SAFETY REQUIREMENTS FOR CYCLISTS DURING CAR IMPACTS TO THE LEGS

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ABSTRACT

The term vulnerable road user (VRU) is most commonly associated with pedestrians and in particular children and the elderly. In many European countries cyclists make up a significant number of VRU casualties – typically around one-third. In the context of the European 6th Framework Integrated Project APROSYS (Advance PROtection SYStems), a study was conducted to examine the safety requirements for cyclists and whether these were addressed by current pedestrian safety assessments of cars.

An examination of accident statistics was first conducted to determine the principal accident scenarios for cyclists. Since insufficient cyclist cases were recorded in a detail database of VRU accidents compiled during APROSYS, a programme of virtual testing was then conducted. The objective was to identify the most significant parameters during cyclist impacts with a range of cars sizes and the likely injury consequences. The primary region of investigation was impacts to the legs and knees – the points of first contact.

The study indicated that cyclists interacted differently with cars than pedestrians, resulting from the geometric configuration of their legs, the presence of the bicycle and their elevated riding position. The potential for injury was different and the current sub-system impactor tests used by Euro NCAP and for vehicle certification purposes did not address all these differences. It was determined that the relevance of the current pedestrian impact safety assessments of cars for cyclists could be improved by minor changes to the test parameters. However, the study also identified new injury mechanisms that may require further biomechanical investigations.

Although this study has considered a wide range of cyclist impact configurations it should not be considered as definitive. Further work including physical testing is needed in order to take forward improved safety test procedures.

INTRODUCTION

Cycling is a popular mode of transport associated with commuting, sport and leisure activities. The bicycle has been in existence for over 100 years, but has had to share the roads with other forms of transport. Cyclists, along with pedestrians are known as vulnerable road users as they do not have the protection of a structure around them and do not have passive safety features associated with their bicycles, such as airbags and seatbelts, to improve their chances of surviving an accident. Of the 37,000 people killed on European roads every year, 2000 of them are cyclists and 7000 are pedestrians, while several hundred thousands are injured (European Commission, Directorate-General for Energy and Transport, 2008).

Few researchers have considered in detail the differences between cyclists and pedestrian accidents. One of the first attempts to reconstruct bicycle accidents using a mathematical technique was performed by Huijbers and Janssen (1988). One of their principle conclusions was that vehicle shape had a considerable influence on the relative head impact velocity of the cyclist. Other papers by Maki et al. (2003) and Verschueren et al. (2007) have investigated cyclist accidents by using modelling techniques, but only Maki reviewed accident statistics for both road user types, although no modelling was performed for pedestrians.

There are fundamental differences between the two user groups in terms of their kinematics and injuries sustained, Carter et al. (2005); Janssen and Wismans (1985) and Otte (2004). Cyclists strike the vehicle in a different orientation and contact different parts of the vehicle, which have different levels of stiffness.

Similarities do exist between the two road users, such as the exposure of limbs to direct contact with the vehicle and the impact speeds. However, cyclists have a higher centre of gravity compared to pedestrians due to their positioning on the bicycle and their feet not being in contact with the ground on impact. In the majority of cases, a cyclist will also be travelling at a greater speed compared to a pedestrian. This has consequences for their impact conditions with the vehicle.

Nevertheless, current European legislation (European Parliament and Council 2003) that has been targeted at protecting pedestrians, assumed that the introduction of pedestrian legislation would also contribute to protecting cyclists, as they generally come into contact with the front of the vehicle.

This paper examines and contrasts the differences between cyclists and pedestrians from the first point of contact with a vehicle, that is impacts to the legs.

BASIS OF MODELLING

Preliminary cyclist related activities in APROSYS (Hardy et al, 2007, Bovenkerk et al, 2008) have reported that the Detailed Accident Database from Work Package (WP) 3.1 did not contain sufficient bicyclist cases to examine the type, range of injuries or the severity of the injuries sustained by bicyclists. Therefore, a programme of parametric studies using mathematical models was conducted to examine vehicle to bicyclist impacts during loadings to the legs, to ascertain the likelihood and extent of injuries. In order to draw comparisons with pedestrians, since the current legal and consumer sub-system lower leg impactor tests are designed for pedestrians, vehicle to pedestrian impacts were also included in the parametric study.

Bicycle, cyclist and pedestrian models

Physical dimensions were measured from an adult aluminium bicycle frame and an FE model was developed in LS-DYNA. The main tubing was represented by shells and joined together by using localised rigid bodies at the frame joints. It was assumed that the joints do not fail, but the region immediately surrounding the joints had the capability to deform. This was to allow for the collapse mechanism observed in a series of dynamic tests that were conducted.

Figure 1. Finite element model of adult bicycle.

The bicycle model, see Figure 1, was constructed with aluminium properties for the main tubes, with the seat and handlebars constructed of a rigid material. The wheels were modelled by representing the spokes as beams and the tyres as an elastic material.

A human model, as developed by Cranfield Impact Centre from a previous project (Howard et. al 2000), was used to model the cyclist and the pedestrian and by virtue of the properties and dimensions represented an average 50th percentile human of 16 to 35 years of age. The bicycle and human model combination is shown in Figure 2.

Figure 2. Human and bicycle model combined.

The bicycle model was developed to include pedals and cranks to accommodate the human model's feet and create a more realistic starting position for the simulation. The cranks had the ability to turn through 360 degrees by the use of a cylindrical joint positioned at the bottom bracket. The steering column and front forks of the bicycle were further advanced to represent the movement of the handlebars if they were struck by a vehicle.

Details of the pedals and crank with the feet positioning is shown in Figure 3.

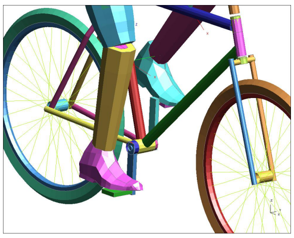


Figure 3. Details off pedals and crank.

A contact characteristic was defined for the feet to pedal and crank contact. However, for the hand to handlebar connection an altogether different arrangement was required. As the geometry of the hands, including the fingers and compression of the soft tissue were not modelled in detail, a spring was used to represent the hand to handlebar connection. At a designated force and displacement level the spring extended to simulate the releasing of the hand from the handlebars. The springs for each hand were programmed to work independently. Based on a literature search, the displacement release level was set at 10 mm with an 860N force level (Incel et al 2002).

Four different sizes of vehicle were considered in the parametric study:

- Supermini
- Large Family Car (LFC)
- Multi-purpose vehicle (MPV)
- Sports utility vehicle (SUV)

The geometric shapes and stiffness characteristics of each vehicle model were based on the results from APROSYS WP 3.1, Carter (2006) and Martinez et al (2006), respectively.

INITIAL GEOMETRIC CONSIDERATIONS

A number of factors need to be considered in examining the suitability of the pedestrian lower leg impactor for use to assess the safety of cyclists during impacts with passenger vehicles. The first concerns the relative positioning of a cyclist's lower limbs, as compared to a pedestrian's, with respect to the front geometry of these vehicles. Two difference 'stances' were considered for the cyclist, struck leg up (SLU) and struck leg down (SLD), and two difference 'stances' were considered for the pedestrian, struck leg forward (SLF) and struck leg back (SLB). This is illustrated for the four different vehicle sizes in Figure 4 to Figure 7.

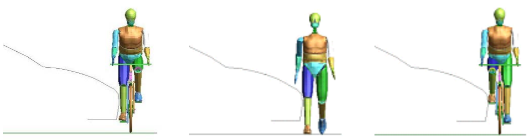


Figure 4. Cyclist and pedestrian leg positioning with respect to Supermini front.

In the case of impacts with the Supermini model, the knee region of the pedestrian's struck leg (middle picture of Figure 4) is just below the bonnet leading edge with subsequent bumper impacts lower down the lower leg. The knee region of the pedestrian's non-struck leg is similarly positioned. Conversely, for the cyclist in the struck leg down configuration (left most picture of Figure 4), the knee is just above the bonnet leading edge. In addition, although the height of the cyclist's head is almost the same distance from the ground plane, the pelvis is significantly higher up. The cyclist's non-struck leg is positioned with the knee well above the bonnet leading edge and only the foot overlapping the bonnet leading edge. In the case of the cyclist in the struck leg up configuration, (right most picture of Figure 4), the locations are effectively reversed from the previous cyclist case. Therefore, already the likelihood of different levels for the leg injury indices from the simulations for pedestrians and cyclists seems clear.

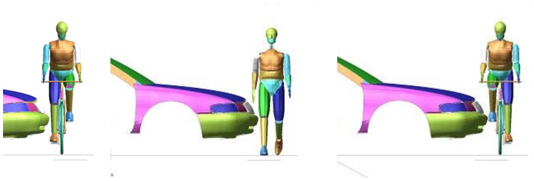


Figure 5. Cyclist and pedestrian leg positioning with respect to Large Family Car front.

In the case of impacts with the Large Family Car model, the knee regions of the pedestrian's struck leg (middle picture of Figure 5) and the non-struck leg are close to the top of the bumper. Conversely, for the cyclist in the struck leg down configuration (left most picture of Figure 5), the knee is above the top of the bumper but below the bonnet leading edge and the non-struck leg is positioned with the knee well above the bonnet leading edge and only the foot overlapping the bumper. In the case of the cyclist in the struck leg up configuration, (right most picture of Figure 5), the locations are effectively reversed from the previous cyclist case. Again, the likelihood of different levels for the leg injury indices from the simulations for pedestrians and cyclists seems clear.

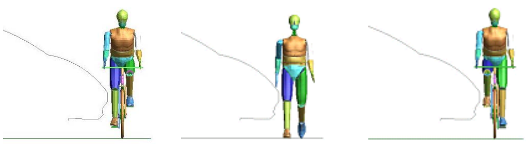


Figure 6. Cyclist and pedestrian leg positioning with respect to MPV front.

In the case of impacts with the MPV, the knee regions of the pedestrian's struck leg and the non-struck leg are below the bonnet leading edge (middle picture of Figure 6). Conversely, for the cyclist in the struck leg down configuration (left most picture of Figure 6), the knee is just above the bonnet leading edge and the non-struck leg is positioned with the knee well above the bonnet leading edge but the foot below the bonnet leading edge. In the case of the cyclist in the struck leg up configuration, (right most picture of Figure 6), the locations are effectively reversed from the previous cyclist case. Again, the likelihood of different levels for the leg injury indices from the simulations for pedestrians and cyclists seems clear.

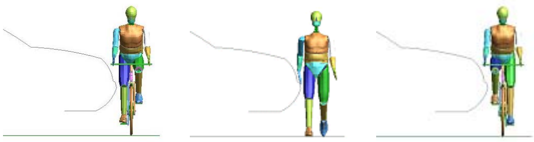


Figure 7. Cyclist and pedestrian leg positioning with respect to SUV front.

In the case of impacts with the SUV model, the whole of the pedestrian's lower body is below the bonnet leading edge (middle picture of Figure 7). Similarly, for both cyclist configurations the legs and a significant proportion of the pelvis are below the leading edge of the bonnet. For the SUV, the likelihood is that similar levels for the leg injury indices from the simulations for pedestrians and cyclists may occur.

SIMULATION PARAMETERS

Simulations were conducted at vehicle impact speeds of 5, 10 and 15 m/s with the cyclist or pedestrian aligned with the centre-line of the vehicle and stationary. The two different cyclist 'stances', struck leg up (SLU) and struck leg down (SLD), and the two different pedestrian 'stances', struck leg forward (SLF) and struck leg back (SLB), were used for human model.

The following parameters were monitored on the stuck leg and non-struck leg of the pedestrian or cyclist model: accelerations at the tibia (accelerometer location in the same relative vertically position compared to the knee joint as in the sub-system leg impactor), bending moments at the knee and shear forces at the knee.

In the cases of the leg bending moments and shear forces, a sign convention was used to identify in which directions the knee was bending and shearing, since it changes according to the vehicle geometry, between cyclists and pedestrians and between initial leg orientations. In the simulations the car moved from left to right, according to the view point shown by the geometric vehicle and cyclist/pedestrian configurations in the Figures 4 to 7 above. The sign convention is defined in Figure 8.

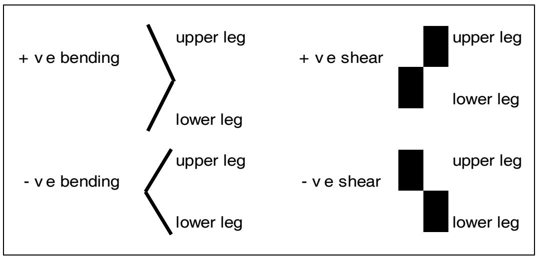


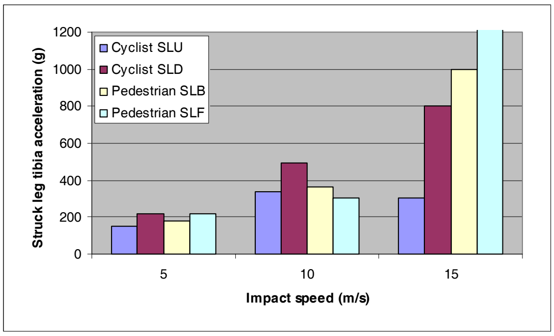
Figure 8. Sign convention for knee bending and shear.

Therefore, by reference to the pedestrian configuration given by the middle picture in Figure 4, the pedestrian's struck leg will initially experiences positive bending, due to movement of the knee in the direction of car movement and relative to the hip and ankle regions of the struck leg. Shear force were similarly defined so that positive shear represented movement of the upper leg to the right relative to the lower leg (or the movement of the lower leg to the left relative to the upper leg). The inverse was the case for negative shear.

RESULTS

Impact forces – Supermini

The maximum tibia accelerations for the struck leg, Figure 9, were all above the 150g level set for the EEVC WG17 lower leg impactor test – although it is important to point out that 150g may not be a sufficiently robust or bio-mechanically correct criteria for a human leg. The levels increased with increasing vehicle speed and until at the highest speed the cyclist and pedestrian values were generally similar. For the non-struck (or second struck) leg the tibia acceleration levels were generally lower than for the struck leg and generally similar at each car impact speed.



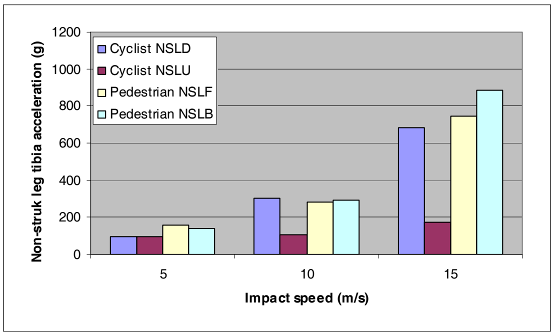


Figure 9. Tibia accelerations for the struck and non-struck legs.

The maximum bending moments for the struck leg, Figure 10, were reversed for cyclists compared to pedestrians although the numerical values were generally lower for cyclists. The positive bending moments for pedestrians were in-line with the injury mechanism assessed by the lower leg sub-system impactor. Therefore, these results suggested the possibility of an alternate injury mechanism for cyclists. The knee ligaments were then loaded in the reverse direction and specifically the lateral collateral ligaments on the outside of the knee were subjected to tensile loadings.

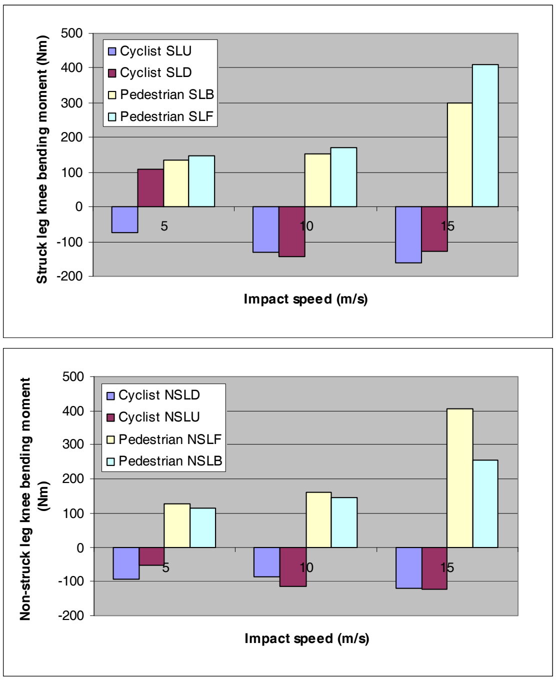


Figure 10. Knee bending moments for the struck and non-struck legs.

The maximum bending moments for the non-struck leg also showed an asymmetry between the cyclist and pedestrian cases but again the numerical values were generally lower for cyclists. However, now, the negative bending moments for cyclists reflected a direction of bending compatible with the injury mechanism assessed by the lower leg sub-system impactor (medial collateral ligaments, on the inside of the knee, in tension). In contrast, these results now suggested an alternate injury mechanism for the non-struck or second struck leg of pedestrians. This situation has real world implication for pedestrians.

In these simulations, at a car impact speed of 10 m/s, the results for the non-struck leg of the pedestrian were probably on the borderline of injury/no injury.

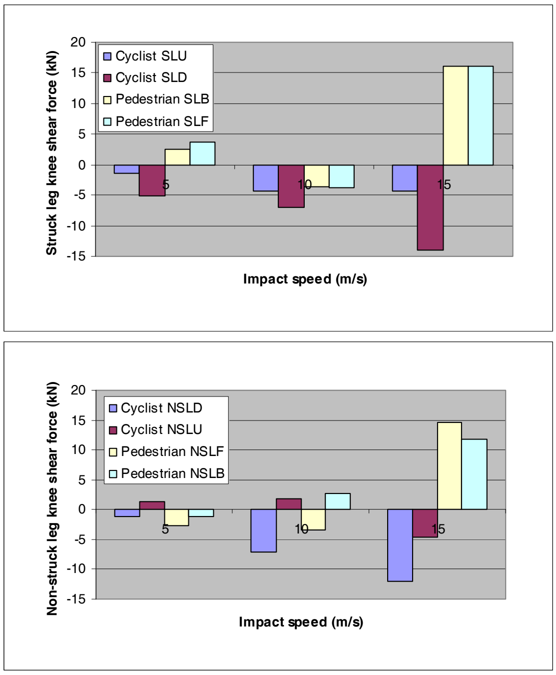


Figure 11. Knee shear forces for the struck and non-struck legs.

The maximum shear forces for the struck and non-struck legs, Figure 11, showed a mixed trend for cyclists and pedestrians. In general, the numerical values of the cyclist and pedestrian results were similar at each impact speed for the struck leg cases and mostly similar at each impact speed for the non-struck leg cases. The values at each speed were lower for all the non-struck leg cases.

Impact forces – Large Family Car

The maximum bending moments for the struck leg, Figure 12, were reversed for the cyclist cases with the struck leg up compared to the cyclist case with the struck leg down and all pedestrian cases. The trend was the same for the non-struck leg results, except at an impact speed of 5 m/s. In almost all scenarios the numerical values were lower for cyclists than pedestrians and lower for the non-struck leg than the struck leg.

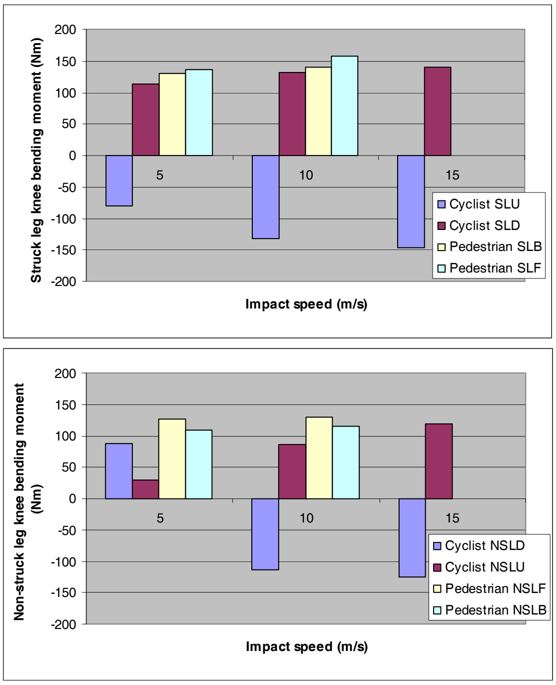
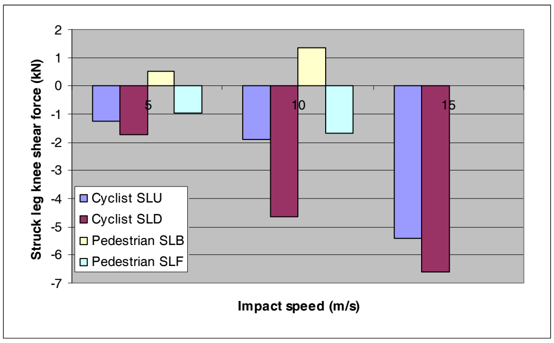


Figure 12. Knee bending moments for the struck and non-struck legs.

The negative values for the cyclist struck leg up scenarios again highlighted the possibility of an alternate injury mechanism, where the knee ligaments were loaded in the reverse direction from the injury mechanism assessed by the lower leg sub-system impactor. For the non-struck leg cases the positive values again highlighted the possibility of an alternate injury mechanism, in this case for all pedestrian scenarios and many of the cyclist scenarios. As in the case of the Supermini, this situation has real world implication for pedestrians and some cyclists.



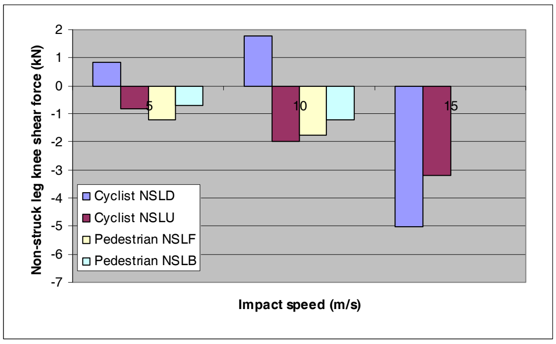
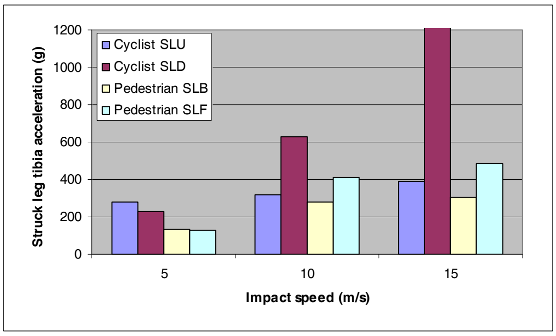


Figure 13. Knee shear forces for the struck and non-struck legs.

The maximum shear forces for the struck and non-struck legs, Figure 13, showed a mixed trend for cyclists and pedestrians. In general, the numerical values of the cyclist results were higher than the values from the pedestrian results at each impact speed for the struck and non-struck leg cases. The numerical values at each speed were generally lower for all the non-struck leg cases.

Impact forces – MPV

The maximum tibia accelerations for the struck leg, Figure 14, were nearly all above the 150g level set for the EEVC WG17 lower leg impactor test – although as mentioned earlier, it is important to point out that 150g may not be a sufficiently robust or bio-mechanically correct criteria for a human leg. The levels increased with increasing vehicle speed and the cyclist values were generally higher than the pedestrian values at each impact speed. For the non-struck (or second struck) leg cases, the tibia acceleration levels were generally lower than for the struck leg cases and the cyclist results were generally lower than the pedestrian values at each speed.



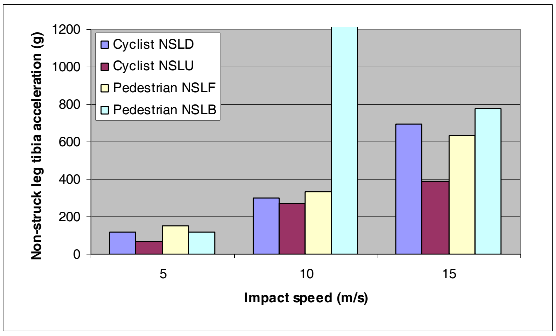


Figure 14: Tibia accelerations for the struck and non-struck legs

As in the case of the large family car impacts, the maximum bending moments for the struck leg, Figure 15, were reversed for the cyclist cases with the struck leg up compared to the cyclist cases with the struck leg down and all the pedestrian cases.

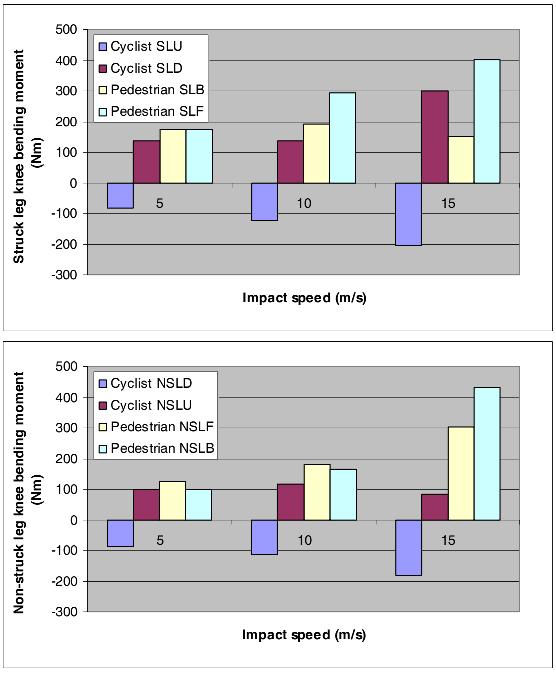


Figure 15. Knee bending moments for the struck and non-struck legs.

The trend was the same for the non-struck leg results. In all scenarios the numerical values were lower for cyclists than pedestrians and lower for the non-struck leg than the struck leg.

The same possibility of an alternate injury mechanism for cyclist struck leg up cases (negative values) again existed - as it does also for cyclists in the non-struck leg up cases and for all the pedestrian non-struck leg cases.

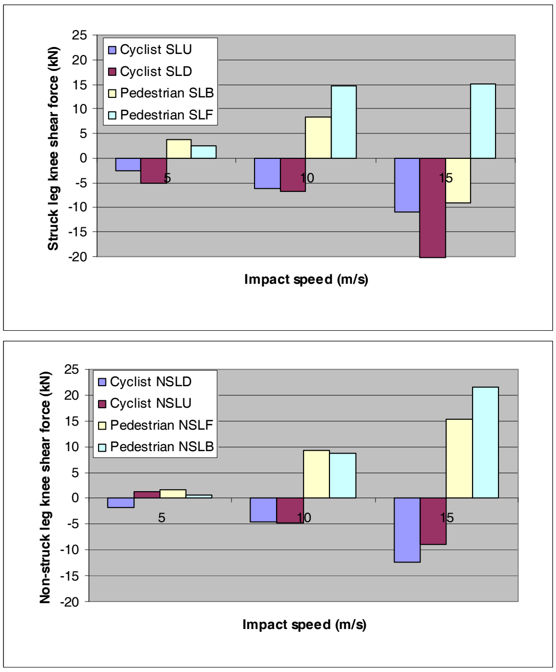


Figure 16. Knee shear forces for the struck and non-struck legs.

The maximum shear forces for the struck and non-struck legs, Figure 16, showed a clearer trend than for the previous vehicles with most results from the cyclists cases the reverse sign of those from the pedestrian cases. The numerical values were generally lower for the cyclist cases compared to the pedestrian cases at each impact speed and the numerical values at each speed were generally lower for the non-struck leg cases – with the exception of the pedestrian cases at an impact speed of 15 m/s.

Impact forces – SUV

The maximum tibia accelerations for the struck leg, Figure 17, were generally below the 150g level set for the EEVC WG17 lower leg impactor test for impacts at 5 m/s but at higher speeds the values were all above this limit – although as mentioned earlier, it is important to point out that 150g may not be a sufficiently robust or bio-mechanically correct criteria for a human leg. The levels increased with increasing vehicle speed and the cyclist values were generally lower than the pedestrian values – except at an impact speed of 5 m/s. For the non-struck (or second struck) leg cases, the tibia acceleration levels were generally lower than for the equivalent struck leg cases - except at an impact speed of 15 m/s - and the cyclist results were generally lower than the pedestrian values – except at an impact speed of 5 m/s.

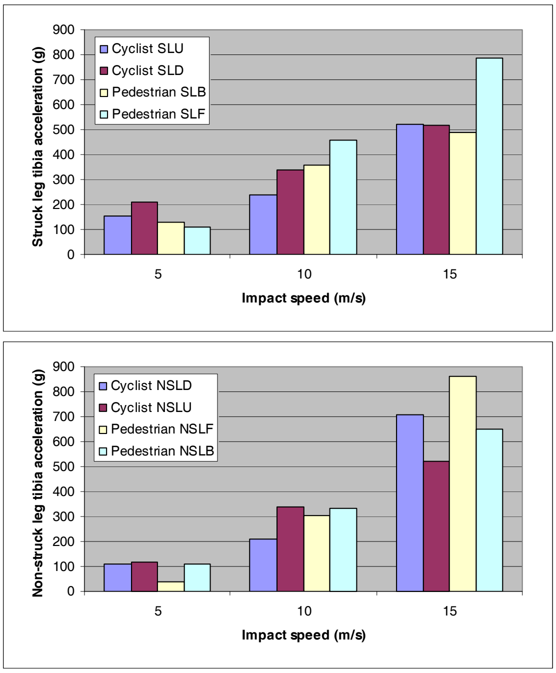
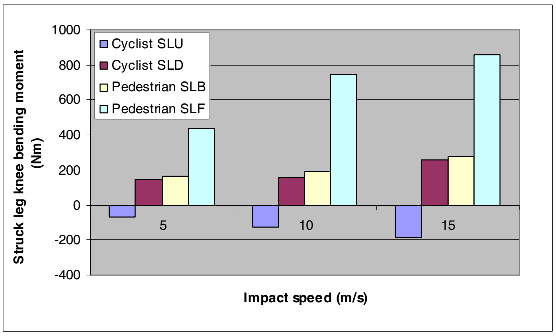


Figure 17: Tibia accelerations for the struck and non-struck legs.

As in the cases of the large family car and MPV impacts, the maximum bending moments for the struck leg, Figure 18, were reversed for the cyclist cases with the struck leg up compared to the cyclist cases with the struck leg down and all the pedestrian cases – again highlighted the possibility of an alternate injury mechanism from that tested for by the lower leg sub-system impactor. However, the trend was different for the non-struck leg results where all the values were the same (positive) sign – a direction of bending in the reverse direction from the injury mechanism assessed by the lower leg sub-system impactor. This situation has real world implication for pedestrians and cyclists.



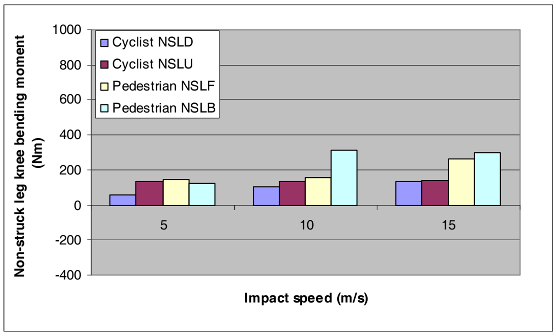


Figure 18: Knee bending moments for the struck and non-struck legs.

In all scenarios the numerical values were lower for cyclists than pedestrians (marginally in some cases) and lower for the non-struck leg than the struck leg.

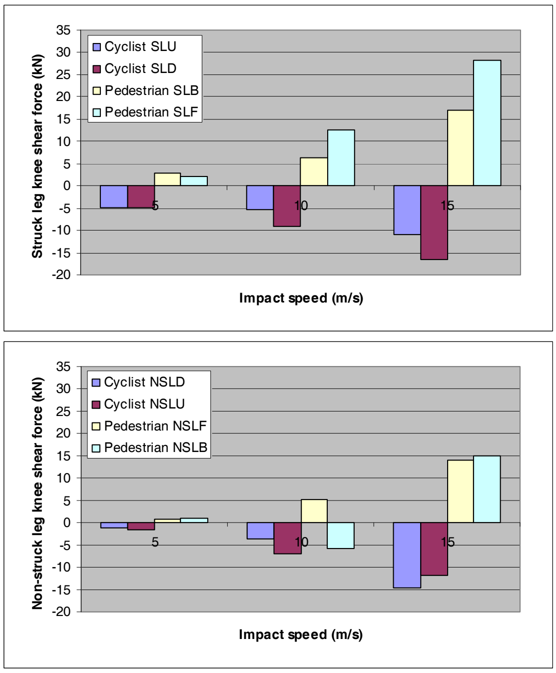


Figure 19. Knee shear forces for the struck and non-struck legs.

The maximum shear forces for the struck and non-struck legs, Figure 19, showed a clearer trend than for the Supermini and Large Family Car, with most results from the cyclist cases the reverse sign of those from the pedestrian cases. In the struck leg cases, the numerical values were generally lower for the cyclist cases compared to the pedestrian cases – except at an impact speed of 5 m/s. In the non-struck leg cases, the numerical values were generally similar for the cyclist and pedestrian cases at each impact speed. The numerical values at each speed were generally lower for the non-struck leg cases.

DISCUSSION

In this parametric study of the differences and similarities between comparable cyclist and pedestrian impact scenarios, the numerical values of the leg injury indices were lower for cyclists in nearly two-thirds of the scenarios. In just over one-fifth of the scenarios the values were similar and in just over one-eighth of the scenarios the cyclist values are higher.

With only one exception (tibia accelerations during impacts with the SUV at 15 m/s) the leg injury indices were lower for the non-struck (or second struck) leg than for the struck (or first struck) leg. But this did not mean that the non-struck leg would register injury indices that were below the threshold values.

Over the range of impact speeds, the cyclist tibia accelerations were slightly lower than those for pedestrians. In general, the SUV was the vehicle model that produced the lowest range of tibia accelerations values across the cyclist and pedestrian impact scenarios and impact speeds. The geometric shape and, in particular, the height of the bumper may have been contributory factors in this situation.

Over the range of impact speeds, the cyclist knee bending moments (numerical values) were lower than those for pedestrians. In general, the Supermini and Large Family Car were the vehicle models that produced the lowest ranges of knee bending moment values across the cyclist and pedestrian impact scenarios and impact speeds.

Over the range of impact speeds, the cyclist knee shear forces (numerical values) were either lower than or similar to those for pedestrians, except for one vehicle model, the Large Family Car, where the values were higher than those for pedestrians. Nevertheless, the Large Family Car was the vehicle model that produced the lowest range of knee shear force values across the cyclist and pedestrian impact scenarios and impact speeds.

The simulation results have confirmed the initial geometric considerations, that differences in cyclist and pedestrian injury risks were likely. In fact, the simulations have demonstrated that this was not solely attributable to the numerical value of the injury indices but also the sign of the values, indicating the mode of deformation under the action of the applied loads.

Therefore, the physical positioning of a cyclist, particularly height from the ground, in front of a vehicle is an important consideration for meaningfully evaluating the injury risk potential of an impact. The orientation of the cyclists' limbs is also an important consideration in assessing cyclist safety. The current testing regimes assume that a vulnerable road user presents themselves for impact with a vehicle in a straight legged 'gait'. This is not wholly accurate for a pedestrian but for a cyclist it is even more unrealistic, given the range of leg orientations during the rotation of the crank. Recognition of the important physical orientation differences between cyclists and pedestrians immediately prior to an accident is fundamental to providing the same levels of protection for both.

Another aspect of the differences between cyclists and pedestrians is the presence of the bicycle itself. In addition to the physical positioning differences that arise, as discussed above, the inertia of the bicycle can have an important role in the kinematics of the cyclist. The struck leg may be pinned between the front of the vehicle and the bicycle, inducing differences in the loads applied to the legs and the duration of these loadings. To represent this situation it may be necessary to represent an element of the bicycle mass in a testing regime to enhance cyclist safety. Further analytical work will be necessary to determine if this is necessary or not and if so, the magnitude of this mass, its position and its attachment to a sub-system leg impactor.

In the parametric study the struck leg knee bending moments for the cyclist struck leg-up scenarios were consistently the opposite sign of those for all the pedestrian scenarios, as they were also for the entire Supermini to cyclist impact scenarios, except at a vehicle speed of 5 m/s. This implied a 'reverse' bending situation compared to conventional thinking for pedestrian impacts and raises the question as to whether the current knee bending criteria for pedestrians are relevant for cyclists in these scenarios. Similarly, while the non-struck leg bending moments in all the pedestrian impact scenarios had a positive value, this now indicated a 'reverse' bending phenomenon and raises the issue of whether the current testing regimes adequately protect pedestrians. There were also some cyclist impact scenarios where the non-struck leg bending moments also indicated this same 'reverse' bending phenomenon.

The current legform criteria are based on the assumption that, using the sign convention defined in this report (see Figure 8), the lateral knee bending is positive during loading of the leg by the car - that is, the knee is forced forwards in the direction of car motion whilst the ankle and hip joints lag behind. One of the consequences of this motion is that the medial ligaments in a pedestrian's leg experience tensile forces and if these are too high they may cause ligament damage – work defining the characteristics of this mode of knee bending have been reported by a number of researchers including Levine et al (1984) and Kajzer et al (1993). Damage to other knee ligaments may also occur. If the loading is reversed, negative using the sign convention above, with the knee lagging behind the hip and ankle joints, the lateral collateral ligaments on the opposite (outer) side of the knee experience tensile forces. The injury criterion used for knee bending in the current sub-system impactor leg does not represent the capabilities of the knee in this opposite (or reverse) model of bending.

Therefore, where this type of bending occurs in the real world or in realistic computer simulations of the real world, then no biomechanical criterion exists that can be applied to assess the potential for injury risk. To address the safety requirements of cyclists (and the non-struck leg of pedestrians) where this reverse mode of bending occurs, research to identify the capabilities of the lateral collateral ligaments of the knee will be needed and implementation of these characteristics in a test impactor. In addition, the procedure of conducting a test for this reverse bending scenario will need to be addressed.

The lateral knee shear forces from the simulations also had values for cyclists that in many cases were the opposite sign to those for pedestrians. Further investigations to understand the exact mode that is addressed by the current testing regimes is needed and then further research may be required to determine if the human knee behaves in a symmetric manner under the application of lateral shearing loads.

In general, the numerical values for the lower leg injury indices from these simulations suggested that the current pedestrian consumer and legislative test criteria are likely to be appropriate to provide adequate levels of safety for cyclists. Nevertheless, improvements in the testing procedures to enhance the levels of safety for cyclists are feasible. In summary, among the factors that should be considered are:

- The appropriate height above the ground for the positioning of a lower leg sub-system impactor;
- Representation of the knee region in other than a 'straight' orientation;
- The possible need to represent an element of bicycle mass;
- The appropriate criteria to assess injury risk in lateral modes of knee bending;
- Review, and if necessary, determine the appropriate criteria to assess injury risk in lateral modes of knee shearing.

CONCLUSIONS

1. The impact forces that the legs of a cyclist are exposed to during a collision with a car can be subtly different than those experienced by a pedestrian.
2. The greater pelvis height of the cyclist generally causes the impact points to be lower down on the cyclist's legs.
3. Depending on vehicle shape, generally for vehicles having a low bumper or low bonnet leading edge height, the struck leg knee bending moments and shear forces can be in the opposite direction to those experienced by a pedestrian when struck by the same vehicle.
4. New injury criteria and adjusted impact test procedures are needed to address the differing needs of cyclists in providing a safety environment equivalent to that for pedestrians.
5. Use of any new criteria and use of the existing pedestrian criteria for cyclist impact tests should be reviewed taking into account leg and knee heights, use of an impactor with a bent knee and the influence of the bicycle mass (or an element of it).

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REFERENCES

Bovenkerk, J., Hardy, R.N., Neal-Sturgess, C.E., Hardy, B. J., van Schijndel - de Nooij, M., Willinger, R. and Guerra, L. J. (2008), "Biomechanics of real world injuries and their associated injury criteria", APROSYS EC Project Report Deliverable D3.3.1, AP-SP33-001.

Carter, E., Ebdon, S. and Neal-Sturgess, C. (2005), "Optimization of passenger car design for the mitigation of pedestrian head injury using a genetic algorithm", Proceedings of Genetic and Evolutionary Computation Conference, pp. 2113, June 2005, Washington DC, USA.

Carter, E. (2006), “The generalised geometry corridors, generic shapes and sizes of the vehicle fleet covering cars, MPVs and SUVs”, APROSYS document AP-SP31-007R, Deliverable D3.1.2A.

European Commission, Directorate-General for Energy and Transport (ed.) (2008), EU Energy and Transport in Figures, European Communities, Belgium.

European Parliament and Council, (2003), Directive 2003/102/EC of the European Parliament and of the Council of 17th November 2003 relating to the protection of pedestrians and other vulnerable road users before and in the event of a collision with a motor vehicle and amending Council Directive 70/156/EEC, Directive ed., EU, Brussels, Belgium.

Hardy, R.N., Watson, J. W., Carter, E., Neal-Sturgess, C.E, Joonekindt, S., Yang, J., Hermann, K., Baumgartner, D., Guerra, L.J., Martinez, L. (2007), “Impact conditions for pedestrians and cyclists”, APROSYS document AP-SP32-009R, Deliverable D3.2.3.

Howard, M., Thomas, A., Koch, W., Watson, J. and Hardy, R.N. (2000), “Validation and Application of a Finite Element Pedestrian Humanoid Model for use in Pedestrian accident simulations”, Proc. of the Int. IRCOBI Conference on the Biomechanics of Impacts, Montpellier (France).

Huijbers, J. J. W. and Janssen, E. G. (1988), "Experimental and Mathematical Car-Bicycle Collision Simulations", Proceedings of 32nd Stapp Car Crash Conference, October 1988, P215, paper SAE 881726, SAE, Atlanta, Georgia, USA.

Incel, N.A., Ceceli, E., Durukan, P.B., Erdem, H.R., Yorgancioglu, Z.R. (2002), “Grip Strength: Effect of Hand Dominance”, Singapore Med J 2002 Vol 43(5), pp 234-237.

Janssen, E. G. and Wismans, J. S. H. M. (1985), "Experimental and Mathematical Simulation of Pedestrian-Vehicle and Cyclist-Vehicle Accidents", Proceedings of 10th International Technical Conference on Experimental Safety Vehicles, pp.977-988, July 1985, Oxford, England.

Kajzer, J., Cavallero, C., Bonnoit, J., Morjane, A., Ghanouchi, S. (1993), “Response of the Knee Joint in Lateral Impact: Effect of Bending Moment”, International IRCOBI Conference on The Biomechanics of Impacts, September 8-9-10th 1993 Eindhoven (The Netherlands), pp 105-116.

Levine, R. S., Begeman, P. C., King A. I. (1984), “An Analysis of the Protection of Lateral Knee Bracing in Full Extension using a Cadaver Simulation of Lateral Knee Impact”, American Academy of Orthopedica Surgical, 17th August, 1984.

Maki, T., Kajzer, J., Mizuno, K. and Sekine, Y. (2003), "Comparative analysis of vehicle-bicyclist and vehicle-pedestrian accidents in Japan", Accident Analysis and Prevention, vol. 35, no. 6, pp. 927-940.

Martinez, L, Guerra, L.J., Ferichola, G., García, A., Yang, J., Yao, J. (2006), “Stiffness corridors for the European flee”, APROSYS document AP-SP31-009R, Deliverable D3.1.2B.

Otte, D. (2004), "Use of Throw Distances of Pedestrians and Bicyclists as Part of a Scientific Accident Reconstruction Method", in SAE (ed.), 2004 SAE World Congress, Vol. Accident Reconstruction 2004, paper 2004 -1-1216, 8th-11th March 2004, Detroit, Michigan, USA, SAE International, USA.

Verschueren, P., Delye, H., Depreitere, B., Van Lierde, C., Haex, B., Berckmans, D., Verpoest, I. Goffin, J., Vander Sloten, J. and Van der Perre, G. (2007), "A new test set-up for skull fracture characterisation", J. Biomechanics, vol. 40, no. 15, pp. 3389-3396.