PARAMETRIC STUDY ON THE EFFECT OF THE FOOTWELL GEOMETRY, DYNAMIC INTRUSION AND OCCUPANT LOCATION ON HYBRID III LOWER LEG INJURY CRITERIA

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ABSTRACT

Inclusion of lower leg injury criteria in the new European Frontal Impact Legislation has meant that lower leg loads for front seat occupants and footwell deformation have to be considered as part of the vehicle design process at the concept stage.

The Hybrid III dummy with instrumented lower legs is the tool selected for measuring the lower leg injury criteria and it is essential to have a full understanding of the lower leg interaction, with the deforming footwell, control pedals and dashboard, in order to determine how these effect leg kinematics and loading mechanisms.

The LLIMP (Lower Leg Injury and Methods of Prevention) Vehicle Design project is a collaborative research project undertaken by MIRA and sponsored by Rover Group, Ford Motor Company and Jaguar Cars. Its aim is to gain an understanding of the effect which car design has on lower leg kinematics and loading mechanisms. As part of this project a finite element lower leg model has been developed and fully correlated to crash and sled tests. The effect of over 30 different parameters which affect lower leg kinematics and loads have been studied, and their effect on lower leg loading will be evaluated later in the project using the finite element lower leg model. These parameters take account of vehicle structure, occupant kinematics and footwell geometry. The results of the parametric study have been collated to produce a set of lower leg design guidelines, to assist in vehicle structure and restraint system design and as part of the vehicle development cycle.

The paper presents the formulation of the parameters, and how different parameters effect lower leg kinematics and injury criteria.

INTRODUCTION

With the increasing awareness over disabling lower leg injuries, reflected in the introduction of lower leg injury criteria in the new European Frontal Impact Protection, Directive 96/79/EC, automobile manufacturers are now focusing considerable attention on footwell design. The Lower Leg Injury and Methods of Prevention (LLIMP) Vehicle Design Project (Ref 1) is investigating lower leg kinematics and loading mechanisms with a view to improving vehicle structural and footwell design. The Vehicle Design Project is an industrial collaborative research project sponsored by Rover Group, Ford Motor Company and Jaguar Cars with the research managed by the Motor Industry Research Association (MIRA).

The objective of the initial phase of the project is to evaluate the sensitivity of the current instrumented Hybrid HIII lower leg to the factors which effect lower leg kinematics and to collate these to produce a set of guidelines for footwell, pedal/footrest and restraint system design. In order to achieve this objective, lower leg kinematics and loading mechanisms were investigated to determine how different footwell environments affect loads and injury criteria (Ref 1). The project has identified five main phases in kinematics of the lower leg, each having a characteristic loading mechanism. A finite element computer model of the Hybrid III lower leg has been developed (Ref 2), to be used in evaluating the effect of over 30 different parameters on the lower leg kinematics, loading and injury criteria.

CHARACTERISATION OF LOWER LEG KINEMATICS

The lower leg loads are generated by a complex interaction between the feet and the footwell, caused by the relative motion of the occupant's legs (controlled by the restraint system) and the footwell surfaces (controlled by the deformation of the front bulkhead). Crandall (Ref3), Sakurai (Ref4) and Zuby (Ref 5) all show the importance of the timing and magnitude of the initial footwell acceleration on impact with the foot, termed 'inertial slap'. The rapid acceleration of the foot and tibia on impact with the footwell, produces a high inertial axial force in the tibia, which as it moves rearwards with angular acceleration produces high bending moments in the upper tibia. Zuby (Ref 5) and Kruger (Ref 6) and many others consider the effect of total footwell intrusion and deformation. These usually produce high axial loads and lower tibia bending moments, generated as the ankle reaches the end of its travel or locks up. Further compressive forces and bending moments are generated as a result of lower leg entrapment. They also comment on the importance of the initial feet position relative to the footwell (on or off pedals and footrests) on lower leg loads.

In the initial phase of the LLIMP project (Ref 1) lower leg load data, from a database of both offset deformable and fixed barrier frontal crash tests were analysed, from which 5 main phases of lower leg kinematics have been proposed. These are shown in Figure 1.

In analysing the lower leg data from the crash test database the existence and duration of each phase and magnitude of the loads within the phases vary dramatically dependent on vehicle structure, leg location and crash test scenario. In vehicles with high intrusion the phases tend to be compressed with high lower tibia bending moments following longitudinal ankle lock-up. Low intrusion vehicles may have lower probability of ankle lock-up but high upper tibia bending moment and lower tibia axial loads from heel impact with the footwell. As lower leg kinematics are intrinsically linked to loading mechanisms and magnitudes, these also must be considered in evaluating the effect on footwell footrest and pedal design.

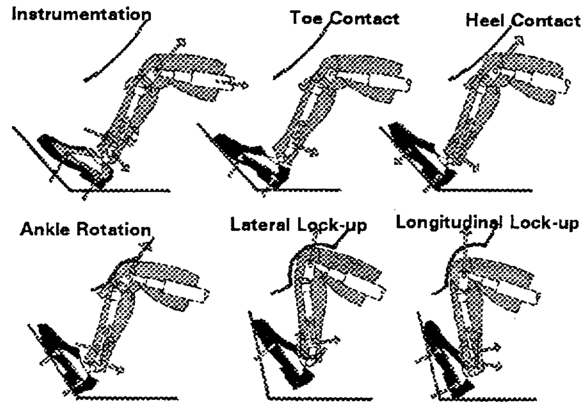

Figure 1 Lower Leg Kinematic Phases

PARAMETRIC STUDY MODEL CONSTRUCTION

To undertake the parametric study a rigid body finite element (FE) model of the Hybrid III with a validated lower extremity was placed inside a simplified model of a vehicle cabin. From the LLIMP Vehicle Design Project baseline crash data (Ref1) it was possible to identify most of the areas where the greatest detail should be applied in the FE model. The lower leg and occupant model has already been presented (Ref 2) which has provided a comprehensive review of the level of detail needed in modelling the lower extremity. In the current part of the study attention has been concentrated on the modelling of the vehicle cabin.

The aim of the finite element model is to provide a simplified environment to investigate the sensitivities of the lower extremity, to the factors effecting their kinematics and loads. To achieve this it was necessary to understand the motions of both the occupant and the left and right side of the footwell. It is proposed that the model will be developed to allow facia intrusion to be accurately simulated. However, at this time, the level of modelling detail required for this has not yet been established.

DUMMY AND LOWER LEG MODEL DEVELOPMENT

Probably the greatest area of importance in the modelling of the dummy is ensuring the accurate representation of it's anthropometry. But, due to the analysis being concentrated on the effects of the lower extremities, it was not necessary for the upper areas of the model to be constructed to the same level of detail. In order for the general kinematics of the dummy to be achieved, it is only necessary for the upper body segments of the dummy to be of the correct size and mass distribution with accurate centres of mass and moments of inertia. The joints of the upper dummy are greatly simplified using the available LS-Dyna3D joint definitions. For the most part, the upper segments were modelled using rigid ellipsoidal representation for the abdomen, upper torso and upper limbs (see Figure 2).

The lower extremity was modelled using accurate geometry giving the body segments' accurate mass distribution, moments of inertia and centres of gravity.

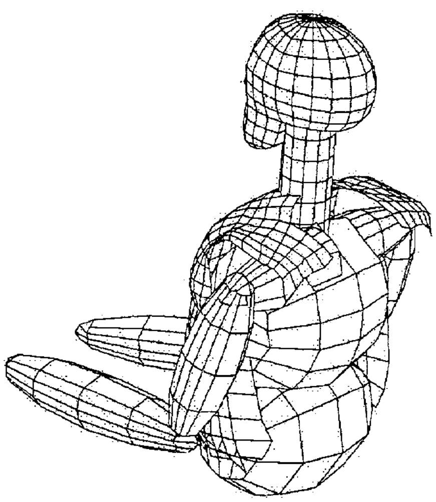

Figure 2 : Model of the upper part of the occupant

The dummy's skeletal structure was modelled as a rigid structure with arrangements of springs and dampers joining the limbs at the locations of the current load-cells (see Figure 3). The load development at these load-cells will be higher than in a real Hybrid III leg since by nature the model lacks compliance in the rigid skeletal structure. As a result, all the forces are transmitted directly to the load-cells and joints. Our experience in the use of this model shows that in most instances the output of these load-cells can be scaled to compensate for the non-compliance. The associated joints are modelled using pre-defined LS-Dyna3D joint models. The ankle, knee and hip joint stiffness characteristics are modelled using non-linear torsional springs and dampers.

The flesh of the lower extremities and the feet were modelled using correlated foam materials, each of which was geometrically accurate. The advantage of accurate geometric representation was an improvement in contact interaction with the vehicle cabin environment.

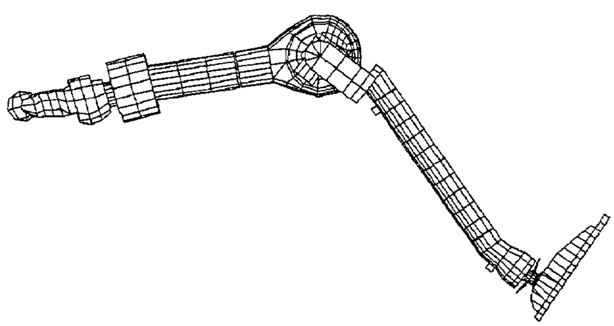

Figure 3 : Model of Hybrid III Leg Structure

Due to the complexity of both the ankle joint and the tibia load-cells, detailed consideration has been given to the method in which these components should be modelled.

VEHICLE CABIN MODEL DEVELOPMENT

In the LLIMP programme two levels of FE cabin model were developed. The first was an arbitrary cabin with common footwell angles derived from a series of sled tests used in the validation of the FE lower extremity model (see Figure 4). This was used as a guiding tool for determining the level of detail required for a generic baseline cabin model. The early stages of the parametric study required a series of analysis runs to be undertaken with a series of arbitrary intrusion profiles derived from the ranges seen in the baseline crash tests. Each run was used to vary what are believed to be the main parameters that affect the loading mechanisms of the lower extremity. The aim of this was to verify the general behaviour of the lower extremity from the interaction and driven reaction of an intruding cabin structure.

The second level of model was then defined with very simplified interaction requirements, whilst still being able to provide accurate interaction and driven reaction characteristics with the occupant foot and lower leg. The cabin geometry was based on a C-class vehicle (mid sized). This was derived from data provided by Ford, Rover and Jaguar, along with their input on occupant positioning.

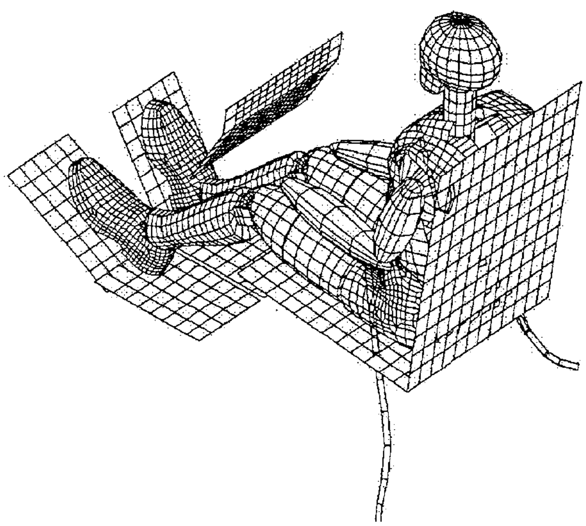

Figure 4: Model of occupant in cabin

The simplified cabin model makes it possible to reduce the number of input variables during the interaction between the occupant and cabin. In particular, by treating the left and right side of the cabin in front of the occupant as separate, it became very easy to control the reaction effects of the occupant to structure. Both levels of cabin model were built around this philosophy.

Using this approach it was possible to define facia stiffness characteristics for each leg impact, and well defined intrusion characteristics for the footwell region. For simplicity, the facia was geometrically defined for the mid-sized vehicle but was treated as a rigid but moveable part in car-line only. This allowed for an effective means of controlling the knee interaction stiffness characteristics through the use of non-linear springs.

The cabin floor and adjoining sides were treated as a single rigid immovable part. Both the footrest and the right side of the footwell were then treated as movable rigid parts that were geometrically accurate. Prescribed translations and rotations were then applied to these parts to mimic the effect of footwell intrusion relative to the occupant.

A typical accelerator pedal was modelled to represent the average shape from the vehicle platforms in the baseline crash tests. This was mounted relative to a rigid movable bulkhead. The prescribed motion of the bulkhead was defined from analysis of the motions experienced in general from the baseline crash data. To represent the reaction load of the pedal on the foot during the impact event , a rotation spring was defined about the pedal pivot pin.

For the current programme of work, the positioning of the right foot is confined to the area of the accelerator pedal. Because of this, it was assumed that any lower extremity contact with the steering column shrouding would have a negligible effect on the loading of the lower leg. Therefore, it was not necessary to incorporate a steering column into the model.

To overcome the need to accurately represent the restraint system, as only the lower extremity injuries were being studied, a prescribed excursion of the pelvis was defined. This method allowed the tight control of the variables applied to the occupant and the relative cabin intrusion for the parametric study.

LOWER LEG PARAMETRIC STUDY

Methodology

Initial experience within the LLIMP project has shown that the optimum method for reducing lower leg loads to a predetermined level is by using a combination of different parameters rather than one alone. For example to reduce the probability of longitudinal ankle lock-up occurring, rather than just reducing footwell intrusion, with large modifications to vehicle structure, it can be better achieved by combining the effects of reduced pelvis forward motion (seat and restraint system), foot initial position (increasing the foot/tibia angle) and reducing footwell rotation. To enable this methodology to be successfully applied to vehicle design the sensitivity of the Hybrid III lower leg must be evaluated both in terms of kinematics and loads for all parameters. From this the optimum parameters, at both the vehicle concept and development stages, can be selected, for achieving the best solution for least vehicle modification.

In an appraisal, over 30 different parameters were judged to have a significant effect on lower leg kinematics and loading mechanisms. To conduct a full parametric study evaluating the sensitivity of each parameter with its interaction with other parameters would be extremely difficult and time consuming, even using the F.E. lower leg and cabin model. However two factors can be used which significantly simplify the problem.

Firstly, from the analysis of lower leg kinematics two main loading mechanisms have been identified: inertial loading, which predominantly occurs in Phases 1 and 2, and quasi-static loading in Phases 4 and 5. Only parameters which affect each specific loading mechanism need be evaluated in combination.

Secondly, most passenger vehicles are designed around a standard sized occupant (nominally 50^{th} percentile male), with seat and steering wheel adjustment to accommodate the variance in the population. Therefore components such as control pedals, footrests and dashboard are all located within a relatively standard envelope for most vehicles. A baseline cabin model was formulated whose component locations were based on the median locations as measured from a number of different sized passenger cars. As most vehicles component locations will not be significantly different to the median cabin model the problem of combining the effect of different location parameters was significantly reduced. Obviously the effect of the different seating positions in sports cars or sport/utility vehicles would be treated as special cases.

The parametric study commenced by assessing the sensitivity of each parameter individually. The effect of combining parameters was then evaluated where parameters were strongly linked. An example of this is for the specific loading mechanism of ankle lock-up, where footwell translation, footwell rotation and pelvis forward motion are intrinsically linked.

In the parametric study all the parameters which potentially affect lower leg kinematics and loading have been divided into three main categories.

- Vehicle structure
- Occupant kinematics
- Footwell geometry

Table 1 shows the main parameters for each of the above categories. Initial results of the parametric study are given below, whilst more in-depth computer simulation is on going for each of the parameters.

Structural Characteristics

The structural performance of the vehicle has a significant affect on Hybrid III lower leg kinematics and subsequent loading. The intrusion profile of the footwell is dependent upon the vehicle structure's load paths and the interaction of rigid components (engine, gearbox, etc) with the footwell. The intrusion profile of the footwell can be considered a combination of translational and rotational motions, see Figure 5.

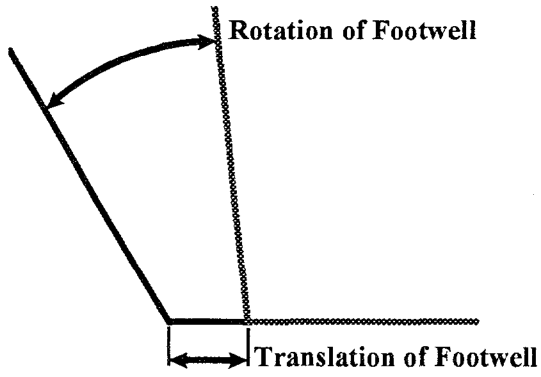

Figure 5: Footwell Motion

Analysis of vehicle crashes from the LLIMP crash test database, shows maximum footwell translations of 250mm, and rotations of 25°. With maximum pelvis forward trajectory of 300mm, this produces over 600mm relative motion at the foot.

Quasi-static loading is produced when the ankle rotates and reaches its end stop. Further rotation produces a bending moment in the tibia which increases the resulting tibia index. In a typical vehicle this occurs after an ankle rotation of approximately 45°. At the same time a pelvis forward motion or footwell translation of 200mm represents an ankle rotation of approximately 24°. It is clear that a combination of intrusion and pelvis forward motion increases the likelihood of ankle lock-up.

Ankle lock-up and subsequent loading is sensitive to both translation and rotation of the footwell.

Totally eliminating intrusion into the passenger compartment during the European frontal crash test is extremely challenging with current vehicle design. However load path management should aim to control the levels of intrusion and in particular minimise footwell rotation. This will greatly reduce the risk of ankle lock-up and the subsequent increase in tibia loading.

Figure 6 shows the reduction in tibia bending moment that can be achieved with a 50% reduction in footwell rotation. This delay and reduction in quasi-static load is due to the reduced footwell rotation delaying the onset of ankle lock-up and subsequent tibia bending moment.

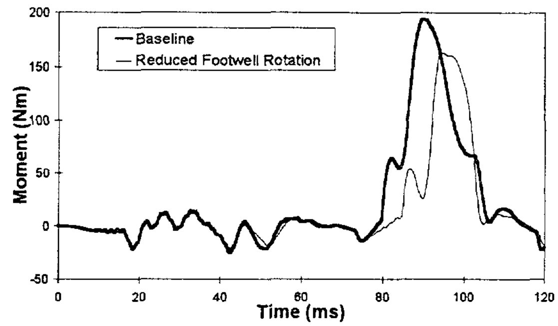

Figure 6: Effect of Reduced Footwell Rotations on Bending Moment

The generic baseline model used 100mm translation, 20° rotation and 230mm pelvis forward motion.

Occupant Kinematics

The motion of the pelvis had a significant effect on the level of ankle rotation and subsequent tibia loading. The greater the pelvis forward motion the greater the level of ankle rotation. This results in increased quasi-static lower leg loading.

This pelvis forward motion is controlled by the seat, restraint system and knee contact with the instrument panel. Effective management of these systems can reduce the level of pelvis forward motion. However it cannot be entirely eliminated as it is necessary in reducing occupant injuries due to vehicle deceleration.

Figure 7 shows the reduction in tibia bending moment that can be achieved with a 25% reduction in pelvis forward motion.

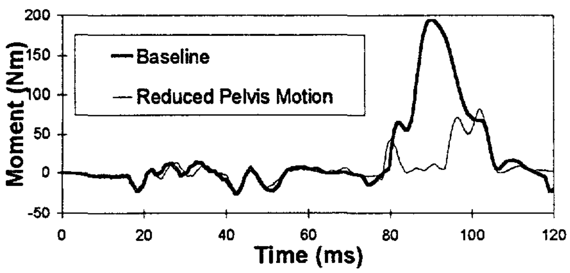

Figure 7: Effect of Reduced Pelvis Motions on Bending Moment

Figure 8 shows the reduction in tibia compressive load, F_z during the quasi static loading phase which runs from approximately 75 to 105ms. However the inertial loads 20 to 60 ms remain unaffected.

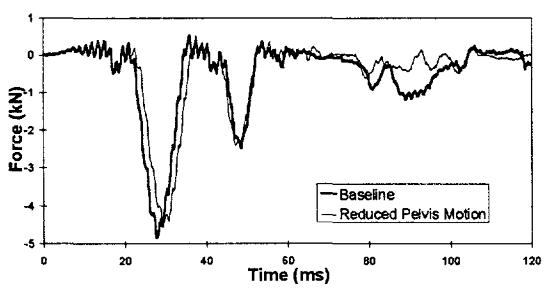

Figure 8: Effect of Reduced Pelvis Motions on Compressive Load

The lower leg loads are very sensitive to the magnitude and timing of pelvis forward motion.

If tibia loads are to be minimised it is important that the intrusion, ankle lock-up and pelvis forward motion should be controlled. If ankle lock-up can be delayed the subsequent tibia loads are reduced.

The lower leg kinematics determine the interaction of the knee with the knee bolster. The entrapment of the knee in the bolster has an affect on the three dimensional response of the lower legs and the axial load that can develop.

Footwell Geometry

The initial geometry of the footwell has a significant affect on lower leg kinematics and subsequent loading. The angle of the footwell affects the inertial and quasi-static loading on the lower leg.

A shallower footwell angle will result in reduced upper tibia inertia loading. This will increase tibia axial load but the current tibia index is much more sensitive to bending moments. The shallower angle also increases the amount of ankle rotation which is necessary to achieve ankle lock-up. This delays ankle lock-up and therefore reduces subsequent tibia loading. The distance of the footwell from the occupant also affects the tibia loads. The greater the distance the greater the relative velocity of the lower legs and the vehicle structure. This increases the inertia loads that are produced when the feet contact the structure. This distance also determines the degree of ankle rotation before lock-up. This affects the timing of lock-up and subsequent tibia loading.

Further Studies

Further analysis of the parameters that affect lower leg loading is being conducted.

The stiffness of the footwell determines the load that is transferred though the vehicle structure to the occupant. This has an affect on the lower leg loads during the inertial and quasi-static phases.

The three dimensional response of the Hybrid III lower leg is an important aspect of understanding the loading mechanisms. The geometry and intrusion characteristics of the footrest and pedals determine the stability of foot contact. Instability leads to lateral ankle rotation and subsequent tibia lateral bending moment. This lateral bending moment can be greater than the longitudinal bending moment.

Further parametric studies will determine the contributions that these and other parameters have on lower leg loading.

CONCLUSIONS

With increasing awareness of lower leg injuries and inclusion of lower leg injury criteria in the new European Frontal Impact Directive, automobile manufacturers are now focusing on footwell, footrest and control pedal design. An objective of the Lower Leg Injuries and Methods of Prevention Vehicle Design Project is to produce a set of footwell design guidelines to assist the vehicle designer in selecting the optimum parameters. Experience has shown that the best method of reducing lower leg loads is by reducing the effect of a number of parameters rather than concentrating on one.

The objective of the parametric study was therefore to evaluate the sensitivity of the HIII lower leg to the effect of changing over 30 parameters for both kinematics and loads. In order to conduct such a large study a Finite Element lower leg model has been developed and validated to both sled and crash test lower leg data.

The parameters have been divided into three main categories:-

- Vehicle Structure
- Occupant Kinematics
- Footwell Geometry

Analysis of the main parameters have shown the relationship between both footwell rearward and pelvis forward motion result in reducing the tibia / foot angle and therefore increase the probability of ankle lock-up occurring. Reducing footwell rotation delayed the onset of ankle lock-up and reduced tibia bending moments, while reducing pelvis forward motion reduced both axial loads and bending moments. Increasing the initial foot angle also delayed ankle lock-up and subsequent tibia loading.

The lower leg with the associated cabin model now provides a powerful tool for footwell design as the complex dynamic interaction between the lower leg and footwell can be simulated. The parametric study has identified the critical parameters, with their loading mechanisms, which can be used to optimise footwell design.

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Vehicle Structure		
Dynamic Intrusion	Rotation start	ms
	Rotation initial acceleration	rad^{-2}
	Rotation rate	rad^{-1}
	Rotation total amount	rad
	Translation start	ms
	Translation initial acceleration	ms^{-2}
	Translation rate	ms^{-1}
	Translation total amount	m
	Pedal lateral motion	m
	Footrest lateral motion	m
Occupant Kinematics	Pelvis forward motion total amount	m
	Pelvis forward motion rate	ms^{-1}
	Seat base angle	deg
	Seat anti-submarine characteristics	kNm^{-1}
	Initial foot/tibia angle	deg
	Heel longitudinal location	m
	Heel lateral location	m
Footwell Geometry	Toeboard angle	deg
	Footwell-toeboard curvature	$degm^{-1}$
	Pedal upper pivot location	m
	Footrest/pedal longitudinal location	m
	Footrest/pedal lateral location	m
	Footrest/pedal width	m
	Pedal distance of travel	m
	Pedal stiffness characteristics	kNm^{-1}
	Footrest/pedal surface friction	N
	Footrest angle	deg
	Footwell stiffness characteristics	kNm^{-1}
	Carpet/underlay thickness	m
	Carpet/underlay characteristics	kNm^{-1}
	Carpet friction	N
	Lower dashboard longitudinal location	m
	Lower dashboard angle	deg
	Lower dashboard characteristics	kNm^{-1}

Table 1 Footwell Design Parameters