COMPARISON OF KNEE/FEMUR FORCE-DEFLECTION RESPONSE OF THE THOR, HYBRID III, AND HUMAN CADAVER TO DYNAMIC FRONTAL-IMPACT KNEE LOADING

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ABSTRACT

As part of a program to develop improved knee-thigh-hip injury criteria, the dynamic force-deflection responses of twenty knee/femur complexes from eleven unembalmed cadavers were measured under knee loading directed along the length of the femur. An interface that was molded to the shape of each cadaver's knee was used to distribute applied loads across the patella and femoral condyles. A fixed femoral head boundary condition was used to minimize inertial effects, allowing the skeletal stiffness of the knee/femur complex to be characterized. Average knee/femur stiffness is 0.37 kN/mm. This value primarily represents the stiffness of the femur because the molded-knee interface minimizes the contribution of knee compliance to the whole knee/femur stiffness.

Corridors developed from the cadaver knee/femur force-deflection responses were used to evaluate the response of the knee/femur complex of the Hybrid III and THOR. Prior to about 2 mm of deflection, the Hybrid III is 2.4 times stiffer than the upper bound of the cadaver response corridor and the THOR is 1.9 times stiffer. After 2 mm of deflection, the Hybrid III knee/femur complex response is approximately sixteen times stiffer than the upper bound of the cadaver corridor, while the THOR knee/femur response is approximately three times stiffer.

INTRODUCTION

A recent analysis of the NASS database indicates that the current FMVSS 208 knee-thigh-hip (KTH) injury criterion of 10-kN peak femur force, which is based on the fracture tolerance of the femur to high-rate axial loading applied at the knee, may not adequately prevent hip injuries. In particular, this analysis indicates that the risk of AIS 2+ hip injuries is higher than the risk of femur or knee injury in frontal crashes of later-model airbag-equipped vehicles, and also that the risk of hip injury is higher in frontal crashes of newer, airbag-equipped vehicles than in crashes of vehicles without airbags (Kuppa and Fessahaie 2003). Hip injuries are of substantial concern because of their long-term debilitating potential and because they account for the majority of life years lost from injury to the knee-thigh-hip complex (Kuppa et al. 2001). As a result of these findings, an effort is underway to develop improved KTH injury criteria.

As a first step in this effort, Rupp et al. (2002) analyzed previous biomechanical data and suggested that likelihood and location (along the KTH) of injury from knee loading depend not only on the magnitude of the applied load, but also on the applied rate, the skeletal compliance of the KTH, and the effective mass of the KTH (i.e., the inertial response of the KTH that is affected by the flesh mass coupled to the thigh, the mass of the leg coupled to the knee, and the mass of the torso coupled to the hip). To successfully develop and implement injury criteria in ATDs, the skeletal stiffness and the effective mass (or inertial response) of human KTH response should be characterized. ATDs that have appropriate skeletal stiffness and inertial response should have a biofidelic response when interacting with energy-absorbing knee restraints and other stiffer components located near the knee restraints.

A study by Horsch and Patrick (1976) quantified the skeletal response of five knee-plus-distal-femur sections obtained from three unembalmed cadavers using flat-faced pendulum knee impacts. Inertial effects were removed from the measured responses by rigidly fixing the cadaver sections at a location that corresponds to the location of the femur load cell. The Horsch and Patrick fixed-femur skeletal response data were used to develop and validate the response of Hybrid III midsize male ATD knee/femur complex (Foster et al. 1977). Figure 1 shows the design of the Hybrid III femur and knee complex, which is essentially rigid with the exception of an approximately 8-mm-thick rubber pad on the anterior surface of the knee. The compliance of this padding was selected so that the response of the Hybrid III knee and distal femur (i.e., the knee and femur load cell or load cell blank) is comparable to a target response developed from peak knee impact forces measured by Horsch and Patrick.

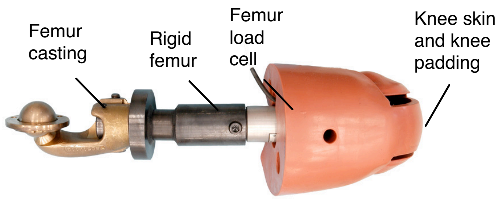

Figure 1. Hybrid III knee/femur complex.

Several researchers have conducted whole-body knee impacts on unembalmed cadavers to quantify the complete response (skeletal stiffness and inertial effects) and tolerance of the knee/femur complex to knee loading by a flat, rigid impactor (Powell et al. 1975, Melvin et al. 1975, Donnelly and Roberts 1987). A free-back boundary condition was used in these studies that is similar to the boundary conditions during knee-to-knee-bolster loading in real-world frontal crashes. Because knee loading rates used in these studies are substantially higher than knee loading rates in frontal crashes of newer-model airbag-equipped vehicles (as measured by Hybrid III femur load cells in FMVSS 208 compliance testing), the inertial component of force in these tests is significantly greater than the inertial component of knee/femur response that would be expected at more realistic loading rates (Rupp et al. 2002).

Donnelly and Roberts (1987) compared the free-back whole-body knee impact response of nine unembalmed cadavers to the Hybrid III ATD under similar test conditions. The Hybrid III was found to produce knee impact forces that were almost three times higher than those produced by a cadaver. Differences between the Hybrid III and cadaver knee impact responses were attributed to the rigidity of the Hybrid III femur and the more rigid coupling of the thigh mass to the femur in the Hybrid III.

The THOR knee/femur complex, shown in Figure 2, was designed to address a perceived lack of biofidelity in the response of the Hybrid III (Shams et al. 1999). The THOR knee is similar to the Hybrid III knee and therefore conforms to the Hybrid III knee response specification developed from the Hosch and Patrick data. The only difference between the THOR and Hybrid III knees is that the THOR knees employ rigid hemispherical caps on the lateral and medial aspects that are intended to provide a more humanlike interaction with knee bolsters. To reduce knee impact forces and better match the Donnelly and Roberts data, the THOR has a compliant element in the mid femur and redistributes some of the femur mass to the thigh flesh.

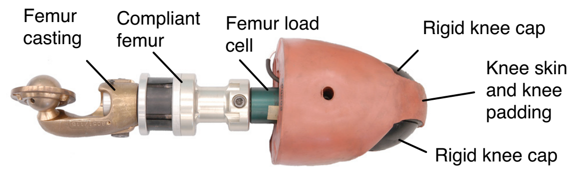

Figure 2. THOR knee/femur complex with Hybrid III upper femur casting.

A recent study conducted by Rupp et al. (2002) provides data on the skeletal knee/femur force-deflection responses of thirteen whole knee/femur complexes from seven unembalmed cadavers to knee loading directed along the length of the femur. The femoral head was rigidly supported in an acetabular cup so that the measured knee/femur complex responses were largely independent of inertial effects. Knee-loading rates that are representative of knee-to-knee-bolster impacts that occur in frontal crashes of newer model vehicles were used. Load was applied to the knee through a molded-knee interface, which distributed applied loads over the patella and femoral condyles and consequently reduced the effect of the compliance of the patellofemoral joint on whole knee/femur response. Under these loading conditions, the average stiffness of the cadaver knee/femur complex was determined to be 0.36 kN/mm.

This paper describes an expanded set of cadaver knee/femur response data from the original Rupp et al. (2002) study and describes the development of a new cadaver knee/femur force-deflection response corridor for dynamic knee loading by a molded-knee interface. The knee/femur responses of the THOR and Hybrid III were determined and are compared to the cadaver response corridor.

METHODS

Cadaver Knee/Femur Response Tests[1]

Prior to testing, the lower extremities (including the left and right femurs, legs, and feet) were removed from an unembalmed cadaver pelvis by disarticulating the hip joints. Flesh was removed from the proximal femur to expose both the proximal

[1] The rights, welfare, and informed consent of the subjects who participated in this study were observed under guidelines established by the U.S. Department of Heath and Human Services on Protection of Human Subjects and accomplished under medical research design protocol standards approved by the Committee to Review Grants for Clinical Research and Investigation Involving Human Beings, Medical School, The University of Michigan.

femur and femoral head. The specimen was then mounted in the test apparatus, illustrated in Figure 3, such that it was inverted from a normal seated orientation. The head of the femur was inserted into a hemispherical “acetabular” cup that was mounted to a rigid support post. The femur was oriented so that an axial load was applied along a direction that was parallel to the vector defined by the midpoint between the medial and lateral femoral condyles and the center of the femoral head. A 0.5-mm-thick sheet of rubber was placed between the femoral head and acetabular cup to reduce stress concentrations on the femoral head.

The knee was supported and loaded by a knee interface that was molded to the shape of the knee of each specimen. This minimized the risk of knee fracture by distributing the applied loading over the patella and femoral condyles. Also, by simultaneously loading the patella and femoral condyles, the contribution of knee compliance to whole knee/femur deflection is minimized.

The fixed femoral head boundary condition has been shown to minimize inertial effects (Rupp et al. 2002). Consequently, the force history applied to the knee is the same as the force history at the femoral head, allowing the skeletal component of the dynamic skeletal stiffness of the knee/femur complex to be measured independently from the inertial response of the knee/femur.

For all tests, a dynamic load was applied to the knee of the test specimen by pneumatically accelerating a 250-kg platform into a linearly translating ram connected to the molded-knee interface, which is initially in contact with the knee. A combination of Hexcel (9.5-mm cell diameter) and 13-mm-thick flotation foam was used at the interface between the ram and the weighted platform to control the rate of loading and limit the magnitude of force applied to the knee/femur complex. The pneumatic accelerator was pressurized to achieve a platform impact velocity of about 1.2 m/s, which produces loading rates at the knee that are similar to loading rates measured by the Hybrid III femur load cell during FMVSS 208 compliance testing of newer model vehicles (Rupp et al. 2002).

A load cell attached to the ram just behind the molded-knee interface measured force applied to the knee during each test. To obtain force applied to the knee, the ram load cell measurement was inertially compensated using ram acceleration and the mass between the load cell center-of-gravity and knee surface. The reaction force at the femoral head was measured by a load cell positioned behind the acetabular cup. A laser mounted on the test fixture measured the motion of the ram, which corresponds to the deflection of the knee surface relative to the femoral head. Based on analyses of the frequency content of the raw data, all forces and displacements were low-pass filtered using a 4th order Butterworth filter with a cutoff frequency of 300 Hz.

Fracture force, time-to-fracture, and loading rate were determined from the applied force histories, as illustrated in Figure 4. Based on high-speed video of the test specimen during impact loading, fracture force was always considered to be the first peak in the force history, so that time-to-fracture force is the same as time-to-peak force. Time-to-fracture was defined as the time required for the force to rise from 500 N to the first peak in the force curve. Since the loading portion of the curve was generally linear, loading rate was calculated as the slope of the force curve, based on a least-squares fit of a straight line connecting 15% and 85% of the first peak in the force curve. The loading portions of the force-deflection curves established using applied force and ram displacement were also generally linear. It was therefore possible to calculate an axial stiffness for each test specimen in the same manner that loading rate was calculated from the force histories.

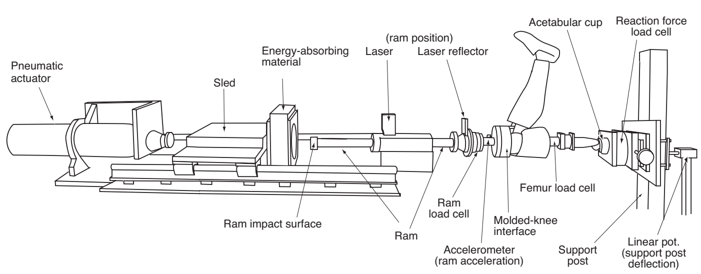

Figure 3. Apparatus used for dynamic femur response assessment.

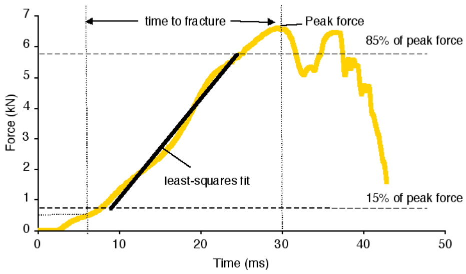

Figure 4. Typical applied force history showing loading rate, time-to-fracture, and peak force.

<u>Test Subjects and Test Numbers</u> – Table 1 provides information on the three female and eight male cadavers from which specimens were obtained for testing. Data from subjects 1 through 5 were previously reported by Rupp et al. (2002). With the exception of subjects 5 and 11, both the left and right knee/femur complexes from each subject were used in the hip tolerance testing also described by Rupp et al. Table 1 lists *t*-scores for these cadavers obtained using the osteogram method, which uses a calibrated x-ray of the phalanges to determine *t*-score. The *t*-score is a measure of relative bone mineral density reported as the number of standard deviations above or below the mean bone mineral density of a 25- to 50-year-old reference population of the same gender. Osteogram data are comparable to dual x-ray absorptiometry (Yang et al. 1994). The mean *t*-score for the specimens used in these tests is -0.46 ± 1.25, which indicates that the bone conditions for these cadavers were within the normal range.

Test IDs beginning with the same two-digit number were conducted on left and right knee/femur complexes from the same cadaver. Tests with IDs ending in RF and LF correspond to right and left knee/femur complexes, respectively.

<u>Development of Response Corridor</u> – Response corridors were developed from force-deflection data from all cadaver tests using a procedure similar to that described by Hardy et al. (2001) and Cavanaugh et al. (1986). As a first step in developing these corridors, ram displacement was zeroed at a level that corresponded to an applied force of 100 N. This level of force typically occurred at less than 1 mm of ram motion from its initial position. Force-displacement data were then interpolated to generate discrete force values at regular increments in displacement. At each increment in displacement, the average and ±1 SD (standard deviation) responses were calculated from force data from all of the cadavers. Piecewise linear approximations of the ±1 SD curves were then visually established.

An attempt was made to normalize the force-deflection responses from different size cadavers to that of a midsize male using equal-stress equal-velocity scaling (Eppinger 1978). However, equal-stress, equal-velocity scaling did not reduce the scatter in the response data. Consequently, the unscaled force-deflection data from each test subject were used to develop the target knee/femur force-deflection corridor.

Comparison of Hybrid III, THOR, and Cadaver Knee/Femur Responses

To compare the responses of the THOR and Hybrid III knee/femur complexes to the new cadaver corridor, the THOR and Hybrid III were tested using the apparatus illustrated in Figure 3. Multiple tests were performed with each knee/femur complex.

Table 1. Test Subjects and Test Identifications

Subject Number	Gender	Age	Stature (cm)	Mass (kg)	*t*-score	Test IDs	
						Left	Right
1	M	75	180	81	0.1	19LF	19RF
2	M	41	176	91	0.7	22LF	22RF
3	M	60	178	82	-0.9	24LF	24RF
4	F	86	168	68	-1.6	25LF	25RF
5	M	62	183	91	0.1	26LF	
6	M	71	183	77	-0.2	27LF	27RF
7	F	65	163	82	-2.3	28LF	28RF
8	M	45	185	75	-1.6	30LF	30RF
9	F	79	165	91	-1.4	31LF	31RF
10	M	54	178	109	2.0	32LF	32RF
11	M	52	183	109	0.3		33RF
	Mean	*63*	*177*	*87*	*-0.43*		
	sd	*14*	*8*	*13*	*1.25*		

Prior to all testing with the Hybrid III, the response of the Hybrid III knee was verified using the standard calibration procedure (SAE Dummy Testing Equipment Subcommittee, 1998). The THOR knee response was factory-certified immediately prior to testing.

The loading conditions for these tests were similar to those used in the cadaver knee/femur response tests. Specifically, the weighted platform was accelerated to a velocity of approximately 1.2 m/s prior to ram impact and load was applied to the anterior surface of the knee through a custom molded-knee interface. The Hybrid III and THOR knee/femur complex was positioned such that the femoral head was supported by a fixed acetabular cup and load was applied along a vector connecting the midpoint between the femoral condyles and the center of the femoral head.

For all ATD tests, a preload of 100-200 N was applied to the knee to ensure that the knee interface was in contact with the knee and that it was properly positioned prior to impact loading. The effect of this preload on the comparisons between the Hybrid III, THOR, and cadaver knee/femur response is small (about 1 mm) for loading through the molded-knee interface, which distributes the preload forces over the entire knee surface and consequently reduces the deflection caused by the preload.

Applied force and compression of the knee/femur components were measured. Because the Hybrid III and THOR produced substantially higher forces at lower deflections than the cadavers, it was necessary to measure the horizontal motion of the support post at the level of the acetabular cup and subtract it from the displacement of the ram before establishing the knee/femur force-deflection responses.

Hybrid III and THOR knee/femur stiffness was calculated in one of two ways depending on the character of the force-deflection response. For the THOR, which has a generally linear response, stiffness was calculated by linear regression of the pooled force data from all of the force-deflection curves between 15% and 85% of the peak force. For the Hybrid III, which had a bilinear response, least-squares fits were separately performed over low and high force ranges to better characterize stiffness. The low force range was between 0.5 and 2 kN, while the high range included forces greater than 5 kN.

RESULTS

Cadaver Knee/Femur Response Tests

Results of the molded-knee interface cadaver tests are listed in Table 2, while Figure 5 shows the force histories from all of the knee/femur response tests. As indicated, the force histories are approximately linear. Although a 1.2-m/s platform impact velocity was used in all tests, the actual loading rates applied at the cadaver knee varied from 0.15 to 0.80 kN/ms due primarily to variations in subject stiffness. The average loading rate was 0.43 ± 0.16 kN/ms.

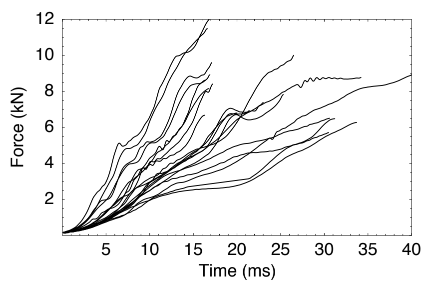

Figure 5. Force histories from all cadaver knee/femur response tests conducted using molded-knee interfaces at a 1.2-m/s platform velocity.

Figure 6 shows the force-deflection responses from all cadaver tests with the molded-knee interface at a 1.2-m/s platform impact velocity. These responses are also generally linear. The stiffness values calculated from these curves range from 0.21 to 0.54 kN/mm. The average stiffness is 0.37 ± 0.8 kN/mm. To ensure that equal weighting was given to the data from the subjects where only one knee/femur complex was tested (tests 26LF and 33RF), average stiffness was calculated from a dataset comprised of the average stiffness from left and right knee/femur complexes from the same cadaver and the data from tests 26LF and 33RF.

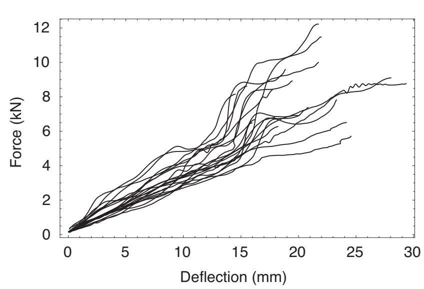

Figure 6. Force-deflection responses from all cadaver knee/femur response tests conducted using molded-knee interfaces at a 1.2-m/s platform velocity.

Table 2. Results from Cadaver Knee/Femur Response Testing at a 1.2-m/s Platform Velocity with a Molded-Knee Interface

Test ID	Time to Peak Force (ms)	Loading Rate (kN/ms)	Deflection at Fracture (mm)	Stiffness (kN/mm)
19LF	35.6	0.15	18.3	0.33
19RF	36.8	0.17	16.1	0.42
22LF	31.1	0.35	21.3	0.45
22RF	20.2	0.80	20.7	0.44
24LF	36.0	0.23	24.6	0.25
24RF	36.4	0.19	25.0	0.21
25LF	30.2	0.35	23.5	0.33
25RF	27.6	0.40	21.1	0.34
26LF	28.0	0.38	20.6	0.34
27LF	21.3	0.58	15.6	0.42
27RF	21.7	0.50	17.7	0.33
28LF	25.3	0.41	16.8	0.32
28RF	25.2	0.28	20.0	0.21
30LF	38.3	0.36	29.5	0.36
30RF	46.0	0.26	28.2	0.36
31LF	21.8	0.55	14.6	0.45
31RF	25.1	0.35	18.2	0.29
32LF	22.2	0.62	19.1	0.44
32RF	23.4	0.57	19.8	0.40
33RF	22.3	0.78	20.4	0.54
Mean	*28.4*†	*0.43*†	*20.5*†	*0.37*†
sd	*6.9*†	*0.18*†	*3.7*†	*0.08*†

†Calculated using averages of data from subjects where both left and right sides were tested.

Figure 7 shows the average ±1 SD responses calculated from the data shown in Figure 6 and the response corridor generated from these data. The cadaver force-deflection response corridor is based on a piecewise approximation of the ±1 SD responses. The approximation to the +1 SD curve passes through the origin, the point (2 mm, 1.5 kN) and the point (22 mm, 11.5 kN). The approximation to the -1 SD curve is linear and passes through the origin and the point (22 mm, 5.7 kN). The slope of the upper bound on the corridor is initially 0.75 kN/mm and decreases to 0.5 kN/mm after 2 mm of deflection, while the slope of the lower bound on the corridor is 0.26 kN/mm. The slope of the average response is approximately 0.39 kN/mm, which is comparable to the value determined by averaging the stiffness values from each cadaver test. Figure 8 shows the individual cadaver force-deflection data relative to the cadaver response corridor (shaded) and indicates that the corridor is representative of the original data.

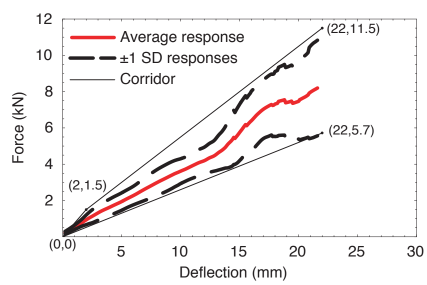

Figure 7. Mean and ±1 SD knee/femur force-deflection responses and corridor developed from cadaver responses to molded-knee interface loading at a 1.2-m/s platform velocity.

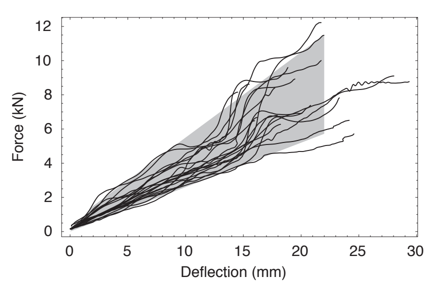

Figure 8. Cadaver response corridor (shaded) compared to the cadaver force-deflection data used to develop the corridor.

Comparison of Hybrid III, THOR, and Cadaver Knee/Femur Responses

Table 3 lists the loading rates and stiffness values calculated from the responses of the Hybrid III and THOR knee/femur complexes to loading by the molded-knee interface. Figure 9 illustrates the average applied force histories and loading rates from loading of the THOR and Hybrid III knee/femur at a platform impact velocity of 1.2 m/s. Differences in applied loading rate are primarily from differences in Hybrid III and THOR knee/femur stiffness.

Table 3. Results of ATD Response Testing at a 1.2-m/s Platform Velocity with the Molded-Knee Interface

Knee/Femur Complex	Average Loading Rate (kN/ms)		Stiffness (kN/mm)	
	0.5-2 kN	> 5 kN	0.5-2 kN	> 5 kN
THOR	0.6	0.6	1.4	1.4
Hybrid III	0.5	1.7	1.8	8.1
Average Cadaver	*0.43*	*0.43*	*0.37*	*0.37*

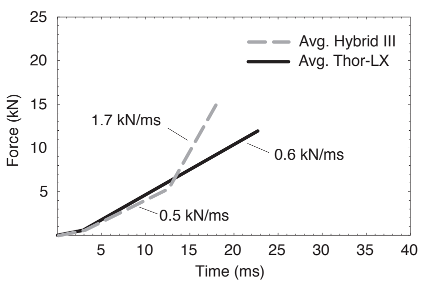

Figure 9. Average force histories from loading of the THOR and Hybrid III knee/femur complexes with the molded-knee interface at a 1.2-m/s platform velocity.

The force-deflection response of the Hybrid III knee/femur complex to loading by the molded-knee interface is shown relative to the cadaver response corridor in Figure 10. The Hybrid III response is characterized by a two-piece linear fit. The initial stiffness is approximately 1.8 kN/mm, which reflects the compression of the knee padding. After about 2 mm of compression, the stiffness of the Hybrid III knee/femur complex increases to approximately 8.1 kN/mm. This rather rapid increase in stiffness is attributed to the molded-knee interface limiting expansion of the knee padding so that after some amount of compression the knee padding becomes essentially incompressible.

The force-deflection response of the THOR knee/femur to loading by the molded-knee interface is shown in Figure 11. Unlike the Hybrid III, the force-deflection responses measured on the THOR are generally linear with a stiffness of 1.4 kN/mm.

Both the Hybrid III and the THOR knee/femur responses are stiffer than the 0.5 kN/mm upper bound on the cadaver knee/femur force-deflection corridor. Prior to about 2 mm of deflection, the Hybrid III is 2.4 times stiffer than the upper bound of the cadaver response corridor and the THOR is 1.9 times stiffer. After 2 mm of deflection, the Hybrid III knee/femur complex response is approximately sixteen times stiffer than the upper bound of the cadaver corridor, while the THOR knee/femur response is approximately three times stiffer.

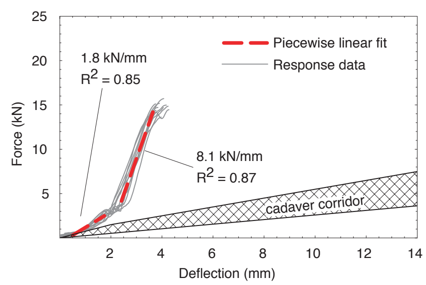

Figure 10. Force-deflection responses for loading of Hybrid III knee/femur complex by a molded-knee interface at a 1.2-m/s platform velocity relative to the new cadaver response corridor.

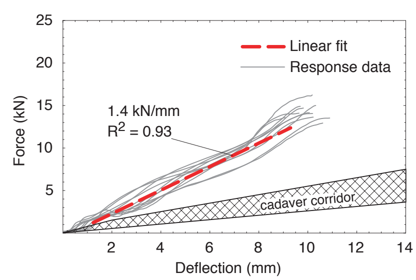

Figure 11. Force-deflection responses for loading of THOR knee/femur complex by a molded-knee interface at a 1.2-m/s platform velocity relative to the new cadaver response corridor.

DISCUSSION

Cadaver Knee/Femur Response Tests and Development of the Response Corridor

Twenty tests were conducted to measure the response of the cadaver knee/femur complex to distributed knee loading applied through a molded-knee interface. Loading rates used in these tests are representative of loading rates measured by the femur load cell during knee-to-knee-bolster loading in

FMVSS 208 compliance testing with unbelted Hybrid III ATDs in newer-model airbag equipped vehicles (Rupp et al. 2002). These tests were conducted with the femoral head fixed in a hemispherical acetabular cup. The fixed femoral-head boundary condition allows for the characterization of the knee/femur response independently of inertial effects, which would tend to increase the forces produced by knee loading. Consequently, knee/femur response data collected in this study primarily characterize the skeletal stiffness of the knee and femur.

Data collected from other biomechanical studies are not comparable to the whole knee/femur skeletal force-deflection responses measured in this study. Data from free-back whole-body knee impact studies, such those from Donnelly and Roberts (1987), contain inertial effects that cannot be removed and are therefore not directly comparable to the data collected in this study. Data collected by Horsch and Patrick (1976) do not contain inertial effects, and are consequently more comparable to the current work. However, differences in loading rates and a lack of published force-deflection data prevent direct comparisons between the findings of Horsch and Patrick and the current study. Also, Horsch and Patrick did not include the whole femur in their "fixed-back" tests.

Comparison of Hybrid III, THOR, and Cadaver Knee/Femur Responses

Both the Hybrid III and THOR knee/femur complexes tested in this study were designed to comply with a target response developed from the cadaveric knee and distal femur responses reported by Horsch and Patrick. However, because Horsch and Patrick only used the distal portion of the femur, target stiffness is too high for characterizing the axial stiffness of the whole femur. While the padding of the Hybrid III knee, which is the only compliance in the knee/femur complex, was sufficient to meet the stiffer criteria based on the Horsch and Patrick data, it cannot represent the compliance of the whole femur that has been characterized in this study because the knee padding can only modulate forces associated with deflections less than its 8-mm thickness.

The THOR employs the same knee padding used in the Hybrid III, but also has a 31-mm-thick compliant element in the mid femur to better match peak forces measured in the Donnelly and Roberts data. Therefore, the THOR has a less stiff force-deflection response over a greater range of knee/femur deflections. However, the THOR skeletal knee/femur stiffness is still greater than the upper bound on the cadaver force-deflection corridor.

The high skeletal mass, relative to cadavers, and the higher stiffness of the Hybrid III and THOR knee/femur complex, relative to the new cadaver corridor, indicate that under comparable knee loading conditions, the Hybrid III and THOR will tend to produce higher knee impact forces over shorter impact durations than the cadaver. Because the force applied to the knee bolster by the ATD knees in crashes depends on the knee/femur skeletal stiffness and inertial contributions of the knee/femur complex and other body regions, both the inertial response and skeletal stiffness of the human knee/femur complex should be represented in the design of ATDs. This will result in an ATD knee/femur complex that has a biofidelic response over a range of loading rates, and consequently can be better utilized to predict the likelihood of knee, thigh, and hip injuries in real-world frontal crashes.

The current study quantifies skeletal knee/femur stiffness under specific loading conditions. A future study will characterize the coupling of leg, torso, and flesh mass to the knee/femur complex under dynamic knee impact and will provide data on the contribution of inertia to whole knee/femur response. Future work will also explore and compare ATD and cadaver knee/femur stiffness to frontal-impact loading by a flat-plate knee interface.

CONCLUSIONS

Cadaveric knee/femur stiffness data were collected under distributed knee loading through a molded-knee interface at a loading rate that is representative of knee-to-knee-bolster loading in compliance testing of newer model vehicles. A fixed femoral-head boundary condition was used to remove inertial effects from the measured responses. Force-deflection data from the cadaver tests were used to develop a new knee/femur response corridor, which was then used to evaluate the force-deflection responses of the THOR and Hybrid III knee/femur complexes. Prior to about 2 mm of deflection, the Hybrid III is 2.4 times stiffer than the upper bound of the cadaver response corridor and the THOR is 1.9 times stiffer. After 2 mm of deflection, the Hybrid III knee/femur complex response is approximately sixteen times stiffer than the upper bound of the cadaver corridor, while the THOR knee/femur response is approximately three times stiffer.

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