Knee injuries in pedestrians and cyclists resulting from impacts with passenger cars – Frequency and associated factors based on Swiss insurance claims data

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Abstract The relevance of knee injuries in accidents involving passenger cars and pedestrians or cyclists is not clear. Past studies using different research methods and data sources came to different conclusions. This study aims to analyse the frequency of knee injuries based on a new dataset from insurance claims data in Switzerland. The study sample contains 340 real-world accidents, each representing an impact between one passenger car and one pedestrian or cyclist. Injury descriptions, accident details and vehicle information were extracted from medical and police reports and insurance data. In 123 pedestrian and 217 cyclist accidents, knee ligament injuries were sustained in eight accidents, which represents 16% of the accidents with injuries of the lower extremities (excluding superficial injuries). In total, 37 knee injuries were reported, of which 13 were knee ligament ruptures and 10 were bone fractures in the knee area. It was observed that ligament injuries were mostly diagnosed three or more days after the injury, which might explain the different prevalence of ligament injuries in different data sources. Based on this analysis, knee ligament ruptures are relevant for the assessment of modern vehicles and should therefore be considered in virtual testing procedures addressing the protection of pedestrians and cyclists.

Keywords Vulnerable Road User, Pedestrian, Cyclist, Knee injuries, Knee ligaments.

I. INTRODUCTION

In 2018, 22% of all road fatalities in the European Union were pedestrians and 8% were cyclists [1]. In Switzerland, in addition to 109 fatally injured pedestrians and cyclists, 1,723 pedestrians (15 times as many) and 5,028 cyclists (46 times as many) were reported to have been seriously or slightly injured [2].

As pedestrians and cyclists have to rely heavily on the partner protection of the vehicle they are colliding with, the assessment of passive safety measures of passenger cars plays an important role in improving the safety of vulnerable road users (VRUs) [3].

The EU-funded research project VIRTUAL [4] aims to develop open access assessment procedures using open source human body models (OS-HBMs) to enhance the safety of different kinds of road users. Pedestrians and cyclists are part of the road user groups addressed in the project.

In order to determine the requirements of HBMs, it is important to define their intended use [5]. To set meaningful priorities and identify on which body regions and injury types the virtual assessment should focus, it is highly recommendable to use epidemiological data, which can help to identify the most severe injuries, the most frequent injuries or injuries related to the highest costs or medical impairment.

An analysis of detailed AIS codes from the Swedish accident database STRADA [6-7] showed a low frequency of knee ligament injuries. In other studies [8-9] a low frequency of knee ligament injuries was also reported. In contrast, knee injuries are one of the body regions that are currently adressed in pedestrian safety tests by Euro NCAP [10] and legislations. Furthermore, research is ongoing to develop new legform impactors [11-12]. Knee ligament injuries are also frequently observed in post mortem human subject (PMHS) tests, even more often than tibia fractures [13-15]. Therefore, to identify the appropriate level of detail for the virtual assessment of knee injuries when using HBMs, a new data source that significantly differs in its origin from the previously analysed data samples was consulted.

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The aim of this study was to identify the frequency of knee ligament injuries for pedestrians and cyclists impacted by modern passenger cars based on insurance data that cover the whole injury course.

II. METHODS

The underlying data for this study are extracted from the AXA insurance accident database in Switzerland. The original sample contains all motor vehicle liability cases of passenger cars with at least one harmed person from 2015 to 2019. In liability cases, the insurer receives all relevant accident data, including police reports and medical documentation. The short description of these cases in the database (n=26,034) was screened for pedestrian and bicycle accident-related keywords in English, French, Italian and German: "Pedestrian, passer-by, child, walk, run, sprint, cross, zebra, bike and bicycle". The search terms did not include body-region or injury related terms to avoid any bias towards a specific type of injury. All data were filtered for involved vehicles with a year of market introduction after 2012. The sample was restricted to these newer cars, as the focus was set on modern vehicle fronts that comply with pedestrian safety legislation.

The remaining cases were double-checked for comprehensiveness and those where the pedestrian or the cyclist was not injured (in some cases they were involved as a witness only) were excluded.

The final set of cases (n=340) was analysed in detail manually: 262 cases were closed and 78 were still open when collecting the data in 2019. Injury descriptions, accident details and vehicle information were extracted from medical reports, police reports and insurance data.

The dataset was further filtered to include cases with "injury of the lower extremity". These were further categorised into cases with "superficial injuries only", "knee injury" and fractures of pelvis, femur, tibia, fibula, ankle or feet. All other non-superficial injuries of the lower extremities were classified as "other". This detailed classification is shown in Table I.

TABLE I
INJURY CLASSIFICATION

Knee injury	**Femur fracture**	**Tibia fracture**	**Fibula fracture**	**Ankle fracture**
Distal femur fracture	Proximal femur fracture	Tibia midshaft fracture	Proximal fibula fracture	Distal tibia fracture
Proximal tibia fracture	Femur midshaft fracture		Fibula midshaft fracture	Distal fibula fracture
Patella injury				Talus fracture
Knee ligament injury				
Meniscus injury				
Knee cartilage injury				
Patella tendon injury				
Quadriceps tendon injury				

The conflict situation associated with the cases with knee injury were classified according to Lindman *et al*. [16] - [17].

III. RESULTS

The final baseline sample (n=340) included 123 (36.2%) pedestrian and 217 (63.8%) cyclist accidents. Table II shows the gender of all VRUs in the dataset. The pedestrian group consisted of slightly more females (55.3%), whereas the cyclist group included more males (61.8%).

TABLE II
GENDER VS. VRU GROUP

Gender	Pedestrian	Cyclist	Total
Female	68	83	151
Male	55	134	189
Total	123	217	340

Fig. 1 shows that in 150 cases (44.1%) an injury of the lower extremity occurred. Of these, 71 occurred in pedestrians (57.7% of all pedestrians) and 79 in cyclists (36.4% of all bicycle accidents). In these 150 cases, two-thirds (n=100) were only slight superficial injuries, such as contusions and skin excoriations. The types of injury in the other third (n=50) are shown in Figure 2. According to the classification in Table I, injuries in the area of the knee were most frequently observed (38%), followed by pelvis fractures and foot fractures. In 16% (n=8) of all cases with injuries of the lower extremities, knee ligament injuries were observed (red bar in Figure 2). Ligament injuries occurred in three cyclist accidents (14% of all cyclists with non-superficial lower extremity injuries) and five pedestrian accidents (17% of all pedestrians with non-superficial lower extremity injuries).

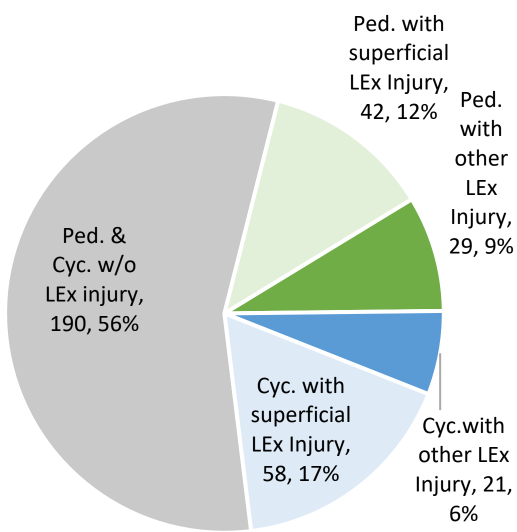


Fig. 1. Share of pedestrians (Ped.) and cyclists (Cyc.) with an injury of the lower extremities (LEx) (n=340).

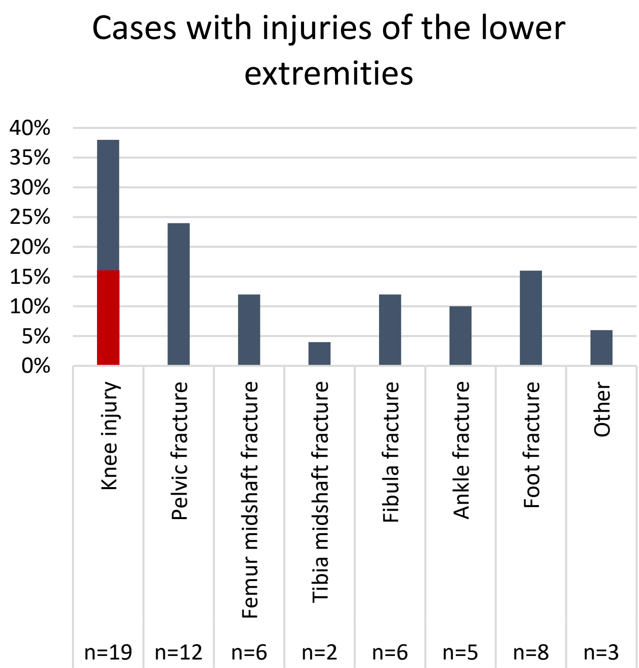


Fig. 2. Relative frequency of different types of non-superficial injury of the lower extremity (n=50 cases, with 61 categories of injury). Knee ligament injuries are shown as a red bar.

The age distribution of pedestrians with knee injuries is shown in Figure 3. The youngest VRU with a knee injury in the data sample was 25 years old (yo). No knee injury was reported in children. Eighteen out of 19 subjects with a knee injury (94.7%) were between 40 and 89 yo.

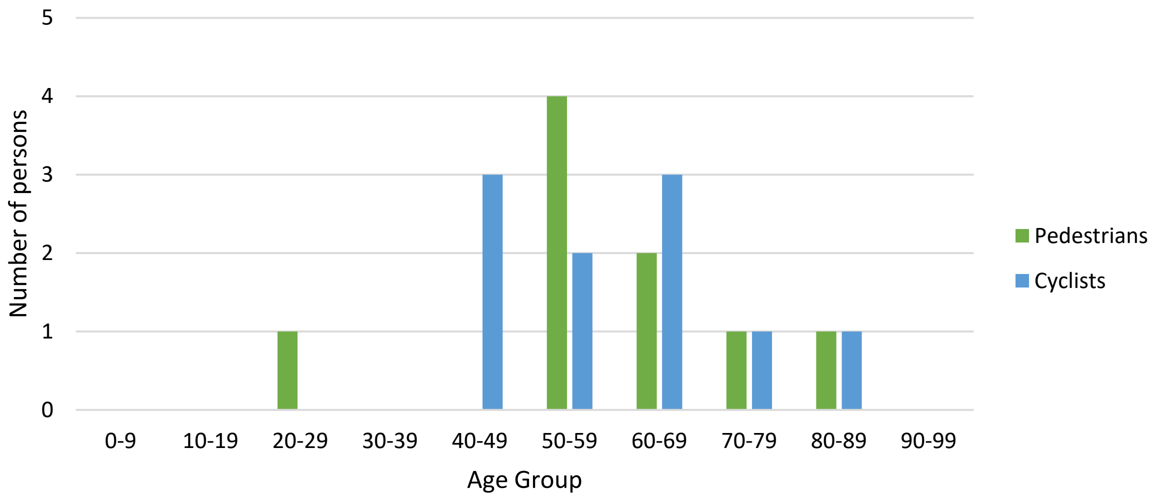


Fig. 3. The number of involved VRUs with knee injuries in each age group.

Of the 19 cases with a knee injury, all 37 injury types are listed in Table III, comparing pedestrians and cyclists. Of these, 22 injuries were sustained by pedestrians and 15 by cyclists.

TABLE III
KNEE INJURY TYPES IN THE 19 CASES WITH KNEE INJURIES

Injury	Pedestrians	Cyclists	Total
Ligament ruptures	9	4	13
Tendon ruptures	1	0	1
Cartilage damage	1	2	3
Meniscus damage	4	5	9
Bone fractures	7	3	10
Patella fractures	0	1	1
Total	22	15	37

Table IV and Table V give an overview of all accidents with an injury of the knee and the type of conflict situation for pedestrians [16] and cyclists [17], respectively.

Six (46.2%) of the ligament ruptures were ACL ruptures, seven (53.8%) were MCL ruptures. No ruptures of the PCL and LCL were found. All bone fractures in the knee area were tibia plateau fractures. In total, 13 ligament ruptures account for 35.1% of all injury types (n=37), whereas 10 bone fractures represent 27.0% of all injury types.

TABLE IV
PEDESTRIAN ACCIDENTS WITH KNEE INJURIES

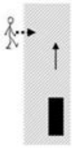
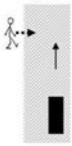
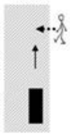
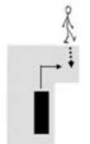
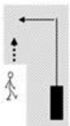
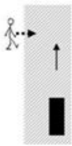
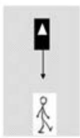
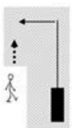
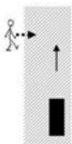
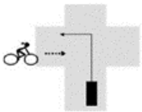
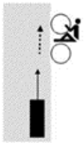
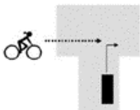
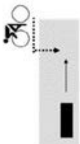
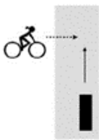
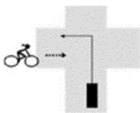
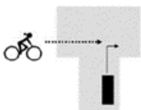
Conflict Situation [16]	Conflict Situation Pictogram	Gender	Age	ACL	PCL	MCL	LCL	MM (medial meniscus)	LM (lateral meniscus)	Articular cartilage	Patella tendon	Femur fracture	Tibia fracture	Patella fracture
SCPPL		m	25	le.		le.							le.	
SCPPL		m	50					ri.						
SCPPR		m	53			le.							le.	
RT/OD		w	56	ri.		ri.							ri.	
LT/SD		w	58						ri.				ri.	
SCPPL		w	64	le.		le.		le.					le.	
Reversing		w	65	le.		le.			le.	le.	le.			
LT/SD		m	72										ri.	
SCPPL		w	88										ri.	
Total				4	0	5	0	2	2	1	1	0	7	0

TABLE V
CYCLIST ACCIDENTS WITH KNEE INJURIES

Conflict Situation [17]	Pictogram	Gender	Age	ACL	PCL	MCL	LCL	MM (medial	LM (lateral meniscus)	Articular cartilage	Patella tendon	Femur fracture	Tibia fracture	Patella fracture
LT/LD		m	42					le.		le.				
Reversing		w	43											le.
SD		m	47	le.										
Door		w	56	ri.		ri.		ri.						
RT/LD		m	58										ri.	
SCPCLOD		w	60										ri.	
SCPCR		m	60					ri.		ri.				
SCPCL		w	60					ri.						
LT/LD		w	73			le.			le.					
RT/LD		m	88										ri.	
Total				2	0	2	0	4	1	2	0	0	3	1

IV. DISCUSSION

Limitations

Several limitations are to be considered when interpreting the results of this study. Although starting with 340 accidents, the number of cases turned out to be rather low when performing detailed analyses, leading to a rather small sample with lower extremity and therefore also knee injuries. No physical accident parameters, such as impact speed, could be analysed. Moreover, it is not known whether vehicle impact, a secondary impact on the road or a different impact led to the specific injuries. Not being able to differentiate between different impacts might also be the reason for the high frequency of pelvic injuries, as previous studies have revealed that they are often related to ground impact [18-19].

Passenger cars covered in the dataset

In the current study, it was decided to select the dataset based on the year of market introduction of the vehicle instead of the year of recording. It was originally planned to only use cars that were introduced after 2014, as Euro NCAP had started to test with the new legform impactor Flex-PLI at that time [10]. However, this resulted in a sample that was too small, ultimately. By increasing the range to two more years, the number of cases in the sample was doubled.

Out of 340 cases, only 19 included cars that were introduced to the market during 2017 or 2018. The main reasons for this might be the latency of the claims process and the average age of 11.1 years of passenger cars on European roads [20].

The numbers of pedestrian and cyclist accidents according to the year the involved passenger cars were introduced to the market are shown in Table VI.

TABLE VI
YEAR OF MARKET INTRODUCTION OF PASSENGER CARS WITHIN THE CONSIDERED DATASET

Introduction year	Pedestrian	Cyclist	Total
2012	28	62	90
2013	32	49	81
2014	21	39	60
2015	23	37	60
2016	16	14	30
2017	1	11	12
2018	2	5	7
Total	123	217	340

To double-check that only “modern” (i.e. cars designed to meet pedestrian safety requirements) cars were included in the analysed sample, the Euro NCAP assessment scores of cars involved in cases with a knee injury were reviewed. Sixteen out of the 19 car models documented in our sample had received the highest possible score (6 points). The three remaining cases achieved 5.8, 4.9 and 4 points. It must be mentioned, however, that the real-world accident scenarios seen in the present dataset are very heterogeneous and therefore not comparable to Euro NCAP test conditions and the resulting ratings.

Age and gender of pedestrians and cyclists with knee injuries

The significantly higher number of males found in the cyclists group matches with the Swiss national statistics [21]. Amongst pedestrians, females are injured more often than males, while male cyclists sustain injuries more frequently than females. This could be caused by different exposures. There were no figures available with regard to kilometres travelled by cyclists and pedestrians of both genders in Switzerland as a comparison with the current study.

While Martin *et al.* [8] found ligament injuries mainly among young pedestrians when analysing French accident data, this was not the case in the current study. There was no clear trend with respect to age.

However, a statistical analysis of this factor was not performed in the current study as the age distribution of the whole dataset was not analysed. Age is not one of the standard parameters in the dataset and therefore had to be manually excluded. This was only done for cases with knee injuries only.

Difference between Cyclists and Pedestrians

Although there were more cyclist accidents than pedestrian accidents in our sample, the number of cases with injuries of the lower extremities was finally very similar, indicating higher odds for pedestrians to sustain injuries of the lower extremities compared to cyclists. The relative frequency of cases with ligament injuries within the cases with non-superficial injuries of the lower extremities was only slightly higher for pedestrians (17%) compared to cyclists (14%). Within the cases with knee injuries, ligament injuries were more often prevalent in pedestrians (5 out of 9) than in cyclists (3 out of 10). This can be explained partly by the different positioning of the knee when impacted by a passenger car. The knee of a cyclist is higher compared to a pedestrian's and it is also in a different posture, causing different loading patterns [22]. A pedestrian's knee gets impacted directly by the car front, causing strain on bones and a bending torque that results in strains of knee ligaments. For cyclists, knee loading depends on the crank posture at the moment of impact. Whether the knee of the struck-side leg is straightened or not at the time of impact has a large effect on the structures in contact with the knee.

Types of knee injury

The fact that MCL was more often injured than the other ligaments can be explained by the fact that the knee of the struck-side leg gets bent laterally, causing elongation of MCL and not of LCL. As no LCL rupture showed up in our dataset, it seems that knee injuries were mainly related to the struck-side leg. There was no obvious trend regarding the occurrence of ligament injuries with or without distal tibia fractures.

Frequency of knee injuries

When comparing this dataset with other accident databases, a higher relative frequency of knee ligament injuries was observed in our study. In Paas *et al*. [9] only 1.8% of pedestrians with lower extremity injuries reported knee ligament injuries, whereas we observed knee ligament injuries in 7% of pedestrians and 4% of cyclists with injuries of the lower extremities. A reason for this might be the vast amount of information in our dataset per case, which includes the entire medical treatment. It is not clear if this is the case for conventional in-depth accident databases.

Figure 4 shows the number of days between the accident and confirmation of the specific knee injury through medical imaging. Bone fractures were mostly confirmed on the day the accident happened or on the following day. In fact, 50% of the fractures were diagnosed on the same day, 70% within the first two days. Ligament injuries were rarely diagnosed on the day of or on the day after the accident. More than 75% of all ligament ruptures were confirmed after three or even more days. In two cases, it took up to a month until persistent knee pain resulted in an MRI (magnetic resonance imaging) to confirm a ruptured ligament, and in one case it took three months. This might be a result of bone fractures being more obvious than knee ligament ruptures. Treatment strategies might also play a role (i.e. if the treatment strategy does not require a detailed diagnosis, no MRI will be carried out). This latency in confirming injuries indicates that it is likely that knee injuries are less prevalent in other data samples.

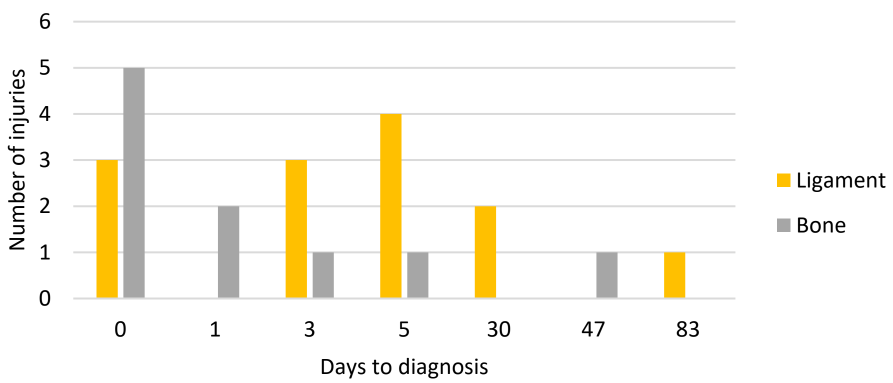


Fig. 4. Number of days that elapsed between accident and diagnosis.

Outlook

According to the analysis of this sample, knee ligament injuries should not be excluded from the virtual assessment of VRU protection. Ligament and meniscus injuries are well known for requiring long rehabilitation phases. However, long term consequences such as posttraumatic osteoarthritis after ACL or meniscus injuries are even more critical [23]. These facts highlight the impact of ligament injuries and the importance of preventive means.

Further research is needed to obtain a clearer picture regarding risk groups, differences in risk for pedestrians and cyclists and types of ligament injury. Therefore, simulations using HBMs with detailed (ideally age- and gender-dependent) knee models should be performed to further investigate open questions. The available real-world cases could be reconstructed to validate the assessment capabilities and injury criteria in order to avoid an over-prediction when using PMHS test data results with missing muscle activity only [15-22], [24].

V. CONCLUSIONS

Insurance claims from 340 accidents of pedestrians or cyclists impacted by modern passenger cars were analysed. Based on this analysis, knee injuries, and more specifically knee ligament injuries, should be considered in virtual assessment procedures. The study highlighted that the diagnosis of knee ligament injuries is often confirmed rather late in the treatment process. This was identified as a possible explanation for the varying prevalence reported in different accident studies using different data sources.

VI. ACKNOWLEDGEMENTS

This study received funding from the European Union Horizon 2020 Research and Innovation Programme under Grant Agreement No. 768960.

VII. REFERENCES

[1] European Commission, Directorate General for Transport (2018) *Annual Accident Report 2018.*

[2] Bundesamt für Strassen ASTRA (2020) *Strassenverkehrsunfall-Statistik 2019.*

[3] Zander, O., Gehring, D-U, van Ratingen, M. (2015) Beyond Safety Legislation: Contribution of Consumer Information Programmes to Enhanced Injury Mitigation of Pedestrians during Accidents with Motor Vehicles. *Proceedings of International Technical Conference on the Enhanced Safety of Vehicles,* 2015, Gothenburg, Sweden.

[4] *VIRTUAL* (2020) https://projectvirtual.eu/. Accessed 1 April 2020.

[5] Cronin, D. S. (2011) Explicit Finite Element Method Applied to Impact Biomechanics Problems. *Proceedings of IRCOBI Conference,* 2011, Krakow, Poland.

[6] Leo, C., Klug, C., Ohlin, M., Linder, A. (2019) Analysis of pedestrian injuries in pedestrian-car collisions with focus on age and gender. *Proceedings of IRCOBI Conference,* 2019, Florence, Italy.

[7] Leo C, Klug C, Ohlin M, Bos N, Davidse R, Linder A. (2019) Analysis of Swedish and Dutch accident data on cyclist injuries in cyclist-car collisions. Traffic Injury Prevention, 20sup2:pp.160-162.

[8] Martin, J-L, Lardy, A., Laumon, B. (2011) Pedestrian Injury Patterns According to Car and Casualty Characteristics in France. *Annals of Advances in Automotive Medicine*, 55: pp.137–146.

[9] Paas, R., Huber, R., Wilsmann, J., von Bülow, R. M., Kompaß, K. (2018) Pedestrian Leg Injury Distribution in German in-depth Accident Study for Leg Impactor Development. *Proceedings of IRCOBI Conference,* 2018, Athens, Greece.

[10] European New Car Assessment Programme Euro NCAP (*Pedestrian Testing Protocol Version 8.0*.) https://cdn.euroncap.com/media/1465/euro-ncap-pedestrian-protocol-v80-june-2014.pdf. Accessed 29 March 2020.

[11] Isshiki, T., Konosu, A., Takahashi, Y. (2016) Development and Evaluation of the Advanced Pedestrian Legform Impactor Prototype which can be Applicable to All Types of Vehicles Regardless of Bumper Height - Part 1: Finite Element Model. *Proceedings of IRCOBI Conference,* 2016, Malaga, Spain.

[12] Isshiki, T., Antona-Makoshi, J., Konosu, A., Takahashi, Y. (2018) Simplifying the Structural Design of the Advanced Pedestrian Legform Impactor for Use in Standardized Testing. *Proceedings of IRCOBI Conference,* 2018, Athens, Greece.

[13] Forman, J. L., Joodaki, H., *et al.* (2015) Whole-body Response for Pedestrian Impact with a Generic Sedan Buck. *Stapp Car Crash Journal*, **59**: pp.401–444.
[14] Song, E., Petit, P., *et al.* (2017) New Reference PMHS Tests to Assess Whole-Body Pedestrian Impact Using a Simplified Generic Vehicle Front-End. *Stapp Car Crash Journal*, **61**: pp.299–354.
[15] Kerrigan, J. R., Arregui-Dalmases, C., Foster, J., Crandall, J. R., Rizzo, A. (2012) Pedestrian Injury Analysis: Field Data vs. Laboratory Experiments. *Proceedings of IRCOBI Conference,* 2012, Dublin, Ireland.
[16] Lindman, M., Jakobsson, L., Jonsson, S. (2011) Pedestrians interacting with a passenger car; a study of real-world accidents. *Proceedings of IRCOBI Conference,* 2011, Krakow, Poland.
[17] Lindman, M., Jonsson, S., *et al*. (2015) Cyclists interacting with passenger cars; a study of real-world crashes. *Proceedings of IRCOBI Conference,* 2015, Lyon, France.
[18] Klug, C., Weinberger, M., *et al.* (2015) Pelvic and femoral injuries in car-to-pedestrian accidents. *Proceedings of IRCOBI Conference,* 2015, Lyon, France.
[19] Mallory, A., Fredriksson, R., Rosen, E., Donnelly, B. (2012) Pedestrian Injuries by Source: Serious and Disabling Injuries in US and European Cases, 2012, Seattle, USA.
[20] ACEA (2019) *Average Vehicle Age.* 2019. https://www.acea.be/statistics/tag/category/average-vehicle-age. Accessed 30 March 2020.
[21] Beratungsstelle für Unfallverhütung BFU (2019) *Sinus 2019: Sicherheitsniveau und Unfallgeschehen im Strassenverkehr,* 2018, Bern.
[22] Ito, D., Yamada, H., Oida, K., Mizuno, K. (2014) Finite element analysis of kinematic behavior of cyclist and performance of cyclist helmet for human head injury in vehicle-to-cyclist collision. *Proceedings of IRCOBI Conference,* 2014, Berlin, Germany.
[23] Lohmander LS, Englund PM, Dahl LL, Roos EM. (2007) The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. The American journal of sports medicine, 35(10): pp.1756–1769.
[24] Sun, Z., Gepner, B., Spratley, E. M., Toczys, J., Kerrigan, J. R. (2017) New Approaches to Pedestrian Knee Joint Biomechanics. *Proceedings of IRCOBI Conference,* 2017, Antwerp, Brussels.