

Sports concussions: can head impact sensors help biomedical engineers to design better headgear?

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Sport-related concussion is a major public health concern. In a recent BJSM publication, McGuine *et al* conducted a randomised controlled trial (RCT) to evaluate whether soccer headgear would reduce the rate or severity of concussions in adolescent athletes ($n_{\text{headgear}} = 1505$, $n_{\text{no headgear}} = 1545$).¹ Both ‘control’ athletes (who wore no helmets) and the athletes who wore soccer headgear had similar concussion rates and recovery times after a concussion. In another study, headgear was also found to be ineffective in reducing concussion rates or recovery times in rugby union.²

DOES PADDING THE HEAD HELP REDUCE CONCUSSIONS?

Padding may seem like the most intuitive way to protect the head from injury. So why might this approach not be concussion-proof? Adding a foam pad can help ‘soften the blow’, by increasing the loading area and absorbing some of the impact energy. However, given a regular thickness pad, substantial impact energy is still transmitted to the head and produces a sharp head/skull acceleration. The skull acceleration in turn shakes and deforms its contents—the brain.

Traditionally designed helmets and padding reduce focal loading and head linear accelerations that are associated with skull fracture risk.³ However, head rotation has been hypothesised to be a main contributing factor to closed-head, concussion-type injuries and verified through animal/computational models for the last 50–60 years.⁴ Despite this, regulatory standards on helmets use linear acceleration-based criteria, but do not address rotational head kinematics. The US National Operating Committee on Standards for Athletic Equipment only recently posted a revised American football helmet standard to include a peak rotational acceleration criterion. This came into effect in November 2019.

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CAN RESEARCHERS EVALUATE PROTECTIVE EQUIPMENT OR OTHER EFFORTS TO LIMIT CONCUSSIONS WITHOUT RCTS FOR EVERY DESIGN?

Novel materials to further improve absorption of impact energy and protective gear to reduce head rotation still need to be designed and tested. However, it is resource-intensive to evaluate every potential design with the type of RCT conducted by McGuine *et al*. Instead, wearable sensors⁵ and computational modelling⁶ may provide alternative study designs to efficiently evaluate new protective equipment and reduce the need to use concussions as an endpoint.

Wearable human head impact sensors typically measure linear and rotational kinematics of the head during impact, which are factors associated with head injury. While biomedical engineers still do not understand the exact relationship between head accelerations and concussion risk, such impact sensor data may also be applied as inputs to drive computational head models and simulate mechanical deformations of the brain as a result of impact⁶; this could provide a more direct measure of brain injury risk.

CURRENT STATE OF HEAD IMPACT SENSORS: CAN THEY PREDICT CONCUSSIONS?

Head impact sensors commonly mount inertial sensors (accelerometers and/or gyroscopes) on helmets or other headgear, on skin, in the ear or on teeth. In the Berlin Consensus Meeting’s 2017 systematic review on concussion screening methods,⁷ sports and exercise medicine specialist Dr Jon Patricios and colleagues concluded that head impact sensors did not provide useful information in the diagnosis of concussions. The four sensor studies included in the review used helmet-based sensor systems. There have been studies showing large errors in using such sensors to measure head/skull accelerations of individual impacts, due to helmet dislocation.⁸ While helmet-based sensors may be valuable in estimating summary exposure statistics over

a larger number of players and events, they do not provide the high accuracy needed to measure accelerations of individual impacts that may cause injury.

EMERGING TECHNOLOGY: MOUTHGUARD SENSORS WITH VIDEO VERIFICATION OF IMPACTS

In a previous study, we have compared in vivo measurement accuracy of headgear-mounted, skin-mounted and mouthguard-mounted sensors.⁵ Skin-mounted sensors had an average of 150% error in estimating head rotational velocity due to skin motion, and skull cap-mounted sensors had an average of 110% error in rotational velocity. We showed tighter coupling between the mouthguard (figure 1) and the skull, with greater potential to accurately measure skull accelerations.

Video verification of impacts may still be important in addition to the use of sensors.⁷ Head impact sensors, essentially inertial measurement units, are sensitive to extraneous accelerations from any source (eg, sensor manipulation). Such spurious recordings are not necessarily mild—they could have tens of g’s of linear acceleration similar to injury events, due to the low mass of the sensors. We have shown the need to conduct video review of impacts or design cross-validated head impact detection algorithms. These are needed to identify potential false positives (detecting spurious nonimpact events) and false negatives (failure to detect head impacts due to improper filtering/thresholding).⁹ Many sensor exposure and concussion studies do not include video validation.

BUT BIOLOGY IS NOT SO SIMPLE!

Even with the advent of accurately measured verified head impacts from sensors directly coupled to the skull like the mouthguard, there may not be a simple relationship correlating skull kinematics with injury risk. While skull rotational kinematics are now being recognised as important in mild closed-head brain injuries, they may still have non-linear relationships with injury risk due to highly non-linear brain mechanics. The amount of error in rotational kinematics measurements are therefore not direct indicators of degree of accuracy in estimating the effects on the brain. In comparison, brain tissue deformation parameters such as strain are more direct measures of mechanical input to the brain, and may be more promising injury risk parameters.



Figure 1 Instrumented mouthguard. Inertial sensors can be embedded into custom-formed athletic mouthguards to measure head impact biomechanics. The mouthguard couples tightly to the upper dentition to directly measure accelerations of the skull.

Currently in the brain injury biomechanics field, there are efforts to gather large human injury datasets of accurately measured head impact kinematics, from which brain tissue deformation parameters can be simulated with computational models. Such efforts will help to validate injury risk criteria and improve both safety standards and the design of protective equipment.

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