THE EFFECT OF HYBRID III LOWER LEG KINEMATICS ON LOADING MECHANISMS AND INJURY CRITERIA

A.R. Payne
MIRA
J. Green
Rover Group
A.V. Thomas
Jaguar Cars
D. Midoun
Ford Motor Co.
United Kingdom
Paper Number 98-S1-O-16

ABSTRACT

With the ever increasing survivability of road traffic accidents due to the introduction of airbags, and the proposed implementation of the new European Frontal Impact Legislation, motor manufacturers are now focusing on reducing lower limb injuries. To achieve this, there is a need to develop a better understanding of lower leg injury mechanisms, and lower leg interaction with the intruding footwell.

An industry collaborative group was established, which included Ford, Jaguar and Rover, with the research being managed by the Motor Industry Research Association MIRA. The Lower Leg Injuries and Methods of Prevention (LLIMP) Vehicle Design Project was to focus on footwell and restraint system design. A program of crash tests, including both Front fixed Barrier and Offset deformable tests were conducted and an evaluation of the analysed results from lower leg and footwell instrumentation was conducted. This identified five distinct phases in lower leg kinematics, which are affected by both the footwell intrusion profiles and Hybrid III dummy lower leg positions and geometry. The interaction of the dummy lower leg and the foot have also been investigated using HyGe sled test techniques, with both static and dynamic intruding footwells.

The paper presents the five phases of lower leg kinematics, plus the interaction between the dummy foot and footwell on the lower leg kinematics. The paper will then investigate the options for controlling these for reducing lower leg injury criteria.

INTRODUCTION

Lower leg injuries to car occupants are relatively common in road traffic accidents. As a result of legislation already in place to reduce injury through seat belts and the use of airbags there has been a significant improvement in passenger survival in road traffic accidents. There continues to be however a significant level of disabling lower leg injuries as a result of footwell intrusion.

Motor manufacturers are now focusing on improving the safety of car occupant, particularly in relation to lower leg injury, especially with the proposed implementation of the new European Frontal Impact Legislation, European Directive 96/79/EEC, which includes the use of Hybrid III crash dummies and lower leg injury criteria.

The Lower Leg Injury and Methods of Prevention LLIMP Project is devised to link the injuries from road traffic accidents with the kinematics and loading mechanisms experienced by Hybrid III dummies in crash tests. The LLIMP project consists of two individual research projects, Biomechanics and Vehicle Design, working independently but in parallel. While the Biomechanics Project is researching actual lower leg injuries and injury mechanisms, the Vehicle Design Project is investigating the kinematics and loading mechanisms in the Hybrid III lower leg in view of better vehicle structural, pedal and footrest design. The Vehicle Design Project is an industrial collaborative project sponsored by Rover Group, Ford Motor Company and Jaguar Cars and the research managed by the Motor Industry Research Association (MIRA). In a phased approach the project has conducted a programme of frontal crash tests using enhanced lower leg and footwell instrumentation in order to achieve a better understanding of lower leg kinematics and loading mechanisms. Development of a finite element computer model of the lower leg correlated to component, system and crash test data is being used to evaluate the sensitivity of the Hybrid III lower leg for different footwell impact scenarios to improve footwell, pedal and footrest design. Although concentrating in the initial phases on the current Hybrid III instrumented lower leg, as specified in the new European legislation, the performance and sensitivity of advanced Hybrid III lower legs will be evaluated in later phases.

The paper presents the initial phase of the project in which the lower leg kinematics and loading mechanisms from the baseline crash tests have been analysed and how these affect lower leg injury criteria.

LOWER LEG AND FOOTWELL INSTRUMENTATION USED IN THE FRONTAL CRASH TESTS

The data from the instrumented Hybrid III lower legs has been analysed from over 20 crash tests. These have included results for driver and passenger lower legs in both offset deformable and front fixed barrier crash tests with standard and enhanced levels of lower leg and footwell instrumentation.

Lower Leg Instrumentation

The instrumented Hybrid III lower leg, prescribed in the European Frontal Legislation (96/79/EEC) is used to assess potential lower leg injuries. The lower leg, shown in Figure 1, is essentially a steel skeleton with ball joints at the hip and ankle, and a pin joint at the knee. The individual steel sections are covered with a vinyl outer flesh, being used in combination to produce the correct anthropometric static and dynamic characteristics. The lower leg injury criteria, Upper and Lower Tibia Index, used to assess the probability of a complex tibia fracture, and Tibia Compressive Force Criterion (TCFC), fracture to the tibia at the Knee and Ankle joints, are calculated from the loads generated in the tibia. These are measured at load cells located at the top and bottom of the tibia shaft, the European directive requiring the measurement of two bending moments My and Mx, plus the Axial Force Fz.

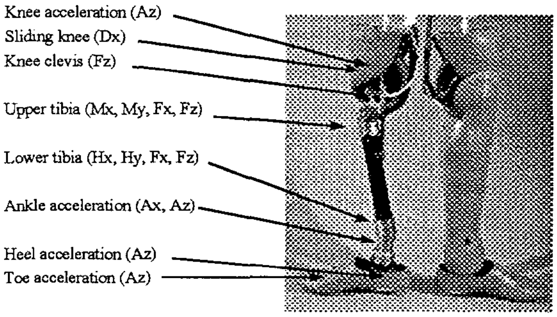

Figure 1 Lower Leg Instrumentation

As a major part of the LLIMP project was to gain a better understanding of lower leg kinematics, lower leg 4 axis load cells were supplemented with accelerometers mounted in the toe, heel, lower tibia (immediately above the ankle) and the upper tibia (immediately below the knee). In the majority of the baseline tests uniaxial accelerometers were located at the toe, heel and knee in the axial direction with Biaxial in axial and longitudinal directions at the ankle. However triaxial accelerometers can be located at all these locations from which the 3-dimensional motion of the lower leg can be analysed.

Footwell Instrumentation

In order to evaluate the dynamic deformation of the footwell, an array of instrumentation was used; Figure 2 showing the typical instrumentation specification. Accelerometers were located on the brake and accelerator pedals, plus close to the toe and heel impact points to both inboard and outboard feet. These were used to define the main toe and heel impact times and magnitudes, as well as impacts, between the footwell and rigid components in the engine bay. However, as the accelerometers were in a deforming part of the vehicle structure, and changed orientation during the impact, integrated footwell velocities and displacements should be used with extreme caution. To accurately assess dynamic floor displacements potentiometers can be used, even with dummies installed.

Dynamic intrusions were measured at both the bottom and top of the footwell; the lower intrusion producing the footwell translation, while the upper intrusion when taken from the lower, footwell translation produced the footwell rotation. Although these only gave the intrusion profile at the centre of the footwell; pre- and post-test static measurements were used to evaluate the deformation at all points in the footwell, while accelerometers gave an indication of the timing of the intrusion. Without dummies, an increased array of potentiometers can be used, so a 3-dimensional map of footwell deformation can be produced.

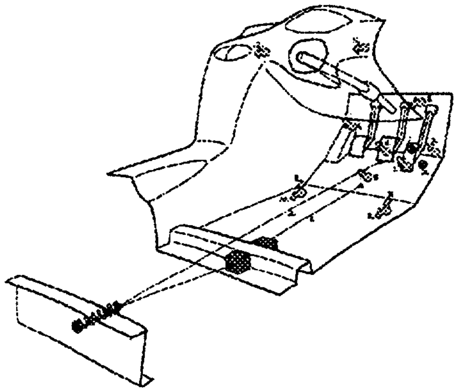

Figure 2 Footwell Instrumentation

ANALYSIS OF LOWER LEG KINEMATICS

In order to evaluate lower leg kinematics and loading mechanisms in frontal crash tests five main phases of lower leg kinematics have been proposed after analysing results from baseline crash tests. These proposed phases have been formulated as follows and are shown in Figure 3:

- Phase 1 - Toe Contact
- Phase 2 - Heel Contact
- Phase 3 - Ankle Rotation
- Phase 4 - Lateral Ankle Lock-up
- Phase 5 - Longitudinal Ankle Lock-up

As such the phases existence and length vary greatly dependent on the vehicle crash test scenario and lower leg orientation and location. For each of these kinematic phases the loading mechanisms have been evaluated and the relative magnitude of the forces, bending moments and accelerations derived.

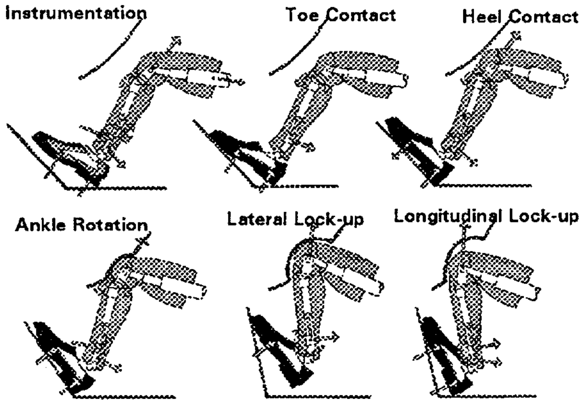

Figure 3 Lower Leg Kinematic Phases

Phase 1 - Toe Contact

On initial impact with the barrier, the vehicle starts to decelerate, so the occupant moves forward relative to the vehicle. The whole leg 'slides' forward either depressing the accelerator pedal or moving towards a footrest or footwell. (Analysis of crash tests have shown that in most cases the foot moves slightly rearward under the initial acceleration of vehicle run-up pulling the foot off the footrest or footwell producing a gap which has to close before toe contact).

The toe then impacts the footwell or footrest directly, or the accelerator pedal 'bottoms-out' on its end stop causing the toe to rapidly accelerate. However as the lower leg and heel are still moving forward the foot has to rotate round the ankle, in dorsiflexion, producing low axial loads and tibia bending moments.

Phase 2 - Heel Contact

On heel impact with the footwell, the heel rapidly accelerates, making the foot momentarily rotate in plantaflexion reversing the toe acceleration. Due to the heel's proximity to the ankle the acceleration affects the whole tibia producing ankle accelerations and lower tibia Fx and Fz loads as the heel and ankle are accelerated to the footwell velocity. With the pelvis and knee still moving forward relative to the footwell, the tibia has to rotate about the ankle and knee and therefore undergoes angular acceleration producing an upper tibia My bending moment. If the relative velocity between the heel and footwell is large then the combination of the higher axial load Fz and upper Tibia, My, produces upper Tibia Index peaks. These being inertia loading mechanisms.

Phase 3 Ankle Rotation

With the foot now in full contact with the footwell and the tibia rotating about the knee and ankle as the pelvis continues to move forward, both lower leg accelerations and loads reduce from those produced in Phase 2. Phase 3 will continue until either the ankle rotation has reached its limit causing 'ankle lock-up', or the knee or tibia impacts the lower dashboard changing the inertia loading mechanism to quasi-static.

Phase 4 Lateral Ankle Lock-up

Lateral ankle lock-up usually only occurs for the driver, where the feet are located on pedals or footrests. If the foot is not centrally located on the pedal or footrest, or there is lateral motion of either, the heel 'slips off' producing ankle rotation in either inversion or eversion. With the maximum lateral ankle rotation of 30 degrees, lateral ankle lock-up can occur rapidly, producing an instantaneous rise in both upper and lower tibia Mx bending moment. The loading mechanism changes from inertial to quasi-static.

Pure lateral ankle lock-up is not normally accompanied by a rise in the longitudinal bending moment. However, as the ankle continues to move forward, the ankle stop contact surface will rotate from a lateral to a combined lateral / longitudinal direction which produces a gradual rise in the My bending moment, particularly in the lower tibia.

Phase 5 Longitudinal Ankle Lock-up

Longitudinal ankle lock-up occurs either from the ankle reaching its longitudinal rotational limit, from Phase 3, or by rotation of the ankle end stop surface following lateral ankle lock-up, in Phase 4. If pelvis to footwell relative velocity is still high or there is considerable footwell rotation at the time of longitudinal lock-up, then the lower tibia bending moment immediately rises producing a peak in the lower tibia index. The rapid rise in lower tibia index My bending moment is often followed by 'Heel Jump' in which the heel actually leaves the footwell, reducing the lower legs' loads before impacting with the footwell with another immediate rise in loads.

Following ankle lock-up the magnitude of Fz and My loads, and therefore upper and lower tibia index peak, depend on the amount of pelvis forward or footwell rearward motion left. In vehicles where lock-up occurs before large amounts of footwell intrusion the My bending moments can be considerable while if lock-up occurs at the limit of pelvis forward motion after footwell intrusion there will be a negligible increase.

APPLICATION OF KINEMATIC PHASES TO CRASH TEST DATA

Two examples are now used to demonstrate how the proposed lower leg kinematic phases can be applied to lower leg test data.

- HyGe Sled Test with no dynamic intrusion
- Baseline Offset Deformable Crash Test

HyGe Sled Test

Although the primary purpose of a series of HyGe sled tests was to correlate the development of the lower leg finite element model it allows the lower leg kinematics to be observed and linked directly to loading mechanisms. Figure 4 shows the lower leg accelerations and loads with the lower leg motion in each of the kinematic Phases. In this example the sled is given the B-post acceleration for a medium sized vehicle with the RH lower leg impacting a rigid footwell inclined at 60 degrees

Phases 1 & 2

As the foot was initially inclined at the same angle as the rigid footwell the toe impacts at 26 ms, only 4 ms prior to the heel impact, with a relative velocity of 5 m/s. Toe acceleration peaks before rapidly reducing with heel impact at 30 ms. Heel acceleration peaks at 32 ms with the lower tibia Fz and upper tibia My rising rapidly to peak at the same time. These are produced by inertia loading mechanisms accelerating the tibia in both translation and rotation. The combination of these causes the upper tibia index peak.

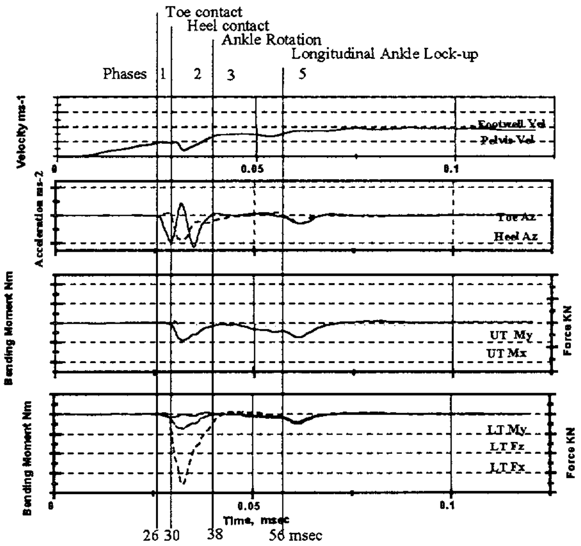

Figure 4 Lower leg test data. HyGe sled test

Phase 3

Ankle rotation occurs from 38 - 56 ms and with minimal inertial loading; all the accelerations and loads reduce to a minimum.

Phase 4

As the footwell is stable, with no feet stability problems, no lateral lock-up occurs and therefore Phase 4 is omitted.

Phase 5

Ankle rotation occurs until 56 ms when longitudinal lock-up occurs. As there is no dynamic footwell intrusion and the pelvis reaches it maximum forward trajectory, shortly after lock-up, tibia axial loads and bending moments rise only gradually to peak at 61 ms producing the lower tibia index peak. These are produced by quasi-static loading mechanisms which actually load up the femur and slightly increases pelvis acceleration.

As can be seen the proposed Kinematic phases and associated loading mechanisms have been validated as the actual lower leg motion can be observed. In crash tests it is very difficult to directly observe lower leg kinematics so therefore the Phases are evaluated from the footwell and lower leg instrumentation data.

Baseline Offset Deformable Crash Test

The second example, shown in Figure 5, shows the instrumentation data for a RH lower leg in a RH offset deformable crash test. With the foot on the accelerator pedal. All 5 kinematic phases are represented.

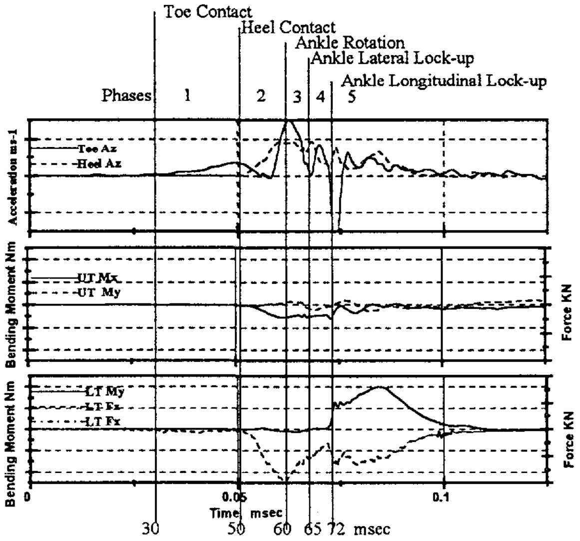

Figure 5 Lower leg test data - Baseline deformable crash test

Phase 1 Toe Contact

Accelerator pedal impacts the end stop at 30 ms producing a rise in toe acceleration as the foot starts to rotate.

Phase 2 Heel Contact

Heel impacts the footwell at 50 ms with rise in heel and ankle accelerations. Lower tibia Fz and upper tibia My and Mx rise under inertia loads producing the upper tibia index peak at 61 ms.

Phase 3 Ankle Rotation

After the peak inertia loads at 60 ms the lower leg accelerations and loads reduce under ankle rotation.

Phase 4 Lateral Ankle Lock-up

At 65 ms the ankle locks-up laterally in eversion, as the foot slips off the accelerator pedal inboard. This is identified by the reversal in the upper tibia Mx bending moment and slight increase in lower tibia My, indicating that the lock-up has a longitudinal component. Ankle rotation continues as the heel moves forward, the ankle stop contact surface rotates with an increasing longitudinal component.

Phase 5 Longitudinal Ankle Lock-up

At 72 ms the ankle locks up longitudinally while dynamic footwell intrusion occurs producing an instantaneous rise in lower tibia My. The lower tibia index peaks at 84 ms. As the loading mechanism changes from inertial to quasi-static the upper tibia My actually reverses, reducing the upper tibia index.

Application of the proposed kinematic phases to lower leg crash test data has assisted in evaluating the complex loading mechanisms which occur in the lower leg during the dynamic interaction between the feet and the footwell.

EFFECT ON DIFFERENT LOWER LEG KINEMATICS ON LOADING MECHANISMS

The Kinematic Phase analysis technique has been applied to a large number of lower leg results from the LLIMP project baseline crash tests. These have highlighted several different types of lower leg kinematics and their associated loading mechanisms. The following 4 examples demonstrate how the Kinematic Phases are affected under differing impact environments.

High Footwell Intrusion Rotation and Translation

With rapid footwell translation and rotation occurring, while the foot is in contact with the footwell, the kinematic phases get compressed and several are omitted. Figure 6 shows the RH lower leg results for a small vehicle in a RH Offset Deformable crash test.

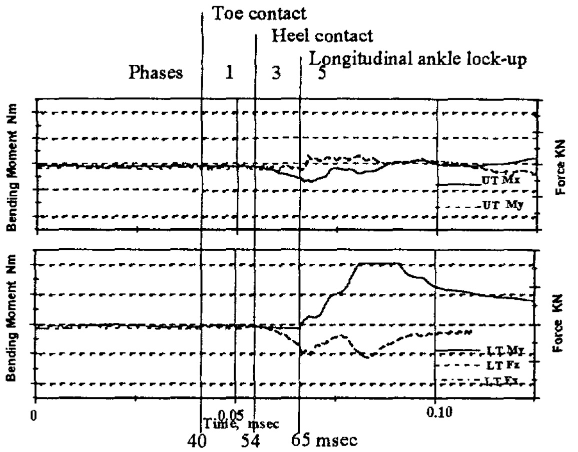

Figure 6 Lower leg test data - High Intrusion Rotation and Translation

Phases 1 and 2 are clearly defined with toe contact at 40 ms and heel contact at 54 ms, producing the rise in tibia axial loads. However before the lower leg translational and rotational accelerations peak under inertial loading, longitudinal ankle lock-up occurs at 65 ms, kinematic phase 5 starts, while phases 3 and 4 are omitted.

As already seen if longitudinal lock-up occurs during dynamic footwell rotation, the lower bending moment rises very rapidly producing a high lower tibia index which in this example occurs at 83 ms.

Analysis of the baseline crash tests have shown the importance of both the magnitude and timing of footwell translation and more particularly rotation on firstly causing ankle longitudinal lock-up and secondly high quasi-static loads. Reducing the amount of footwell rotation decreases the probability of lock-up occurring but also if the intrusion can be delayed or its rate reduced the loads produced after lock-up can be minimised.

Wheelarch Footrest Design

In LHD vehicles the LH foot is often placed on a footrest directly attached to the wheelarch. In offset deformable crash tests the LH front wheel impacts directly on the wheel arch producing both rearward translation and rotation of the footrest. Two different types of footrests are normally used and these have significant affect on the lower leg kinematics and loading mechanisms.

Stable Footrest

Figure 7 shows the lower leg loading for a LH leg placed on a stable, relatively rigid footrest. After toe and heel contact, Phases 1 and 2, at 8 and 12 ms respectively, the foot remains on the footrest with minimal lateral movement. As the heel contact occurred early due to its initial proximity with the footrest, inertia loads are very low.

In Phase 3 (ankle rotation) there are several rises in Fz and upper My, which start at 54 ms, indicating the commencement of wheel arch intrusion producing a secondary increase in inertial loading. At 65 ms a combination of longitudinal and lateral ankle lock-up occurs as shown by the series of increases and decreases in all the bending moments as the heel moves in 'jerks' rearwards. At 85 ms heel rearward motion stops producing a rise in lower tibia My due to the quasi-static loading following lock-up.

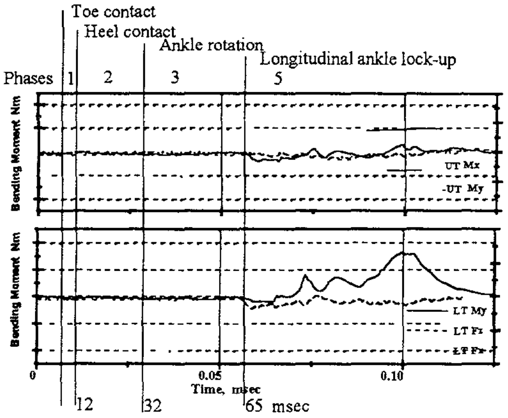

Figure 7 Lower leg test data - Stable left hand footrest

Unstable Footrests

The other type of footrest used for the LH leg in LHD vehicles is a foam moulding which is located around the wheelarch, but not directly attached to it. This is located under the underlay and carpet with a flat plastic plate on the carpet outer. Figure 8 shows the lower leg results for such for a footrest in an offset deformable barrier crash test.

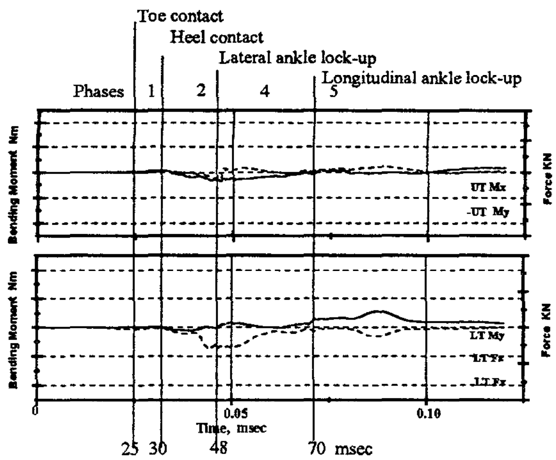

Figure 8 Lower leg test data - Unstable left hand footrest

As with the stable footrest, toe and heel contact occur early at 25 and 30 ms respectively. However under the initial impact the under carpet moulding rotates around the wheel arch causing the heel to move inboard with the ankle rotating in 'eversion'. As the heel continues to move laterally and forward, lateral ankle lock-up occurs at 48 ms. This can be identified by the rapid reversal in the upper tibia Mx bending moment as the loading mechanism changes from inertial to quasi-static in the lateral direction.

As seen before the lateral ankle lock-up does not produce a significant rise in the lower My bending moment. However as heel forward motion continues as it no longer has any support, total ankle lock-up occurs at 70 ms producing a peak in the lower tibia My bending moment and tibia index.

These two examples show how footrest design has a direct effect on the lower leg kinematics and loading mechanism. Stable footrests reduce the probability of lateral ankle lock-up, however, as forward motion of the foot is restricted longitudinal lock-up is much more likely. Unstable footrests inevitably produce lateral lock-up which can also be followed by longitudinal lock-up.

High Inertia loads without pedals or footrests

Even without the effect of pedals and footrests, high rates of intrusion can still produce high inertia and quasi-static loads following longitudinal ankle lock-up. Figure 9 shows the lower leg results from a passenger in a front fixed barrier crash test.

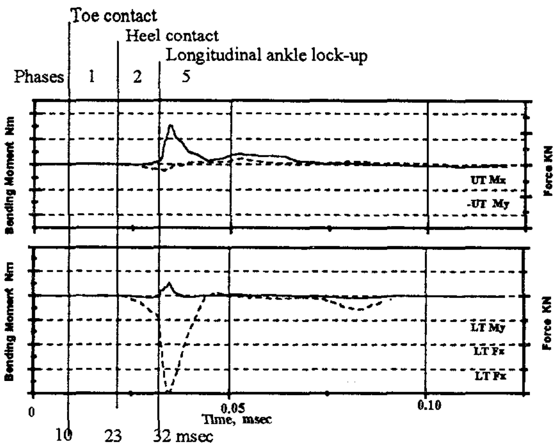

Figure 9 Lower leg test data - High inertia loads, passenger side

With the feet located in very close proximity to the footwell, toe contact occurs at 10 ms, with negligible effect on forces or bending moments as the toe slides up the footwell. Heel contact occurs at 23 ms producing a gradual rise in axial loads and upper tibia bending moments. However, with the onset of dynamic intrusion, longitudinal ankle lock-up occurs rapidly, at 32 ms, producing instantaneous rises in both lower tibia Fz and My with both upper and lower tibia index peaking at 34 ms. The ankle lock-up has occurred so early in the test that it has affected both the femur compressive load and pelvis acceleration as the pelvis to vehicle relative velocity is still significant.

This example shows again that it is not only the magnitude of intrusion that is the significant factor on lower leg loads but also the timing. High inertia and quasi-static loads are produced if a high rate of intrusion occurs while the foot is in direct contact with the footwell.

Analysis of lower leg kinematics and loading mechanisms has been conducted on the majority of lower leg data in the baseline crash test database. Initial evaluation indicates that the smaller footwells, steeper tibia angles and increased intrusion associated with small vehicles tends to compress the kinematic phases decreasing the time to ankle lock-up with the probability of higher quasi-static loads. Increased footwell areas and shallower tibia angles delay the time to initial toe and heel impact increasing both axial and rotational inertia loads but have a lower probability of longitudinal ankle lock-up.

Timing of intrusion also has a significant effect on lower leg loads. If this occurs during initial heel impact or longitudinal lock-up the inertial or quasi-static loads generated are significantly higher. Therefore the highest rate of intrusion should occur either prior to heel impact or during Phase 3 (ankle rotation) minimising the effect on lower leg loads.

CONCLUSIONS

Application of increased levels of instrumentation to both the Hybrid III lower leg and vehicle footwell has lead to better understanding of lower leg kinematics and loading mechanisms. Five main lower leg kinematics Phases have been proposed for which the loading mechanisms have been evaluated. A programme of HyGe sled tests have been used to validate these kinematic phases and to link these directly to the loading mechanisms. The 5 main kinematic phases are:

- Toe contact
- Heel contact
- Ankle Rotation
- Lateral ankle lock-up
- Longitudinal Ankle Lock-up

The kinematic analysis technique has been applied to the lower leg data in the LLIMP project baseline crash test database and several different types of lower leg kinematics and lower leg loading mechanisms have been evaluated.

Smaller footwells with higher levels of intrusion, tend to compress the kinematic phases causing longitudinal lock-up to occur earlier, with the probability of higher quasi-static loads. However, larger footwell heel contact is often delayed, producing a higher relative impact velocity and therefore higher inertia loads. Reducing the amount of intrusion obviously decreases the probability of longitudinal ankle lock-up. However changing the time of the highest rate of intrusion away from either the heel contact or ankle lock-up reduces lower leg quasi-static loads.

Pedal and footrest instability cause lateral ankle lock-up which then lead to higher quasi-static loads in longitudinal lock-up. Stable footrests reduce the probability of lateral lock-up and therefore injury criteria.

These conclusions are subject to limits of biofidelity of the lower leg of the Hybrid III dummy, and are therefore potentially useful in evaluating alternative improved dummy designs.