A Salute to Basic Mechanics in Understanding Injury Causation

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I. INTRODUCTION

The IRCOBI conference has been a mainstay of my professional life. I first attended the IRCOBI conference in 1995 in Brunnen in Switzerland, as a 21-year-old mechanical engineering graduand of Trinity College Dublin (Ireland), having completed a final year project with Garry Lyons on whiplash injuries. I generally understood little at that conference, and felt intimidated. People with strong German accents spoke about a “Hick” score and something that sounded like “Aah Eeeh Ess”. However, I also recall introducing myself to Murray Mackay and also Claude Tarriere’s memorable keynote talk titled “Children are not miniature adults” [1]. I was hooked and I have attended the conference most years since then. My first IRCOBI conference paper was in 1998, on temporomandibular joint injuries during whiplash [2], based on my PHd work.

Between 2008 and 2019 I was a member of the IRCOBI Council, including terms as Secretary, Vice-President and President. I remember the thrill when I was invited by Jeff Crandall and Murray Mackay to join the Council. IRCOBI was an organization I really wanted to participate in. While it involved much hard work, I think we were a strong team[2] and I made lasting friendships. I learned plenty and it was also a lot of fun.

It is thus startlingly thirty years since my first IRCOBI conference attendance. I have to accept that a large part of my working life is behind me, and this Bertil Aldman Award has given me the opportunity to stop and look back on the field and my own place in it. I have the great fortune to be able to work freely on any engineering topic I choose, through my position in the School of Engineering at Trinity College Dublin (TCD) since 2001. I have done so with limited research funds, and while I certainly benefited from a supportive departmental environment, there is no wider injury biomechanics group at TCD[3]. I have therefore collaborated extensively with colleagues outside of my university, and I have been drawn to research which is “simple”, i.e low cost.

II. OUTLINE OF THIS PAPER

As I will only get this opportunity once, I am going to try to do three things.

- **Part A:** First, I will give you my perspective on the current status of injury biomechanics research, and I will make a guess about its future.
- **Part B:** Then I will describe what I have learned from the combination of collision data, video analysis, first principles impact modelling, tissue testing and computational models[4].
- **Part C:** Finally, I have some reflections on what IRCOBI means to me as a community.

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[2] In particular the then IRCOBI Board which was comprised of Barclay Morrison (Vice-President), Duane Cronin (Treasurer) & Kai-Uwe Schmitt (Secretary).
[3] There are however leading experts in other aspects of biomechanics from whom I learned a lot, e.g. Patrick Prendergast, David Taylor & Daniel Kelly.
[4] This paper does not dwell much on experimental impact testing, or finite element modelling. Clearly these are essential tools for injury biomechanics research, and they central to the annual conference programme (eg Schinagl et al. 2023, Wu et al. 2024, Shin et al. 2024 & Schauble et al. 2024).

III. PART A

Where the field is now

IRCOBI was founded in 1973[5] (the year of my birth), largely in response to the very high fatality and injury rates prevalent on the roads in the US and Europe at that time. The fundamental research presented at IRCOBI[6] was the basis for many practical interventions which contributed to the significant reduction in road fatalities evident in many countries over the subsequent decades. Murray Mackay gave an excellent overview of this in Gothenburg in 2013 [3]. Briefly, IRCOBI has seen presentations on restraint systems, crash test dummy advances, computational models, human tissue testing and the diversity of collision configurations and people that need to be protected. A review of the conference papers over the decades shows a fascinating evolution of our scientific understanding and technological progress, all freely available[7]. In terms of road safety interventions, much of the low hanging fruit has thus already been picked, and it has brought significant benefits. There has been the widespread introduction of seatbelts and airbags. Most vehicles have energy absorbing structures and survival spaces, which act to reduce occupant compartment intrusion. The acceleration imposed on the occupant is reduced via restraint systems composed of both airbags and seatbelts. Manufacturers in many jurisdictions are now required to consider the protection of rear-seat passengers, cyclists and pedestrians, as well as front-seat vehicle occupants. As a result, injury and fatality rates at a given collision severity have greatly reduced for most automotive vehicle collision scenarios [4].

Over the years the remit of IRCOBI has expanded to include non-standard transport related collisions, blast protection and sports injuries. The scientific understanding of these injury modes is generally quite well-developed (except at a tissue and cellular level), but interventions are far more rudimentary than in the automotive sector, and standards are largely lacking. For example, there is no requirement for pedestrian safety on the front-end of subways and trains, despite high annual fatality numbers [5]. Safety standards for wheelchair users in transport remain voluntary [6]. Apart from helmet standards, and despite high injury rates in sport, safety standards for athlete protection are largely lacking, yet standards have been instrumental in delivering improved automotive safety.

A glimpse of the future

The biggest challenges for general accidental injury prevention are today largely outside the realm of pure scientific understanding, and lie rather in challenges with engineering, implementation and policy. Given that the fundamental principles of crash protection are well understood, the biggest obvious challenges with the biomechanics of injury prevention lie in dealing with variability in crash conditions, and also with variability in the anthropometrics and frailty of the people to be protected. Gunter Siegmund's thought-provoking Bertil Aldman talk in 2018 [7] argued (in the context of whiplash) that protecting for the average case may be missing the point, and that we need to find ways to protect those who are more vulnerable.

For pedestrians and cyclists, subsystem impactor tests have led to substantial reductions in vehicle front-end aggressivity towards vulnerable road users. However, the range of contact locations on the body and the inevitable occurrence of ground contact have challenged the implementation of further benefits. It could be argued that the anticipated benefits of active safety technologies (such as collision avoidance systems) have contributed to a decline in research funding for passive safety measures aimed at protecting pedestrians and cyclists. Sadly, these active safety features have not yet fully delivered on their obvious potential.

Overall, it is therefore no surprise when looking at recent IRCOBI papers that much attention is given to the ability of finite element computational models to replicate the diversity of human occupants (eg [8]), which in turn requires a detailed understanding of structural and mechanical properties of human tissues (eg [9]), and a range of physical models (eg [10]) to test and validate designs and computational models. It is a pity that injury studies at the cellular level (such as [11]) are less frequently presented at recent IRCOBI conferences.

These advances can potentially combine towards the development of a digital twin (eg. [12]) for injury protection purposes. This might lead to a new era of personalized impact protection, but there lies a long road ahead, with plenty of material for future conferences[8]. Furthermore, in the shorter term, expected changes in seating positions associated with the anticipated roll-out of automated vehicles is leading to much pre-emptive

[5] There has been some strong continuity: of the founding members from 1973, Murray Mackay has attended this conference as recently as 2023.

[6] For example, the 1973 IRCOBI conference papers address topics such as vehicle occupant head injuries from the steering wheel, injury tolerance to blunt abdominal trauma and field accident damage as a basis for crash testing. The 1974 IRCOBI conference papers address topics such as shoulder belt forces and thorax injuries, head injuries to children and child restraint systems.

[7] Around 2015 the IRCOBI Council made the full set of past and present conference papers freely available: Conference Proceedings › IRCOBI.

[8] A Google search for digital twin and vehicle restraint systems shows this remains in its infancy.

research on the development of restraint systems for alternative occupant seating positions (eg. [13]), so far it seems without any clear understanding of their field effectiveness.

IV. PART B

Collision Data

Collision data collection is expensive and frequently unglamorous, but it is essential for understanding a problem, and for developing representative load cases with which to design standards and equipment interventions. Major automotive collision data collection programs such as the German in-depth accident study (GIDAS) have followed the pioneering work of Hugh de Haven[9], who started his Automotive Crash Injury Research Project in 1953. These detailed databases require specialist collision reconstruction crews and are expensive to develop and maintain[10]. In the context of my long-standing interest in the mechanics of pedestrian collisions, the GIDAS database proved essential to show empirically how bumper design and bonnet leading edge height do change lower limb injuries for pedestrians. There was also a surprisingly weak correlation between head injuries and vehicle impact speed for cases where the pedestrian's head struck the windscreen directly, possibly due to failure properties of windscreens [14], thus complicating pedestrian head protection. In a separate GIDAS assessment of pedestrian injuries from ground contact, we found no fatal cases directly associated with ground contact [15], despite the high stiffness of head-ground contact collisions observed in later cadaver tests [16]. Nonetheless, for collision speeds below 40 km/h, a majority of the injury costs to pedestrians could be attributed to ground contact, yet so far this topic has received little attention from vehicle manufacturers. We should work to change this, perhaps through altered front end geometry, controlled braking, or renewed efforts to maintain the pedestrian on the vehicle following the initial collision.

For cyclist collisions, underreporting is a major challenge, with a large discrepancy between hospital data and police recorded statistics. Our recent Irish national self-reported cyclist collision survey found that single cyclist collisions account for nearly 30% of cyclist collision cases [17], but these were much less likely to have been reported to the police. Many of these single cyclist collisions are partially caused by poor infrastructure, and notwithstanding the subjectivity of the reporting, loss of tyre traction in slippery conditions and interactions with tram tracks and curbs were common contributory factors [18]. Different fall types were also identified, including skid out, pitch-over and topple over, potentially guiding future safety intervention.

Thousands of pedestrians are killed/injured annually by collisions with trains [19], and subway-pedestrian collisions are an important component of this injury burden. Although trespassing and suicide attempts are frequently cited in this context, very little has been understood about the biomechanics of these collisions, and train fronts have generally not evolved to protect pedestrians [20]. Our recent analysis of New York City subway collision incidents has shown that jumping, lying and standing are all relevant pedestrian poses, with about a 30% fatality rate. A large majority of collision speeds are below 55 km/h. Despite the severity of these collisions, it is clear that they can be made to be survivable [21], and indeed most pedestrian collisions with passenger vehicles at these speeds are survivable [22]. Intriguingly, subway pedestrian fatality rates are higher in elevated stations (which do not include drainage troughs [5]), for which we have recently also provided evidence of a protective effect using computational modelling [20].

Video analysis

Video is an extraordinarily powerful non-invasive means to gather information relating to physical events. A major development has been the huge increase in availability of video evidence of collisions, from CCTV and dashboard cameras for automotive cases to broadcast video for sporting collisions. This information is frequently available on sites such as YouTube, and it is now often possible to access a representative video of a collision configuration of interest. Despite their limitations, these videos represent a rich source of information. I will focus here on examples relating to pedestrian, cyclist and sporting collisions.

The risk of an injury/fatality arising from pedestrian or cyclist impact with a vehicle is largely a function of the vehicle impact speed and the age of the pedestrian/cyclist, but the outcome is also very substantially determined by the shape and stiffness of the vehicle front-end structures. The vehicle structures striking the different body regions, and the effective mass of the latter depends strongly on the relative height of the pedestrian and the vehicle. We explored this is in detail in [23]. Figure 1a shows a "wrap projection" case in which a pedestrian is struck substantially below their centre of gravity, causing them to rotate onto the bonnet. There follows a head

[9] Hugh de Haven survived a midair collision himself, and is a giant in the field of injury prevention [Gangloff, 2013].
[10] My own country (Ireland) has not been a leader in this.

impact on the windscreen. After vehicle braking, there is separation of the pedestrian from the vehicle and a head-first ground contact[11]. Figure 1b shows a high-fronted vehicle striking a pedestrian close to their centre of gravity. There is much reduced whole-body rotation compared to the wrap projection case, and due to the geometry of the vehicle, there is a head strike on the windscreen, even without much rotation of the body. Due to the shocking absence of vehicle braking in this case[12], there is no noticeable separation of the pedestrian from the vehicle, and there was a subsequent run-over of the pedestrian's body by the vehicle wheels (not shown here).

In sporting collisions, video analysis is greatly facilitated by the large amount of broadcast video associated with certain sports. In men's rugby, frame-by-frame video analysis of upper and lower body tackle configurations in cases which resulted in a player being removed from play for a head impact assessment (Figure 2a) led us to the conclusion that the tackler is at substantially higher risk than the ball carrier, especially in upper-body tackles [24, 25]. When multiple camera views are available, methods such as model-based image matching can be used to estimate three-dimensional kinematics directly from the video [26, 27]. There is much less availability of video for women's sport, although this is a growing field (eg. [28]).

A study of ACL injuries in noncontact events in men's rugby (Figure 2b) found that ACL injuries occur more frequently in sidestepping manoeuvres when first contact is through the heels rather than the balls of the feet [29]. Recently, we have analyzed knee landing mechanics in Gaelic Athletic Association football[13], showing that existing strength and conditioning programs may not provide adequate preparation for on-pitch demands.

Fig 1a: Low speed pedestrian wrap projection, adapted from [30].

Fig 1b: Pedestrian forward projection[14].

[11] Pedestrian ground contact is much less predictable than vehicle to pedestrian contact. This has been the subject of a number of computational and experimental studies (eg, Shang et al., 2020, Shang et al., 2018, Crocetta et al., 2015).

[12] Computational modelling evidence suggests that controlled vehicle braking after first contact with the pedestrian might be used to reduce pedestrian ground contact injuries (Zou et al., 2019).

[13] To be presented at the 2025 IRCOBI conference.

[14] Youtube, reference no longer available.

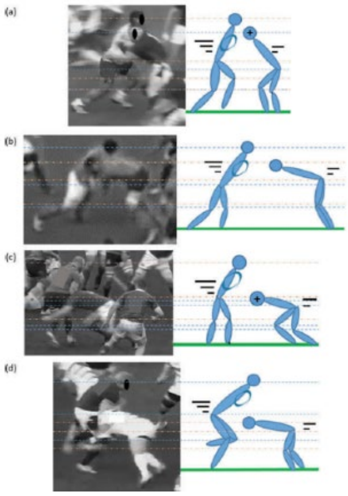


Figure 2a: Upper and lower-body tackles in rugby, adapted from [24].

Fig 2b: Foot-ground contact during a cutting movement in rugby, adapted from [29].

Computer vision

I have made the case for video analysis and for mechanical models in investigating injury biomechanics. In recent years, with major improvements in computer vision and human pose estimation facilitated by convolutional neural networks, labelled training data and other machine learning approaches (eg [31, 32]), I have focused on methods of extracting biomechanics understanding directly from video. While there remains much to develop, a "pipeline" involving 2D key point pixel position extraction of key body parts (typically joint locations) from video (eg [33]), "lifting" these 2D key points to 3D spatial coordinates using trained machine learning models (eg [31]), and then using this as input to computational impact models has great potential [34], see Figure 3. Applications of this kind of methodology to a rugby tackle [35, 36], a single cyclist fall [37] and to subway to pedestrian collisions [20], have been used to estimate impact forces, the effect of changing initial conditions, and to estimate the influence of a protective response[15]. This is also the basis for the sports technology start-up KineMo, of which I am co-founder[16].

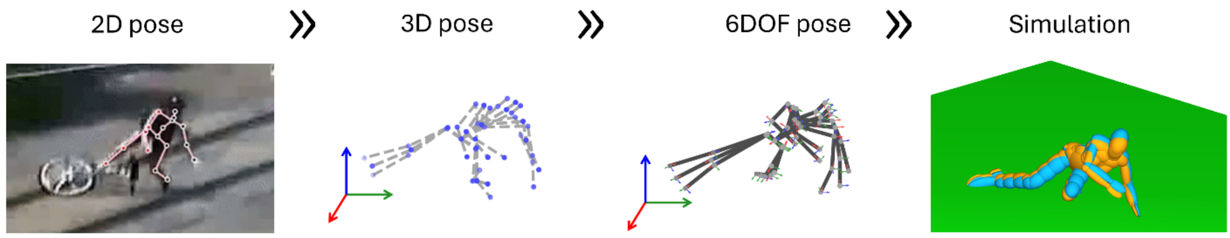


Figure 3. Pipeline of impact prediction from video:
Extraction of human pose from video, adapted from [34].

First principles impact models

After I finished my PhD on temporomandibular joint injuries arising from low-speed rear impact collisions (Figure 4) at Trinity College Dublin in 2000, I was lucky to work for Denis Wood's forensic engineering office. Dr Wood had by then already authored many excellent papers, especially on estimating vehicle impact speed from residual crush, and from pedestrian projection distances [eg [38], [39]]. I admire his focus on "simple models" as a starting point to understanding collisions.

[15] As an example, we were able to assess whether arm positioning during a cyclist fall might reduce head impact forces 37. Gildea, K., et al., *Forward dynamics computational modelling of a cyclist fall with the inclusion of protective response using deep learning-based human pose estimation.* Journal of Biomechanics, 2024. **163**..

[16] KineMo uses single camera technology to quantify assessment of athlete movement competency for injury prevention/rehabilitation.

Fig 4a: Me with model of head, neck & jaw, ca. 1997.

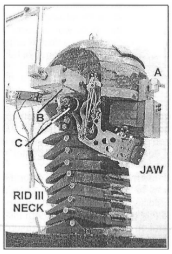


Fig 4b: Details of Physical model, adapted from [2].

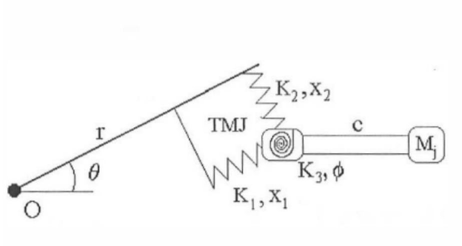


Fig 4c: Model of head & temporomandibular joint, adapted from [2].

Invoking the principle that "all models are wrong but some are useful" [17], and the decree to "make everything as simple as possible, but no simpler" [40], here are four basic impact models I have found to be of broad utility [see Figure 5]:

1. Model 1: a single degree of freedom spring mass impact model (Figure 5a).
2. Model 2: two finite masses colliding, modelled as an equivalent spring mass system (Figure 5b).
3. Model 3: a colinear momentum interchange model (Figure 5c)
4. Model 4: an eccentric impact momentum model (Figure 5d).

These models lead to several useful insights, which serve as a starting point when considering a collision scenario:

- Model 1: the stiffness (k) and mass (m) determine the natural frequency (ω_n), which together with the initial impact speed (v) fully determines the time history of the acceleration/force interaction. The time to peak force/peak acceleration $(\pi/(2\omega_n))$ and the magnitude of peak force $(mv\omega_n)$ and peak acceleration $(v\omega_n)$ are directly predicted.
- Model 2: the equivalent mass system yields similar findings, with the benefit of being applicable to cases where both bodies are moving, such as two athletes colliding, or a low-speed rear impact.
- Model 3: the colinear momentum model shows that the velocity change in a colinear collision depends directly on the mass ratio of the colliding bodies $(m_{2,1}/(m_1+m_2))$, and the initial impact speed (V). The average acceleration $(\bar{a})$ is proportional to the square of the impact velocity (V) and inversely proportional to the crush depth (d_{max}).
- Model 4: the eccentric impact model shows the relationship between mass moment of inertia (I), the initial impact speed (V_b) and the eccentricity (h) of an impact (i.e. the perpendicular distance between the mass centre and the line of action of the applied force). This model yields linear and angular velocity changes as a function of the inertia and geometry of the collision.

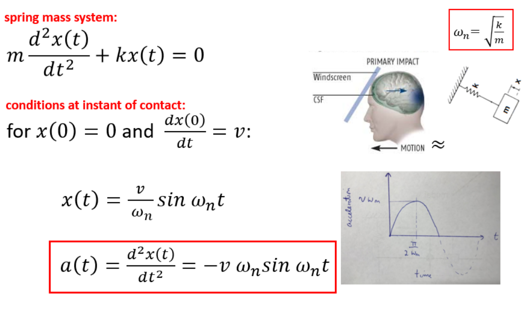


Fig 5a: Model 1: 1DOF single mass linear impact, adapted from [41].

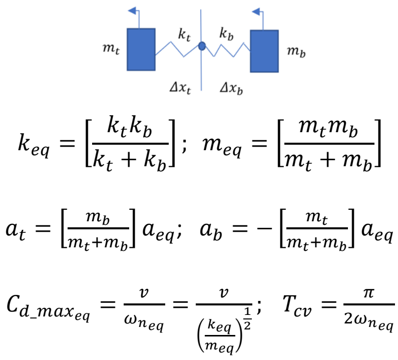


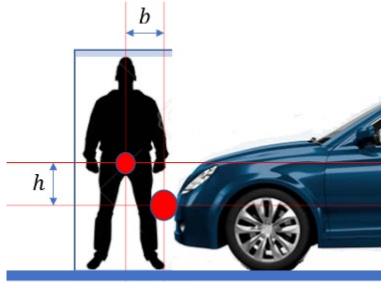
Fig 5b: Model 2: Two mass linear impact, adapted from [41].

[17] Commonly associated with George Box from a 1976 paper, but it may have earlier origins.

$$\Delta v_{1,2} = \left[\frac{m_{2,1}}{m_1+m_2}\right] V;$$

$$\bar{a} = \left[\frac{V^2}{2d_{max}}\right]\left[\frac{m_{2,1}}{m_1+m_2}\right]$$

Fig 5c: Model 3: two mass colinear momentum and acceleration/crush model [41].



$$\begin{bmatrix} m & M & 0 \\ 0 & -Mh & I \\ 1 & -1 & -h \end{bmatrix} \begin{Bmatrix} v_a \\ V_a \\ \omega_a \end{Bmatrix} = \begin{Bmatrix} MV_b \\ -MV_b h \\ 0 \end{Bmatrix}$$

Fig 5d: Model 4: two mass eccentric momentum model, adapted from [41].

In example applications, we used Model 1 to estimate pedestrian head-ground contact stiffness [16], head impact kinetics during soccer heading [42], and single leg landing ground reaction forces in Gaelic Athletic Association football[18]. A variant was used to derive countermeasure thickness to limit head acceleration in subway-to-pedestrian collisions [21]. We applied Model 2 to characterize low-speed rear impact automotive collisions [43] & [44]. A variant of Model 3 was used in Monte Carlo models of the relationship between car size and injury risk [45, 46]. We applied Model 4 to show the impact of bumper height on pedestrian impact severity and whole-body pedestrian rotational velocity. It also shows the relatively low influence of vehicle mass changes on pedestrian injury outcome [23]. A variant of Model 4 was used to link pedestrian projection distance to vehicle impact speed for forensic applications [47].

A two-segment ordinary differential equation model of a vehicle-to-pedestrian collision was included in [23] to illustrate the primacy of geometry and inertia in determining pedestrian kinematics during vehicle impact, see Figure 6. Despite the model's simplicity (a rotational joint at the neck with no rotational stiffness), the relative movement of the head with respect to the crash test dummy's torso during the wrap movement on the vehicle bonnet is successfully reproduced.

These models are of course a gross simplification and are unsuitable for anything such as detailed equipment design, but they do form a useful yardstick for interpreting trends in experimental data, and for assessing predictions from more detailed models. In my time as soft tissue editor of the Journal of the Mechanical Behavior of Biomedical Materials [23] I was struck by one reviewer's comments, criticizing the authors of an experimental paper for having no theoretical framework with which to interpret their findings. The basic mechanical models presented above provide such a framework for many collision applications. More generally, it might be argued that the philosophy of science should play a stronger role in our field than it currently does.

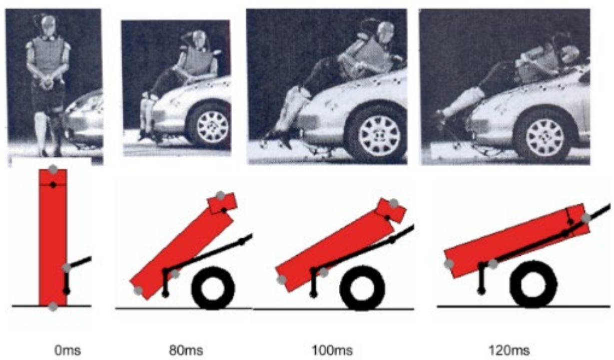


Figure 6: Two segment pedestrian model illustrating the primacy of inertia and geometry on determining pedestrian kinematics, adapted from [23].

[18] To be presented at the 2025 IRCOBI conference.

Computational models

Computational models (either multibody or finite element) can analyse complex scenarios, and are the backbone of much of the research currently presented at IRCOBI. The very wide variety of geometry and material properties for humans and vehicles are however both an opportunity and a challenge for detailed models. On the one hand, for equipment design and optimization in applications where specific load cases are clearly defined[19], detailed finite element models are an essential companion to experimental testing, increasingly even replacing experimental testing. On the other hand, where detailed computational models are used for exploratory studies, the very wide variety of geometry and material properties, combined with the time investment needed to develop and run finite element models leads to risks. Deterministic predictions from such models are in the best case useful for predictions specific to that load environment. In the worst case, they are so reliant on the myriad input parameters/assumptions that it is a challenge to draw meaningful conclusions beyond those already available from simpler models[20]. It is because of this that I am most excited by the stochastic finite element models of the type developed by Matthew Reed and colleagues at the University of Michigan (eg. [48]), or investigative models seeking a general understanding of soft tissue injury mechanisms, such as [49]. In my own limited finite element studies, we sought to establish trends based on sensitivity studies, rather than focus on absolute values. For example, our assessment of lateral bending of the knee for side-struck pedestrians found that increasing knee flexion reduced the lateral bending in the knee [50]. In retrospect, I think we could (should?) have shown this with a multi-body model instead[21].

Multibody models are useful for comparative analysis, for example in providing a biomechanical explanation for the increased pedestrian risk for high-fronted vehicle such as SUVs compared to passenger cars [51]. Sadly, despite this understanding, there has been a huge increase (70%) in pedestrian fatalities in the US in the last 15 years [52], correlating closely with a major increase in the proportion of SUVs [53][22].

Combining multibody modelling with genetic algorithms and other large parameter sweeps can address the wide variety of real-world scenarios. With this approach we derived vehicle front shapes that minimize pedestrian whole-body injury risk for a wide range of vehicle contact speeds, pedestrian sizes and pedestrian gait poses [54], [55]. These findings corresponded well with empirical measurements from GIDAS data of pedestrian risk from different vehicle shapes, referred to earlier [14]. Large parameter sweep models are also useful for exploratory studies, for example in categorizing different pedestrian ground contact landing mechanisms [56], estimating the benefits of controlled braking for reducing pedestrian head to ground contact risk [57], and in estimating the benefits of drainage troughs as a means to prevent runover in subway to pedestrian collisions [20].

Simplified analytical models combined with Monte Carlo methods are an even more effective means to facilitate large parameter sweeps to handle uncertainty, and have been useful in deriving reconstruction methods for vehicle speed estimation from pedestrian projection distance [47, 58], and in assessing vehicle braking in low speed rear-end collisions [59].

To conclude on modelling, Hermann Steffan from Graz University of Technology once said to me something to the effect of "if I want to do my thinking before I set up my model, I use multibody modelling, whereas if I want to do my thinking afterwards, I use finite element modelling". Though I am at least partly misquoting him, I believe there is strong value in this sentiment.

Tissue testing

Basic mechanics and models can only get you so far! It is difficult to overstate the value of experiments, especially when considering complex materials. Muscle tissue accounts for about half of human body mass. In a collision scenario, the passive properties of muscle generally predominate, except at very low speeds[23] [60]. During my PhD work on whiplash in the late 1990s I used rudimentary combinations of string and rubber bands to model the non-linear stretch properties of the muscles of the mandible, see Fig 4. Notwithstanding the obvious limitations of this approach, this seeded a long-standing interest in the three-dimensional stress-strain properties of skeletal muscle, and how to implement these in finite element models.

Skeletal muscle has a beautiful hierarchical structure, with muscle fibres surrounded by collagen fibres at different length scales, see Figure 7a. Through a program of uniaxial mechanical testing of isolated muscle

[19] For example, assessing whether a specific vehicle or vehicle component is compliant with a standard impact test.
[20] Make everything as simple as possible but no simpler" [16].
[21] Ibid.
[22] There are likely also other confounding factors involved, such as obesity.
[23] Siegmund et al show that muscles can matter in higher severity impacts or loading scenarios [60].

samples in tension and compression [61-63] (Figure 7b), it became clear that conventional transverse isotropy cannot capture the essential mechanical characteristics of this abundant tissue [64] (Figure 7c). I am intrigued by the tension-compression asymmetry, with orders of magnitude higher stiffness in tension than in compression, regardless of the direction of loading (fibre/cross-fibre). This does not comply with basic Poisson's ratio expectations. Despite various experimental studies to visualize the microstructure [65, 66] (Figure 7d) and modelling attempts [67, 68] (Figure 7e&f), I have not been able to fully link the microstructural components to the macro-level stress strain response. To the best of my understanding, representations of skeletal muscle in human body impact models remain largely phenomenological and do not fully capture this observed tension-compression asymmetry or the highly viscoelastic nature of the tissue [62, 63]. Improving the representation of human soft tissue in finite element models remains an important aspect of injury biomechanics research.

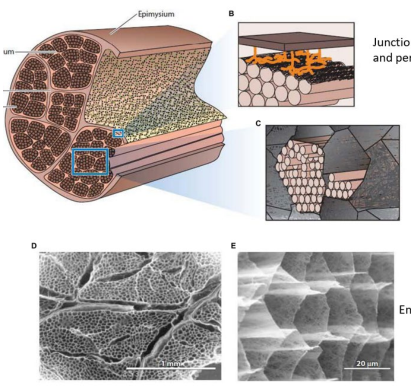


Fig 7a: hierarchical structure of muscle tissue, adapted from Purslow's experiments [69].

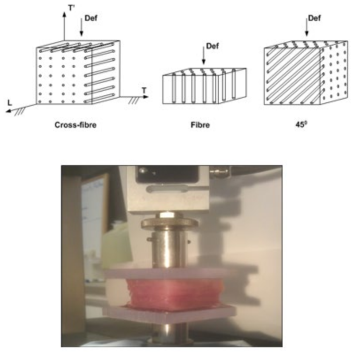


Fig 7b: Mechanical testing testing of isolated fresh skeletal muscle samples.

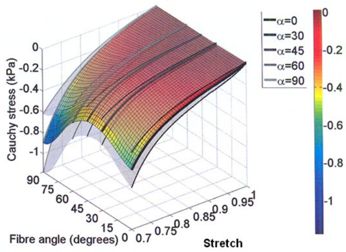


Fig 7c: muscle compressive strain nonlinearity and anisotropy, adapted from [61].

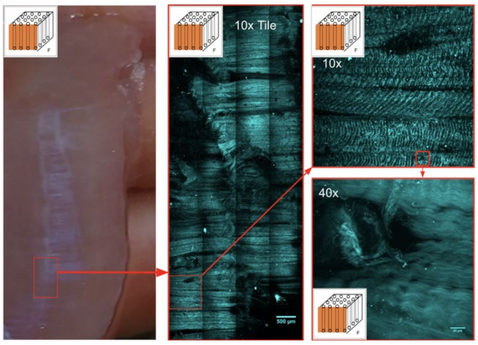


Fig 7d: muscle perimysium at different length scales, adapted from [66].

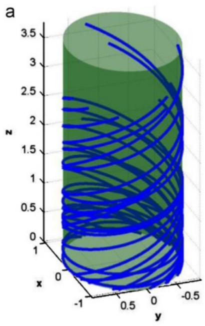


Fig 7e: model of skeletal muscle and collagen fibres, adapted from [70].

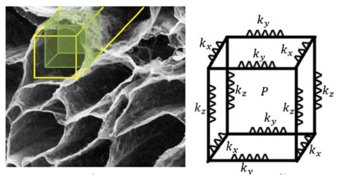


Fig 7f: inverse model of skeletal muscle [68].

V. PART C

The future of IRCOBI

As a research community, I see that IRCOBI is looking healthy. Comparing the participation low point in around 2009 (when the attendance at the conference in York dipped below 100) to today (with around 300 participants for several years running), we see strong evidence of the need for, and the interest in, injury biomechanics research. In human terms, I'd like to argue to the converted about the importance of gathering annually at IRCOBI. I think the proliferation of journals and online meetings actually increases the value of in-person conference gatherings. I recognize there are sustainability issues associated with travelling, but I believe we need to make these events as affordable as possible for young people in particular, and I know that IRCOBI has made great investments in student participation.

As an organization, I think IRCOBI is well set up to replenish its membership and to continue to provide a demanding but encouraging face-to-face conference environment. The free availability of all the conference papers is a major bonus. I encourage IRCOBI to further embrace its teaching remit, as well as the research forum.

The strength of IRCOBI is as a discussion forum, and as a record of the state-of-the-art. If you disagree with anything I have written here, I would welcome the opportunity to discuss it with you, at the conference or afterwards[24], especially as some of what I have presented are my views, rather than facts.

VI. CONCLUDING COMMENTS

Finally, from a personal perspective, although I come from a distinctly academic background[25] with great parental support, I never particularly rated my own abilities, and I did not envisage a career in research. However, I was the first engineer in my family and I have been very fortunate to have had a number of mentors who encouraged, challenged and inspired me. My PhD supervisor Garry Lyons instilled in me the love of learning and teaching. I have already saluted my first employer Denis Wood. Patrick Prendergast challenged me on the use of the scientific method and to publish more, including my book on pedestrian and cyclist impact [23], which carried a certain opportunity cost in terms of grants and research papers, but which was a rewarding experience. In that spirit, please consider your younger colleagues, and take the time to nurture them, as it will probably be one of the most impactful things you can do.

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VIII. REFERENCES

1. Tarriere, C. *Children are not miniature adults*. in *IRCOBI*. 1995.
2. Lyons, C., C. Brady, and S. CK. *Rear impact inflicted temporomandibular joint injury*. in *IRCOBI* 1998. Gothenburg.
3. Mackay, M. *IRCOBI - Past, Present and Future*. in *IRCOBI*. 2013.
4. NSC. *Car Crash Death and Rates*. 2025; Available from: https://injuryfacts.nsc.org/motor-vehicle/historical-fatality-trends/deaths-and-rates/.
5. Hall, D., et al., *Detailed Analysis of New York City Subway Pedestrian Incidents From 2019.* Transportation Research Record: Journal of the Transportation Research Board, 2023. **2677**(11): p. 642-650.
6. Appleyard, B., *Best Practice Guidelines - Transportation of People Seated in Wheelchairs*. 2019.
7. Siegmund, G. *Soft Tissue Neck Injuries and Other Important Things*. in *IRCOBI*. 2018.
8. Fichera, C., C. Flannagan, and J. John. *Quantifying Sex-differences in Anthropometry: a Bayesian approach*. 2024.
9. Robinson, A., et al. *Comparison of Individual Rib Cage Shape Variation with Regression Predictions*. in *IRCOBI*. 2024.
10. Brumbelow, M. *Reassessing PMHS Rib Fractures in Front Sled Tests to Improve Modern Restraint Systems*. in *IRCOBI*. 2024.
11. Hue , C., et al. *Interval-Specific, Blood-Brain Barrier Disruption In Vitro After Repetitive Primary Blast Injury*. in *IRCOBI*. 2013.
12. Dygalo, V., A. Keller, and A. Shcherbin, *Principles of application of virtual and physical simulation technology in production of digital twin of active vehicle safety systems.* Transportation Research Procedia, 2020.
13. Gepner, B., et al. *Evaluation of GHBMC, THUMS and SAFER Human Body Models in Frontal Impacts in Reclined Postures*. in *IRCOBI*. 2022.
14. Li, G., et al., *The influence of passenger car front shape on pedestrian injury risk observed from German in-depth accident data.* Accid Anal Prev, 2017.
15. Shang, S., et al., *Detailed assessment of pedestrian ground contact injuries observed from in-depth accident data.* Accid Anal Prev, 2018. **110**: p. 9-17.
16. Shang, S., et al., *Kinematics and dynamics of pedestrian head ground contact: A cadaver study.* Safety Science, 2020. **127**: p. 1-20.
17. Gildea, K., D. Hall, and C. Simms, *Configurations of underreported cyclist-motorised vehicle and single cyclist collisions: Analysis of a self-reported survey.* Accid Anal Prev, 2021.

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[25] Both of my parents were professors, and my grandfather and several other relatives are/were also professors.

18. Gildea, K. and C. Simms, *Characteristics of cyclist collisions in Ireland: Analysis of a self-reported survey.* Accid Anal Prev, 2021.
19. Paden, B.E., et al., *On the feasibility of life-saving locomotive bumpers.* Accident Analysis and Prevention, 2016. **89**: p. 103-110.
20. Hall, D., K. Gildea, and C. Simms, *Drainage Troughs as a Protective Measure in Subway–Pedestrian Collisions: A Multibody Model Evaluation.* Appl. Sci., 2024.
21. Hall, D. and C. Simms. *An Energy-absorbing Countermeasure Concept for Subway-to-Pedestrian Collisions Using Numerical and Analytical Modelling Techniques*. in *IRCOBI*. 2023.
22. Rosen, E., H. Stigson, and U. Sander, *Literature review of pedestrian fatality risk as a function of car impact speed.* Accident Analysis & Prevention, 2011. **43**: p. 25-33.
23. Simms, C. and D. Wood, *Pedestrian and cyclist impact - a biomechanical perspective*. Solid Mechanics and Its Applications, ed. Gladwell. 2009: Springer.
24. Tierney, G.J., et al., *Risks associated with significant head impact events in elite rugby union.* Brain Injury, 2016. **30**(11): p. 1350-1361.
25. Tierney, G.J. and C. Simms. *The effect of intended primary contact location on tackler head impact risk*. in *IRCOBI*. 2017.
26. Tierney, G.J., et al., *Analysis of ball carrier head motion during a rugby union tackle without direct head contact: A case study.* International Journal of Sports Science & Coaching, 2019. **14**(2): p. 190-196.
27. Tierney, G.J. and C. Simms. *Assessment of a high tackle on ball carrier inertial head kinematics in rugby union*. in *IRCOBI*. 2018.
28. Dane, K., et al., *Are recommended tackle techniques associated with superior performance outcomes? A retrospective video analysis study of elite women's rugby union.* Journal of Sports Sciences, 2024. **42**(24).
29. Montgomery, C., et al., *Mechanisms of ACL injury in professional rugby union: A systematic video analysis of 36 cases.* British Journal of Sports Medicine, 2018. **52**(15): p. 994-1001.
30. CBC. *B.C. pedestrian caught on camera being struck by car raises safety concerns*. 2014; Available from: https://www.cbc.ca/news/canada/british-columbia/b-c-pedestrian-caught-on-camera-being-struck-by-car-raises-safety-concerns-1.2846033.
31. Li, W., et al. *Exploiting Temporal Contexts with Strided Transformer for 3D Human Pose Estimation*. in *CVPR*. 2022.
32. Pavllo, D., et al., *3D human pose estimation in video with temporal convolutions and semi-supervised training.* 2019 Ieee/Cvf Conference on Computer Vision and Pattern Recognition (Cvpr 2019), 2019: p. 7745-7754.
33. Cao, Z., et al., *OpenPose: Realtime Multi-Person 2D Pose Estimation Using Part Affinity Fields.* Ieee Transactions on Pattern Analysis and Machine Intelligence, 2021. **43**(1): p. 172-186.
34. Gildea, K. and C. Simms. *KinePose Framework for Computer Vision-Aided Reconstruction of Pose and Motion in Human Body Models*. in *IRCOBI*. 2024.
35. Weldon, C., et al. *Forward and Inverse Dynamics Reconstruction of a Staged Rugby Tackle*. in *IRCOBI*. 2019.
36. Blythman, R., et al., *Assessment of deep learning pose estimates for sports collision tracking.* Journal of Sport Sciences, 2022: p. 1885-1900.
37. Gildea, K., et al., *Forward dynamics computational modelling of a cyclist fall with the inclusion of protective response using deep learning-based human pose estimation.* Journal of Biomechanics, 2024. **163**.
38. Wood, D. *Collision Speed Estimation Using a Single Normalised Crush Depth-Impact Speed Characteristic*. in *SAE*. 1992. Society of Automotive Engineers.
39. Wood, D., *Impact and movement of pedestrians in frontal collisions with vehicles.* Proceedings of Institute of Mechanical Engineers, Part D, Automobile Engineering, 1988. **202**: p. 101-110.
40. Robinson, A. *Did Einstein really say that?* 2018; Available from: https://orbitermag.com/einstein-really-say/.
41. Simms, C., *Multibody Dynamics, Lecture Notes, TCD*. 2025.
42. Tierney, G., J. Power, and C. Simms, *Force experienced by the head during heading is influenced more by speed than the mechanical properties of the football.* Scand J Med Sci Sports, 2021. **31**(1): p. 124-131.
43. Nishimura, N., C. Simms, and D. Wood, *Impact characteristics of a vehicle population in low speed front to rear collisions.* Accident Analysis and Prevention, 2015. **79**: p. 1-12.
44. Wood, D., et al., *Dynamic response in low speed rear impact and inferences for injury potential*, in *EVU*. 2016.
45. Wood, D. and C. Simms, *Car size and injury risk: a model for injury risk in frontal collisions.* Accident Analysis & Prevention, 2002. **34**(1): p. 93-99.
46. Wood, D.P., et al., *Limits for survivability in frontal collisions: Theory and real-life data combined.* Accident Analysis & Prevention, 2007. **39**(4): p. 679-687.
47. Wood, D., C. Simms, and D. Walsh, *Vehicle pedestrian collisions: Validated models for pedestrian Impact and Projection.* Proceedings of the Institute of Mechanical Engineers Part D, 2005. **219**(2): p. 183-196.
48. Reed, M.P., et al. *Computing Head Inertial Properties for Human Volunteers using a Parametric Head Model*. in *IRCOBI*. 2024.
49. Singh, D. and D. Cronin. *Relationships Between Continuum Lung Tissue Strains, Alveolar Wall Strains and the Potential for Injury*. in *IRCOBI*. 2022. Porto.

50. Li, G., J. Yang, and C. Simms, *The influence of gait stance on pedestrian lower limb injury risk.* Accident Analysis and Prevention, 2015. **85**: p. 83-92.
51. Simms, C. and D. Wood, *Pedestrian risk from cars and sport utility vehicles - a comparative analytical study.* IMechE Journal of Automobile Engineering, 2006. **220**: p. 1085-1100.
52. IIHS. *Fatality Facts 2022 Pedestrians*. 2025; Available from: https://www.iihs.org/topics/fatality-statistics/detail/pedestrians.
53. DOT., U. *Number of U.S. Truck Registrations by Type*. 2025; Available from: https://www.bts.gov/browse-statistical-products-and-data/national-transportation-statistics/number-us-truck.
54. Li, G., J. Yang, and C. Simms, *Safer passenger car front shapes for pedestrians: A computational approach to reduce overall pedestrian injury risk in realistic impact scenarios.* Accid Anal Prev, 2017: p. 97-110.
55. Li, G., J. Yang, and C. Simms, *A Virtual Test System Representing the Distribution of Pedestrian Impact Configurations for Future Vehicle Front-End Optimization.* Traffic Injury Prevention, 2015. **in press**: p. unknown.
56. Crocetta, G., et al., *The influence of vehicle front-end design on pedestrian ground impact.* Accident Analysis and Prevention, 2015. **79**: p. 56-69.
57. Zou, T., S. Shang, and C. Simms, *Potential benefits of controlled vehicle braking to reduce pedestrian ground contact injuries.* Accid Anal Prev, 2019. **129**.
58. Simms, C., D. Wood, and D. Walsh, *Confidence limits for impact speed estimation from pedestrian projection distance.* Journal of Crashworthiness, 2004. **9**(2): p. 219-228.
59. Wood, D., et al. *The influence of vehicle braking on target vehicle dynamics in low speed rear-end collisions*. in *EVU*. 2019.
60. Siegmund, G., D. Chmimich, and B. Elkin, *Role of Muscles in Accidental Injury*, in *Accidental Injury - Biomechanics and Prevention*, N. Yoganandan, A. Nahum, and J. Melvin, Editors. 2015, Springer.
61. Van Loocke, M., C.G. Lyons, and C.K. Simms, *A validated model of passive muscle in compression.* Journal of Biomechanics, 2006. **39**: p. 2999-3009.
62. Van Loocke, M., C.G. Lyons, and C.K. Simms, *Viscoelastic properties of passive skeletal muscle in compression: Stress-relaxation behaviour and constitutive modelling.* Journal of Biomechanics, 2008. **41**(7): p. 1555-1566.
63. Van Loocke, M., C.G. Lyons, and C.K. Simms, *Viscoelastic properties of passive skeletal muscle in compression: cyclic behaviour.* Journal of Biomechanics, 2009. **42**(8): p. 1038-1048.
64. Simms, C., M. Van Loocke, and C. Lyons, *Skeletal Muscle in Compression: Modelling approaches for the Passive Muscle Bulk* International Journal of Multiscale Computational Engineering, 2012. **10**(2): p. 143-154.
65. Mohammadkhah, M., C. Simms, and P. Murphy, *Visualisation of Collagen in fixed skeletal muscle tissue using fluorescently tagged Collagen binding protein CNA35.* J Mech Behav Biomed Mater, 2017.
66. Hennessy, N. and C. Simms, *Skeletal Muscle Extracellular Matrix Structure Under Applied Deformation Observed Using Second Harmonic Generation Microscopy.* Acta Biomaterialia, 2023.
67. Gindre, J., et al., *A structural model of passive skeletal muscle shows two reinforcement processes in resisting deformation.* Journal of the Mechanical Behavior of Biomedical Materials, 2013. **22**: p. 84-94.
68. Valentin, T. and C. Simms, *An inverse model of the mechanical response of passive skeletal muscle: Implications for microstructure.* J Biomech, **99**, 2020.
69. Purslow, P.P., *Muscle fascia and force transmission.* Journal of Bodywork & Movement Therapies, 2010. **14** p. 411-417.
70. Gindre, J., et al., *A Structural Model of Passive Skeletal Muscle shows Two Reinforcement Processes in Resisting Deformation* JMBBM **22**, 84-95, 2013.