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BIOMECHANICS OF HEAD INJURY IN OLYMPIC TAEKWONDO AND BOXING

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ABSTRACT: Objective: The purpose was to examine differences between taekwondo kicks and boxing punches in resultant linear head acceleration (RLA), head injury criterion (HIC15), peak head velocity, and peak foot and fist velocities. Data from two existing publications on boxing punches and taekwondo kicks were compared. Methods: For taekwondo head impacts a Hybrid II Crash Dummy (Hybrid II) head was instrumented with a tri-axial accelerometer mounted inside the Hybrid II head. The Hybrid II was fixed to a height-adjustable frame and fitted with a protective taekwondo helmet. For boxing testing, a Hybrid III Crash Dummy head was instrumented with an array of tri-axial accelerometers mounted at the head centre of gravity. Results: Differences in RLA between the roundhouse kick (130.11±51.67 g) and hook punch (71.23±32.19 g, d=1.39) and in HIC15 (clench axe kick: 162.63±104.10; uppercut: 24.10±12.54, d=2.29) were observed. Conclusions: Taekwondo kicks demonstrated significantly larger magnitudes than boxing punches for both RLA and HIC.

KEY WORDS: taekwondo; boxing injuries; head injury; biomechanics

INTRODUCTION

In recent years, a number of publications concerning the biomechanics of head injury and sport-related concussions in contact sports and martial arts have provided insight into the mechanics of head injury in sport [1,7,25,26]. Most noteworthy are the live head impact studies in American football, and boxing [1,26] as they employ new technology (i.e., head impact telemetry system [HITS]) that allows for real-time side-line monitoring of head impacts.

Broglio et al. [1] provide an in-depth analysis of American football head impact in high school athletes. Analyses included a multi-factorial measure to predict concussion risk. Resultant rotational acceleration (5582.3 rad·s^{-2}), resultant linear acceleration (RLA = 96.1 g) and impact location (front, side, or top) were determined to be most predictive of concussion in high school football athletes. These values were in close agreement with those on head impact biomechanics in collegiate and professional football athletes [9, 10, 21].

Most recently, the same technology (HITS), used in the aforementioned football [9, 10], were employed during boxing sparring sessions [26] to gain insight into the impact biomechanics and influences on cognitive function post-head impacts. Biomechanical impact data were of low magnitude (males: 30 ± 21 g, 2571 ± 1852 rad·s^{-2}, 43 ± 100 head injury criterion [HIC]; females: 28 ± 17 g, 2533 ± 1524 rad·s^{-2}, 32 ± 66 HIC) compared to data from American football (9). However, peak acceleration data (males = 191 g, 17156 rad·s^{-2} ,1652 HIC, females 184 g, 13113 rad·s^{-2}, 1079 HIC) reveal the possibility of severe head injury even during training bouts [26]. In both male and female boxers no significant deficiencies in neurocognitive function were observed.

The first known study on head impacts in kicking-oriented martial arts was that by Schwartz et al. [25] A Hybrid II crash test dummy (Hybrid II) head and neck mounted to an immovable concrete post was used. Karate practitioners were instructed to strike the Hybrid II with various techniques (i.e., kicks and hand strikes) and the peak RLA reported was 120 g (technique not specified). Using similar methods with boxers, linear and rotational accelerations along with other head injury measures (e.g., HIC, Gadd Severity Index) were assessed in Olympic style boxing [27,29]. These studies [27,29] employed more biofidelic instrumentation (i.e., anthropometric test dummies and human subjects) than previously reported [7] in taekwondo, and provided an empirical understanding of the magnitudes and biomechanical characteristics of live head impacts in boxing.

Taekwondo is a modern fighting sport, which gained full-medal status at the 2000 Olympic Games (Sydney, Australia), and has since continued its place on the Olympic stage. The concussion incidence has been reported to be four times greater, over a 15-year period, compared to American football [23]. A recent laboratory study [8] on the effects of taekwondo kicks on head injury measures recorded comparable head accelerations from the turning kick (72.8 ± 25.3 g) to head impacts in boxing (71.2 g) [26] but higher than in American football (24.7 g) [2]. Furthermore, subsequent research [7] reported that average impacts (130 g) of the turning kick far surpassed those reported in other sports. These head injury measures support earlier claims [20,22,24,31] of the dangers of head kicks in taekwondo and provide grounds to further investigate injury prevention interventions to ensure safety of the athletes and progression of the sport in the Olympic Games and other world-class events.

Due to the scarcity of head injury biomechanics research in taekwondo, a logical step is to contrast boxing and taekwondo to gain further insight into injury mechanisms. Here, we present a statistical analysis of results gathered in previous studies performed by our group [7] and another one [29]. Consequently, the purpose of this study was to assess commonly executed attacking techniques from two combat sports and the effects of these strikes on potential head injuries. It is anticipated that this statistical analysis will provide a meaningful comparison for application within the sports medical field, especially in concern for improvement of protective headgear used in both sports.

MATERIALS AND METHODS

The methodology for both studies is provided in depth elsewhere [7,29]. Table 1 is a summary of methods and instrumentation used. Differences in the methods are most evident from the accelerometer configuration (boxing [29]: one tri-axial accelerometer mounted at the head centre of gravity plus six tri-axial accelerometers mounted in the 3-2-2-2 set-up vs. taekwondo (7: one 500 g tri-axial accelerometer mounted at the head centre of gravity).

TABLE 1. SUMMARY OF METHODOLOGY FOR TAEKWONDO [19] AND BOXING [14]

METHODS	BOXING (Viano et al. 2005)	TAEKWONDO (Fife et al. 2012)
SUBJECTS	11 males (weight=76.5±22.1 kg, height=177.2±9.2 cm)	12 males (age 22.5 ± 3.5 years, height 176.9 ± 7.2 cm), weight 70.8 ± 8.6 kg)
TECHNIQUES	Forehead punch	Turning kick
	Hook	Clench axe
	Jaw	Front axe
	Uppercut	Jump back
		Spinning hook
VARIABLES	RLA	RLA
	HIC	HIC
	Fist velocity	Foot velocity
	Head velocity	Head velocity
ATD	H3D head, neck and torso	H2D head and neck mounted to height adjustable frame
ACCELEROMETER	Tri-axial Endevco 7264-2k) at COG and 6 in 3-2-2-2 configuration	One Tri-axial (PCB Piezotronics 356A66
MOTION ANALYSIS	Kodak HG2000 high speed camera at 4500 Hz	Eight OQUS 3-series infrared cameras at 500 Hz

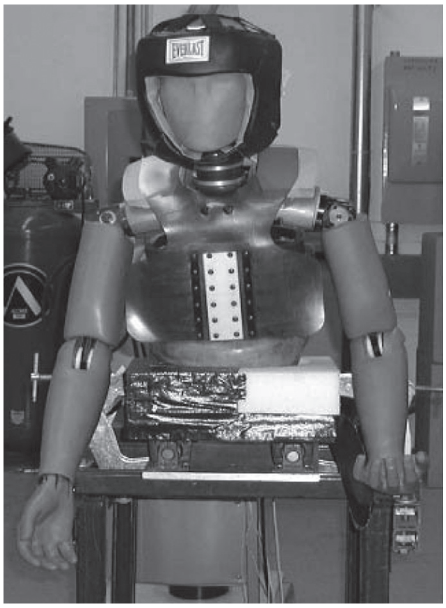

FIG. 1. HYBRID III DUMMY USED FOR BOXING HEAD IMPACT STUDY

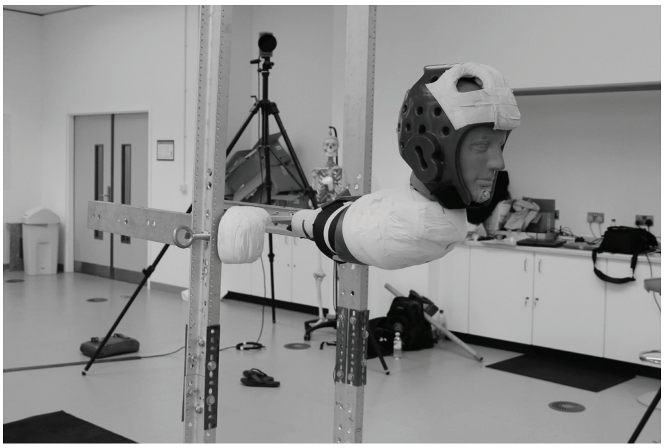

FIG. 2. HYBRID II DUMMY USED FOR TAEKWONDO HEAD IMPACT STUDY

The benefits of using the accelerometer configuration as employed by the boxing study must be understood in that variables such as rotational acceleration are measurable, whereas the use of one centrally embedded accelerometer in taekwondo allows for only resultant linear acceleration.

Additionally, the boxing investigation employed the use of one high-speed camera at 4500 Hz for a two-dimensional motion analysis of head and fist velocities while the taekwondo study used eight OQUS infrared cameras at 500 Hz for three-dimensional observations. Furthermore, the ATDs were mounted in different ways in that the (boxing) head, neck, and torso (figure 1) were positioned for punching impacts (height not indicated) and the Hybrid II (taekwondo) head and neck were mounted to a height-adjustable aluminium frame (figure 2). It should also be noted that all taekwondo participants were provided the opportunity to execute kicks at the average standing head height of taekwondo athletes from the 2004 Summer Olympic Games (Athens, Greece) [13]. It is understood that during taekwondo and boxing competitions, athletes position themselves in an appropriate fighting stance, which may not reflect full standing heights. However, in an effort to provide subjects with a controlled height that is relative for all athletes in their respective weight categories, published average heights [13] were used in taekwondo [7]. Also, due to the idiosyncrasies of both combat sports, that is the target (head) is not stationary (e.g., laboratory studies), competitors must respond to and adjust accordingly, thereby possibly leading to discrepancies in head impact magnitudes observed during live competition (technology currently available in boxing [26] but not taekwondo). Both published studies [7,29] compared in this analysis reported obtaining institutional ethical review board approval and adherence to ethical standards set out by the Helsinki Accord.

Statistical analysis

Distributional characteristics were verified before statistical analysis and coefficients for skewness and kurtosis calculated. A one-way ANOVA was used on log-transformed data to determine differences between kicks and punches, while the Tukey HSD for unequal sample sizes was employed for pairwise comparisons. The level of significance was set to an effect size of 0.20 [12].

RESULTS

There was a significant difference between techniques (eta^2=0.565). Tables 2-5 display the descriptive statistics and pairwise comparisons of effect sizes for RLA, HIC15, head and foot/fist velocities, respectively.

DISCUSSION

This study aimed to compare head impact mechanics of common striking techniques used in two combative Olympic sports. When considering the skills assessed, the hook punch and turning kick yielded the largest RLA values. Notable differences in these sports are that boxing is a primarily head-oriented striking event whereas taekwondo has traditionally been a sport where points are awarded mostly for body shots. Although these sports differ in attack zones, recent rule changes by the World Taekwondo Federation (WTF) [28] encourage head kicks (from 1 point head kick allocation to 4 points for spinning head kicks as of this writing) and a marked difference in game tactics in taekwondo has been reported [11]. Furthermore, Koh and Yang [14] also reported increases in head impacts and possible concussions as a result of the rule changes between 2004 and 2011.

Although the aim of both sports is to either win by point superiority or knockout, differences such as round time constraints and the

TABLE 2. COMPARISONS OF RESULTANT LINEAR ACCELERATION (G) IN TAEKWONDO AND BOXING

Taekwondo (n=12)	Boxing (n=11)	d (95% CI)
Roundhouse: 130.11 ± 51.67	Hook punch: 71.23 ± 32.19	1.39 (-27.85 – 20.41)
	Jaw: 51.50 ± 42.03	1.67 (-27.56 – 26.51)
	Uppercut: 17.11 ± 19.26	3.12 (-26.12 – 14.50)
	Forehead: 52.26 ± 42.08	1.65 (-27.58 – 26.52)
Front axe: 34.49 ± 17.89	Hook punch: 71.23 ± 32.19	1.49 (-17.54 – 11.61)
	Jaw: 51.50 ± 42.03	0.58 (-24.26 – 10.70)
	Uppercut: 17.11 ± 19.26	0.94 (-9.18 – 12.32)
	Forehead: 52.26 ± 42.08	0.60 (-24.26 – 10.73)
Clench axe: 54.95 ± 20.08	Hook punch: 71.23 ± 32.19	0.62 (-17.60 – 12.48)
	Jaw: 51.50 ± 42.03	< 0.20
	Uppercut: 17.11 ± 19.26	1.92 (-9.44 – 13.30)
	Forehead: 52.26 ± 42.08	< 0.20
Jump spinning hook: 98.90 ± 27.11	Hook punch: 71.23 ± 32.19	0.94 (-14.40 – 19.96)
	Jaw: 51.50 ± 42.03	1.39 (-13.95 – 26.22)
	Uppercut: 17.11 ± 19.26	3.50 (-11.84 – 14.88)
	Forehead: 52.26 ± 42.08	1.36 (-13.98 – 26.23)
Jump spinning back: 83.82 ± 57.14	Hook punch: 71.23 ± 32.19	0.28 (-32.05 – 19.30)
	Jaw: 51.50 ± 42.03	0.65 (-31.68 – 25.48)
	Uppercut: 17.11 ± 19.26	1.71 (-30.62 – 13.09)
	Forehead: 52.26 ± 42.08	0.63 (-31.70 – 25.50)

TABLE 3. COMPARISONS OF HEAD INJURY CRITERION IN TAEKWONDO AND BOXING

Taekwondo (n=12)	Boxing (n=11)	d (95% CI)
Roundhouse: 672.74 ± 540.89	Hook punch: 78.96 ± 69.84	1.88 (-304.16 – 43.15)
	Jaw: 48.78 ± 20.87	2.13 (-303.90 – 14.46)
	Uppercut: 24.10 ± 12.54	2.24 (-303.79 – 9.65)
	Forehead: 47.81 ± 20.11	2.13 (-303.90 – 14.02)
Front axe: 56.88 ± 54.87	Hook punch: 78.96 ± 69.84	0.36 (-40.92 – 31.40)
	Jaw: 48.78 ± 20.87	0.21 (-30.84 – 12.54)
	Uppercut: 24.10 ± 12.54	0.94 (-30.10 – 8.35)
	Forehead: 47.81 ± 20.11	0.24 (-30.81 – 12.12)
Clench axe: 162.63 ± 104.10	Hook punch: 78.96 ± 69.84	0.95 (-57.95 – 42.23)
	Jaw: 48.78 ± 20.87	1.77 (-57.13 – 14.10)
	Uppercut:	2.29 (-56.61 – 9.70)
	Forehead: 47.81 ± 20.11	1.79 (-57.11 – 13.68)
Jump spinning hook: 300.19 ± 144.35	Hook punch: 78.96 ± 69.84	2.03 (-79.64 – 43.30)
	Jaw: 48.78 ± 20.87	2.94 (-78.73 – 15.27)
	Uppercut: 24.10 ± 12.54	3.38 (-78.29 – 10.79)
	Forehead: 47.81 ± 20.11	2.96 (-78.71 – 14.85)
Jump spinning back: 462.95 ± 556.72	Hook punch: 78.96 ± 69.84	1.18 (-313.81 – 42.45)
	Jaw: 48.78 ± 20.87	1.37 (-313.61 – 13.71)
	Uppercut: 24.10 ± 12.54	1.47 (-313.51 – 8.89)
	Forehead: 47.81 ± 20.11	1.38 (-313.61 – 13.26)

TABLE 4. COMPARISONS OF HEAD VELOCITY ($m \cdot s^{-1}$) IN TAEKWONDO AND BOXING

Taekwondo (n=12)	Boxing (n=11)	d (95% CI)
Roundhouse: 4.73 ± 1.67	Hook punch: 3.08 ± 0.96	1.24 (0.29 – 1.81)
	Jaw: 2.89 ± 0.95	1.39 (0.44 – 1.95)
	Uppercut: 2.85 ± 0.86	1.46 (0.52 – 1.97)
	Forehead: 3.07 ± 0.72	1.36 (0.42 – 1.79)
Front axe: 3.09 ± 0.64	Hook punch: 3.08 ± 0.96	< 0.20
	Jaw: 2.89 ± 0.95	0.25 (-0.11 – 0.82)
	Uppercut: 2.85 ± 0.86	0.32 (-0.04 – 0.83)
	Forehead: 3.07 ± 0.72	< 0.20
Clench axe: 3.82 ± 1.05	Hook punch: 3.08 ± 0.96	0.73 (0.14 – 1.30)
	Jaw: 2.89 ± 0.95	0.93 (0.33 – 1.49)
	Uppercut: 2.85 ± 0.86	1.01 (0.42 – 1.52)
	Forehead: 3.07 ± 0.72	0.84 (0.25 – 1.27)
Jump spinning hook: 3.99 ± 1.37	Hook punch: 3.08 ± 0.96	0.77 (0.00 – 1.34)
	Jaw: 2.89 ± 0.95	0.94 (0.17 – 1.50)
	Uppercut: 2.85 ± 0.86	1.01 (0.24 – 1.52)
	Forehead: 3.07 ± 0.72	0.87 (0.09 – 1.29)
Jump spinning back: 4.43 ± 0.78	Hook punch: 3.08 ± 0.96	1.56 (1.12 – 2.13)
	Jaw: 2.89 ± 0.95	1.79 (1.35 – 2.35)
	Uppercut: 2.85 ± 0.86	1.93 (1.49 – 2.44)
	Forehead: 3.07 ± 0.72	1.81 (1.37 – 2.24)

impact mechanisms must be taken into consideration. The length of an Olympic boxing match may consist of up to three 3-minute rounds, and taekwondo includes three 2-minute rounds [28]. El Ashker [5] reported an average of 3.71 punches (a total of 33.4 for a match) landed to the head per minute by winners during Olympic boxing bouts, whereas in taekwondo [11], the average of 1.22 head blows per minute (a total of 7.32 for a match) is approximately three times lower than in boxing. The deleterious effects of repetitive head impacts experienced by boxers are well documented and supported in other sports, such as ice hockey [16] and American football [17]. In taekwondo, although a competitor may experience a handful of blows during the course of one competition or a competitive season, the resultant effect of one blow may amount to a severe head injury [3]. Recent medical studies of deceased professional athletes with diagnosed sport-related-concussion point to sequelae of chronic traumatic encephalopathy [17]. The high incidence of concussion in taekwondo along with the results of the current study support further investigation into the effects of concussive impacts during competition and the resultant presentation of clinical signs and symptoms as well as competent medical care at ringside.

TABLE 5. COMPARISONS OF PEAK FOOT AND FIST VELOCITIES (m·s^{-1}) IN TAEKWONDO AND BOXING

Taekwondo (n=12)	Boxing (n=11)	d (95% CI)
Roundhouse: 11.91 ± 1.75	Hook punch: 11.03 ± 3.37	0.35 (-0.64 – 2.34)
	Jaw: 9.24 ± 1.70	1.55 (0.56 – 2.55)
	Uppercut: 6.67 ± 1.53	3.18 (2.19 – 4.09)
	Forehead: 8.25 ± 1.50	2.24 (1.25 – 3.13)
Front axe: 8.92 ± 1.67	Hook punch: 11.03 ± 3.37	0.85 (-1.14 – 1.80)
	Jaw: 9.24 ± 1.70	< 0.20
	Uppercut: 6.67 ± 1.53	1.40 (0.46 – 2.31)
	Forehead: 8.25 ± 1.50	0.42 (-0.52 – 1.31)
Clench axe: 11.73 ± 1.62	Hook punch: 11.03 ± 3.37	0.29 (-0.63 – 2.28)
	Jaw: 9.24 ± 1.70	1.50 (0.59 – 2.51)
	Uppercut: 6.67 ± 1.53	3.21 (2.29 – 4.11)
	Forehead: 8.25 ± 1.50	2.23 (1.31 – 3.11)
Jump spinning hook: 10.61 ± 0.98	Hook punch: 11.03 ± 3.37	0.20 (-1.79 – 0.75)
	Jaw: 9.24 ± 1.70	1.04 (0.48 – 2.04)
	Uppercut: 6.67 ± 1.53	3.17 (2.62 – 4.08)
	Forehead: 8.25 ± 1.50	1.92 (1.37 – 2.81)
Jump spinning back: 10.56 ± 1.40	Hook punch: 11.03 ± 3.37	0.20 (-1.79 – 0.99)
	Jaw: 9.24 ± 1.70	0.86 (0.06 – 1.86)
	Uppercut: 6.67 ± 1.53	2.66 (1.87 – 3.57)
	Forehead: 8.25 ± 1.50	1.60 (0.80 – 2.48)

The techniques compared in this study consisted of both push-like actions, where the distal and proximal segments move simultaneously, and swing-like techniques, where the movement commenced at the most proximal segment and then down the "kinetic chain" to the most distal segment. The literature, not only in martial arts but also other sports such as baseball pitching [4] and kicking in soccer [30], demonstrates that swing-like motions tend to produce the highest distal segment velocities. As the force imparted to the head is dependent on both the mass involved and the change in velocity, the effective mass in each of the techniques compared should be considered [27]. The main results in this study highlight the fact that the highest RLAs and HICs are produced by swing-like techniques, i.e. the turning kick, the spinning hook kick, the spinning back kick and the hook punch. This is important clinically as the medical staff may anticipate more severe injuries due to these techniques.

Even though the head injury-related variables demonstrate that swing-like techniques can cause higher RLA and HIC, it is noteworthy that the rotational acceleration, not recorded in this study, can cause shear strains inducing diffuse axonal injury and haemorrhaging of vascular structures [19]. Although the potential danger associated with an axe kick to the nuchal region that caused a subarachnoid haemorrhage in a healthy 23-year old male was recently reported [3], the technique recorded a relatively low RLA and HIC in the current study.

It was previously suggested that because of the high rotational accelerations and resultant shear strains on the brain imparted to the head of boxers, these athletes were at a higher predisposition to the long-term effects (i.e. chronic traumatic encephalopathy) of repeated head blows compared to American gridiron football players [29]. Recent medical reports [16,17], however, do indicate that repeated head blows in American football and other sports may result in chronic traumatic encephalopathy, a pathology originally suggested to be only observed in boxing [29].

A limitation to the taekwondo study was the inclusion of only resultant linear accelerations of the head. Live biomechanical observations [1] of diagnosed concussions in American football point to a multi-factorial mechanism of injury (i.e. linear acceleration, rotational acceleration, impact location), which not only includes RLA but also rotational accelerations. As with most martial arts, when attempting to strike the head to knock out the opponent, the point of impact is usually the lower jaw (e.g. chin). This is also the case for the taekwondo turning kick, which, with a higher RLA than the boxing hook punch, is suggested to lead to peak rotational accelerations occurring at the head that may be alarming.

A recent study [18] reported young children (10.0 ± 1.7 years) to be able to impart rotational accelerations to the head of a Hybrid dummy of 1625.12 ± 1178.31 rad·s^{-2} compared to rotational accelerations recorded in boxing of 9306 ± 4485 rad·s^{-2} 928). Although the adult Olympic male boxers produced larger rotational accelerations than the young taekwondo children, it is interesting to note that in American football, high school games led to virtually the same impact of 1669 ± 1249.41 rad·s^{-2} [1]. Future research in taekwondo should take into consideration other mechanical factors than concussion, such as rotational accelerations, which result in high shear forces on the brain.

CONCLUSIONS

The next question which should be asked is: where do these data put the clinician when making decisions and understanding the mechanisms involved in head injuries during a taekwondo competition? Until the technology utilized in boxing and American football becomes available in taekwondo, it is difficult to make direct recommendations for the ringside physician/medical personnel. One important take home message is the importance of improved medical care and recognition of head injuries in both boxing and taekwondo at all levels and ages. Possibly the most appropriate step is to ensure medical personnel employed at these full-contact events keep up to date with recommendations made by the International Sport Concussion Group [15] to ensure that the best care is provided. It is also important for the national and international sport governing bodies of especially taekwondo to employ qualified medical personnel at all events, as recommended by others [6,23].

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