Quantification of subconcussive impact forces to the head using a forensic model

D.C. Tong, T.J. Winter, J. Jin, A.C. Bennett, J.N. Waddell

Sir John Walsh Research Institute, University of Otago, 310 Great King Street, Dunedin 9010, New Zealand

Abstract

Concussive and subconcussive head injury is a global phenomenon that affects millions of people each year. Concussive injury has been extensively studied in sport, which has led to a greater understanding of the biomechanical forces involved and guidelines aimed at preventing athletes from playing while concussed. Subconcussive forces by definition do not meet the threshold for concussion but nonetheless may have significant long term consequences due to the repetitive pattern of injury to the head. Quantifying these impact forces using a forensic head model provides the groundwork for future studies by establishing a range or threshold of subconcussive impact forces that could be correlated with clinical assessments. The use of a forensic head model has distinct advantages in terms of ethics and safety.

1. Introduction

Concussive and subconcussive injury is a global phenomenon, being likened to a silent epidemic due to the large numbers of young people, in particular, who sustain head injuries in sports and military activities [1]. In 2006, nearly four million people were estimated to have sustained concussive injuries while playing sport in the USA alone [2].

The definition of concussion can be variable, however in a consensus statement on concussion in sport from a conference held in Zurich in 2008, concussion was defined as “a complex pathophysiological process affecting the brain induced by traumatic biomechanical forces” [3]. Despite there being no consensus on a prior definition, several common features were unanimously agreed upon and include direct or indirect force transmission to the brain, rapid onset but transient impairment of neurologic function, neuropathological changes as a result of concussive injury, and no abnormalities seen on standard imaging studies – emphasising the functional impairment of concussion rather than structural injury per se [3]. The recognition that concussive effects may be more enduring has led to a number of psychological and cognitive evaluations to be employed, as well as the proposal of a graduated return to play protocol in sporting situations.

Studies have been carried out to investigate the biomechanics involved in concussive impact using the head impact telemetry system of helmet-mounted accelerometers in American football as an in vivo model of sports injury to the head [4–8]. Research such as this has shown that impacts to the front, side and apex of the head may be potential predictors for concussion [5,9]. Linear and angular acceleration are also considered as important factors in decision points for predicting concussion, however which of the two is more important remains unclear [5,10–12]. One study found that an angular acceleration greater than 5582 radians/s2 and linear acceleration above 96.1 g (g = 9.81 m/s2) acted as predictors for concussion [4]. This type of research has allowed safety equipment to be evaluated and modified to improve its effectiveness at preventing head injury [12,13]. However, the relationship between clinical outcome and these impact forces requires further investigation and remains a difficult area in determining long term effects [14].

The term chronic traumatic encephalopathy (CTE) is widely used in the literature and reflects not only the repetitive nature of the trauma sustained but also recognises the complex pathophysiology involved in functional impairments. These would include personality changes, memory loss, and speech and gait abnormalities [15–18], as well as distinct neuropathological signs at macroscopic and cellular levels [1,15,16,18]. As CTE is diagnosed post mortem, current research is directed at establishing diagnostic tools, including biomarkers [18].

CTE can be classified symptomatically into four stages with corresponding neuropathological changes. Stage I CTE symptoms include headache, decreased attention and concentration. Stage II involves short term memory loss, depression and explosive
irritability. Stage III symptoms also include cognitive function impairment and stage IV is associated with dementia, aphasic behaviour and aggression [15]. Furthermore, the sequelae of repeated concussive injury appear to be more severe than once thought and there is evidence that suggests the recovery time may be lengthened as a result of repetitive trauma [19]. A large proportion of the literature describes CTE in well-known contact sports such as boxing, American football and rugby [17], whereas other sports such as ice hockey, soccer and the martial arts are less well-described or viewed as less risky. However, CTE has been reported in soccer as a result of repeated heading of the ball, for example, despite soccer being regarded as a non-contact sport and carrying minimal risk of head injury according to previous studies [17,20]. Similarly, martial arts including karate and taekwondo have not traditionally been identified as mainstream contact sports but concussive and subconcussive injuries in training and competition feature prominently [21–25]. One prospective study reported over 1000 kicks or strikes to the head during a 10 day taekwondo tournament resulting in mild concussion to total loss of consciousness [24].

The Japanese martial art of kendo uses protective equipment, including a helmet, with repeated strikes to the head with a bamboo sword being not only common but encouraged during training and competition. Studies looking at safety in kendo regarding repetitive strikes to the head concluded that although a single blow to the head with a bamboo sword is unlikely to produce head injury, the effects of repeated strikes to the head are unknown and require more research [26,27]. Our study describes an innovative use of a simulated skull model used in forensic science research to quantify the impact forces to the head in kendo using a bamboo sword.

1.1. Aims and hypothesis

The aims of this study were as follows: to construct a system that could record impact forces simulating strikes to the head using a bamboo sword (shinai); to quantify these forces using a quartz sensor; and finally to establish a minimal standard of acceptable impact from these data. The hypothesis was that although the initial impact force may be similar between individuals, the force transmitted after the initial impact may be lengthened as a result of repetitive trauma [19]. A large proportion of the literature describes CTE in well-known contact sports such as boxing, American football and rugby [17], whereas other sports such as ice hockey, soccer and the martial arts are less well-described or viewed as less risky. However, CTE has been reported in soccer as a result of repeated heading of the ball, for example, despite soccer being regarded as a non-contact sport and carrying minimal risk of head injury according to previous studies [17,20]. Similarly, martial arts including karate and taekwondo have not traditionally been identified as mainstream contact sports but concussive and subconcussive injuries in training and competition feature prominently [21–25]. One prospective study reported over 1000 kicks or strikes to the head during a 10 day taekwondo tournament resulting in mild concussion to total loss of consciousness [24].

A standard adult-size shinai typically used in kendo was utilised as the striking tool for this study and is comprised of four bamboo slats of equal length bound together with leather fastenings and a leather handle (Fig. 2). A standard adult-size shinai weighs 510 g and is 120 cm long.

A laptop computer attached to a bioamp and MacLab unit (ADInstruments, Dunedin, New Zealand) was used to capture the impact forces from the quartz sensor and lasers. LabChart 7 Pro software (ADInstruments) was used to record and analyse the data.

2.3. Conditions

Three conditions were used in this study – skull, scalp and protected. Direct impact on the quartz sensor simulated impact force on the skull. In order to simulate the protective effect and anatomical thickness of a scalp layer, a strip of 4 mm thick two-component condensation cured silicone (Deguiform, Degudent, Germany) was used. This strip was placed over the quartz sensor. In the protected condition, a strip of cotton material (the same material used in the manufacture of the protective helmet used in kendo and sourced from a manufacturing company, Katou Budogu, Osaka, Japan) was added to the silicone strip over the quartz sensor. This baseplate providing support and stability for the quartz sensor array during data collection. The quartz sensor was framed between two metal guards that created a visual and protective guide for striking. Three pairs of laser sensors were mounted within the guard framework. The first pair of lasers acted as a trigger to initiate the recording of data on the computer once the laser beam was interrupted by the shinai travelling towards the quartz sensor during the strike. The second and third pair of lasers (T1 and T2) were used to determine velocity of the strike measuring the fixed distance of 50 mm between the lasers over the time between T1 and T2 activation. The T1 and T2 sampling rate was 2 kHz and the piezoelectric quartz force sensor sampled at a rate of 20 kHz. Fig. 1 shows the construction for impact sensor testing.

A standard adult-size shinai typically used in kendo was utilised as the striking tool for this study and is comprised of four bamboo slats of equal length bound together with leather fastenings and a leather handle (Fig. 2). A standard adult-size shinai weighs 510 g and is 120 cm long.

A laptop computer attached to a bioamp and MacLab unit (ADInstruments, Dunedin, New Zealand) was used to capture the impact forces from the quartz sensor and lasers. LabChart 7 Pro software (ADInstruments) was used to record and analyse the data.

2.3. Conditions

Three conditions were used in this study – skull, scalp and protected. Direct impact on the quartz sensor simulated impact force on the head using a bamboo sword (shinai); to quantify these forces using a quartz sensor; and finally to establish a minimal standard of acceptable impact from these data. The hypothesis was that although the initial impact force may be similar between individuals, the force transmitted after the initial impact may be of longer duration with more energy penetrating into the head due to variations in technique and physical build.
material strip was 6 mm thick and reinforced with rows of stitching 5 mm apart – typical in the construction of a kendo helmet. Condition order was counterbalanced across all participants.

2.4. Calibration

Static in place calibration was conducted to determine the relationship between the quartz force sensor and force-voltage recordings by loading the sensor to 900 N in a universal testing machine (Instron 3369; Instron, Norwood, MA, USA) and setting the subsequent microvolt readouts to 0 and 900 N on the units conversion tool of the LabChart 7 Plus software. Real time data were organised using the peak analysis tool in the LabChart 7 Plus software package.

2.5. Methodology

Participants used the shinai to perform a standard stationary strike to the quartz sensor. Brief demonstrations were given to novice participants to show the basic stance and technique required – specifically the right foot in front of the left foot and the left hand placed at the bottom of the handle with a two handed over-head strike directly onto the quartz sensor to simulate a midline head strike in kendo. The participants performed 10 valid strikes with each condition – skull, scalp and protected. A strike was deemed valid when the shinai impacted on the quartz sensor cleanly without interference such as striking the metal guards. Invalid strikes were excluded from the analysis.

2.6. Statistical analyses

Values outside of three standard deviations of the mean for each participant were considered outliers and removed. Once averages were calculated for each participant across all three conditions, repeated measures analyses of variance were conducted for peak intensity, duration, power and velocity. Shapiro–Wilk statistics and Mauchly’s tests supported each measure for the proposed analysis. Resulting p values were compared to a Bonferroni adjusted alpha level of $p = 0.0125$ (0.05/4).

3. Results

3.1. Peak intensity

As protection increased, the peak intensity significantly decreased across all conditions, $F(2, 34) = 28.70, p < 0.001$. Pairwise comparisons showed that protected ($M = 988.09$ N) was significantly less than skin ($M = 1238.21$ N), which in turn was significantly less than skull ($M = 1739.74$ N).

3.2. Duration

The duration was defined as the time between 50% of a peak’s rise and corresponding fall, removing measurement error that can be incurred by measuring from the baseline. As the layers of protection increased so too did the average duration of peaks, $F(2, 34) = 54.51$, $p < 0.001$. Once again, pairwise comparisons showed that each condition was significantly different from the other with skull, skin, and protection increasing from 0.25 ms to 0.80 ms and 1.18 ms, respectively. Figure 3 summarises results of peak force and duration across the three conditions.

3.3. Power and velocity

Power was defined as the integral of the peak giving a measurement of force transmission across time. No detectable differences in power were observed across conditions giving mean power of 1.78 N across all conditions, $F(2, 34) = 3.30, p = 0.049$. Velocity also remained unchanged across all conditions implying it had no contribution to observed differences (the mean velocity was $12 \text{ ms}^{-1}$; $F(2, 34) = 0.39, p = 0.680$). Figure 4 summarises results for power and velocity across the three conditions.

4. Discussion

Our data clearly indicate that a scalp layer followed by a protective helmet material layer successfully mitigated the peak intensity generated by a kendo strike. However, there are clear indications that the overall energy (power) being transmitted to the target remains the same due to the decrease in peak intensity coinciding with an increase in the duration of the strike. It is probable that the energy is spread across the protective layer which mitigated the peak intensity, yet took longer to completely transmit the energy into the piezoelectric sensor. The explanation for this increase in duration must not be confounded by the possibility of the shinai being in contact for longer periods when striking the protective layers. This potentially could arise due to the soft protective layers slightly enveloping the shinai before it is bounced off the solid metallic piezoelectric sensor.

The limitations of this study include the small number of participants and subjective striking techniques with each participant. Despite the small number of participants however, statistically significant results were still able to be obtained showing the decrease...
in impact force through protective layers. The subjectivity of the strike lies in the ability to relax the fingers and palms immediately after point of impact (tenouchi) and is a differentiating feature of experienced kendo practitioners which may affect the striking technique of the participants in our study. Furthermore, the striking platform was mounted on a stand with the sensor fixed at a height of 180 cm. As the participants were of various heights ranging from 159 cm to 192 cm, the fixed height of the target may or may not contribute to further variability of strikes. The strengths of this study include the successful use of a forensic head model system in quantifying impact forces and setting a minimum standard of acceptable impact forces on which comparisons and further studies may be based upon. The advantage of using a forensic head model consisting of separate layers simulating the scalp and skull is that it is anatomically more accurate than a solid crash test dummy head, for example. This type of system has been used in ballistic and forensic science research with the use of polyvinyl silicone to simulate scalp and polyurethane to simulate bone [28,29]. Further advantages include cost effectiveness, ease of construction and removing ethical issues with using human test subjects [30,31].

Our findings are of great interest when considering studies of protective head equipment, concussion, subconcussion, and CTE. Given our findings that typical head protection in kendo successfully mitigated the peak intensity but not the total power being transmitted, the question of what type of force is necessary to elicit subconcussive injury still needs to be investigated. If peak intensity is the key factor associated with subconcussive force then it would appear that any head protection is effective and we need only to determine a minimum subconcussive threshold. However, if the overall power still peaks above this subconcussive threshold, there remains the potential for negative effects to still occur over time. Furthermore, repeated exposure to low peak, high power trauma might also contribute to subconcussion. In either of these situations, protective head gear would need to be modified accordingly to prevent long term effects. However, at the time of writing, the sparse amount of literature in this area gives no indication of minimum thresholds or types of force that can induce negative effects associated with subconcussive injury. It is hoped that our study provides some groundwork in quantifying these impact forces and forms a basis towards more detailed future biomechanical analysis. This would involve building on our own methodology, for example, constructing a more complex forensic head model with a simulated scalp, skull and brain. Ultimately, the aim is to transfer our findings into a clinical setting to determine minimum

Conflicts of Interest/Disclosures

The authors declare that they have no financial or other conflicts of interest in relation to this research and its publication.

Acknowledgements

The authors gratefully acknowledge the support provided by the ANZAOMS Research and Education Trust in funding this study.

References


