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Posterior Cruciate Ligament Response to Proximal Tibia Impacts

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ABSTRACT

There is currently no acceptable injury threshold for posterior cruciate ligament (PCL) injuries in frontal crash testing. This paper outlines the approach used to develop an impact protocol to determine PCL response of isolated post mortem human subject (PMHS) lower limbs. The protocol will eventually be used to conduct proximal tibia impacts to PMHS lower limbs for comparison to proximal tibia impacts in the Hybrid III (HIII) midsize male anthropomorphic test device (ATD). This comparison will be done in an effort to relate PMHS tibia subluxation and PCL injury timing to HIII knee slider displacement. Ultimately, a PCL injury threshold will be determined through this relationship.

INTRODUCTION

Shearing and bending of the knee joint are recognized as two important injury mechanisms associated with frontal impacts. In a frontal collision, the automobile is decelerated over a short period of time. Due to inertia the occupant lower extremities travel until arrested by safety belts, air bags or the knee bolster/steering column. In frontal crashes impact loading of the flexed knee by the knee bolster/steering column causes the PCL to be the most frequently injured ligament at flexion angles near 90°, the PCL bears 95-100% of the load resisting tibia subluxation (Butler et al., 1980; Wascher et al., 1993).

35%-82% of all injuries to the PCL are sustained in traumatic motor vehicle accidents (Cross et al., 1984; Fanelli, 1993; Freeman et al., 2002; Menche et al., 1999; Lee, 2003; Richter et al., 2002). Knee tendon and ligament injuries have been shown to account for 2.5% of all frontal impact injuries (Atkinson et al., 2000). Knee tendon and ligament ruptures, sprains and injuries to the articular surface contribute a medical cost of approximately 150 million dollars and associated

Life Years Lost to Injury (LLI) of approximately 3,780 years (Kuppa et al., 2003). These estimates are conservative since knee ligament injuries are often detected 6-24 months after the event. Additionally, the cost of knee ligament injuries is based on the injury scale (AIS) and not on the disability involved. Knee ligament injuries have been shown to cause significant long-term disability and reduced quality of life (Atkinson et al., 2000; Fanelli et al., 1995; Gill et al., 2003; Harner et al., 2000).

Viano et al. (1978) conducted research into the interaction of the proximal tibia and knee bolster/steering column. In this study a bolster impacted the tibia/knee of human cadavers and ATDs to assess biomechanical response, mechanism of injury, and ligament failure characteristics. Viano et al. (1979) attempted to assess these injuries using restrained cadavers and ATDs. From these two studies, Mertz et al. (1989) characterized the mean biomechanical stiffness of the midsize male human knee to be 1.49 kN/cm.

This knee stiffness value was used in the creation of the ATD knee slider mechanism. This mechanism consists of a deformable rubber block sandwiched between moveable steel housings. The ATD femur and tibia are pinned together through the knee slider. As the tibia translates posteriorly on the femur, a potentiometer measures the displacement of the steel housing surface due to deformation of the rubber block.

The purpose of the knee slider was to develop a repeatable method to measure tibia displacement (subluxation) with respect to the femur. Mertz (1993) proposed a "performance limit" of 15 mm for knee slider displacement of the midsize male ATD. Kuppa et al. (2001) proposed this performance limit as the injury criteria for 50% probability of AIS 2+ injury to the midsize male ATD knee.

An impact resulting in 15 mm of tibia subluxation in an ATD would likely result in severe human PCL injury. Thus, the current guideline for lower extremity safety may not be conservative enough to prevent PCL injuries in frontal vehicle crashes. To fully quantify the probability of PCL injury a better relationship between the timing of human PCL injury, tibia subluxation and ATD knee slider displacement is needed.

Knee Anatomy?

The PCL is known as the fundamental stabilizer of the knee and is the main restraint to posterior translation of the tibia when the knee is in a flexed position. The ligament originates on the anteromedial portion of the intercondylar notch of the femur and runs obliquely, twisting with the anterior cruciate ligament (ACL) in a common synovial sheath, to the insertion point on the posterior tibial spine (Figure 1).

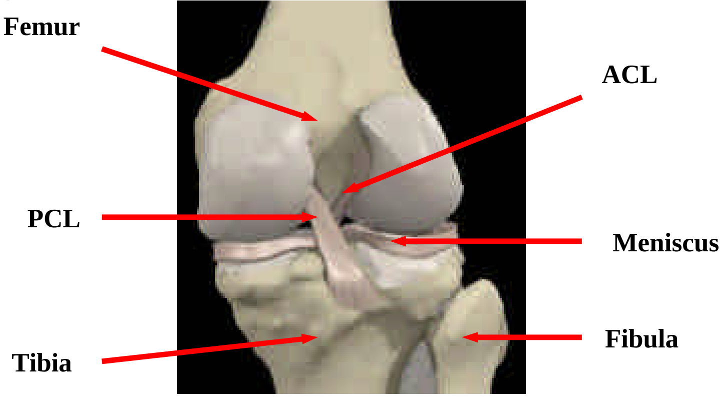

Figure 1: Posterior View of Right Knee (Primal Pictures, 2001)

METHODS

The experimental parameters for this study were developed from 10 frontal crash tests conducted at The Vehicle Research and Test Center in East Liberty, Ohio from June to October 2002. The automobiles tested were the Honda Accord, Dodge Neon and Mitsubishi Montero. These tests were run according to FMVSS 208 and instrumented according to SAE J211. The ATD occupant data were examined for maximum knee slider displacement greater than 5 mm. This analysis provided a sample size of n = 10 (5 drivers and 5 passengers) for the midsize male ATD.

Due to the complex nature of occupant movement during an impact, the exact ATD kinematics and lower extremity geometry could not be verified for these crash tests. Therefore, several assumptions about the loading scenario were made. 1) Pre-crash ATD positioning served as the initial position (Figure 2a). 2) The impact position was determined from assuming a pinned lower extremity undergoing rotation. The thigh moved parallel to the plane of the seat until the moment of impact (Figure 2b). 3) And an occupant coordinate system consistent with SAE J1733 was used.

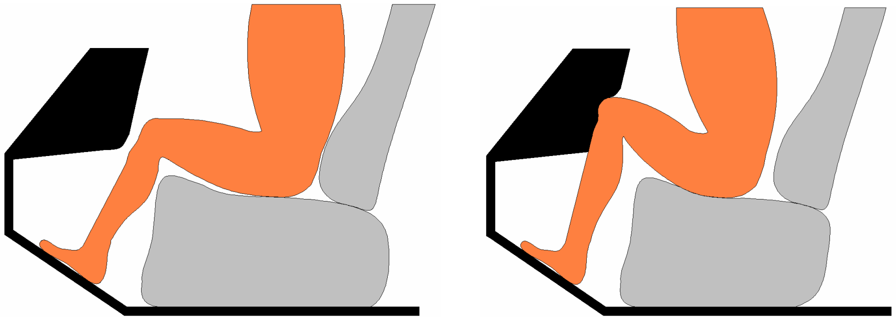

Figure 2: a) Approximate Initial ATD Leg Position b) Approximate Impact ATD Leg Position

The initial ATD lower extremity geometry was obtained from the pre-crash positioning measurements for ATD thigh and leg length and initial pelvic angle, tibia angle, steering column angle and knee-to-steering column distance. The impact ATD lower extremity geometry was obtained from rotating the tibia about the pinned ankle until contact with the knee bolster. From this geometry the impact flexion angle between tibia and femur was determined to be near 100°. The occupant coordinate system SAE J1733 consisted of a set of axes each on the ATD tibia and femur. With the lower extremity extended, these axes coincided. But with the lower extremity flexed, the tibia and femur axes no longer corresponded.

In the crash tests the impact force was generated by the interaction between the ATD with the knee bolster/steering column and floor pan (Figure 3).

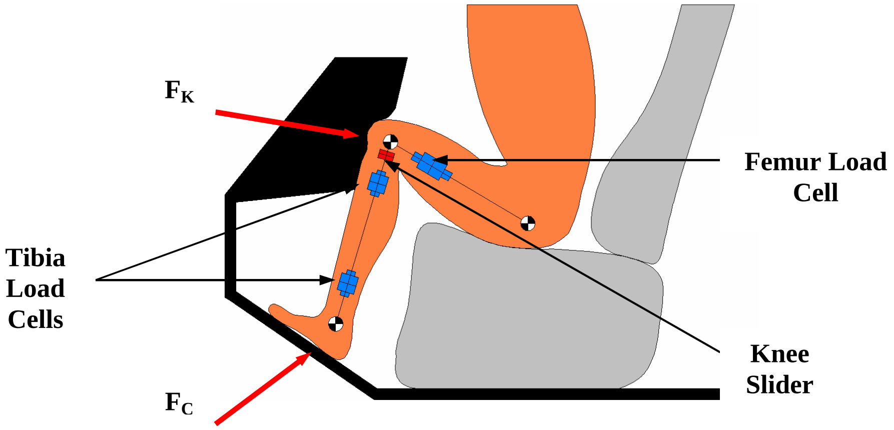

Figure 3: Approximate Impact Forces, Load Cell and Knee Slider Locations

As shown in Figure 3, the impact forces were the result of the lower extremity interaction with the knee bolster/steering column and floor pan. The two tibia load cells and single femur load cell are shown in their approximate positions. The knee slider is shown below the tibia-femur connection and the approximate centers of rotation of the ankle, knee and hip joints are shown in the crosshatched circles.

After determining the ATD impact positioning, the normal components of the mean forces on the tibia and femur and slider displacements for the occupants were calculated (Table 1). The resultant x-axis impact force on the tibia was calculated from the sum of the femur load cell force, knee slider force, and the upper tibia load cell force, all in the tibia x-axis direction. This force represented the mean estimated impact load to the proximal tibia of the ATDs in the crash tests.

Table 1. Crash Test Occupant Mean Values

Mean Values	HIII Midsize Male (n=10)
Femur Load Cell Z-Axis Force (N)	7590
Femur Loading Rate (N/ms)	841
Knee Slider X-Axis Displacement (mm)	10.4
Knee Slider Displacement Rate (mm/ms)	0.97
Knee Slider Loading Rate (N/ms)	145
Knee Slider X-Axis Force (N)	1540
Upper Tibia Load Cell Z-Axis Force (N)	1575
Upper Tibia Load Cell X-Axis Force (N)	440
Resultant Impact X-Axis Force (N)	9530

Since ligament failure has been shown to be rate sensitive (Kennedy et al., 1976; Kerrigan et al., 2003; Lee et al., 2002; Mow et al. 1997), the knee slider displacement and displacement rate were chosen to replicate the dynamic crash lower extremity impact conditions. Tibia compressive load was replicated to mimic the upper tibia load cell z-axis force seen in the crash test data. The mean values occurred at the same point in time as the maximum knee slider displacement. In an effort to compare these variables, the occupant crash data mean values were normalized to be equal to one and corresponding standard deviations compared using error bars (Figure 4). Axial femur force, loading rate, and knee slider force were used as secondary checks to correlate the ATD component level tests with the crash mean data.

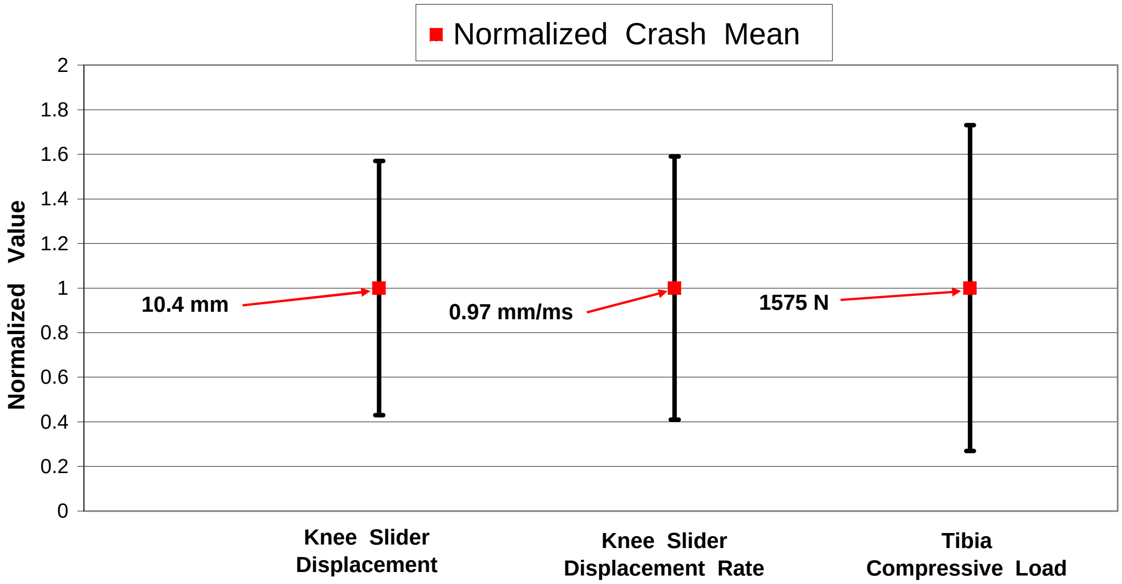

Figure 4: Normalized Values for Crash Test Mean Data (n = 10)

The range of the ±1 standard deviation error bars for the crash mean data were fairly wide. This was mainly due to the inherently variable nature of ATD response in crash testing. Even with the same vehicle and impact conditions the ATD experienced wide-ranging forces and deflections. Additionally, the vehicle type and interior geometry created variations in ATD response. This crash data variability was noted and component ATD tests were conducted in an effort to generate knee slider displacement, displacement rate and tibia compressive load as close to the crash data mean as possible.

RESULTS

After the data analysis from the crash tests was performed, component level tests were performed. These tests were run in two phases to replicate the ATD loading and displacement seen in the crash tests. Phase I consisted of proximal tibia impacts to a seated HIII midsize male ATD and Phase II consisted of proximal impacts to a fixed HIII midsize male ATD lower extremity.

Phase I: Seated ATD Proximal Tibia Impacts

The first phase of testing consisted of lower extremity impacts to a seated HIII midsize male ATD. The purpose was to: 1) verify the impact interface selection, 2) determine the impact location on the tibia, 3) determine a method of creating tibia compressive load, and 4) develop a correlation between mean crash forces and impactor energy.

Because of the wide variation in knee bolster geometries and materials in vehicles used in the crash tests, an impact material was needed to replicate the loading characteristics of a typical knee bolster. The knee bolster of a 2002 Jeep Liberty was chosen as a representative of the vehicles used in the crash tests. This bolster was tested for force-deflection characteristics. Tests showed the knee bolster had an average stiffness ranging from approximately 2200 to 6300 N/cm at a displacement rate of 2.54 cm/min (Figure 5).

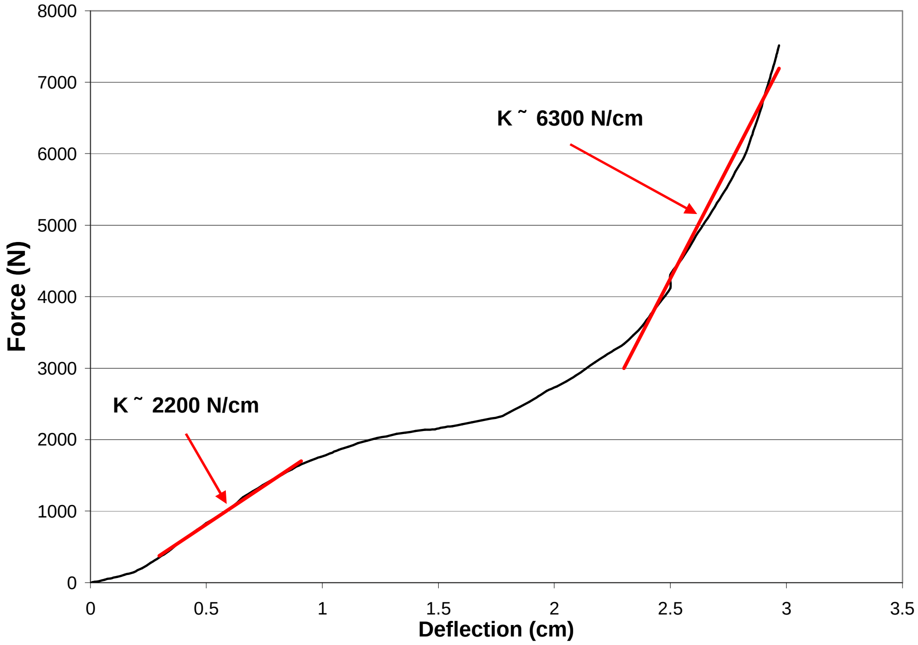

Figure 5: Force-Deflection Characteristics of 2002 Jeep Liberty Knee Bolster

1) A high-density polyurethane material, Last-A-Foam® FR-7104 (General Plastics Manufacturing Company, Tacoma, Washington), was selected based on its stiffness of approximately 3500 N/cm at 2.54 cm/min. The FR-7104 foam geometry was adjusted until the seated ATD impact response imitated that of the crash test occupants. 2) Impacts to the proximal tibia 5.72 cm below the center of rotation of the knee were found to reproduce the tibia displacement and displacement rate values. 3) Tibia compressive load was applied over the surface of the distal femur/knee bumper via a contoured aluminum plate and seat belt loading straps positioned on the medial and lateral sides of the leg. 4) A linear pneumatic impactor with a mass of 22.75 kg was used for all the impacts (Figure 6).

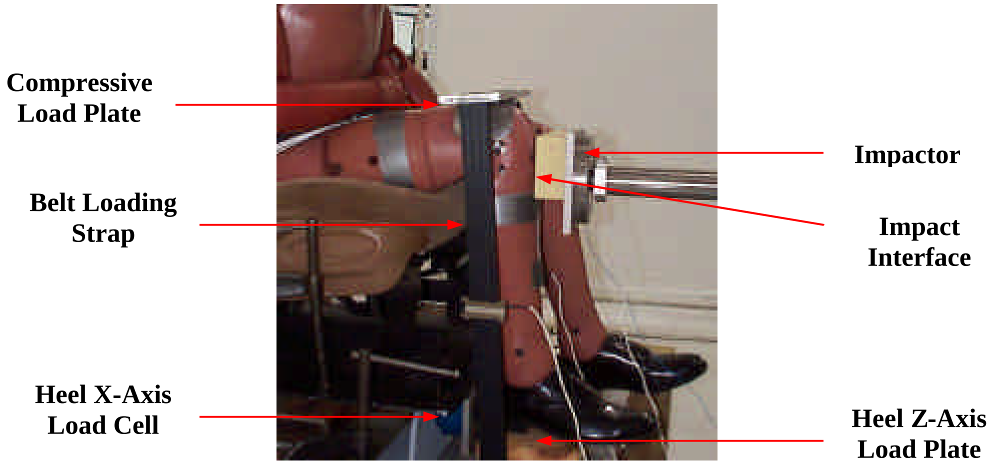

Figure 6: Seated ATD Test Setup

The seated ATD impacts were conducted in an iterative fashion, with some parameters held constant and others varied over a series of several tests until the knee slider displacement, displacement rate, and tibia compressive load were replicated from the crash occupant mean values (Figure 7).

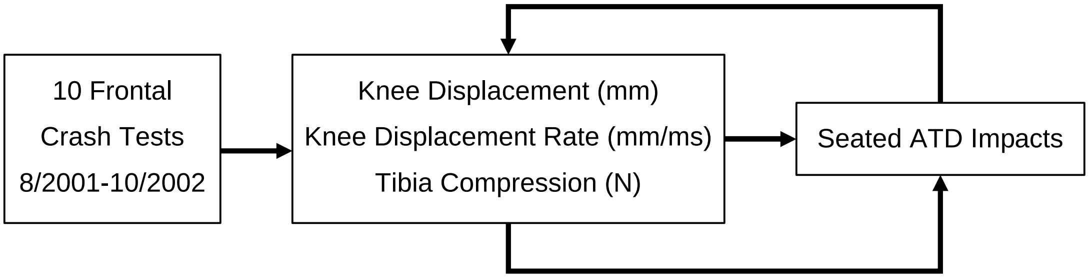

Figure 7: Test Iteration for Full ATD Impacts

The iterative approach to seated ATD impact testing resulted in approximately 100 J required to replicate the occupant crash loads and displacements. This impact energy was found from a series of 7 repeatable impacts to the seated ATD and translated to an average impact velocity of roughly 3.0 m/s. For these 7 impacts, average knee slider displacement of 8.0 mm, displacement rate of 0.93 mm/ms, and compressive load of 1683 N were found (Figure 8).

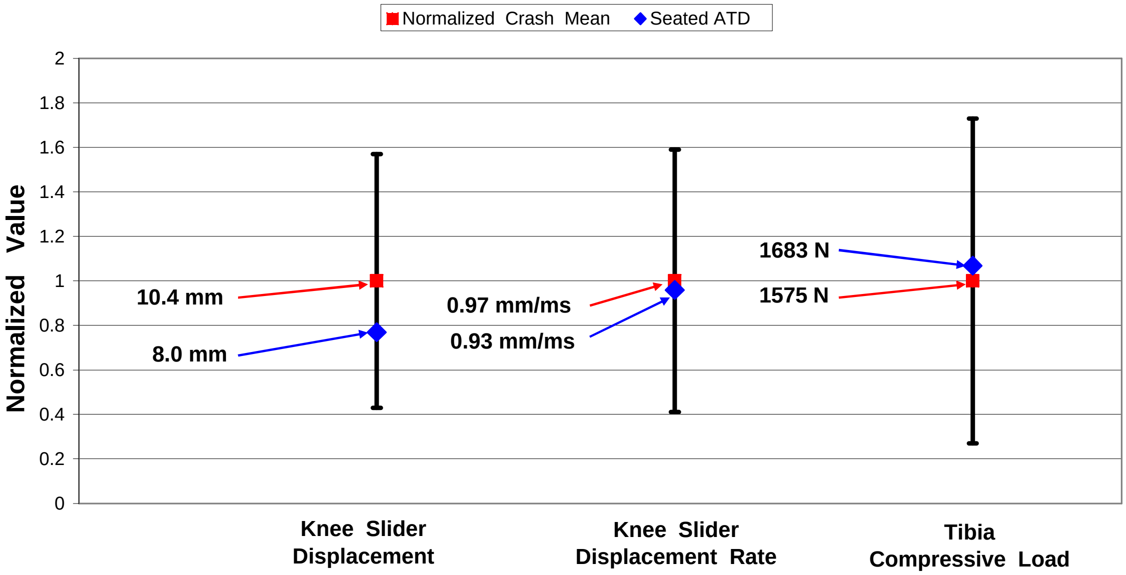

Figure 8: Normalized Values for Crash Test Mean Data (n = 10) and Seated ATD Impacts (n = 7)

The normalized impact values for the seated ATD were near the crash mean values and fit well within the ± 1 standard deviation error bars for the normalized occupant crash mean data. Even though the seated ATD impacts differed from the crash mean values, these tests were only conducted as a method to verify impact interface characteristics, impact location, and compressive loading, and to generate an approximate impact energy. These parameters were then used as a starting point to initiate impact testing iterations with the fixed ATD lower extremity.

Phase 2: Fixed ATD Lower Extremity Testing

Testing for phase 2 consisted of applying the impact scenario from full-seated ATD testing to a fixed ATD lower extremity with 100 J used as the initial impact energy. The purpose of this iterative testing to the fixed lower extremity was to replicate the loading and displacement rates seen in the crash mean data. This was the crucial step in the component level tests, as the final PMHS lower extremity impact conditions would be essentially the same as those produced in the fixed ATD lower extremity tests. Inertial effects were eliminated by rigidly mounting the femur (Figure 9).

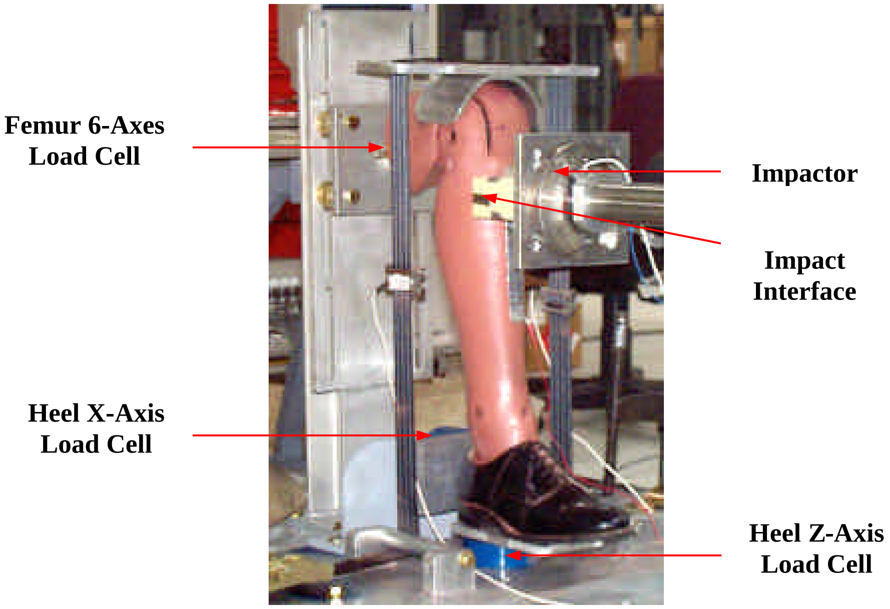

Figure 9: Fixed ATD Lower Extremity Test Setup

A series of impacts was performed on the fixed ATD lower extremity. The impact energy was iterated until repeatable impacts resulted in consistent knee slider displacement, displacement rate, and compressive load near that of the crash mean values (Figure 10).

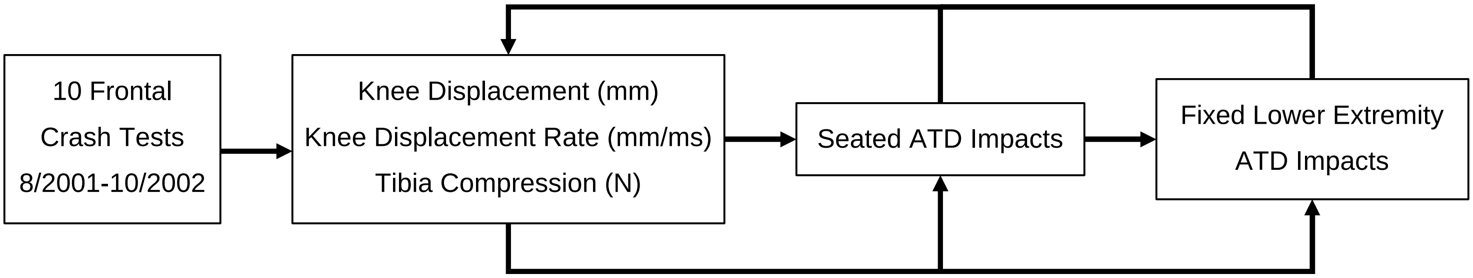

Figure 10: Test Iteration for Fixed ATD Lower Extremity Impacts

The result of these iterative impacts was two repeatable tests that resulted in average knee slider displacement of 11.2 mm, displacement rate of 1.02 mm/ms, and compressive load of 1672 N (Figure 11).

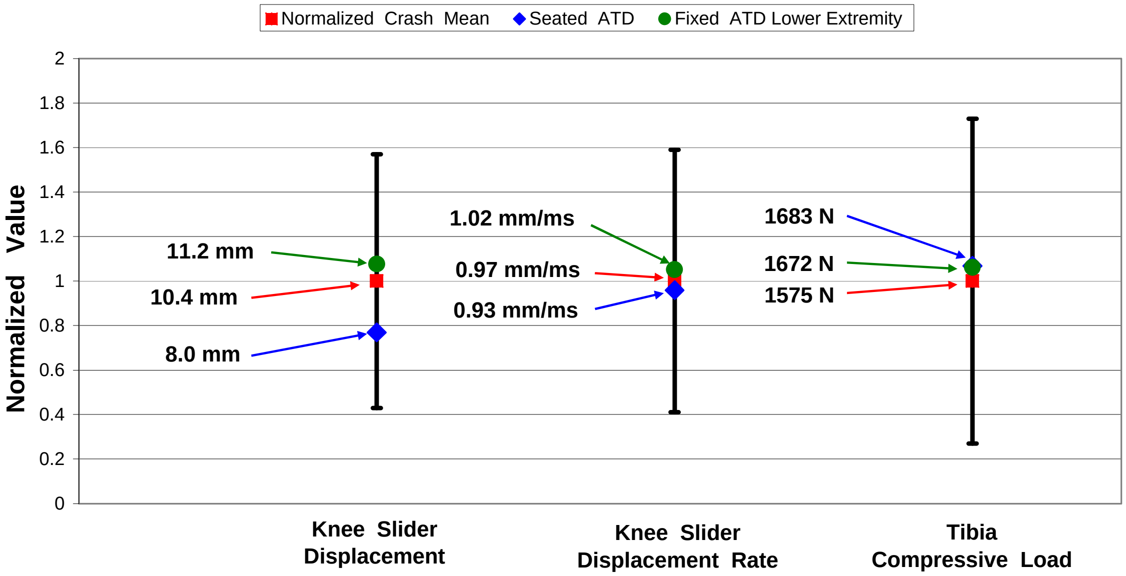

Figure 11: Normalized Values for Crash Test Mean Data (n = 10), Seated ATD Impacts (n = 7) and Fixed ATD Lower Extremity Impacts (n = 2)

The fixed ATD lower extremity values were larger than those seen in the crash mean data seated ATD impacts but were still very near the mean for the crash data. (The correlation between isolated ATD lower extremity and crash data was the most important consideration, not the comparison between the isolated ATD lower extremity and seated ATD.) Impact energy of approximately 125 J was required to produce the knee slider displacement, displacement rate, and compressive load. This energy translated to an impact velocity of approximately 3.3 m/s. It was this impact velocity that would be used as the baseline value for the future PMHS proximal tibia impact testing to determine PCL injury threshold.

CONCLUSIONS

Frontal crash test data were analyzed to develop the typical conditions seen for a Hybrid III midsize male ATD lower extremity. Specifically, the HIII lower extremity crash data were analyzed for knee slider displacements greater than 5 mm and associated loading scenario. After the development of crash condition parameters, component level impacts were performed on a seated HIII ATD and fixed HIII ATD lower extremity. These impacts were iterated until the ATD response mimicked that of the frontal crash test mean data. Upon completion of the fixed ATD lower extremity impacts, it was concluded that 125 J of impact energy would serve as the baseline to simulate the typical frontal crash impact for future isolated PMHS proximal tibia impacts. This energy correlated to an impact velocity of approximately 3.3 m/s with a 22.75 kg impactor. In the PMHS proximal tibia impacts the behavior of the PCL to tibia subluxation will be studied. This behavior will then be used to document PCL injury threshold for comparison with the HIII midsize male ATD knee slider response.

ACKNOWLEDGEMENTS

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DISCUSSION

PAPER: **Posterior Cruciate Ligament Response to Proximal Tibia Impacts**

PRESENTER: ***Adam Bartsch, The Ohio State University***

QUESTION: *Guy Nushultz, DaimlerChrysler*

Your error bars seem to be large enough to drive a truck through, and it would seem that if I just did, you know, random--If everything was completely random, the means would be fairly, fairly close. So, I'm not sure what--What are you trying to tell us with that type of information? You're showing the means. One other question that relates to that: A lot of times, those sliders--they stick. And if you don't get perfect loading--I mean, if you get perfect loading, it looks like you're doing it or very close to it. You might get 'em to slide back and forth. But in reality, every once in awhile you get a little sticking and you get somewhat of a different response.

ANSWER: Okay. Refresh my memory-the first question is error bar-

Q: The first question is the error bar is large enough to drive a truck through…

A: Okay. I--I would agree with you there. The error bars are basically a method to say, Are we within our limits? It's basically stating: how do we define how close we are so we can move on to the next step. Do we say it's 10%, 20% of the mean? Is it plus or minus 1 standard deviation? Once plus or minus 1 standard deviation was what we decided on, it turns out to be really close. Maybe we could have said within 20% of the crash mean data and we still would have been right on. Basically, it's just--It's a measure to signify that we're within our limits.

Q: The only point is that I don't--I'm not sure that it tells you a whole lot because in one case, you're going from the bottom all the way up, and from close to zero to as high as you can possibly go. And so, you're basically spanning the space of your possible solutions.

A: I think, in this kind of testing, that sort of variance is prevalent, and that was from the actual crash data. There's nothing we can do about that variance because that's actual crash test data. So, it's how you would define the limits that is important. If you have a better method to determine that, I would be very happy to talk to you about that.

And the second question was, refresh my memory?

Q: Was sticking-the slider sticking.

A: Oh! The slider sticking. I guess, yeah, that's definitely a potential problem. That definitely happens. I think with the ball slider mechanism, that's been reduced; but yeah, off-axis loading could definitely be an issue. That's something that we don't know from the crash tests because we just have the output data. If there was sticking, there's actually maybe more displacement and maybe it's actually a little more severe than what's indicated up there (on the plots).

Q: Okay. Thank you.

A: You're welcome.

Q: *Matt Philippens, TNO Automotive, Neitherlands*

On the full body test, do you have any idea how the seating support of your full body affects your results because-?

A: We didn't worry about that because all we did was we made sure that we took the crash data. We have numbers-we have X, Y and Z values from crash data. We just wanted to replicate that in the lower extremity, paying attention to if we replicated all the numbers, then our tests were “crash-like”. Let's say our femur load was 10 kN that doesn't work since that violates our femur load constraint. So, there's other parameters that are in there like femur load, tibia index, etc., things that were checks, in addition to all those values, that we used to make sure that we were hitting our marks and within our limits on the other parameters. But in terms of full dummy inertial effects, things of that nature, we didn’t worry about that. The way we impacted isolated ATD legs eliminated inertial effects. Basically, the way we picked the parameters eliminated the need to worry about that because we, essentially, replicated a crash just with the dummy. We didn't worry about it because the dummy doesn't care whether it's getting hit with a ram or whether it's in a car.

Q: No, of course, but did you compare with a PMHS, right? The effect of how the PMHS is supported by the seat and the support of the dummy by the seat will affect your results, if you make the comparison between the two of them.

A: Wait, say that-say it one more time. Sorry. Can you repeat that?

Q: Well, if you have a dummy or a PMHS in the seat, the way they are supported--

A: Oh. We're doing-We’re just doing isolated PMHS lower extremities.

Q: Oh, okay.

A: Okay? So, we took-we took crash data and we wanted-we want to somehow figure our impact scenarios for isolated PMHS legs.

Q: *Jason Kerrigan, University of Virginia*
That was a very interesting talk. I have actually two quick questions.

A: Okay.

Q: First question is the PCL's actually, to my knowledge, is composed of two functional bundles: an anterior lateral and a posterior medial bundle. Have you looked at any of the structural characteristics of the knee, such as--As far as I know, there are functional bundles in different orientations-in flexion and extension, and different areas of the PCL are taut. So, have you decided which of these bundles you'll look at or whether both of these bundles are actually affected in this type of loading? And, my second question before you start is the DVRT. Were you going at the anterior location to put on the DVRT because it seems like you'll have to take quite a bit of the flesh and everything out from inside the knee and do a lot of--? Have you actually done that yet or--?

A: No. Let me answer that question. We haven't done it yet (insert the DVRT), so we're very new at it. We've been checking around, seeing people that have done it before and getting feedback. I don't know how it will go. If you have any experience with that, I'd be glad to talk to you.

Q: Yeah, it seems like it might be a lot easier to get the DVRT on from the posterior side.

A: That--That's a question that if we want to compromise the posterior capsule integrity. Going in anterior-medially, we feel that there will be a lot less disruption for the joint capsule.

Q: Yeah, but the impact is anterior, correct?

A: Yeah, but it's below the insertion point. It's--but it's below the knee joint. Yeah, it's impacted at the tibial tuberosity location. I'm sorry I didn’t make that clear. What was the first question?

Q: From the bundles, the two different bundles: Have you looked at the structural--?

A: That's kind of a gray area in terms of--I guess ideally we'd like to fit as much instrumentation in as possible. If there's only room to put one or two (gages) in there, that's the sort of thing where we might gage one bundle and the other bundle.

Q: The reason I was asking is because it's possible with that loading type that the--only one of the bundles might become taut so you put the DVRT on the other bundle. You might not get any results.

A: Well, this is kind of new research and it's something that we kind of have to flesh out.

Q: No, it's a very interesting study. Thank you.

A: Okay. Thanks. Thanks for your questions.