Applying the Concept of the Power Index to the Prevention of Concussion in Sports and the Improvement of Headgear

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Introduction

Traumatic brain injury (TBI) encompass a vast spectrum of disorders to the brain as a result of mechanical insult and are a leading cause of death and disability in today’s society [1]. Protective helmets have greatly contributed to the overall reduction of the head injury problem, but are designed predominantly to prevent serious and severe injuries. In sports where severe head injuries are a concern, as well as in many other activities, helmets have been introduced successfully.

Whereas the disabling and fatal consequences of severe head injury are obvious, this is less so for mild traumatic brain injury (MTBI) or concussion. In many contacts sports, even those in which helmets have been introduced to prevent serious head injuries, concussions continue to occur. Medical research is making progress in assessing and treating concussion, but the prevention of these injuries has lacked behind due to the limited understanding of the biomechanics of this type of closed head injury.

New techniques have been developed to quantify the risk of concussion in head impacts. Principles of these techniques are presented here and their possible applications in contact sports are discussed.

Mild Traumatic Brain Injury Risk

Concussion has long been considered a relatively mild form of brain injury as it presents a very limited threat to life. This injury, however, can have serious consequences as it may affect the immediate state of consciousness, with a potential of impaired cognitive abilities, and reduced physical-, behavioural-, or emotional functioning. As a unique occurrence, concussion does not necessarily present an immediate danger and recovery can be complete if neurological symptoms have completely disappeared. The potential danger lies in the fact that before complete recovery, which in itself is hard to assess, the brain tolerance is reduced and successive head impact can result in an even more serious head injury. This effect of successive or repeated loading has also been speculated for sub-concussive blows to the head, and without the appearance of an acute injury, the brain can show symptoms of sustained reduced capacity, known as chronic traumatic brain injury (CTBI).

The biomechanics of closed head injury has been studied for several decades, but limited knowledge still exists on how and why concussion occurs. It is commonly accepted that concussion is a form of diffuse brain injury, and a result of inertial effects throughout the entire brain matter caused by contact and non-contact loading on the head. What areas of the brain are affected is hard to predict and depends on many parameters such as the direction and the type of loading. Typically, inertial responses of the head to impact are characterized by its acceleration in time.

Head Impact Power: HIP

Many functional relationships between head acceleration and the probability of brain injury have been proposed, such as the Severity Index [2] and the Head Injury Criterion [3]. Both SI and HIC are functions approximating the Wayne State University Concussion Tolerance Curve (WSTC) [4], which defines the tolerance of the human brain to impact on the basis of a combination of average head acceleration and time duration of this acceleration.

Newman et al. [5] observed that instead of using the general function $a_{ave}^{2.5} \cdot T = constant$, as applied in the SI and HIC, but simply using $a_{ave}^{2} \cdot T = constant$, provides a better approximation of the WSTC. Moreover, this also provides a physical meaning to this function. Here $a_{ave}$ designates the average head acceleration and $T$ designates the time duration over which the acceleration is experienced. Rewriting this simple approximation of the WSTC provides:

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1 Numbers in square brackets designate the references at the end of this document.
\[
\frac{v^2}{T} = \text{constant}
\]

with: \(v\) = velocity change of the head.

Equation (1) provides a quantity that is proportional to the rate of change of kinetic energy or power. Based on this observation, Newman et al. hypothesize that the risk of MTBI correlates to the magnitude of the rate of change of kinetic energy that the head undergoes during impact. A general expression for the rate of change of kinetic energy for any rigid object, is of the form:

\[
\text{Power} = P = \sum m \overline{a} \cdot \overline{v} + \sum I \overline{\alpha} \cdot \overline{\omega}
\]

with:
- \(\overline{a}\) = linear acceleration (m/s\(^2\))
- \(I\) = mass moment of inertia (Nms\(^2\))
- \(m\) = mass (kg)
- \(\overline{\alpha}\) = angular acceleration (rad/s\(^2\))
- \(\overline{\omega}\) = angular velocity (m/s)

Equation (2) is simply the scalar sum of the rotational and the translational power terms, and follows the trend of viscous response for soft tissue [6]. With all terms expanded and the inertial characteristics of the human head are introduced, the Head Impact Power (HIP) is obtained:

\[
\text{HIP} = 4.50 a_x \int a_x dt + 4.50 a_y \int a_y dt + 4.50 a_z \int a_z dt + 0.016 \alpha_x \int \alpha_x dt + 0.024 \alpha_y \int \alpha_y dt + 0.022 \alpha_z \int \alpha_z dt
\]

Correlation between HIP and MTBI

Since 1997, Biokinetics has been conducting research into the biomechanics of MTBI in professional American football athletes of the National Football League. The overall methodology is based on reconstruction of concussive and non-concussive head impacts [7]. Video data of multiple cameras capturing the same impact event are analyzed, and relative kinematics of the colliding heads (or head with respect to the playing field) are resolved. These events are then reconstructed with Hybrid-III crash test dummy head-neck systems, as illustrated in Figure 1.

The dummy heads are equipped with arrays of accelerometers to establish the linear and angular head accelerations. HIP as well as several other criteria are calculated for each player involved in the impact. Statistical correlations are studied between these criteria and the injury diagnosed by the team physicians.

To date over 140 incidents of head-to-head and head-to ground impacts are
analyzed, and 24 cases have been reconstructed with and without the occurrence of concussion. The statistical analysis has resulted in a probability function shown in Figure 2 [8], which predicts the risk of concussion as a function of HIP. Furthermore, Head Impact Power proves to correlate better to concussion than any other currently used injury criterion. This injury probability function is essential in devising prevention strategies. Not only does it allow quantifying protection offered by helmets, it also allows having a measurable parameter to assess the impact severity in an actual game situation.

Application of HIP in Contact Sports

For the purposes of this research, it is assumed that the mechanical characteristics of the brain are basically equal for all subjects studied, and no previous pathology is assumed for the subjects. The use of the HIP probability function for concussion as given in Figure 2 therefore extents to all types of head impact, particularly of other athletes of similar anthropometry. If an impacted subject can be reasonably represented by the Hybrid-III head-neck system, then the probability of concussion can be predicted using the HIP resulting from the head’s linear and angular accelerations, irrespective of the loading conditions.

This consideration allows a wide use of the HIP to assess the risk of concussion in contact sports, both with and without the current use of headgear. Different sports impose different threats or impact loading conditions, but do not change the principle of HIP.

Similarly, the HIP allows the evaluation of headgear in the prevention of concussion, which is not addressed by current helmet standards. Currently, knowledge from the NFL MTBI research program is being considered in American football helmet design. By doing so, manufacturers are not only complying with current standards, but are beginning to broaden the protective range of their helmets to include protection against lower level head injuries. Future endeavours to use HIP as a performance criterion should include sport specific studies to characterize the level of impact.

References