data were sampled at 10,000 Hz using a DSP TRAQ-P data analysis system and digitally filtered to SAE J211 channel class 180. Video data were taken from each test using either a Kodak Ekta-Pro high speed (1000 fps) monochrome video camera or a high-speed (1000 fps) Kodak RO color imager. All data were transformed when appropriate to the local body segment coordinate frame using the SAE sign convention (positive x, y, and z axes point anterior, right, and inferior, respectively). Load cell data

were debiased using offsets recorded in an unloaded state immediately prior to initial positioning. Tibial plateau load was calculated by subtracting the femur tieback load from the axial load recorded by the knee load cell. An orthopaedic surgeon evaluated post-test x-rays and performed detailed necropsies of each specimen to evaluate the injuries sustained during testing. All statistical analyses were performed using a standard one-tailed student t-test assuming equal variance with a significance level of p < 0.05.

RESULTS

Fractures of the foot/ankle complex and tibial plateau were documented in these tests. Foot and ankle fracture occurred in 15 specimens, and tibial plateau fractures were produced in 5 of those specimens (Table 1). The remaining five specimens were excluded from analysis because they either suffered only an artifactual mid-shaft tibia fracture at the bone/potting interface (4 specimens) or sustained no injury due to failure of the knee constraint (1 specimen). All tibial plateau fractures were classified as Schatzker VI bicondylar fractures and were associated with severe comminution and disruption of the articular surface (Figure 4). A significant avulsion fracture of the anterior cruciate ligament (ACL) insertion at the tibial plateau was a common feature in all of these specimens. Fractures of tibial plateau were never associated with soft tissue injuries of the knee or artifactual mid-shaft fractures. All five of the tibial plateau fractures occurred in the test series in which footplate intrusion was limited to 6 cm. Two specimens suffered soft tissue injuries of the cruciate knee ligaments when the footplate intrusion was 16 cm. No fractures of the femoral condyles were noted in this study.

Table 1. Data summary for all tests. The first of the middle two letters in the specimen ID denotes whether the specimen was embalmed (E) or fresh frozen (F). Peak load lag time refers to the difference between the time of peak tibial plateau load and the time of peak mid-shaft tibia load

Test	Specimen ID	Age	Sex	Height	Mass	Peak	Peak load	Foot/	Tibia	Artifactual
				(cm)	(kg)	Plateau	lag time	ankle	Plateau	mid-shaft
						Load (N)	(msec)	fx	fx	fx
3B	99-EF-104-L	67	F	163	63.6	6266	15.4	•	A&PCL	
3C	98-EF-95-L	57	F	173	72.7	4521	1.5			•
3D	97-EM-76-L	47	М	178	52.3	4871	0.7	•	ACL	
4 A	97-EM-76-R	47	М	178	52.3	N/A	N/A	•		•
4B	99-FF-17-L	74	F	160	60.0	2431	7.5	•		
4C	99-FF-17-R	74	F	160	60.0	4831	0.9	•		•
4D	98-FF-98-R	44	F	163	60.0	7080	13.0			•
4E	98-FF-98-L	44	F	163	60.0	7189	2.5			•
4F	99-EF-104-R	67	F,	163	63.6	3701	3.3	•		
4G	98-FF-100-R	42	F	168	71.4	6470	0.0	•	6	•
5A	97-EM-88-L	59	M	170	47.7	7354	0.4	•	•	
5B	97-EF-77-R	63	F	160	55.9	6444	8.1			
5C	99-FF-101-R	62	F	168	52.3	4452	0.4	•	•	
5D	97-EM-88-R	59	M	170	47.7	7007	7.4	•		
5E	97-EF-77-L	63	F	160	55.9	6402	3.5			•
5F	99-FF-101-L	62	F	168	52.3	5032	0.1	•	•	
5G	99-EM-93-R	67	Μ	191	80.5	8855	6.1	•		
5H	99-EM-93-L	67	M	191	80.5	8534	6.4	•		
51	99-FM-102-R	65	M	188	84.1	7363	4.6	•	•	
5J	99-FM-102-L	65	M	188	84.1	6783	0.4	•	•	

The mean peak tibial plateau load for all specimens was 6.0 ± 1.7 kN. The mean femur tieback load was $1.0 \pm .5$ kN. The mean peak tibial plateau load was 6.2 ± 1.4 kN for the 5 specimens suffering a tibial plateau fracture, and 5.9 ± 2.1 kN for the remaining 10 specimens suffering only foot/ankle fracture. This difference was not statistically significant (p = 0.39). Although the

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magnitude of the peak tibial plateau loads was similar whether or not plateau fracture occurred, the timing of the peaks differed. In all tests, axial loads developed and peaked earliest at the most distal locations and progressed proximally. A time lag between the peak mid-shaft tibia measured by the tibia load cell and the peak tibial plateau load calculated by subtracting the femur load from the knee axial load was noted in all tests. This time lag averaged 5.3 ± 4.8 msec for specimens suffering foot/ankle injury only, and 1.2 ± 1.9 msec for specimens sustaining tibial plateau fractures (Figure 5). This difference was statistically significant (p = 0.048) and became even more so when the data from specimens sustaining artifactual mid-shaft fractures were excluded (p = 0.015).



Figure 4. A/P (a) and lateral (b) x-rays of a typical tibial plateau fracture (97-EM-88-L). The fracture is classified as Schatzker VI because of the dissociation of the metaphysis from the diaphysis and the disruption of the articular surface.



Figure 5. Representative time histories of the axial loads measured at the footplate, tibia mid-shaft, and tibial plateau for a specimen sustaining foot/ankle fracture only (a) and a specimen sustaining foot/ankle and tibial plateau fracture (b). The shapes of the curves are similar in both tests until about 15 msec, but the plateau load peaks much earlier in the specimen sustaining the plateau fracture (b).

DISCUSSION

The purpose of this research was to investigate lower leg injury due to dynamic axial loading. Blunt impact loading to the plantar surface of the foot with the knee entrapped and flexed 90° resulted primarily in injury to the foot/ankle complex. However, concomitant tibial plateau fractures occurred in one third of those cases. These tibial plateau fractures were all very severe, "explosive" type Schatzker VI fractures that would be associated with an extremely poor long-term outcome. Previous quasistatic studies have reported difficulty in generating this type of injury (Kennedy and Bailey, 1968). Banglmaier et al. (1999a) described their fractures using a modification of Apley's classification scheme adopted from Roberts (1968), so it is difficult to tell how their fractures would be classified according to the Schatzker scheme. We have chosen the Schatzker classification because it is more common, more descriptive, and amalgamates fractures from many previous classification schemes, including the one used by Roberts (1968) and Banglmaier et al. (1999a). Although Banglmaier et al. did report two bicondylar plateau fractures, it would appear that the Schatzker VI type of tibial plateau fracture has never been produced experimentally before.

We propose that the injury mechanism for the tibial plateau fractures produced in this study is very high axial loading combined with posterior shear loading resulting from tension in the anterior cruciate ligament. The loading of the ACL is due to the geometry of the tibial plateau, which slopes posteriorly at an angle of approximately 10° (Figure 6). Because of this slope, the tibial plateau tends to translate anteriorly with respect to the femoral condyles when subjected to axial loading. This anterior translation is resisted by tension in the ACL. Experimental evidence supports the hypothesis that the ACL was loaded in this test series. ACL tears were noted in two specimens, and significant ACL avulsions were noted in all five specimens suffering plateau fractures. The fact that plateau fractures were never associated with ACL injuries suggests that an intact ACL may be necessary to cause the type of fractures seen in this study. The mechanism of injury described here would not be possible if the motion of the tibia were constrained to pure axial translation, as in Banglmaier et al.'s experiments. This may explain the difference in the types of plateau fractures reported by Banglmaier et al. (1999a) and the Schatzker VI type of fractures reported here.



Figure 6. Sagittal free body diagram of a 90° flexed knee joint showing the tibia, femur, and cruciate ligaments. Bold arrows indicate external forces and ACL tension applied to the bones.

It is also interesting to note that there appeared to be "tradeoffs" between certain injuries. For example, a given specimen might suffer either a knee injury or an artifactual mid-shaft fracture, but never both (Table 1). This may be because catastrophic fracture at either the tibia mid-shaft or plateau absorbed enough energy to prevent injury at the other location. Mid-shaft fractures in particular cause a total disruption of the load path that would likely preclude further injury. However, because the insertion of the tibia load cell may have artificially weakened the shaft of the tibia, it is not possible to say whether mid-shaft fractures would have occurred in a fully intact leg, or what effect they would have had on other leg injuries. The presence or absence of tibial plateau fractures did not appear to be correlated with any particular specimen attribute. The age, mass, and gender distribution of the specimens suffering plateau fractures was nearly identical to the overall sample population. Therefore, we assume that the presence or absence of plateau fracture is explained by individual variation in the relative strength of the tibial plateau versus the foot/ankle complex. In this study, all specimens were impacted with enough energy to cause foot and ankle injury. Injury to the foot/ankle complex limited the amount of force that was transmitted to the tibial plateau. Individuals whose tibial plateaus were substantially stronger than their foot and ankle bones did not suffer plateau fractures, whereas individuals whose tibial plateaus were relatively weaker compared to their foot and ankle bones did suffer plateau fractures. The fact that plateau fractures commonly occurred in matched pairs of limbs supports this hypothesis (Table 1).

A corollary to this argument implies that the failure data obtained from fracturing only a portion of the total sample population does not characterize the entire population, only its weakest part. This observation has important implications for data analysis and injury criteria development. In this study, only one third (5 out of 15) of the sample population was subjected to enough loading to cause non-artifactual fracture of the tibial plateau. Coincidentally, this corresponds to the single impact experiments by Banglmaier et al. (1999a) in which one third (4 out of 12) of the specimens suffered a tibial plateau fracture. Banglmaier et al. correctly pointed out that their single impact methodology underestimated the true fracture threshold of the tibiofemoral joint by selecting for weaker specimens. Because of this, they favored a repeated impact methodology in which all specimens were impacted until gross failure was observed. Although the repeated impact methodology does not select for weaker specimens, it is certainly an unrealistic representation of an automobile crash pulse. Ideally, single impact experiments should be performed that result in injury in every test. That way, the entire specimen population is characterized.

However, it is possible to analytically account for the bias introduced by an impact methodology that selects for only a portion of the specimen population. Statistically, the distribution of tibial plateau failure strengths among the entire population is given by the probability density function. For a normal distribution, this curve is defined by only two parameters: the mean and the standard deviation. The risk of injury is given by the integral of the density function, called the cumulative probability function. Because the mean and median are equivalent in a normally distributed data set, the average failure strength of the entire population corresponds to a 50% risk of injury. Because the density function and cumulative probability functions are defined by only two parameters, only two data points are need to define these curves. For the purposes of this analysis, we will assume that the injury data from both this study and the single impact experiments by Banglmaier et al. (1999b) represent the weakest third of a normally distributed population of tibial plateau failure strengths (Figure 7). Although this assumption is probably not strictly true for either data set, it is a useful approximation. Injury data from the weakest third of a sample population should not show a normal distribution, but should be skewed towards the high end. This is actually the case for both data sets (Table 1; Banglmaier et al., 1999a). Because the data characterizes the weakest third of the specimen population, the maximum failure force represents a 33% risk of injury, and the average failure force represents a 17% risk of injury. Based on these two data points, it is possible to define an injury risk curve that characterizes the entire population.

The analysis is greatly simplified by using the logistic distribution to approximate the normal distribution. The cumulative probability function for the logistic distribution is

$$P(x) = \frac{1}{1 + e^{\frac{-(x-m)}{|b|}}}$$

where $m = \mu$, where μ is the mean of a normal distribution, and $b^2 = (3/\pi^2)^* \sigma^2$, where σ^2 is the variance of a normal distribution. In this analysis, "P" is the risk of injury, and "x" is force. Solving for the force "x" in terms of the risk of injury "p" yields

$$x(p) = m - b \cdot \ln\left(\frac{1-p}{p}\right) \longrightarrow x(1/3) = m - b \cdot \ln 2, \quad x(1/6) = m - b \cdot \ln 5$$

In this study, x(1/3) is given by the maximum tibial plateau failure force (7363 N) and x(1/6) is given by the average tibial plateau failure force (6197 N). Combining the above equations, solving for "m" and "b", and expressing the results in terms of a normal mean and standard deviation yields an estimated tibial plateau failure strength of 8.2 ± 2.3 kN for the entire population. Performing the same analysis on the data from the single impact experiments by Banglmaier et al. (1999a) results in an estimated tibial plateau failure strength of 7.9 ± 2.3 kN for the entire population. Not only are these results in good agreement with each other, they are also in good agreement with the mean failure strength of 8.0 ± 1.8 kN reported by Banglmaier et al. (1999a) in their repetitive impact experiments in which they fractured every specimen.



Figure 7. Normal probability density function representing the distribution of tibial plateau failure strengths for the entire population. The shaded area represents the weakest third of the population. The risk of injury is the cumulative probability function given by the integral of the density function.

Although a single impact methodology is certainly a more realistic representation of an automobile crash, an analysis of the repetitive impact methodology employed by Banglmaier et al. (1999b) provides interesting insights into the fracture mechanics of the tibiofemoral joint. The effect of repetitive impact testing on the failure strength of the tibiofemoral joint is not clear. On the one hand, repeated impacts to a specimen may result in accumulated microscopic damage that eventually causes the specimen to fail at a lower force level than it otherwise would, which may bias the fracture threshold towards a lower value. On the other hand, the repetitive impact methodology requires that all specimens be sequentially impacted until gross, catastrophic failure is observed. Catastrophic failure may occur at a higher load level than fracture initiation, which may bias the fracture threshold towards a higher value. The relative agreement of Banglmaier's single and repetitive impact data suggests that, interestingly, these two effects nearly cancel each other out.

An alternative approach to determining an injury criterion is to perform a logistic regression analysis on data from both injury and non-injury tests. Logistic regression is commonly employed when the test variable is continuous (i.e. force, input energy, age, etc.), but the outcome variable is binary (i.e. injury vs. no injury). A fundamental assumption in logistic regression analysis is that the test variable must be independent of the outcome variable (Hintze, 1998). For example, logistic regression analysis is often successfully performed using input energy, which is unaffected by injury outcome, as a test variable (Banglmaier et al., 1999a). However, the assumption of independence is violated when the test variable is peak force and the outcome variable is injury, because injury affects the ability of an anatomical structure to bear load. Although the incipient point of fracture may occur slightly before the peak force occurs, the very definition of catastrophic failure is that a structure is unable to bear additional load. This may explain the counterintuitive negative logistic regression curve reported by Banglmaier et al. (1999b) when peak force was used as a test variable. In spite of this methodological concern, logistic regression analysis is commonly utilized in biomechanical experiments to determine a peak force injury criterion (Yoganandan et al., 1996; Klopp et al., 1997).

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For automobile safety applications, injury criteria must be expressed in terms of engineering parameters that can be meaningfully measured by an anthropomorphic dummy in a vehicle crash test. Internal structural parameters such as force, moment, acceleration, and displacement are typically used to define injury criteria. Parameters that are independent of injury, such as input energy, are typically external and cannot be measured by a dummy. Therefore, the applicability of logistic regression analysis is often limited in biomechanical experiments designed to develop injury criteria. Fortunately, there is good evidence that peak force is an excellent predictor of injury in cadaver experiments. In this study, tibial plateau force peaked significantly earlier and nearer to the time of peak mid-shaft tibia load in specimens sustaining plateau fracture (p < 0.05). We interpret this finding to mean that fracture caused the natural development of axial load in the knee joint to terminate earlier than it otherwise would have if no injury had occurred. This interpretation suggests that the peak tibial plateau force uniquely defined the time of fracture. Although some error may have been introduced as a result of non-catastrophic failure initiating a load level below the peak, the relative agreement of the single and repeated impact data from Banglmaier et al.'s (1999a) tests suggests that peak force is a good predictor variable for a wide variety of fractures.

The impact scenario utilized in this test methodology is a realistic representation of the loading that may actually occur in a car crash. The impact is delivered dynamically, and the leg is in a position approximating typical driver geometry. However, the realism of this impact scenario is limited somewhat by the lack of active muscle tension and the simplified kinematics that were imposed. Active tension of the gastrocnemius and soleus muscles may preload the tibia axially, causing it to fail at a lower load level than it otherwise would. This aspect of lower limb loading requires further investigation. Also, this study investigated the simplified kinematics of full knee entrapment, which does not occur in all real world crashes. If the knee is not fully constrained, or if the loading is not directly axial, then the knee may be subjected to a somewhat different loading pattern. The load would probably have a smaller axial component, but a greater varus/valgus component. This might result in different, but less severe injuries, such as unicondylar tibial plateau fractures or collateral ligament tears (Kennedy and Bailey, 1968). We believe that the simplified kinematics utilized in this study represent a realistic worst-case loading scenario that is best described by an axial load in jury criterion.

This study is the first to evaluate the axial impact tolerance of both the foot/ankle complex and tibiofemoral joint together. Two advantages were gained by keeping both the knee and ankle joints intact. First, internal joint loading was more realistic due to the anatomical boundary conditions. Previous experiments have been conducted on isolated foot/ankle complexes (Yoganandan et al., 1996; Begeman and Aekbote, 1996) and on isolated tibiofemoral joints (Hirsh and Sullivan, 1965; Kennedy and Bailey, 1968; Banglmaier et al., 1999a). All of these studies imposed a non-physiological boundary condition by constraining the relative motion of the tibia and fibula. Changing the natural anatomical boundary condition may affect both the type of injury produced and the overall injury tolerance. One limitation of this study was the insertion of a tibia load cell, which was a non-physiological addition that resulted in unwanted artifactual injuries and may have changed the natural loading pattern of the leg somewhat. However, the fact that the knee joint, ankle joint, and fibula were kept intact allowed for a much more realistic loading pattern than would occur in an isolated joint with constrained bone motion.

The biggest advantage gained by keeping both the knee and ankle joint intact in this study was that the relative strength of the foot/ankle complex and the tibial plateau could be directly compared for each specimen. This research shows that in pure axial loading of the lower leg with the knee fully constrained and flexed 90°, the foot/ankle complex is the "weak link" of the lower leg complex. Therefore, in order to be conservative, a lower limb injury criterion designed to prevent below-knee axial loading injuries should be based on the injury tolerance of the foot/ankle complex, not the tibial plateau. This finding suggests that the current lower limb axial load injury criterion of 8 kN (Mertz, 1993) may be too high to cover foot and ankle fractures, even though it accurately describes the fracture threshold for tibial plateau injuries.

CONCLUSIONS

This study demonstrates that pure axial, physiological loading of a fully entrapped and 90° flexed knee can result in extremely severe Schatzker VI type tibial plateau fractures. Fracture patterns suggest that an intact ACL may be necessary for this type of injury to occur. The results of this study agree with previous studies showing the average failure strength of the tibial plateau in axial loading to be approximately 8 kN (Hirsch and Sullivan, 1965; Banglmaier et al., 1999b). However, the current study suggests that a conservative lower leg axial loading injury criterion should be based on the failure strength of the foot/ankle complex, not the tibial plateau.

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