The dynamics of concussive head impacts in rugby and Australian rules football

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ABSTRACT

McINTOSH, A. S., P. McCRORY, and J. COMERFORD. The dynamics of concussive head impacts in rugby and Australian rules football. *Med. Sci. Sports Exerc.*, Vol. 32, No. 12, 2000, pp. 1980–1984. A study was commenced in 1998 at the University of New South Wales (UNSW) to investigate the dynamics of head impacts in football which resulted in concussion. Sixty-eight cases of medically verified concussion from Australian Rules Football and 32 from Rugby Union and Rugby League were analyzed. Video of each injury event was analyzed to obtain descriptive data regarding the head impact site and striking object. The video was analyzed quantitatively to obtain estimates of the closing speeds. A secondary analysis was undertaken using the conservation of momentum and energy relationships to estimate the change in velocity of the head during the impact, the change in momentum of the head, and the energy imparted to the head. Ninety-seven cases involved direct head contact, whereas three cases involved impulsive loading via the trunk. The majority of impacts were to the tempero-parietal region, and the striking body segment was commonly the arm or shoulder/thorax. The mean change in velocity of the head and head impact energy for all 97 cases of direct head impact were 4 $m \cdot s^{-1}$ and 56 J, respectively. Head impact energy can be used as a performance criteria for testing and developing headgear for rugby and Australian rules football. **Key Words:** BIOMECHANICS, HEAD INJURY

A study was commenced in 1998 at the University of New South Wales (UNSW) to investigate the dynamics of head impacts in football that resulted in concussion. The overall aim of the study is to develop methods to reduce the incidence and severity of concussion.

In Australia, three versions of contact football are played: rugby union (RU), rugby league (RL), and Australian rules (ARF). In sequential injury surveys performed in elite ARF, the concussion rate has gradually increased from 2.2 to 3.9 per 1000 player hours over the past 5 years (1,3,6,7) for reasons that are unclear. There is only limited prospective data on the incidence and prevalence of concussion in RU and RL; however, it is an area of concern to administrators, players, and the medical fraternity. Therefore, there is a need to examine the mechanisms of concussion in football and methods which might reduce its frequency and severity.

The design process for safety systems requires knowledge of the conditions under which the system is required to operate. With protective headgear, it is necessary to define the nature of the impacts that result in concussion, so that headgear can be developed that will prevent concussion under those conditions. The important parameters to define are impact velocity and energy, head impact sites, the nature of the impacting object, and permissible head acceleration.

To determine the dynamics of head impacts resulting in concussion, it is necessary to measure the kinematics or kinetics of the injury incident. The methods and instrumentation required to measure this in the field renders it virtually impossible. However, the estimation of impact kinematics is slightly less difficult as professional football games are videotaped. Therefore, a method was developed to estimate the head impact speeds in two dimensions from video of the head injury events. From this data a method was derived to estimate the energy transferred to the head during the impact, i.e., the head impact energy (HIE). HIE, combined with information on head impact sites, is intended to be useful in establishing performance criteria for assessing the impact energy attenuation properties of headgear.

METHODS

Sampling Methods

Cases of concussion from ARF, RU, and RL were sampled using two methods. In ARF cases were obtained from the Medical Officers' Injury Surveillance Scheme for the

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period 1995 to 1998, a period during which there were no significant rule changes. In RU and RL, an injury notification scheme was developed whereby team doctors notified UNSW directly about cases during the 1998 season. Injury information was obtained with the written consent of each player. The results presented in this paper relate to a set of impacts resulting in medically verified concussion. Video of each event was obtained through the team, the broadcaster, or the code's administration. Anthropometric data were obtained for the injured and striking player. The striking player's body mass was unknown in approximately 15% of the cases. In these cases, mass was estimated from the video by using a comparison to players of known body dimensions. Winter's (8) anthropometric scaling data were used to estimate segment lengths and masses. The administrators of the three codes, the Australian Rugby Union, the Australian Rugby League, and the Australian Football League, supported the study and gave permission to obtain match videos. The study was approved by the University of New South Wales Ethics Committee on Experimental Procedures Involving Human Subjects (Protocol No. 96060).

Estimation of Head Impact Dynamics

A system was developed for analyzing the impact kinematics from PAL VHS video. The analyses aimed to identify the impact location on the head, the nature of the striking/struck body segment or object, and the speed of the impacting bodies before impact. The selection criteria for video analysis were minimal parallax error, availability of scaling information, and the absence of zooming.

Video sequences were selected and captured onto a PC at 25 frames per second. Body segments were identified on the digital image sequence and the coordinates of the center of each segment recorded at each frame electronically using the WinAnalyze software (Mikromak GmbH, Erlangen, Germany). The image sequence was transformed into real-world coordinates using the dimensions of the players in the majority of the cases. In some cases the field dimensions were used. The velocity of the segments, e.g., head and trunk, were calculated using three-point differentiation. An evaluation of the accuracy and reliability of the system is presented in Appendix A. In short, the results showed that the error in the speed estimates was about 10%, i.e., using cases that would fall into the above selection criteria.

After the video analysis, a number of parameters were estimated. First, the impact closing speeds were calculated from the linear speeds. Next, by using the conservation of momentum and energy principles, a method was developed to estimate the head impact energy. This method involved the following steps and assumptions:

1. The momenta of the striking objects (Hstrike) and head (Hhead) just before impact were calculated using the mass (m) and speed estimates (vi)

$$\text{Total Initial Momentum (Hi)} = \text{mhead } \tilde{v} \text{ head i} + \text{mstrike. } \tilde{v} \text{ strike i}$$

2. The final velocity (vf) of the striking and struck object, assuming that a plastic collision occurred.

$$\text{Total Final Momentum (Hf)} = (\text{mhead} + \text{mstrike})\, \tilde{v} \text{ f} = \text{Hi}$$

3. The change in velocity of the head (Δv) was calculated. This was the vector sum of the head's pre-impact velocity and the final velocity derived from the momentum calculations.

$$\text{Change in head velocity } \Delta v = \tilde{v} \text{ f} - \tilde{v} \text{ head i } (\text{m} \cdot \text{s}^{-1})$$

4. The change in momentum of the head and head impact energy were calculated using the initial and final velocities. Thus, the change in head momentum or "head impulse" was defined as:

$$\text{HImp} = \Delta v \text{ mhead } (\text{kgm} \cdot \text{s}^{-1})$$

5. The head impact energy during the impact was estimated using a conservation of energy approach. It can be seen that total final energy, sum of kinetic, and potential energies (KEf and Pef, respectively) equals the total initial energy plus the work performed on the head, i.e., the head impact energy. Thus,

$$\text{PEi} + \text{KEi} + \text{HIE} = \text{PEf} + \text{KEf}$$

For example, in a simple situation in which the head falls and strikes the ground, the initial KE will be related to its mass and velocity just before impact and its final energy (PE and KE) will equal zero. In this case forces acting through the neck are ignored. Here, HIE is equal to the initial KE and manifests itself in the following way:

$$\text{HIE} = \text{Force} \times \text{Displacement}$$

Hence, work will be performed through force and deformation of the head and ground. In an impact involving two football players, work will be performed through soft tissue deformation and muscle action. When the head is struck by the upper arm, work will be performed on both body segments and the change in work (ΔU) could be divided into two or more components, i.e.,

Conservation of Energy Relationship for the Head of Struck Player:

$$\text{PEheadi} + \text{KEhead i} + \Delta\text{Uhead/arm} + \Delta\text{Uhead/trunk} = \text{PEheadf} + \text{KEheadf}$$

Conservation of Energy Relationship for the Upper Arm of Striking Player:

$$\text{PEarmi} + \text{KEarmi} + \Delta\text{Uhead/arm} + \Delta\text{Uarm/shoulder} = \text{PEarmf} + \text{KEarmf}$$

The magnitudes of head/arm, head/trunk, and arm/shoulder energies, i.e., change in work, are difficult to quantify; the latter two will depend on muscle and joint involvement. An assumption was made that head/trunk and arm/shoulder

TABLE 1. Head injury cases.

Code	No. of Cases	Years
ARF	68	1995–98
RL	25	1998
RU	7	1998
Total	100	

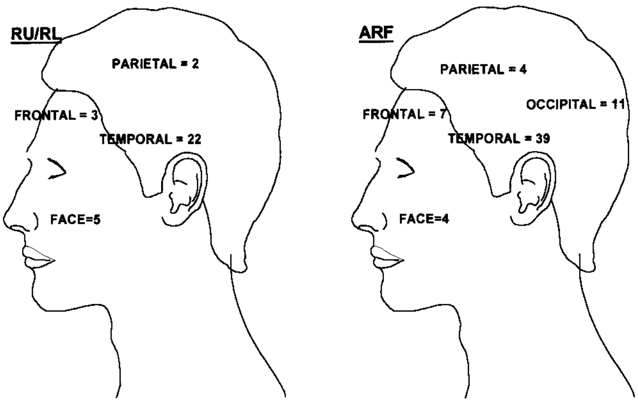

Figure 1—Location of head impacts; left, rugby codes; right, Australian football.

energies were zero, i.e., the player is unprepared and has not braced his neck. This assumption is necessary to reduce the problem to a solvable form. Review of the injury incidents indicates that most ARF players were not aware of the impending impact; they were concentrating on following or playing the ball and took no obvious evasive action. In the majority of cases, for all codes, the subsequent head-neck motion was sufficiently large, but not quantified, to indicate that the neck forces were low. The assumption that arm/shoulder energy was zero is consistent with the decision that only the arm's mass would be involved and that the trunk's mass was not coupled to the arm. It was also assumed that the potential energy of the head remained unchanged during the impact. Thus, the energy relationship for the head was simplified to:

$$\text{HIE} = \Delta\text{Uhead/arm} = \text{KEheadf} - \text{KEheadi} = 0.5\ \text{mhead}\ (\text{vf}^2 - \text{vheadi}^2)$$

RESULTS

A total of 130 cases were sampled from ARF (1995–1998), RU (1998), and RL (1998). It was possible to analyze the head impact kinematics in 100 of these cases. Table 1 presents the distribution per code.

The distribution of head impacts resulting in concussion according to location is presented in Figure 1. This shows that the majority of impacts occurred to the temporal region, with the anterior half of the head, including the face receiving 86% of all impacts. Ten percent of impacts resulting in concussion were occipital and 3% were to the upper body.

Table 2 shows the frequency for the impacting body segments. The results show that the upper arm and upper body (shoulder and chest) were the striking objects in the majority of cases across the three codes.

TABLE 2. Nature and frequency of striking/struck object in head impact (N = 100).

	Body Segment				
Code	Upper Limb	Upper Body	Head	Lower Limb	Ground
ARF	19	24	8	11	7
RL	10	5	2	5	1
RU	2	4	0	0	1
All	31	33	10	16	9

TABLE 3. Mean closing speeds (N = 100).

	ARF	RL	RU	ALL
Mean closing speed (m·s^{-1})	7	6	5	7
SD	3	2	1	2.5
Range	0.2–13.8	3.0–11.4	3.5–7.7	0.2–13.8

In 72% of the cases, there was only one head impact in the injury event. In the remaining cases, it could be observed that more than one impact occurred, e.g., struck with arm and then hit ground. These events were treated as two separate events, and only the event with the greatest head impact energy was used for further analyses, as it was considered that this was most likely to have resulted in concussion.

The mean closing speed was 7 m·s^{-1}. The maximum was 14 m·s^{-1}. Table 3 provides the mean closing speeds for each code. There was no significant difference between the closing speeds in the three codes. These speeds were considered to be reasonable when the running speeds of players were considered.

Mean and standard deviations for Δv, HIE, and HImp are presented in Table 4 for all 97 direct head impacts. The three impulsive impacts were excluded, as it was not possible to derive equivalent impact variables.

DISCUSSION

Video of 100 cases of concussion in football were analyzed to determine the impact dynamics and describe the injury event. Ninety-seven of the cases involved direct contact with the head and in three cases no head contact occurred. The majority of head injuries resulted from direct impact between the head and the upper body or upper limb of a second player. These events occurred when the ball was being contested or during a tackle. Head impacts were generally to the tempero-parietal region. These impacts resulted in medically diagnosed concussion in all cases, with extended LOC being the most severe symptom. No severe head injury was observed, e.g., intra-cranial hemorrhage or skull fracture.

The paper describes an approach to studying injury mechanisms in football that provides estimates of impact speeds, the change in velocity of the head, and the head impact energy. The methods apply basic physical principles, conservation of momentum and energy, to the analysis of head impacts. The accuracy of the initial speed estimates are within 10% of the actual speeds, based on the results described in Appendix A. It is not possible to verify independently the collision speeds in the games; however, the

TABLE 4. Summary of head impact dynamics for direct impacts (N = 97).

	Δv (m·s^{-1})	HIE (J)	Impulse (kgm·s^{-1})
Mean	4	56	29
SD	2	36	11

speeds are consistent with the style of game and capabilities of the players.

The analysis methods utilize fundamental momentum and energy relationships. The validity of the assumptions that the player is unaware and is not applying forces to the head through the neck has not been tested. It was observed that many players did not appear to be expecting the impact, particularly in ARF. The estimation of the striking impact mass requires a similar assumption that only the mass of a defined segment is involved and no forces are transmitted to the rest of the body, e.g., arm to trunk. Again, the validity of this assumption has not been tested. A conservative approach has been taken. Where there was doubt about the body segment involved, e.g., chest or upper arm, the lower mass segment was selected. Therefore, this would influence the calculation of the change in velocity of the head and head impact energy by reducing their magnitudes. This estimate would be reduced further if a factor for neck force was considered. Further experimental and numerical work is planned in this area.

The nature of each football code was reflected in the sample. As the analysis involved only cases in which good quality video was available, RU presented the most difficulties. Notification was received of more head injuries than the seven analyzed, but due to poor quality video or cases where the injury occurred in a ruck or maul, it was not possible to analyze these cases completely. The open nature of general play in ARF and RL, combined with the higher quality video coverage at the first grade level, meant that a greater number of cases could be fully analyzed.

The mean change in velocity of the head and head impact energy for all 97 cases of direct head impact were 4 $m \cdot s^{-1}$ and 56 J, respectively. These estimates compare well with data from other fields. McIntosh and Dowdell (4) reported on pedal cycle accidents resulting in helmet impacts (with or without injury). Helmet testing to replicate the impacts of 18 cases revealed that severe cases of concussion (6 of the 18) occurred from head impacts with a mean speed of 5.5 $m \cdot s^{-1}$. Naturally, the use of helmets and the nature of the surfaces contacted, e.g., unyielding roadway or car versus soft body parts, in cycling and football are hard to reconcile, but the general trends in the relationship between injury and impact velocity or energy are consistent. McIntosh et al. (5) reported on a series of cadaver head impacts using a pneumatic impactor. The results showed that brain injury with structural failure, e.g., skull fractures, occurred with head impacts of energy greater than 200 J. Enouen (2) estimated the head impact energy of pedestrian head impacts with cars using laboratory and accident reconstruction methods. This parameter is comparable with HIE determined in this study. A gross analysis of 18 adult cases shows similar trends between the maximum AIS (MAIS) severity for the head and impact energy. The mean impact energy for three cases of MAIS 0 and 1 was 90 J, for 8 cases of MAIS 2 and 3 150 J, and for 7 cases of MAIS 4-6 290 J. Again, the head impact energy estimates in the football cases fit within this trend, particularly as these represent cases of impacts against unprotected heads.

Therefore, the accuracy of the estimates of head impact dynamics is supported by field tests of the measurement system, comparison with the running speeds in the games, and comparison with the literature describing head injury mechanics.

The results show that concussive impacts tend to occur at the tempero-parietal region in RU and RL. In ARF, occipital impacts also occurred. It was found that concussion occurred with head impacts of 50-60 J. Although RU was poorly represented in the sample, the results reflect human tolerance to impacts more than issues specific to a code.

This information can be applied to the specification of performance criteria for football headgear for the three codes. The most important function of headgear is to attenuate the impact energy, i.e., reduce the impact force and head acceleration for a specified amount of energy. Impact energy attenuation is determined by the amount of deformation of the headgear, which in turn is determined by foam thickness and density. By using HIE in this context, headgear tested at 50 J would need to reduce the resultant head acceleration to at least below 200 gravities to reduce the likelihood of concussion. The observation that impacts occur to the tempero-parietal region suggests that headgear weight could be reduced by improving padding at this site and reducing it elsewhere, with the added benefit of improving thermoregulation. As impacts occurred between the upper arm or shoulder and the head, a compatible interface could be developed between headgear and shoulder pads.

Further work is being undertaken to examine a greater number of cases in RU and ARF at the professional and recreational levels. Headgear is being assessed in the laboratory and trialed in the field. With the continuation of this research, it is anticipated that more effective headgear and personal protective equipment can be developed for the three codes.

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REFERENCES

1. Australian National Health, and Medical Research Council. *Football Injuries of the Head and Neck*. Australian Government Publishing Service, Canberra. 1994, pp. 78–79.
2. Enouen, S. The development of experimental head impact procedures for simulating pedestrian head injuries, *Proceedings of the 37th Stapp Car Crash Conference*, October 27–29, San Diego: SAE Publications, Report P-189, 1986, pp. 199–218.
3. McCrory, P. Neurological injuries in Australian and rugby football. In: B. D. Jordan, P. Tsaris, and R. F. Warren (Eds.) *Sports Neurology*, 2nd Ed. Philadelphia: Lippincott-Raven, 1998, pp. 441–451.

4. McIntosh, A. S., and B. Dowdell. A field and laboratory study of the performance of pedal cycle helmets in real accidents, *Proceedings of 1992 International Conference on the Biomechanics of Impacts*, Sept. 9–11, Verona, Italy, 1992, pp. 51–60.
5. McIntosh, A. S., D. Kalliers, R. Mattern, and E. Miltner. Head and neck injury resulting from low velocity direct head impact, *Proceedings of the 37th Stapp Car Crash Conference*, November 7–8, San Antonio, TX: SAE Publications, 1993, pp. 43–58.
6. Seward, H., J. Orchard, H. Hazard, and D. Collinson. Football injuries in Australia at the elite level. *Med. J. Aust.* 159:298–301, 1993.
7. Victorian Football League Medical Officer's Association. *A three year survey of Victorian football league injuries*, H. Seward and J. Patrick Melbourne, 1986, pp. 11–19.
8. Winter, D. *Biomechanics and Motor Control*, 2nd Ed. New York: Wiley, 1990, pp. 56–57.

APPENDIX A

Assessment of Video Analysis Methods

The accuracy of 2D kinematic analysis depends on the movement occurring in a calibrated plane that is perpendicular to the camera axis. Movement that occurs in a plane that is oblique this plane results in parallax error. Given that the conditions for accurate 2D length measurement rarely occur when recording football games, there will always be an error in the kinematic values derived from the video.

An experimental assessment of the speed estimates derived from video analysis was undertaken to determine the system's accuracy and to identify selection criteria for video analysis. Experiments were undertaken with a subject running through timing gates. The runner was videotaped from a variety of distances and angles. This video footage was analyzed to quantify the differences between the average running speeds calculated from timing gate data and the speeds calculated by the system. Transformation of the image sequence coordinates to real-world coordinates was performed using estimations of body dimensions taken from the known height of a player in the image sequence. This reflected the constraints of the study.

The video camera and tripod were initially positioned 20 m perpendicular to the 5-m timed runway. The camera was then moved along a line that was parallel to the runway and three running trials were recorded at measured intervals along the line so as to replicate a variety of camera projection angles. The video of the running trials was then processed and analyzed. Dimensional data were transformed using the 5-m distance between the timing gates (linear calibration) and the estimated shank length of the subjects right leg (body segment calibration) to determine the difference between the two transformation methods.

The error between the actual recorded running velocity and the velocity obtained from the 2D kinematic analysis as a percentage of the actual running velocity was calculated. The percent error range for the linear calibration method was −4.4 to −13.1%, compared with 3 to −22.3% for the body segment calibration method. The linear method was more accurate at projection error angles greater than or equal to 24°. The linear method underestimated the velocity at all angles, whereas the body segment method overestimated velocity up to and including 17°, after which it began to underestimate the velocity.

The results revealed that there is an error that cannot be eliminated when using 2D video analysis. It appeared that the speed estimation error could be kept below a maximum level of 10% by using the body segment method for projection error angles of less than 20°. This was adopted as a selection criteria for video analysis.