DEVELOPMENT OF A PEDESTRIAN LEGFORM TO ASSESS SENSORS USED IN ACTIVE PEDESTRIAN PROTECTION SYSTEMS

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ABSTRACT

This paper reports on the development of a new legform to test contact sensors of active safety systems that could be used to deploy pedestrian protection systems. To test the systems accurately a test tool is required with properties that are as close as possible to human responses. Current legforms were not designed to test sensors, but were designed to assess passive protection by imparting a concentrated force to selected parts of the vehicle. Due to the characteristics of the legform it is believed that the bumper sensor threshold could be set too high, causing a late deployment or even preventing the active system from deploying. The possibility of serious or life threatening head injuries occurring could be increased if the active system does not deploy as intended.

To achieve a better force distribution on the bumper sensors, the revised impactor needs to be as biofidelic as possible. Data on the mechanical properties of human bone and flesh have been researched and materials selected to provide the most realistic response during a vehicle to pedestrian impact. The purpose of the impactor is to assess contact sensor technology that could be used in active safety pedestrian systems to distinguish an impact between a vehicle and a pedestrian and a vehicle and another object. The paper reviews the legform design specification in terms of its requirements and biofidelity data. Through finite element modelling, the use and limits of the test tool with regard to bumper reference height and the use of an upper body mass are discussed.

INTRODUCTION

With the advent of active safety systems, vehicles are now being fitted with devices to improve the protection offered to pedestrians and other vulnerable road users should they be involved in an impact with a vehicle. These active systems can take the form of pop-up bonnets or A-pillar airbags for example. The method of detection of the pedestrian or other vulnerable road user can be by contact sensors, pressure sensors, infra-red sensors (to name just a few), or a combination of these. The detection systems are usually fitted into the bumper region of the vehicle as this is generally the first point of contact and thus provides the greatest time to determine if deployment should occur or not.

The design and use of active safety pedestrian systems has come about through the requirement for greater levels of pedestrian protection and thus the requirement for pedestrian 'friendly' vehicles. It is hoped that with these systems the number of pedestrians that are killed or seriously injured will reduce. However, to develop and to test the effective deployment of these devices it is important that the properties of the test tool are closely matched to those of the human being. This will provide the most realistic response for the impactor and will provide a more realistic loading characteristic of the bumper and the detection system.

IMPACTOR DEVELOPMENT

Age Selection

Stats 19 pedestrian accident statistics for a period of five years (1997-2001 inclusive) were analysed to highlight which age group was at the highest risk. The Stats19 data displays the information in terms of age of the casualty. It was decided that the statistics could be divided into two main group areas, these being Child and Adult. The child group included the casualties of 0-17 years old and the adult group included casualties of 18-99 years old.

If all severities of injury and both sexes are considered then the number of child casualties is greater than the number adult casualties by less than 1% with approximately 10,026 children and 9,937 adults injured on average per annum (Figure 1). However, this includes slight injuries and although these are of concern the pedestrians that require greatest consideration are the killed and seriously injured casualties. If the total casualties are split into fatal, serious and slight injury categories then the data shows that the adult group makes up approximately 59% of the killed and seriously injured pedestrians. The data suggests that the adult group is an appropriate focus for the development of the new test tool. If the data statistics are split between male and female sexes in the adult category then the males represent approximately 61% of the adult population for the killed and seriously injured pedestrians. The

Stats19 data analysis would suggest that an adult male pedestrian is at most risk of being killed or seriously injured by being involved in an impact with a vehicle.

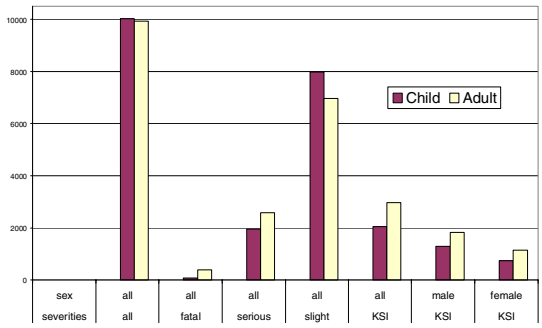

Figure 1. Pedestrian accidents average per annum for child and adult groups (1997–2001 inclusive).

The adult group was selected as the most common. Although the group had been determined the respective 'age' of the impactor had not. This was necessary as it would be used to determine the material properties of the bone. It is known that bone properties reach a peak and then deteriorate with increasing age. Consequently, it was believed that if the properties of the impactor bone were set to those of an elderly person the impactor could be too weak and result in otherwise pedestrian-friendly vehicles being inappropriately assessed. Similarly if the materials were set to those of a young adult (18-20 year old) the bone could be at its strongest and would therefore not truly represent the population. It was decided to design the impactor with the biomechanical properties of a 50-59 year old male. This age bracket will provide a middle position between the old and the young.

Size selection

Current pedestrian legform impactors are representative of a 50th percentile human leg. A concern is that the height of the 50th percentile male may not represent the worst case impact configuration in regard to testing the deployment of active safety systems. For example, child or small adult pedestrians may impart a smaller load upon the sensors and the system may not register an impact with a human and may not deploy. If shorter pedestrians and consequently shorter legforms were used then it is likely that an upper body mass would be required to provide a realistic human body response. It is also likely that the pelvis of the human would contact with the bumper or bonnet leading edge of the vehicle.

Alternatively, the worst case may be a tall elderly person, with longer and potentially weaker limbs – the breaking load required to cause fracture in a lateral impact might be less than for other sized pedestrians. A lower breaking load would suggest that a lower force signal would be recorded by the sensors. There is a general debate as to the 'true worst case'; however, it is believed that protection should be afforded to all potential impact casualties. The initial development of the legform concentrated on a 50th percentile male with the intention that a larger family of the impactors be developed to cover all relevant casualty sizes. The 50th percentile provides a good representation of the population and thus, although it may not be classified as the worst case size, the largest proportion of the pedestrian population will be covered by this size. The intention to develop a 'family' of different sizes would also prevent optimisation of active safety systems to protect only one size of pedestrian.

Finite Element Modelling

With the development of any pedestrian impactor legform it is important to consider the requirement of an upper body mass for the impactor. In actual impacts the mass of the thorax of the human will contribute to the direction of travel. In an impactor the upper body mass may not be necessary for impacts where the vehicle bonnet leading edge does not contact the upper region and pelvis of the legform or where the vehicle does not impact above the centre of gravity of the leg. Impacting above the centre of gravity of the leg would cause the legform to be overridden, which is not believed to be realistic. In impacts with humans, if the impact is above the centre of gravity of the leg but below the centre of gravity of the human, the upper body mass will still cause the body to 'wrap-around' the vehicle.

For children and smaller adults it is possible that the pelvis region of the body will interact with the vehicle bumper or bonnet leading edge. It was decided that the legform would be based on a 50th percentile male, therefore it was important to assess whether the impactor would require an upper body mass for impacts with vehicles that could potentially be fitted with active safety systems.

A finite element modelling (FE) study was performed and two models were set-up in the LS-DYNA code. The first model featured an adapted Hybrid III dummy and the second model consisted of the right leg of the Hybrid III dummy model; both were placed in a standing position and put in front of a vehicle model. The Hybrid III 50th percentile model is an occupant dummy and consequently is designed to be used in a seated position. It was necessary to modify the model to allow it be orientated in a standing position. The

standing model is shown in Figure 2. The knee, ankle and hip joints were rotated to provide a standing dummy. The right leg was straight with the left leg rotated at the hip to provide a realistic walking action with the foot off the ground. It was considered unlikely that the pedestrian would be struck whilst having both feet on the ground and both legs straight. Friction between the pedestrian's shoe and the ground was modelled using a spotweld. (The term spotweld is used in FE modelling and enables the user to define a point to have a pre-determined failure load, in this model once the predetermined load was reached the foot and legform would be free to move). The right arm of the dummy model was placed in a raised position to remove any interference between the arm and the bumper or bonnet leading edge.

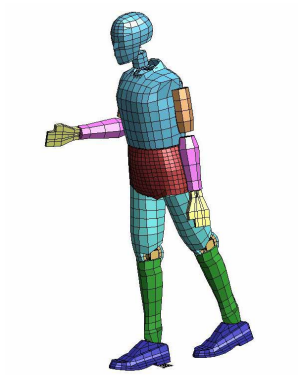

Figure 2. The modified Hybrid III 50th percentile 'pedestrian' dummy model.

To create a separate legform model that could be used to evaluate the need for an upper body mass the modified Hybrid III 'pedestrian' model was further modified. All sections except the first struck leg (right leg) were deleted from the model (Figure 3). The friction generated by the spotweld in the 'pedestrian' model was removed.

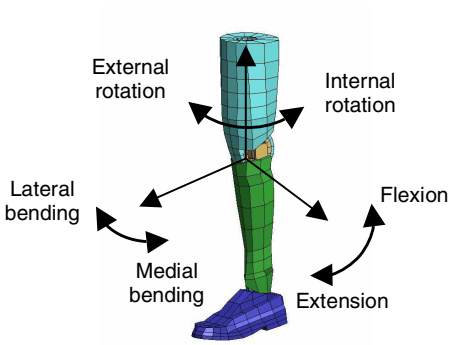

Figure 3. The legform model from the modified Hybrid III 'pedestrian' dummy model.

To replicate the knee joint and to enable it to respond in a humanlike manner the knee was remodelled. The knee was modelled with a spherical joint that consisted of three degrees of freedom. For the lateral and medial directions the knee joint was set to have a plastic response with a stiffness of 200Nm. The lower leg is able to move further in flexion than in extension thus the knee joint was set to have 100 degrees of motion in flexion and 30 degrees in extension. The neutral (standing position) was set at zero degrees.

The 'pedestrian' model and the legform model were impacted by a model of a generic pedestrian-friendly vehicle. To model the vehicle, rigid steel plates were used for the bumper and bonnet with low density foam mounted on the surface. The chassis of the vehicle was represented by rigid plates and springs. These were attached to the rear of the bonnet and the bumper and were given a stiffness of 5kN/m to represent a generic stiffness of a pedestrian-friendly vehicle. The motion of the plates was constrained in all directions except for the direction of travel of the vehicle. Additional mass was added to the rigid plates and distributed to represent the mass of a real vehicle. The bonnet leading edge was inclined at 50 degrees to the horizontal and the bonnet 15 degrees to the horizontal. The vehicle was given an initial velocity of 11.1m/s.

To assess the legform impactor capabilities it was necessary to model the impacts with vehicles of differing bonnet leading edge and bumper top heights. A small study of the heights of a range of vehicles was performed. Table 1 shows the test matrix that was defined for each of the models to provide an assessment of the range of vehicles available.

Table 1.

Matrix of vehicle dimensions used in the models

Height (mm)		
Bonnet leading edge	Bumper top edge	Bumper bottom edge
1000	800	500
1000	700	400
900	650	350
850	600	300
800	550	250
700	500	200
700	450	150
Undefined	400	100

To simulate off-road vehicles the bumper top edge height was set at heights of 700 and 800mm above ground. For the sports car range a bumper top height was set at 400mm with no bonnet contact

defined. The bumper lead was set at 100mm in all model cases.

The two models are shown in Figure 4 immediately prior to impact.

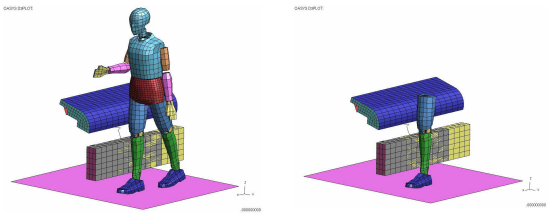

Figure 4. The 'pedestrian' and legform models immediately prior to impact.

The results of the model runs showed that the impact in the region of the legs was essentially complete by 25ms. After this time the pedestrian had 'wrapped around' the vehicle and contacted the bonnet top. It was found that good correlation occurred – in terms of legform kinematics and force on the bumper surface – between the 'pedestrian' and legform models for bumper top heights between 450 and 650mm (Figure 5).

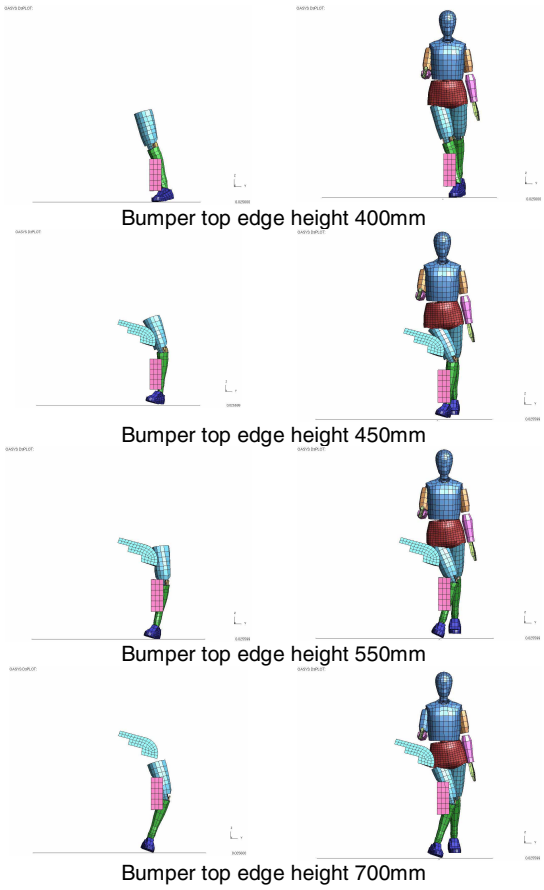

Figure 5. The legform and 'pedestrian' model animations with different bumper top edge heights.

Bumper top edge heights below 450mm exhibited rotation in the legform model on impact with the bumper. The rotation resulted in the anterior surface of the legform contacting the vehicle model. This was not seen in the 'pedestrian' model and was considered to be an unrealistic representation. At bumper top heights greater than 650mm it was noted that the bonnet top was impacting directly with the pelvis of the 'pedestrian' model and thus passed directly over the top of the legform model. This is again believed to be unrealistic; at heights such as these the impactor is likely to require an upper body mass to realistically represent impacts with humans.

Although the kinematics of the legform and the 'pedestrian' model differed significantly at bumper top edge heights below 450mm and heights above 650mm the model kinematics were considered good between these values. A slight additional rotation about the z-axis of the leg was noted to occur in the legform model that was not noted in the 'pedestrian' model. This was believed to be due to the foot altering the inertial properties of the leg due to it not being restrained from rotation at the pelvis. To reduce the possible rotation in the actual legform it was decided that the front section of the foot be removed and the weight added to the heel. The correct legform mass and inertia will be retained without the foot causing it to rotate.

The study into the impact performance of the legform model and the 'pedestrian' model indicated that physical testing with a single 50th percentile legform impactor without an upper body mass would be appropriate with car front profiles that have bumper top edge heights between 450mm and 650mm. Although the modelling suggests that sports cars (whose bumper top edge heights may be below 450mm and are more likely to be fitted with active systems) may not be able to be tested with the legform, the modelling needs to be verified and validated with physical testing.

Biomechanical Property Research

<u>Bone Property Research</u> - To provide a definitive value for the biomechanical properties of human flesh and bone that would cover all sections of the population would be impossible. It is known that the bone properties, for example, change with increasing age. Peak bone strength is reached at an age of approximately 20-29 years, after which the bone strength will gradually reduce. Yamada [1] quotes that the strength of the femur long bone will deteriorate by approximately 17% by the age of 70-79 years from its peak value. The Yamada data shows that the strength of the femur long bones in the selected age group of 50-59 years will be

approximately 8% less than the 20-29 year old group.

In addition to the bone properties varying as the person grows older, it is also reported that the bone properties can vary between people of the same age. Environmental conditions, diet, fitness levels and illnesses are all contributory factors that will affect the strength of the human bones and will contribute to the bones being different for each individual. To provide data that can be used to estimate the strength of human long bones the average values for each age group can be used.

There has been a large amount of research completed into the strength of the human bones. However, the method of testing these bones has often been performed slightly differently in terms of how the specimen is treated prior to testing (whether it is fresh, dried, previously frozen etc) and whether it has been tested dynamically or quasi-statically. Also, the section and direction of the bone tested will affect the output of the results. It was not possible within the scope of this development project to conduct biomechanical testing of human long bones. The research data previously collected together by Yamada [1] has been widely used and acknowledged and for these reasons it was considered to be suitable for use in developing and determining the bone strength that would be used in the legform. One aspect that distinguishes the Yamada data is that all of the specimens used in the research were fresh and unembalmed.

It can be assumed that most impacts between pedestrians and vehicles result in a perpendicular loading to the long bones of the human leg. Due to the perpendicular loading direction the bending properties of the bone material are considered. Yamada reports on the bending breaking load of intact specimens of the femur and tibia that are supported under their ends and loaded with a compression tester with a head of 20mm diameter. The results from the bending breaking load tests performed by Yamada are shown in Table 2.

Table 2.

Bending breaking load (kg) of human wet long bones [1]

Bone	Age Group					Adult Average
	20-39yr	40-49yr	50-59yr	60-69yr	70-89yr	
Femur	277±11	252±5	240±9	238±6	218±11	250
Tibia	296±11	257±11	248±5	244±9	234±9	262
Fibula	45±2	41±4	40±3	38±2	34±2	40

The data shown in Table 2 is for long bones tested in the anteroposterior direction. Most impacts between vehicles and pedestrians are likely to occur in the lateral direction. However, Yamada noted that *"…there is no significant difference in the ultimate strength or in the bending breaking load between the anteroposterior and the lateromedial directions"*. The properties listed in Table 2 were therefore used for determining the material specification for lateromedial loading.

Yamada also reports data for the fibula, which is the bone adjacent to the tibia. It is possible to stand without the fibula being present as it provides little support in the standing position. Its main role is to provide support as the leg twists; without a fibula this motion would not be possible. The bending load required to break the fibula is approximately six times smaller than that of the tibia; the ultimate deflection of the fibula is approximately 37% greater than that of the tibia (Table 3). The fibula can therefore be said to have little contributory effect on the performance of the legform in bending due to it having a larger deflection and significantly lower bending breaking load than the stronger tibia. It was decided that the fibula would not be included in the design of the legform.

Table 3.

Ultimate deflection (mm) of human wet long bones, approximated for lateromedial direction

Bone	Age Group					Adult Average
	20-39yr	40-49yr	50-59yr	60-69yr	70-89yr	
Femur	16.0	14.8	13.8	13.3	12.5	14.4
Tibia	13.0	12.0	11.2	10.9	10.1	11.7
Fibula	21.1	19.0	18.1	17.3	15.3	18.6

The data for the ultimate deflection of the human wet long bones was originally provided by Yamada in the anteroposterior direction. Yamada found that the ultimate deflection in the anteroposterior direction was approximately 30% less than the ultimate deflection in the lateromedial direction for the tibia. The actual difference was not recorded for the femur and fibula but was stated to be similar to the tibia conversion factor. Table 3 shows the ultimate deflection of the human wet long bones adjusted from the anteroposterior direction to the lateromedial direction.

The properties highlighted in Tables 2 and 3 were used in selecting the material that would be used for the bone sections of the legform. The material selected for the bones is an epoxy filled glass fibre cylinder, which is calculated to have properties

similar to the required values discussed above. Both the femur and tibia will be manufactured from the same type of material. To achieve the different performance criteria of the femur and tibia the internal dimensions of the material will be altered. In addition to good stiffness performance, the failure mode of the material is known to be similar to that of bone with little deflection and creep before fracture occurs.

Flesh Property Research - The lower limb of the human consists of the femur, tibia, fibula, ankle and foot bones, numerous muscles, tendons, nerves, veins and fat etc. A legform with individual muscles and tendons would result in a complex device. For the purpose of this legform it was decided that individual muscles and tendons would not be required. For the development of the test tool the 'flesh' will consequently consist of all parts of the human leg apart from the bones and the skin. The bones and the skin are considered separately.

It was found that the biomechanical properties of bone altered with age and it was found that the properties are different even between people of similar ages. It was considered that this would also be the case for the flesh. If the human that was impacted by a vehicle was fit and healthy it is likely that the muscles would be stronger and would need to be represented by a potentially more dense material. On the other hand should the human that is being impacted be of a relatively weak build they will have less muscle mass and consequently the material required to represent the flesh would need to be less dense. In this instance the term dense refers to the amount of muscle compared to the amount of fat and vice versa and not the material property.

Research has previously been performed on the density of human fat and muscle. Human fat is known as adipose tissue and has an approximate density of 0.92g/cm^3 (Table 4). The density of muscle is found to have a greater range than that of the adipose tissue. It is assumed that the difference could be due to the assessment methods and the specimens tested could well have been obtained from people of differing levels of fitness. The density of was found to be approximately 1.08g/cm^3 (Table 4). As the human leg consists of a combination of muscle and adipose tissue the required density of the legform will be within the range of 0.9g/cm^3 and 1.08g/cm^3. Cross-sections of the human leg show that the majority of the soft tissue is muscle, rather than adipose tissue. For this reason the material for the flesh was selected with a density towards the higher end of the range (approximately 1.03g/cm^3 – 1.06g/cm^3).

Table 4.

Comparison of the densities of adipose tissue and muscle

Source	Adipose Tissue (Extracted human fat)	Muscle/rest of body
Ref [2]	0.940	1.082
Ref [3]	0.918	1.100
Ref [4]	0.948	1.090
Ref [5]	0.901	1.061
Ref [6]	0.900	1.100
Ref [7]	0.900	1.060
Average	**0.918g/cm^3**	**1.082g/cm^3**

For pedestrian impacts it is assumed that the person is impacted whilst the weight is directly above one straight leg (on the struck side) with the non-struck leg off the ground. Immediately prior to the impact between a vehicle and a pedestrian it is assumed that the majority of pedestrians will become aware of the impending impact. The awareness of the impending impact is likely to cause the pedestrian to tense the muscles in the leg due to the shock of an impact occurring. In the few impacts where the pedestrian is not aware of the impending impact some of the leg muscles will be tensed anyway as part of the natural walking or running motion. Consequently the material selected for the flesh of the legform will represent the human leg in its tensed state. It was considered necessary to evaluate the hardness of human flesh in the tensed state as this would contribute to achieving a material with humanlike responses.

To measure the hardness of flesh, people were selected that were approximately 50th percentile in height and who were in a good level of health and fitness. A handheld Instron Shore 'A' Durometer (Figure 6) was used to measure the flesh hardness.

Figure 6. The Instron Shore S1 Durometer hardness tester with the Shore 'A' indentor.

The hardness value is determined by the level of penetration of the indentor into the material. If the indentor does not penetrate the material the recorded value will be 100 and if the indentor penetrates the material completely the recorded hardness value will be 0. The Shore 'A' scale was used as this is used to measure the hardness of soft rubbers and plastics.

Each person was tested with the Durometer hardness tester a number of times to provide an average value. Repeating the tests reduced the possibility of anomalous results through the user applying different levels of pressure when using the durometer. Figure 7 shows the procedure used to measure the hardness the legs of the volunteers.

Figure 7. The Shore Durometer hardness tester in use on one of the volunteers.

The hardness of the leg was assessed in both the relaxed and tensed states. Although the whole leg was tested (624 points) on one of the volunteers, the calf and thigh muscles were considered to provide the most relevant results. Along the front of the tibia (shin region) the results would be influenced by the limited amount of flesh between the indentor and the bone.

A summary of the results of the hardness testing of the calf and thigh muscles of the volunteers in both the relaxed and tensed states is shown in Table 5. The hardness was found to be approximately 10A for the muscles in the relaxed state compared to approximately 14A for the muscles in the tensed state.

Table 5.

A summary of the results of the Durometer hardness testing of the volunteers (Shore 'A')

Person	Relaxed		Tensed	
	Calf	Thigh	Calf	Thigh
Volunteer 1	9.64	10.04	15.17	15.17
Volunteer 2	8.89	15.09	14.26	16.90
Volunteer 3	11.98	9.13	12.89	13.69
Volunteer 4	9.48	9.12	11.63	13.28
Average	10.42		14.13	

The front of the tibia of volunteer 1 was tested to investigate what influence the bone being close to the surface had on the hardness value. It was found that the hardness in this region increased to approximately 20 – 25A, but this would not be representative of the hardness of the lateral aspect of the lower limb, which is the most likely bumper contact point in a pedestrian impact. As a result the material specification for the flesh was between 14 and 15 on the Shore 'A' scale, along with a density between 1.03g/cm^3 – 1.06g/cm^3.

Based on the results of the hardness testing and the analysis of the density of the flesh (muscles and adipose tissue) many flesh materials were considered, including soft rubbers and different composition polyurethanes. Figure 8 shows a selection of the materials that have been considered for this application.

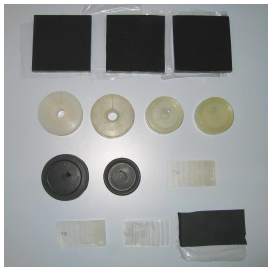

Figure 8. A selection of some of the materials considered for use in making the flesh.

Finally a polyurethane material was selected for the flesh that has a density in the required range and a hardness of approximately 15A on the Shore 'A' scale.

Skin Property Research – The skin of the legform impactor will have three roles.

- To act in compression as the skin of the human would
- To provide protection to the legform as it impacts with the vehicle to make it more robust, and
- The skin layer will be sufficiently thick to represent the clothing that the pedestrians will be wearing.

The human skin layer ranges in thickness from 0.5-4.0mm depending upon the location [8]. The skin layer selected for the legform is a neoprene material that has a thickness of approximately 3mm.

Knee Ligament Research - The knee consists of many tendons and ligaments. Depending upon whether the leg is in its straight position or in its bent position some of the ligaments will be relaxed and some will be tense. If the knee ligaments are damaged, for example in an impact with a vehicle, then the casualty can have problems walking in the future. Ligament damage can lead to many disabilities and can require a long time for healing and rehabilitation [9].

Similarly to the bone and flesh material, the strength of the knee ligaments has been the subject of considerable debate. The ligaments in the current EEVC WG17 legform impactor have an approximate stiffness of 400-500Nm. It has been discussed that this stiffness is higher than the ligaments of the average person and it has been suggested that the stiffness of the ligaments should be nearer to 200Nm. It is unclear whether this stiffness takes into consideration the effects of muscle tension. It was therefore decided that a ligament of approximately 250-300Nm would be used for the initial legform impactor. This range is above that used in the FE modelling, however, once bending ligament stiffness has been agreed by biomechanical groups, it will be possible to adjust the stiffness to the required limit.

The initial design of the ligament is shown in Figure 9. The rounded design allows impacts from different angles to be assessed. The stiffness of the ligament would be altered to represent the stiffness of the human ligaments in the different impact configurations. This allows the active safety systems to be tested in many different impact configurations. For example, the impact to the human could be from the rear where the stiffness in the ligaments would be different to the stiffness in the ligaments if the impact was from the front.

Figure 9. The shape of the ligament will provide an opportunity to tests at different impact angles.

Anthropometric Measurements

It was decided that the legform impactor would represent a 50th percentile male. The measurements for a 50th percentile male were obtained from anthropometric data. For the development of ATD's that are used in vehicles the UMTRI anthropometric data is used. However, the UMTRI measurements are taken with a seated occupant. The leg shape of a seated occupant is different to that of a pedestrian hence the Adultdata [10] source was used.

A volunteer was measured and the results compared with the 50th percentile anthropometric data. It was found that the tibia and knee of the volunteer were within approximately 2-3mm of the measurements for the 50th percentile male. The femur length of the volunteer was found to be slightly longer than that of the 50th percentile male; however, this was not considered to cause concern as the femur section of the impactor would be moulded to the length applicable to position the hip end for mounting to the propulsion system. The anthropometric data was also used to compare the circumference of the volunteer and the 50th percentile male. The human leg is not a perfect circle but in order to evaluate the approximate differences between the radiuses of the leg measurements the legs were assumed to be of circular cross-section.
Table 6 shows a comparison of the measurements of the circumference of the volunteer's leg and the mean adult data.

It was found that the radius of the leg of the volunteer was approximately 1.3mm smaller than the approximate radius of a 50th percentile male. As the leg of the volunteer was used it was necessary to increase the approximate radius of the legform. The skin layer selected for the legform has a thickness of approximately 3mm. This skin layer will increase the radius of the legform and will also provide a small allowance for the thickness of the clothing that the pedestrian would be wearing.

Table 6.

Comparative measurements for the circumference of the 50th percentile male data and the volunteer (mm)

Position	Adult mean data	Approx Radius	Volunteer data	Approx Radius	Difference
Thigh top	590.6	94.01	578.0	92.01	-2.01
Thigh bottom	375.0	59.69	379.0	60.33	0.64
Knee crease	382.2	60.84	365.0	58.10	-2.74
Knee cap	385.0	61.29	373.0	59.38	-1.91
Knee below	360.3	57.35	335.0	53.33	-4.03
Calf max	380.8	60.62	374.0	59.54	-1.08
Talus	244.4	38.90	250.0	39.80	0.89
Above talus	226.0	35.98	224.0	35.66	-0.32
Average					-1.32

Position of the Bone

The position of the bone within the legform is important to provide a realistic human response. During an impact between a vehicle and a human leg the vehicle bumper will compress the flesh (muscles etc.) and then contact the femur or tibia bones. If the bone is incorrectly positioned in the legform, as the vehicle compresses the flesh material it will contact the bone earlier or possibly later than would occur in impacts with pedestrians. To investigate the position of the bones within the

leg, cross-sections of the leg were sourced from the Visible Human Project® [11], [12].

The Visible Human Project® consists of detailed cross-sections of a male and female. The male was transversely sliced in 1mm slices with a total of approximately 1871 slices. The male cadaver was sliced with the foot placed in a downwards position. The slice that represents the base of the heel is approximately slice 1790. This translates to an approximate subject height of 1790mm, which is greater than a 50th percentile male. However, it was assumed that the bone position relative to the outer layer of skin would be approximately the same for each human subject. Therefore, by measuring the bone position of the Visible Human cadaver and applying a correction factor to take into account for the differences in cross-sectional width and depth of the leg (between 50th percentile male and the Visible Human cadaver) the bone could be positioned in the 50th percentile male legform impactor.

Measurements of the cross-sectional position of the bone in the leg of the Visible Human male cadaver were taken at 20mm intervals along the length of the leg. The cross-sectional images were downloaded and opened in photo-editing software. The pixel number relative to the outer edge of the flesh was recorded and the corresponding point on the outer surface of the bone. The pixel numbers were then adjusted to represent a dimension calculated from the number of pixels/cm. The measurements were recorded for the front of the leg flesh to the front of the bone and similarly for the rear of the leg. The cross-section dimensions were also measured from the left side of the leg to the bone and similarly for the right side. The cross-sectional width and depth of the bone was also measured (Figure 10).

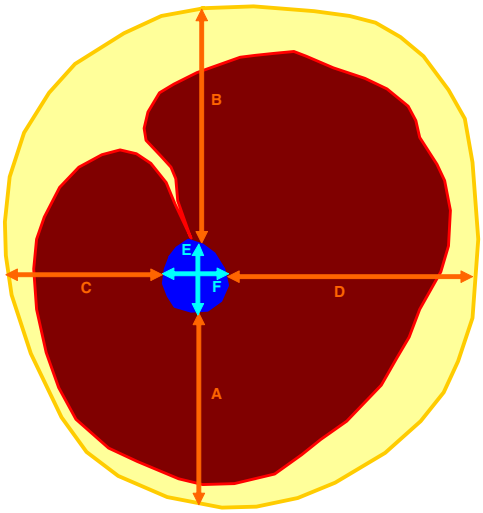

Figure 10. Schematic of a cross-section of the human leg showing the measurements recorded.

The dimensions that were calculated from the Visible Human male cadaver were plotted to check for any erroneous results. These would be highlighted by a misshaped profile. Figure 11 shows the front view profile of the legform.

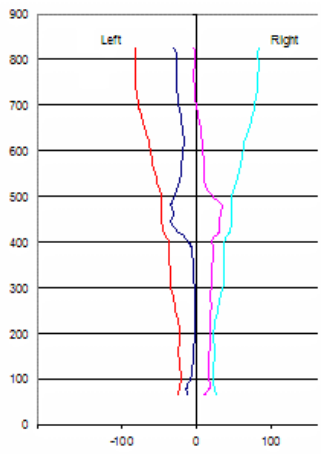

Figure 11. Front profile of the Visible Human male leg created from measurements of the leg.

The bones of the human leg, especially the femur are not straight. It was considered that constructing realistically shaped bones would make the build process very complex and increase the material costs. The shape of the bones would also influence the flight profile of the legform during its propulsion into the vehicle as off-centre masses (due to the shape) would cause the legform to rotate prior to impact, which is an undesirable action. It was therefore decided that the bones for the legform would be manufactured straight. This would have an influence on the position of the bone within the flesh. By using a straight bone the legform impactor would become easier to use as the bone could be removed from the legform and replaced with greater ease. To position the bone as accurately as possible it was considered that the tibia bone, knee region and bottom of the femur were the most important as these were more likely to be impacted by the vehicle.

In addition to positioning the bone within the legform the dimension of the bones themselves needed consideration. It was possible using the same methods as before for obtaining the cross-sectional dimensions of the leg to measure the bone of the Visible Human male cadaver. The femur and tibia bones do not have a perfectly circular cross-section (the tibia has a kite shaped cross-section). Both bones are longer in depth than they are in width at their mid-span position and vice versa at the ends of the bones. The average dimensions of the bones are shown in Table 7. The 'approximate average diameter' is an average of the depth and width values.

Table 7.

Average values for measurements of the cross-sections of the femur and tibia bones

Bone	Average depth	Average width	Approximate average diameter
Femur	26.26mm	30.23mm	28.29mm
Tibia	23.70mm	27.17mm	25.44mm

To retain ease of use and to minimise manufacturing costs it was decided that the bones would be manufactured with a circular cross-section. For the prototype legform the outer diameter of each bone was set to be 30mm as this sized outer diameter was more readily available. The internal diameter was altered to achieve the required bone properties discussed earlier. Although the human femur and tibia bones were found to have different average diameters it was considered that if the outer diameters of the bones were kept the same then it would be possible to insert and remove the bones from either end of the impactor should the bone fracture during its use. The outer diameter (and thus wall thickness) will be reviewed once initial component testing has been completed.

Impactor Foot

It was found during the finite element modelling that the legform rotated slightly at the point of impact which was noted not to occur in the full 'pedestrian' model. The rotation was partly believed to be caused by the foot of the impactor. The front section of the foot was believed to cause the impactor to be unbalanced during the free flight. Consequently, the front of the foot was removed on the legform impactor. By removing the front of the foot section it was intended that it would remove the rotational inertia effects about the longitudinal axis of the lower limb that it caused. This will be confirmed during the full testing of the legform. To retain the foot mass and the inertia effects in the direction of impact, the mass of the foot section removed will be replaced at the heel of the impactor close to the centreline of the bone.

LEGFORM IMPACTOR BUILD

Shaping the Impactor

To replicate the human response it is not only considered necessary to have materials that replicate the human equivalent but also a legform that has a shape of the human leg. To create an exact replica of the leg of the selected volunteer it was decided that it should be moulded. Based on advice from special effects and prosthetics manufacturers regarding the moulding process, it was decided to use a seaweed based extract known as alginate, which is safe to use on the skin and when mixed with water provides an excellent copy of the object being moulded. The alginate has a cure time of approximately 6-8 minutes from the time the water is added. The material needed to be sufficiently mixed and poured within this time.

A wooden box was constructed with steps inside to support the alginate when the volunteer's leg was removed (Figure 12). To achieve a realistic cast, it was necessary for the volunteer to stand with their leg in a straight stance and with the leg muscles tensed.

Figure 12. The wooden box mould showing the support steps and moulding the leg of the volunteer.

Prior to pouring the alginate the leg of the volunteer was covered with petroleum jelly to reduce the possibility of alginate moulding around the leg hairs. The petroleum jelly also acted as a release agent and enabled the volunteer to manoeuvre and slide their leg from the mould without damaging the delicate alginate (Figure 13).

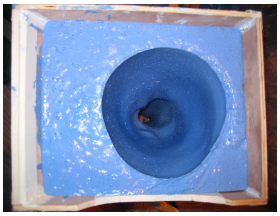

Figure 13. A top view of the alginate legform mould.

The alginate mould is not permanent and therefore plaster casts of the leg were taken within a few hours of the alginate mould being created. The casts were made out of Plaster of Paris and although every attempt was made to remove the air bubbles from the mould as it was poured some surface bubbles were unavoidable. To achieve a smooth finish the legform was smoothed with wet and dry paper and the air bubbles were filled with plaster and filler. Figure 14 shows a side and front view of the plaster cast legform as it was removed

from the mould, prior to the finishing and smoothing process. Throughout the finishing process the plaster leg was checked to ensure that it was dimensionally accurate.

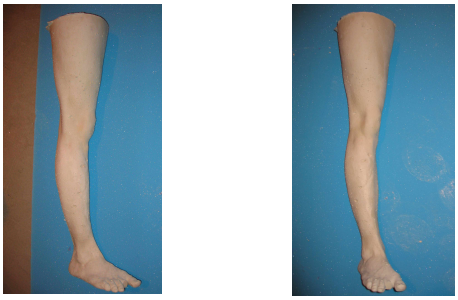

Figure 14. A side and front view of the plaster legform as it was removed from the mould.

It was not possible during moulding of the leg of the volunteer to mould higher than the crotch area. Consequently the legform cast was shorter than required and did not have a hip section. To mould this section of the volunteer would be very complex. It was decided that the top of the plaster legform could be extended to represent the top of the femur and thus the hip section. The profile of the top of the legform was copied and transferred onto sheets of fibreboard. These were cut out and fixed together to create a separate mould (Figure 15). Plaster of Paris was poured into the mould and once cured was removed. The hip section required some refinishing work prior to being attached to the legform itself.

Figure 15. The mould for the top of the femur and hip section.

In order to mould the flesh material, a lightweight, reusable fibreglass mould was made. The fibreglass mould was manufactured in two sections to make the removal of the flesh once it had been moulded much simpler. The surface of the fibreglass mould was smooth and followed the contours of the plaster legform exactly.

As discussed earlier in the paper, the femur and tibia bones are represented by straight cylinders. It was therefore necessary to mould the hollow section in the flesh where the bones would be inserted. To replicate the human leg as much as possible the position of the bone in the flesh was important. The straight bone complicates the accurate positioning of the bone slightly. However, it was decided that the flesh material should be poured into the mould with a metal tube of the correct outside diameter to act as the bone. The metal tube was fixed to a base plate to prevent it from moving during the pouring process. The two halves of the fibreglass mould were then offered up to the tube. The vehicle impact is likely to occur in the tibia and knee regions. Consequently most effort was given to accurate positioning of the straight bone in this region. It was accepted that there would be some deviation from the ideal bone position at the ankle and top of the femur. The position of each half of the mould was then marked and secured in place. The metal tube was used as part of the moulding process only and was removed once the flesh material had cured. Figure 16 shows the two sections of the fibreglass mould and also shows the mould with the metal tube and flesh material during curing.

Figure 16. The two sections of the fibreglass mould and the mould with the flesh during the curing process.

Once cured it was possible to remove the legform flesh from the mould and with the metal tube in place the path of the bone in the leg flesh is clearly visible (Figure 17).

Figure 17. A front and right side photograph of the flesh material. The metal tube used in the moulding process clearly shows the position of the bones.

Knee

The glass-fibre type material selected to represent the bones will fracture should the loads imposed on it be sufficient. The knee ligament is made from metal and thus it is important that the ligament does not impose unrealistic loads on the bone causing it fail prematurely. To overcome the possibility of premature failure and unrealistic stresses induced from the ligament, the ligament is mounted within a sleeve that fits onto the ends of the bones (Figure 18). The sleeves have been designed to support the ligament during its loading and to reduce the stress concentrations between the mating of the materials by having a tapered inner surface. The ligament is secured in the sleeves by the use of roll pins; once the test has been conducted and the entire bone removed from the flesh, the ligament can be removed and changed by removing the pins. The metalwork associated with the knee was kept to a minimum to reduce any effects it would have on the legform in replicating an impact between a vehicle and a pedestrian. The type and thickness of metal used for the sleeves, hip end and foot can be altered to produce the correct inertial effects and centre of gravity position for the legform.

Figure 18. The ligament with sleeves attached. The femur and tibia bones are fitted into the ends of the sleeves.

FUTURE WORK

The legform impactor is currently at the stage of initial testing. The testing phase will involve component tests to evaluate the performance of the material against the required properties. Each of the components will also be tested to evaluate the repeatability and robustness characteristics. It is envisaged that the component tests used in the development phase will also be part of the certification process to ensure that all the components will respond as required. Following the successful completion of the component tests, full legform tests will be performed and the results compared with those from current impactors.

Bone Material

The biomechanical properties of human long bones were found from data produced by Yamada [1]. To verify that the material selected for the bones replicated the human bones, the material will be tested using a similar process to that of Yamada. Yamada used quasi-static loading to test the bending breaking load of wet long bones. To replicate this, the material will be tested in a Hounsfield loading machine with a round bar of diameter 20mm to act as the loading head. The deflection and load to cause failure will be recorded.

Flesh Material

The flesh density has been measured as approximately 1.02-1.04g/cm^3 and so is within the range required for the flesh material. In addition during the moulding process to make each flesh, a small test sample will be poured and will be used to assess the hardness. To determine the robustness of the flesh material the flesh will be subjected to dynamic testing with bones that have a more elastic response than the selected bone material. This will identify the performance characteristics of the flesh.

Knee Ligament

To achieve the desired knee ligament stiffness the selected material will be tested at a component level. This process will be used to certify a batch of ligaments prior to use to establish that each batch will be within a stated tolerance and will return consistent results.

Whole System Testing

Centre of gravity and moment of inertia - Once the component testing is complete the legform will be tested as a whole system to evaluate the moment of inertia and the centre of gravity. If either of these aspects requires adjustment then it would be possible by altering the mass of the material at the hip end, knee and foot.

Dynamic tests - The tests will be conducted using simulated vehicle fronts of varying heights and stiffness and the impact speed will be varied. This test matrix will assess the legform's performance for a generic range of vehicles for which it is expected that this legform could be used and those vehicles to which the active safety systems are expected to be fitted. The dynamic testing will be used to confirm the free flight performance of the legform. A cradle specifically for the legform has been developed to support it during the launch phase and to reduce the possibility of rotation of the legform occurring.

In addition to the tests with the simulated vehicle fronts it is scheduled that full vehicle tests will be conducted with a vehicle that has an active safety

contact sensor system fitted. The response from the vehicle sensors for the legform impactor will be compared with the responses from current full legform pedestrian impactors. It is envisaged that apart from the alteration to the shape of the cradle to support the legform no other changes would need to be made to the current legform propulsion systems.

SUMMARY

Active safety systems are being fitted to vehicles to improve the level of pedestrian protection. To develop and test these systems a test tool was required that had humanlike properties.

As part of the development of the test tool, research was completed into the properties of the femur and tibia bone, the flesh and the knee ligaments. Materials were selected that had the required properties and were expected to provide a realistic humanlike dynamic response.

Anthropometric data was used to select a suitable volunteer whose leg was moulded to provide an exact replica. The plaster cast of the volunteer was used to create a fibreglass mould from which the flesh material was moulded.

The legform is currently at the testing stage, whereby the robustness and repeatability of the test tool will be evaluated and the results used to validate the range of bumper heights for which the tool can be used.

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