AN ANALYSIS OF FORCES ACTING ON THE HEAD FROM THE TAEKWONDO TURNING KICK

by

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ABSTRACT

A Preliminary analysis of forces acting on the head from the taekwondo turning kick

Objective: To assess the effect of the TKD turning kick (RK) and its peak foot velocity (FVEL) on resultant head linear acceleration (RLA), head injury criterion (HIC15) and peak head velocity (HVEL). Methods: Each subject (n=12) performed five repetitions of the RK at the average standing head height for competitors in their respective Olympic weight division. A Hybrid II Crash Test Dummy (H2D) head was fitted with a protective TKD helmet and instrumented with a tri-axial accelerometer (PCB Piezotronics-356A66) and fixed to a height adjustable frame. Acceleration data were captured using Qualisys Track Manager (Gothenburg, Sweden) and processed in accordance with SAE J211-1. Results: The RK produced an RLA of 130.11±51.67g (range: 60.50–217.33g) and HIC15 of 672.74 ± 540.89 (range: 128.40 –1608.70). The mean HVEL from the RK was 4.73±1.67 $m.s^{-1}$ (range: 3.36-9.52 $m.s^{-1}$). Height, weight, and foot velocity predicted 85.6% (SEE = 241.10) of the variance in HIC15 ($p = 0.001$, $f^2 = 5.90$) and of these predictors FVEL was statistically significant ($p = .019$). Conclusions: The RK is of concern because it is the most common technique and most common cause of concussion in TKD and has a high RLA and HIC15. Prevention of concussion in TKD should focus on employing qualified medical personnel, injury monitoring, and safer equipment.

Key terms: Taekwondo, concussion, turning kick, resultant linear acceleration, head injury criterion

CHAPTER 1

INTRODUCTION

A global movement is underway for the prevention of sport-related concussion that is evident from recent reports by the U.S. Centers for Disease Control and Prevention and other sports injury prevention groups (e.g., National Athletic Trainers' Association, The International Conference on Concussion in Sport).[1,2,3] The CDC has gone so far as to refer to sport-related concussions as a "silent epidemic" with 1.5 million traumatic brain injuries and 300,000 sport-related concussions in the United states annually.[1] The full contact Olympic fighting sport of taekwondo (TKD), with 80 million participants worldwide, is not exempt from this dilemma with concussion incidence ranging from 5.5 to 50.2 per 1000 athlete exposures (AE) among TKD athletes.[4-6] Furthermore, a group recently recommended that the World Taekwondo Federation employ a standard of care for the concussed TKD athlete.[7,8]

Along with the high concussion prevalence reported by the CDC, are reports of long- term effects of repeated concussions. A recent report provides histological descriptions of chronic traumatic encephalopathy (CTE) from deceased NFL players.[9] Although concussion and CTE may result from a number of repetitive mechanical forces (linear and rotational acceleration forces), the biomechanics of the most severe injuries are described as resulting from rotational acceleration injuries that cause shear strains between the brain and connective tissues of the skull.[10,11] Shear strains cause diffuse axonal injury (DAI) and hemorrhaging of vascular structures.[10] With the attention of international groups involved with health promotion and injury prevention to this “silent epidemic” and the known sequalae as described in the literature, an investigation concerning the mechanical forces occurring at the brain due to rotational kicks in TKD is warranted.

Pieter and Zemper noted the rotational nature of TKD kicks and the resultant rotational acceleration that may occur at the head during impact.[5] Recent reports of live impact analysis in American football, using a sideline computer system, identified impact forces ranging from 18.02 g to 86.57 g, with one concussion reported at the 86.57 g magnitude.[12,13] Taekwondo kicks register velocities ranging from 13 m/s to 16 m/s, leading to the estimation that impact forces to the head may result in magnitudes greater than 200 g.[5] It has been suggested that impacts to the head exceeding 250 g may result in significant brain damage.[10] Although, TKD kicks have been estimated to be greater than 200 g, to this date no biomechanical investigation of concussion mechanisms exists in TKD. With high magnitude impacts estimated in TKD, athletes may be at a greater risk for significant brain injury.

The injurious results of concussive forces to the head and the biomechanics of sport-related concussion are well documented.[9,12-15] Previous investigations of live impacts to the head during competitive sport have been conducted, but none of these have involved biomechanical analysis of TKD-related concussion.[12,13,16,17]

Additionally, studies examining head impacts in boxing report weight, and peak fist velocity to be significant contributors to head acceleration and head injury outcome.[14] The primary purpose of this study is to investigate impact forces produced by expert TKD athletes' kicks aimed at the head of a Hybrid II 50th Percentile Crash Test Dummy (H2D). This initial investigation is designed to provide an understanding of concussion mechanics as attributed to the TKD turning kick.

An international initiative to reduce the number and severity of sport-related concussions has been identified.[2] Studies of sport-related concussion have focused on sports such as American football, ice hockey, soccer, rugby and other full contact sports. The need for reducing the number and severity of concussion in Olympic style TKD evident although no previous studies have investigated the concussive forces of kicking techniques to the head of competitors. Specifically we intend to examine the following dependent variables (1) resultant head linear acceleration (RLA) (2) head injury criterion15 (HIC), (3) head velocity (HVEL), and evaluate the extent to which weight and peak foot speed of the TKD turning kick predict the magnitude of these variables.

CHAPTER 2

METHODS

Pre-participation screening consisted of completing the Physical Activity Readiness Questionnaire (PAR-Q), along with a demographic and injury history questionnaire to ensure all athletes' physical readiness to participate. In addition, all subjects completed an institutional review board approved informed consent document form. Testing occurred at a biomechanics laboratory. Prior to data collection, subjects were orally briefed on the testing procedures. Participants wore lightweight comfortable fitting athletic wear during testing. Subjects warmed-up and were then asked to perform a series of light kicking techniques, into a small hand held kicking pad for preparation. These same kicking patterns were used during testing. The athletes were asked to begin a familiarization period with the H2D by performing the high turning kick at the head to provide an opportunity to adjust their kicking speed and accuracy. In an investigation on head blows and subsequent concussion in TKD, the high turning kick was reported to be most common cause of diagnosed concussion.[6] Following the familiarization and a brief rest period, each subject was asked to perform five repetitions of the RK aimed at the H2D head. All participants wore a protective foot pad that is commonly used during competition (thickness approximately 1.0 cm).

The H2D neck, mounted to the base of the head, was further secured to an aluminum frame with locations for peg bolts to be fastened at pre-determined increments (Figure 2). The pre-determined peg bolt increments allowed for adjustment of the H2D head and neck to comply with average weight category standing heights (Table.1) of male Olympic TKD participants from the Sydney 2000 Olympic Games as provided from Kazemi.[18] The base of the height adjustable mounting frame was secured with sand filled bags to ensure the structure was not displaced during kicking trials (Fig. 1). To provide a competition-like scenario safely, the H2D was fitted with a protective TKD helmet (Le CAF – Seoul, South Korea) (Fig. 2).

Table 1. Average Olympic weight and heights.[18]

Weight		Height
Under 58kg	Not exceeding 58kg	172.86
Under 68kg	Over 58kg & not exceeding 68kg	176.31
Under 80kg	Over 68kg & not exceeding 80kg	183.21
Over 80kg	Over 80kg	189

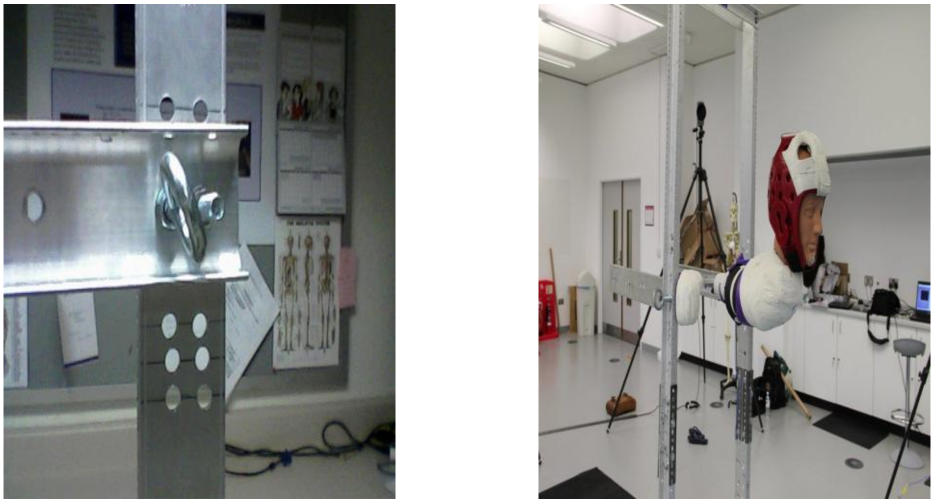

Figure 1. Peg bolt height adjustment (left) and height adjustable H2D (right).

Figure 2. Le CAF TKD Helmet

2.1 Data Acquisition

The H2D head-form was instrumented with a tri-axial accelerometer (PCB Piezotronics 356A66 (Depew, New York) mounted at the head center of gravity to obtain resultant linear accelerations occurring at the head. The accelerometer (Fig. 3) was mounted inside the H2D head on a 4.0 cm x 4.0 cm aluminum plate secured to the head base by four socket head cap screws (Fig. 3). Furthermore, a plastic mounting base (manufacturer provided) that allows for the sensor to be mechanically grounded was glued to the aluminum mounting plate to ensure no movement of the accelerometer occurred during each trial. The accelerometer was interfaced via a 3-channel, battery powered ICP (Integrated Circuit Piezoelectric) (PCB Piezotronics, Depew, NY) sensor signal conditioner and connected to a desktop computer to allow for analysis. Acceleration data were captured using QTM (Qualisys Track Manager) (Gothenburg, Sweden) and processed in accordance with SAE J211-1 channel frequency class (CFC) 1000.[19]

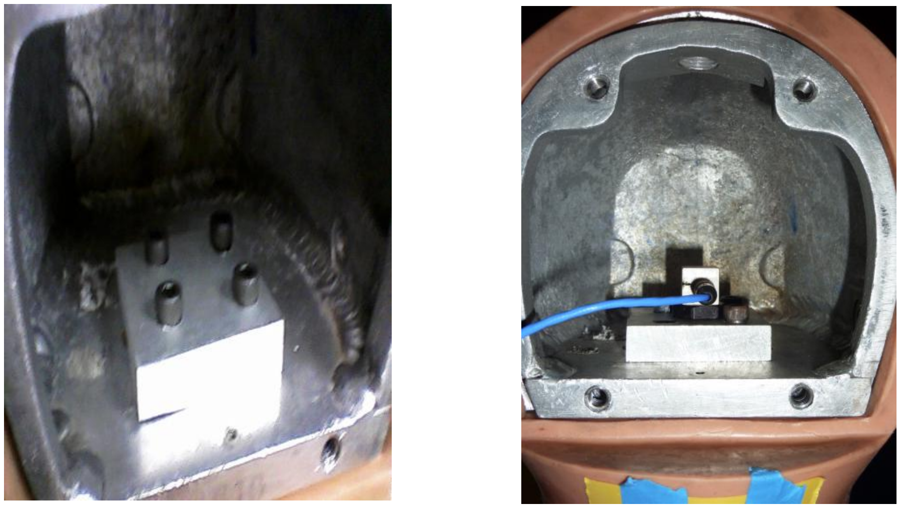

Figure 3. 4.0 cm x 4.0 cm aluminum plate secured to the head base by four socket head cap screws (left). Triaxial accelerometer mounted to base of head (right).

Kinematic data were collected to observe H2D head velocity as well as peak foot speed. To measure peak head velocity at impact, reflective markers were placed on the H2D chin, head apex, and base of the head (Fig. 4). To obtain peak foot velocities for all kicks, reflective markers were secured to the participants' kicking foot at the lateral malleolus and base of the fifth metatarsal (Fig. 5). Kinematic data were collected by eight OQUS 500 infrared cameras (Gothenburg, Sweden). The analog and motion capture data were synchronized at 500 Hz by QTM.

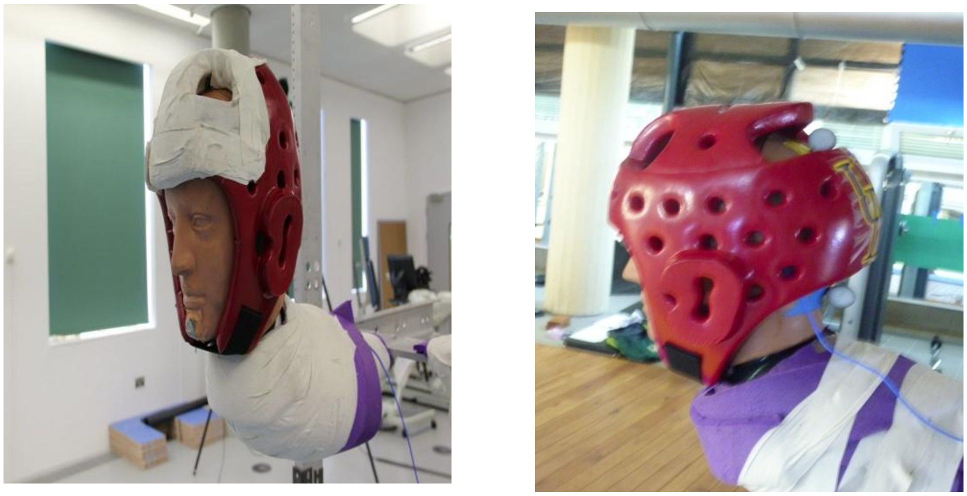

Figure 4. Reflective apex, occiput and chin markers.

Figure 5. Reflective foot markers and foot pad.

2.2 Data Reduction

The HIC is calculated by first retrieving the signal magnitude of the three accelerations in the x, y and z axes at the head center of gravity and calculating the resultant acceleration from Pythagoras theorem during a 15 ms window is then considered in the HIC equation (Fig. 6). This time window of 15 ms has been recommended for analysis of head impacts.[19]

$$HIC = \max_{t_1,t_2}\left[(t_2 - t_1)\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)\,\mathrm{d}t\right)^{2.5}\right].$$

Figure 6. Formula of Head Injury Criterion.

Kinematic data were filtered by a second order Butterworth filter with a cut off frequency of 20 Hz.[20] For the calculation of the foot and head marker linear speeds, the position data were derived, then the signal magnitude of the velocity was calculated.

CHAPTER 3

RESULTS

Data distributional characteristics were verified before statistical analysis and coefficients for skewness and kurtosis calculated. In cases of skewness and/or kurtosis, the data were rank ordered. A multiple regression was employed to assess the contribution of height, weight, and foot velocity to RLA and HIC15, and HVEL. The level of significance was set at 0.05.

Table 2. Means and standard deviations of the bio-demographic and biomechanical data.

Variable	Mean+ SD (95% CI of the Mean)	Minimum - Maximum
Age (years)	22.5 + 3.5 (21.5 - 23.4)	18.0 -27.0
Height (cm)	176.9 + 7.2 (175.1 - 178.8)	164.4 - 189.3
Weight (kg)	70.8 + 8.6 (68.6 - 73.1)	59.1 - 84.6
RLA (g)	130.1 + 51.6 (97.2 - 162.9)	60.5 - 217.3
Head velocity (m.s-1)	4.7 + 1.6 (3.5 - 5.8)	3.3 - 9.5
HIC15	672.7 + 540.8 (329.0 - 1016.4)	128.4 - 1608.7
Foot Velocity (m.s-1)	11.9 + 1.7 (10.8 - 13.0)	9.5 - 15.1

Table 2 shows the descriptive statistics of the bio-demographic and biomechanical data of the subjects. Height, weight, and foot velocity predicted 29.6% (SEE = 50.835.) of the variance in RLA, which was not significant ($p = 0.396$**,** $f^2 = 0.42$). The individual contribution of each predictor of RLA is shown in Table 3.

Table 3. Individual predictors of RLA.

Predictor	b	95%CI	SE	p
Constant	341.7	-814.2 – 1497.7	501.3	0.51
Height	0.03	-8.9 – 8.9	3.8	0.93
Weight	-0.88	-8.8 – 7.0	3.4	0.80
Foot velocity	-13.0	-38.8 – 12.8	11.2	0.27

Height, weight, and foot velocity predicted 85.6% (SEE = 241.10) of the variance in HIC15 ($p = 0.001$, $f^2 = 5.90$). The individual contribution of each predictor of HIC15 is displayed in Table 4.

Table 4. Individual predictors of HIC15

Predictor	b	95%CI	SE	p
Constant	-3473.1	-8955.8 – 2009.5	2377.5	0.182
Height	0.2	-42.1 – 42.6	18.3	0.989
Weight	31.7	-5.8 – 69.2	16.3	0.088
Foot velocity	155.8	33.2 – 278.3	53.1	0.019

Height and weight predicted 36.7% (SEE = 3.363) of the variance in head velocity ($p = 0.275$, $f^2 = 0.58$**).** The individual contribution of each predictor of head velocity is displayed in Table 5.

Table 5. Individual predictors of head velocity

Predictor	b	95%CI	SE	p
Constant	-40.7	-117.2 – 35.7	33.1	0.254
Height	0.28	-0.31 – 0.87	0.26	0.311
Weight	-0.20	-0.72 – 0.33	0.23	0.407
Foot velocity	1.0	0.68 – 2.74	0.74	0.204

CHAPTER 4

DISCUSSION

A review of related literature clearly indicates a high incidence of concussion and head injury in TKD, however to this date no study examined the concussive forces causing these injuries. In this study, peak foot velocity showed a high relationship to HIC values and this was statistically significant ($p = .019$). In a similar sport boxing, peak linear head accelerations and HIC values were reported to be lower than that observed in American NFL head impacts.[14] Previous studies on head impacts in boxing did not find peak fist velocity to be related to HIC but rather boxers' weight.[14] Although weight and height, along with FVEL, accounted for 85.6% of HIC, weight was not a significant contributor to this outcome. Biomechanical investigations of TKD highlight the concept of the “kinetic link” principle to explain the ability for TKD practitioners to produce high foot velocities from kicks and impart high impact forces to a target (e.g., body or head). A boxer's punch (e.g., straight punch), in principle, is more linearly oriented, with the exception of the hook which produced greater peak fist velocities, RLA and HIC values in previous studies.[14,15] This “kinetic link” production of peak foot speed could be responsible for the dangerous HIC values we recorded, irrespective of participants' weight as observed in Olympic boxers.

This study identified the highest HIC values and RLA values to date in sport-related head impacts. One component to instrumentation design that may show more realistic outcomes lies within anthropometric test devices (ATD) used in the industry today and improving the human-like response of ATDs (e.g., H2D) due to head impacts is a popular area of study within the automotive safety industry. The neck of an ATD is the direct link to the head and the design, stiffness and materials of which ATD necks are composed of may affect the outcome of head injury evaluation.[21] Necks with tension adjusting cables in newer H3D models, running through the neck center, are attributed to the calculation of high head injury severity when compared to real life head and neck trauma.[31] In comparison, cylindrical rubber necks (Fig. 4), like those of second generation ATDs (i.e., H2D), are observed to have minimized energy absorption capabilities and are attributed to a reduction in the approximation of head injury.[21] These design characteristics are one component that may be responsible for the results in this study. Although the H3D is the most widely accepted industry standard, a more economical approach for our study was to employ the use of the H2D.

4.1 Implications Involving Sport-Related Concussion

The current study aimed to assess the forces acting on the head involving one specific TKD kick performed by highly skilled athletes. Prior to this investigation, to our knowledge, there was only one study conducted to quantify the head injury severity experienced by martial art practitioners due to head strikes. Schwartz et al. observed a peak head acceleration of 120 g performed by Karate practitioners (technique used not specified).[22] Most recently, a study recruiting Olympic boxers found an overall mean linear acceleration from the hook punch of 71.2 g and a maximum peak head acceleration of 140.6 g from one subject.[14] Walilko et al. also report a mean head acceleration of 71 g produced by heavyweight Olympic boxers aimed at the head of a Hybrid III Crash Test Dummy.[15]

Our study provides insight into the possible head injury severity experienced by elite TKD athletes during full-contact competition. Resultant linear acceleration is a main determinant of HIC values as demonstrated in figure 7. Interestingly, we observed a mean RLA of 130 g with a peak of 217 g by one participant (Fig. 7). These head accelerations clearly surpass those reported in Olympic boxing along with an HIC range of 128.4 to 1608.7. Preliminary biomechanical investigations of head impacts in American football estimated a concussion threshold represented by an HIC of 250, with recent live observations of head-to-head impacts in American football indicating a possible concussion threshold of approximately 96.1 g.[23] With the high incidence of concussion reported in TKD our results are an area for concern.[5,6]

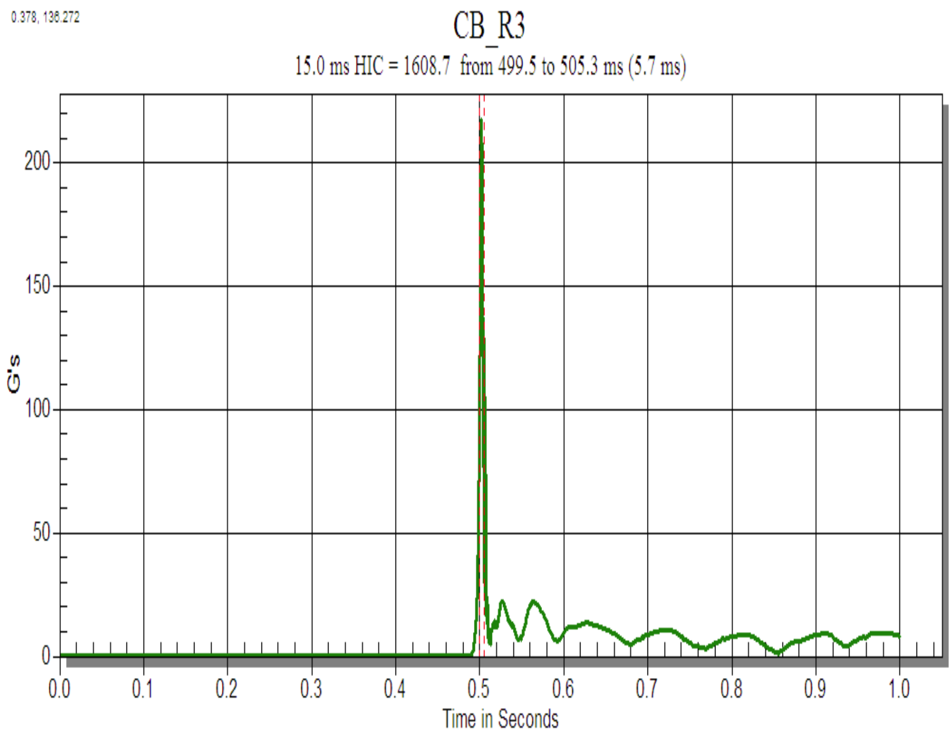

Figure 7. Data record of one trial with RLA = 217 g, HIC = 1608.7.

4.2 Implications for Severe Head Injury

A striking observation within the current data is the fact that the mean HIC values stood at 672. An HIC of 1000 is considered to be life-threatening.[25] A published summary involving the report of HIC values and traumatic head injuries revealed that a HIC value of 667 was associated with a 50% risk of injury in pedestrian accidents.[25] Additionally, eighteen of the twenty-seven cases suffered from skull fracture as a result of HIC values in this high range. We acknowledge that the head injury values (RLA and HIC) recorded in our study may be of the highest severity because participants were striking a non-moving object (no neuromuscular attributes). Although these injury values are expected to be lower during competition, the likelihood of these severe injuries occurring during real TKD competition should be considered.

4.3 Applications to the Sport of TKD

Clinically, our results should be a signal to the medical professionals to prepare for emergency and post-concussive care of the concussed TKD athlete. Not only should medical personnel be aware of the severity of injury possible in TKD but also be up-to-date on recommendations and the standard of care brought forth by the International Conference on Concussion in Sport.[2] There have been two TKD-related deaths have been reported by international media outlet, both due to kicks to the head.[27,28] Despite the low number, based on the high head injury values we report here it is not at all alarming to see the danger associated with such kicks.

An additional area of concern comes from a recent change in scoring guidelines as specified by the World Taekwondo Federation in October of 2010.[29] Over the past 10 years the number of points allocated for a successful kick to the head has increased from one to four for spinning kicks.[29] These changes are believed to be in an effort to increase the spectator interest and excitement, thus increasing world-wide popularity of the sport. It is important for international (e.g., WTF and the International Olympic Committee) and national TKD governing bodies to carefully consider the possible injury outcome of implementing such change in point allocation especially with regard to the head injury values reported in our research.

Banning such kicks from TKD competition is neither practical nor realistic. However, a sensible change that could affect the resultant injury risk of TKD athletes could be modification of protective headgear used during competition. The current headgear design has not been modified in 26 years.[6] Although recommendations by the American Society for Testing and Materials International (ASTM International) were made in 2004, to our knowledge TKD headgear manufacturers have not yet adhered to these safety standards.[26] In an unpublished thesis looking at the effects of various headgear designs, it was reported that as both the helmet thickness and the ability for the foam to dissipate forces increased, HIC value and RLA decreased accordingly. [30] It is understood that concussion does not only occur from linear directional forces but rather a complex contribution of both linear and rotational accelerations. An initial step would be to require manufacturers to adhere to ASTM International specifications for TKD headgear. A step that is likely to improve the safety of the sport.

4.4 Recommendations for Future Studies

We acknowledge that there are multiple mechanisms involved in the production of sport-related concussions and severe head trauma. The current study was limited by considering only resultant linear acceleration, yet it is known that rotational accelerations are also attributed to more severe injury (e.g., diffuse axonal injury, hemorrhage). Previous boxing studies have shown that rotational accelerations developed by Olympic boxers may be more to blame for head injuries in this sport. [14] Furthermore, a recent study including the analysis of live impacts in American football among high school athletes suggests RLA, impact location, and rotational acceleration to be the best predictors for concussion with rotational acceleration being the greatest predictor.[24]

Our study recruited elite athletes which should provide an understanding of the greatest severity that may be expected from the TKD turning kick during competition. With the more than eighty million TKD participants world-wide the largest number of participants can be expected to be from the novice/non-expert levels. Although it could be expected that the severity of injury among non-expert TKD competitors be lower due to lower magnitude impacts, one of the two TKD competitors who recently died was a novice competitor seventeen years of age, suggesting the likelihood for less experienced competitors to fall victim to kicks to the head. To ensure a complete understanding of head injury severity and risks among varying levels of competitors, further analyses should be conducted including not only elite competitors but non-elite competitors as well.

Koh et al. provide an in-depth study using video analyses of TKD competition and reported the five kicks most common to cause concussion in TKD.[31] The RK was reported to be responsible for the most concussions with the axe-kick, jump axe-kick, jump back-kick and jump spinning hook-kick. Our study only considered the most common kick reported to cause concussion; however future studies should consider evaluating the contribution other kicks responsible for concussion in TKD especially when considering the new four point increase awarded for spinning kicks to the head.

CHAPTER 5

CONCLUSIONS

This study was the first to assess variables associated with head injury severity in the Olympic sport of TKD. Previous biomechanical investigations in Olympic boxing and American football provide the groundwork for understanding injury mechanisms and threshold for sport-related-concussion. Our results are intriguing because the high magnitude of RLA and HIC values produced by TKD athletes of all Olympic weight categories were greater than previously reported in boxing and American football. These findings provide a biomechanical understanding of the nature of forces acting on the head during the turning kick in TKD. Further investigations into other measures reported to cause concussion and severe head injury in sport are also warranted.

Interpretation of these results should err on the side of caution as only twelve male subjects were analyzed among elite athletes. Additionally, it must be understood that head injury estimation through the use of ATDs is continually improving and the use of and H2D may downplay the severity of injury reported in this study.

CHAPTER 6

SPECIFIC AIMS

The current dilemma facing sport society, especially athletic associations, medical governing bodies, and in some cases government, is how to best manage concussed athletes and make decisions that will allow retired athletes to maintain a life free from the drastic consequences of repeated concussion.[9] Previous laboratory studies calculate head injury characteristics among Olympic male boxers using an Anthropometric Test Device (ATD).[14,15] These studies compared resultant translational acceleration, rotational acceleration, HIC and ATD head kinematics. To this date no investigation of concussive impacts produced by taekwondo (TKD) kicks exists. Furthermore, only one study [16] on concussive impacts in contact sport report impacts among female athletes, a group readily available for study in the sport of TKD. The objective of our investigation is to examine the following dependent variables (1) resultant head linear acceleration (RLA) (2) HIC,(3) change in head velocity (HVEL), and evaluate the extent to which weight and peak foot speed of the TKD turning kick predict the magnitude of these variables.

The specific aims of this study are:

Aim 1 is to calculate RLA acting on the head of an H2D and determine the contribution of weight and peak foot velocity of the TKD turning kick to RLA:

Hypothesis 1.1: Athletes' kicks of heavy weight (e.g., males: $\leq$ 80 kg and $\geq$ 80 kg, females: $\leq$ 67 kg and $\geq$ 67 kg) will produce greater RLA in comparison to athletes of lighter weight (e.g., males: $\leq$ 58 kg and $\leq$ 68 kg, females: $\leq$ 49 kg and $\leq$ 57 kg).

Falco[32] reports impact forces produced by expert and non-expert TKD participants of lower (53 kg) and higher weights (98 kg) when performing round kicks at varying distances.[32] Expert TKD subjects of lighter weights registered maximum forces of 1143 N compared to heavier subjects resultant maximum force of 3482 N. Their novice counterparts of light weights (46 kg) produced force magnitudes of 193 N compared to heavier novice participants (91 kg) force magnitudes of 3339 N. Walilko's study on Olympic boxer's also supports this hypothesis in reporting that flyweights punches' registered a maximum RLA of 68 g compared to 71 g by super heavyweight boxers.[15]

Hypothesis 1.2: Peak foot speeds of high velocity kicks will produce greater RLA compared to peak foot speeds of lower velocity kicks. It was reported that the peak foot speed of the yongmudo (martial art) high turning kick of 17.2 m/s registered an impact force of 5465 N when compared to the TKD high turning kick foot speed of 16.5 m/s and a resultant impact force of 5419 N.[20]

Aim 2 is to calculate HIC values and determine the contribution of weight and peak foot velocity of the TKD turning kick to HIC values:

Hypothesis 2.1: Athletes' kicks of heavy weight (e.g., males: $\leq$ 80 kg and $\geq$ 80 kg, females: $\leq$ 67 kg and $\geq$ 67 kg) will produce greater HIC values in comparison to athletes of lighter weight (e.g., males: $\leq$ 58 kg and $\leq$ 68 kg, females: $\leq$ 49 kg and $\leq$ 57 kg).

In a study involving punch forces of Olympic boxers [15], the heavyweights produced greater HICs (max HIC = 164) when compared to the flyweights (lighter weight class with max HIC = 101).

Hypothesis 2.2: Regardless of max foot velocity of the TKD turning kick, a relationship between peak foot velocity and resultant HIC values will not exist.

In two similar studies on the biomechanics of boxing punches to the head of an ATD, peak fist velocity was not reported to be correlated to high HIC values. [14,15]

Aim 3 is to calculate HVEL from motion capture data and determine the contribution of weight and peak foot velocity of the TKD turning kick to HEVEL:

Hypothesis 3.1: Athletes of heavy weight (e.g., males: $\leq$ 80 kg and $\geq$ 80 kg, females: $\leq$ 67 kg and $\geq$ 67 kg) will produce greater HVEL values in comparison to athletes of lighter weight (e.g., males: $\leq$ 58 kg and $\leq$ 68 kg, females: $\leq$ 49 kg and $\leq$ 57 kg).

In a study involving Olympic boxers[14], the heavyweights produced HVEL values of 4.2 m/s compared to the flyweights that produced HVEL values of 3.3 m/s. These were found to be significant ($p = 0.017$)

Hypothesis 3.2: Peak foot velocity will not correlate with high changes in head velocity.

Viano et al.[15] and Walilko et al.[15] do not report significant correlation between changes in hand velocity and head velocity.

CHAPTER 7

LITERATURE REVIEW

7.1 Mechanics of Concussion:

Within sport, the blunt force that is seen during collisions is the most common mechanism.[11] From collisions two primary insults to the head may be identified. Coup injuries occur at the point of impact and are due to the brain movement lagging behind that of an accelerating skull.[6] With an anterior blow to the head, the skull translates posteriorly as the brain makes contact against the skull causing an injury at the point of impact on the cortical tissue of the cerebrum.[11]After the brain makes impact with the anterior skull it may continue to rebound 180 degrees to the opposite direction where a second insult occurs, referred to as the counter coup injury (Fig. 1).[11] From these two resultant impacts a variety of pathologies may arise including hemorrhage, hematoma and cortical contusions.

A third mechanism introduces rotational accelerative forces rather than linear accelerative forces as seen in the coupe and counter coupe injuries. As an external force acts on the head, the skull rotates about an axis causing the brain, connected to the skull through connective tissues of the periosteal layer and arachnoid, to also rotate in an opposite direction.[10, 11] This opposite rotational movement of the brain causes a shear strain on the brain as it is indirectly connected to the skull (Fig.8). As a result of shear stress, the brain falls victim to a diffuse axonal injury (DAI). DAI is considered one of the most detrimental injuries to the brain due to its common outcome of a vegetative state of the injured person and likelihood of death.[7]

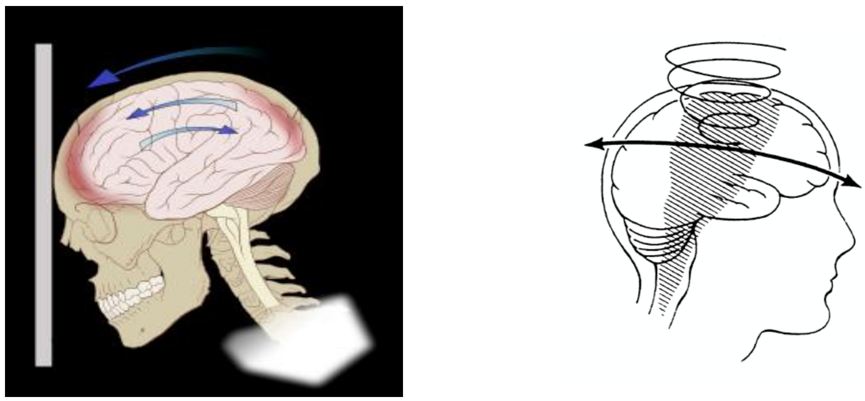

Figure 8. Coup and counter coup concussion injury (left) and rotational acceleration type concussion (right)

7.2 Taekwondo Background

Taekwondo, a full contact modern martial art, has developed into a modern sport since it first debuted in the 1988 Olympics as a demonstration sport and later gained full medal status for the 2000 Olympic Games (Sydney). Elite level Olympic style competitions require all participants to be a certified black belt by the World Taekwondo Federation. Competitors are matched based on one of eight weight category benchmarks. Four consolidated weight categories are used for the Olympic Games (Table 6). Competitions include the full contact combative display similar to Olympic style boxing, however kicking to the chest and head is predominant.

Men's division		Women's division	
Under 58kg	Not exceeding 58kg	Under 49kg	Not exceeding 49kg
Under 68kg	Over 58kg & not exceeding 68kg	Under 57kg	Over 49kg & not exceeding 57kg
Under 80kg	Over 68kg & not exceeding 80kg	Under 67kg	Over 57kg & not exceeding 67kg
Over 80kg	Over 80kg	Over 67kg	Over 67kg

Table 6. Olympic weight categories by gender

7.3 Concussion Incidence and Severity in Taekwondo

The incidence of concussion and injury is often reported by athlete exposures (AEs) where one AE is defined as one athlete participating in a fight when the athlete is exposed to the possibility of being concussed. Each fight requires two people, resulting in two AEs per fight.[5] Severity of concussion is often graded (1 to 4; 4 = highest severity, 1 = lowest severity). However, there are at least 16 concussion-grading scales which provides a dilemma in comparing reports of concussion severity, as no one concussion grading scale uses the same guidelines.[3] The following provides an overview of incidence and severity of concussions in TKD as reported from a limited number of studies.

Since the closed cell foam protective helmet was first introduced in 1985, a number of investigations of head and neck injuries have been reported in TKD.[5,6,8,18,31,33-37] In 1986 Siana et al. first reported concussion incidence (one) at the 1983 World TKD Championships along with five facial fractures.[35] In another study concussion rates were reported to be 0.92 (2 athletes) per 1000 AEs among 96 athletes who participated in the 1988 U.S. Olympic Trials and 5.53 per 1000 AEs at the 1991 World Taekwondo Championships.[36] In 1997 Pieter and Zemper reported 4.12 and 3.25 concussions per 1000 AEs among American adolescent youth TKD athletes.[37] Most recently two studies using videotape analyses identified 365 head blows per 1000 AEs with 11 athletes showing signs of concussion[6] and 226 head blows per 1000 AEs with 50.17 concussions per 1000 AEs respectively.[31] In 2004 a concussion rate of 6.9 per 1000 AEs was recorded among 229 Canadian TKD athletes competing at a national tournament.[18]

Severity of injury can be reported in terms of time loss from training and competition and from the grade of injury severity. Time loss is reported in days missed from sport participation per 1000 AEs. Only one report of time loss within the past 24 years of investigations on concussion in adult TKD athletes is available. Time loss was 7 days or less with 3.23 days per 1,000 AEs for men and 1.82 days per 1,000 AEs for women.[36] Pieter also reported that men suffered more than 21 days of loss from TKD participation (1.17/1,000 AE).[36] Two separate studies by the same research group, reported time loss from concussion in 3274 boys and 865 girls (6 to 16 years old).[37] Rates were 4.12 per

1000 AEs and 3.25 per 1000 AEs for boys and girls respectively with boys owning 25 of the 30 total concussions reported among all athletes.[36,37] Although three studies reported time loss concussions and only one of which provided data for the adult population, an understanding of the level of severity is evident.

Concussion grading scales present a mode for identifying a level of severity and sometimes provide insight into expected return to play. In a report of concussions from six national level taekwondo tournaments (men=1665 and women=774) concussion severity was presented using Nelson's concussion grading scale (0 = least severe to 5 = most severe). Concussion incidence, in respect to severity, was found to be 2.64, 1.47,1.17,0.88/1000 AE for grades 1 through 4 respectively.[34] Although concussion grading is often used for acute concussion, it is not always a clear indicator of severity as each case presents differently and the complete manifestation of symptoms may not be evident until many months after the initial onset of concussive symptoms.[2]

Death may also be a result of concussion injury to the head but reports are scarce. Only two deaths following a kick to the head have been reported.[28] Most recently (July 7, 2009) a 17 year old novice TKD athlete from Singapore died as a result of a kick to the neck by a more experienced athlete leading to brain aneurysm.[28] An earlier report of death in TKD occurred almost ten years ago at an international event where one athlete died due to a blow to the head.[27]

7.4 Impact Force of Hand and Foot Strikes Using an Anthropometric Test Device

Previous studies investigating impacts of kicks to an accelerometer-instrumented head-form do not exist in TKD, however one report by Schwartz et al. was conducted using black belt karate (similar to TKD) practitioners.[22] Although differences (e.g., using fist to strike compared to the foot) may be noted concerning a boxer's punch and a TKD round kick, in order to better understand outcomes and methodology, a review of these studies employing Olympic style boxers and resultant strikes to an 50th Percentile Hybrid III Crash Test Dummy (H3D) is provided Schwartz et al. conducted an investigation recruiting fourteen black belt (commonly considered an expert level) karate subjects who performed twenty various hand strikes and kicks to an instrumented H2D.[22] The H2D neck was mounted to a universal joint allowing motion about three orthogonal axes and was further secured to a steel column that was bolted to concrete floor. Subjects (average height = 173 cm, weight = 76 kg) performed kicks and hand strikes to two heights (125 cm and 175 cm) to represent a "crouched" and upright opponent corresponding to the 50th percentile man. Karate subjects performed strikes while wearing foam hand and foot protection and without protection. The "back-fist" technique produced the highest average resultant linear accelerations, even when compared to kicks. Although no description of specific techniques used by karate subjects was provided, it was reported that punches to the side of the H2D head produced greater head linear acceleration when compared to kicks aimed at the side of the H2D head. Accelerations up to 90 g were recorded on "several occasions" and one acceleration up to 120 g was reported (no specification of the type of technique used).[22]

Viano et al. conducted a study designed to measure impact biomechanics of eleven male Olympic style boxers' punches to the head of an H3D.[15] Four randomly selected punching techniques (hook, uppercut, straight punch, jab) were performed with data collected twice for each technique. The greatest impact force recorded from the hook punch at 4405 $\pm$ 2318 N with an inertial load to the head of 3107 $\pm$ 1404 N and a resulting change of hand velocity of 11.0 $\pm$ 3.4 m/s. Translational head acceleration and rotational head acceleration were found to be 71.2 g and 9306 r/s^2 respectively. The jaw uppercut registered the lowest impact force of 1051 N. The hook produced the highest risk of concussion as indicated by the HIC = 79 (13.8%) and peak rotational acceleration of 9306 r/s.[15]

In a similar study, Walilko et al. investigated impact forces of seven male Olympic boxers' punches (straight, extended or glancing blows).[15] Impact locations of executed punches on the H3D were observed with translational force, hand velocity, and effective punch mass. The severity of impacts were quantified using rotational acceleration, Head Injury Criteria (HIC), and head velocity. Peak punch force (1990 to 4741 N, mean = 3427 N) was recorded with force increasing with weight class (r=0.539, p=0.021). Hand velocity

(9.14 m/s) was observed with motion capture data and an in hand secured accelerometer showing good correlation (no report of level of significance) between videography tracking and in hand accelerometers. Mean linear (2.97 m/s) and rotational (6343 rad/s^2) accelerations were reported to be correlated with weight (linear: r=0.555, p=0.085 and rotational: r=0.524, p=0.026). This study provides insight into the abilities of boxers to produce high impact forces with various punches and the correlations between competitive weight class and head injury characteristics as demonstrated by respective boxers' punches.

7.5 Biomechanics of Taekwondo Kicks

Studies reporting on the biomechanics of TKD kicks are abundant in Chinese and Korean language but are lacking among English language publications. Although reports are few and use a variety of methods (timing lights, high speed motion capture) reports in English language provide insight into the potential force magnitudes that could be observed in relation to concussion mechanics.[38,39]

A recent study observed the effect of different distances from a kicking target on time and impact force. Thirty-one TKD athletes (16-31 years of age) participated in the study and expert athletes' maximum kick force was measured at 3482 N (M =2089.80, SD=634.70) at the shortest distance and 3339 N (M=1537.25, SD=737.43) at the shortest distance for novice athletes.[32] The results of this study indicate that the athletes recruited in this study (average mass = 67.7 kg), although not at the Olympic level, were able to produce impact kick forces (peak=3482 N) comparable to those of middle weight (75 kg) Olympic boxers' impact punch forces (peak=3072 N).[14,32]

In a comparative study between two Korean martial arts (TKD and yongmudo) the TKD high turning kick registered an average impact force of 5419 N compared to the yongmudo high turning kick of 5475 N.[20] They also reported maximum kicking foot velocity of 16.45 m/s with the TKD high turning kick compared to the yongmudo turning kick foot speed of 17.18 m/s. It is interesting to note that average impact force of the TKD turning kick (5419 N) produced by 66.9 kg TKD athletes, when compared to super heavyweight (weight range =91.4 kg to 109 kg) Olympic boxers' punches (4345 N) is higher.[14,20]

7.6 Anthropometric Testing Devices

The automotive and aviation industry have made efforts to ensure human safety for over ninety years.[40] The need for human-like testing devices brought out the development of anthropometric testing devices (ATD) with strict standards for design and instrumentation. In the early 1920s devices were first composed of a simple arrangement of sandbags that represented the rough contour of a human (Fig. 9) and further progressed with the addition of moveable metal hinge joints by the Air Force during World War II.[40] These early designs were the result of efforts by Col. J.P. Stapp and the National Highway Safety Bureau, Department of Transportation.[40] The original ATD was constructed by the Sierra Engineering Company under the initiative of Col. Stapp and anthropometric studies at Wright Patterson AFB, recommended the device to be 200 pounds, 6 feet tall, including strict specifications for limb center or gravity (COG) (Fig. 9). These early specifications were then advanced by the test dummy definitions by the Society of Automotive Engineers in SAE J-963: Recommendation Practice for Anthropometric Test Devices.[21]

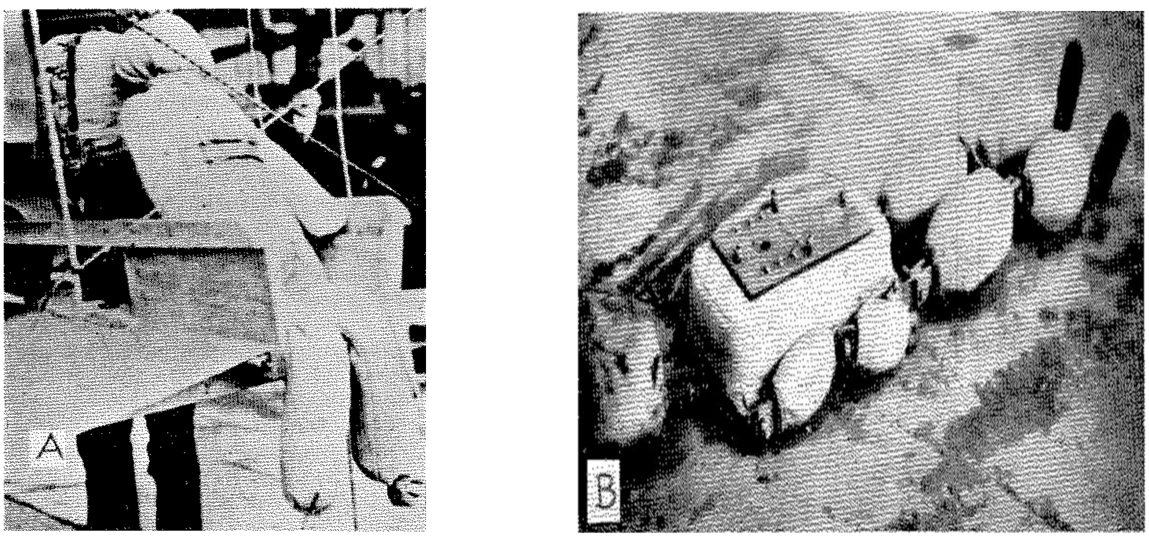

Figure 9. Sandbag ATD (left) (1920s)[40] and The Original ATD (right).

The most current generation of ATDs, still in use by the traffic safety industry today, have since been improved to include a whole collection of ATDs allowing for testing from various impacts including, front, rear, side and specialty test devices (aviation, pedestrian).[40] The two most commonly used ATDs are the Hybrid II 50^{th} Percentile

Crash Test Dummy Male (H2D) and the Hybrid III 50th Percentile Crash Test Dummy Male (H3D). The H2D was designed by General Motors in 1972 and was followed by the General Motors made H3D in 1973. Major differences in each of the models include a modified neck design with rubber cervical discs (Fig. 10) in the H3D to improve the response of the neck during front and rear impacts from sudden head accelerations. Additionally, the H3D face incorporated a depressive jaw (Fig. 10) for the evaluation of facial fractures.[41]

Figure 10. H3D neck with individual cervical disks.

7.6.1 Anthropometric Test Device Neck Performance

The neck of an ATD is the direct link to the head and the design, stiffness and materials of which ATD necks are composed of may affect the outcome of head injury evaluation.[40] Necks with tension adjusting cables, as used in H3D models, running through the neck center are attributed to the calculation of high head injury severity when compared to real life head and neck trauma.[40] In comparison, simple cylindrical rubber necks (Fig. 11) like those of second generation ATDs (H2D) are observed to have minimized energy absorption capabilities and are attributed to a reduction in the approximation of head injury, but do not mimic human-like response to sudden head accelerations.[40]

Spittle provides a comparison of H2D and H3D necks, describing almost identical neck stiffness for the H2D in all directions (flexion, extension, and lateral flexion) due to the consistent neck geometry and rubber.[42] Even though the H3D is praised for its unique cervical vertebrae neck design, it still is attributed to be three to five times stiffer than the human neck and demonstrates poor flexibility in the sagittal plane, and inaccurate rotation of the neck in reference to the head COG.[42,43]

In a comparison of human to ATD head kinematics Scott et al. (1992) observed that human head response to high impacts elicits large ranges of motion, when the H3D lacks the natural response of the head lagging behind the body as seen in human volunteers.[43]

Scott et al. (1992) also observed that the H3D head and neck components act more like a pendulum and this motion can be attributed to the center of rotation about which the head moves.[44] Pintar et al, also confirm the H3D neck to be three to five times stiffer with 555 N/mm of torque at 2.5 m/s to 8 m/s for a human cadaver neck compared to 958 N/mm at 2 m/s and 2160 N/mm at 8 m/s for the H3D and demonstrates poor sensitivity to change in velocity.[44] Despite repeated confirmation that the H3D lacks human-like response to impact it is still the most widely used ATD in the traffic and aviation industry.[21]

7.6.2 Anatomy of the ATD Head

The H2D 50th Percentile Male (Model SA-150-M002) (Fig. 11) was first designed by General Motors in 1972 and credited with having acceptable repeatability and durability compared to previous models. The dummy is made of steel, aluminum brass, polyoxymethylene (Dupont delrin) and other castings with an outer vinyl skin covering (Fig. 12). The head structure weighs 5.1 kilograms and measures 57.2 cm in total circumference, 15.5 cm in width and 19.6 cm in length. The skull is made of a solid aluminum metal casing and allows for an array of accelerometer instrumentation with a removable posterior cap.[40]

 

Figure 11. H2D head and neck assembly (left). Disassembled H2D head and neck (right).

 

Figure 12. Disassembled H2D vinyl skin (left) and metal skull (right).

An important consideration for accelerometer instrumentation is the location of the head's center of gravity. In reference to the Performance Evaluation of the General Motors Hybrid II Anthropometric Test Dummy report, the head center of gravity (COG) is measured 1.19 cm from the base of the head to the COG (bottom to top) and 6.83 cm from the most posterior edge of the base to the COG (back to front) (Fig. 13).[40] Further recommendation from a report on ATD instrumentation and testing cautions that, since only one of three mountable head accelerometers can be exactly at the COG, the sensor size should be at a minimum of one gram and should not be placed more than 1.27 cm from the absolute center to ensure accurate results from resultant head accelerations.[40]

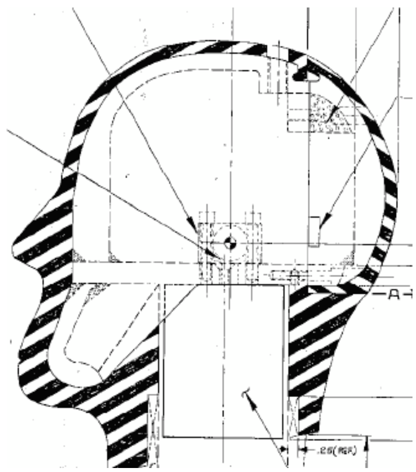

Figure 13. Head center of gravity.[40]

7.7 Head Injury Criterion

The calculation of head injury severity was first determined by a group headed by Lissner at Wayne State University where the Wayne State University Tolerance Curve (WSTC) was determined and refined two years later by Gurdjian in 1962.[45] This first attempt to determine head injury tolerance in humans involved dropping cadaver heads onto solid flat surfaces and later through the work of Gurdjian included other animals and injury mechanisms through which skull fracture and lesser severity concussion was induced. The WSTC is a function of the average translational head acceleration (function of accelerations from all three axes [x, y, and z]) of a given acceleration duration. Since its inclusion into head injury severity approximation research, further attempts to take into account long and short acceleration durations rather than an average of the acceleration duration were made by the development of the Gadd Severity Index (SI). The SI takes into account longer durations as compared to the Head Injury Criterion (HIC). The HIC, which first used a 0.45 millisecond (ms) window of acceleration, now includes 0.15 milliseconds under a head acceleration curve. In both the SI and HIC a severity value of over 1000 indicates acceleration forces dangerous to life.[45]

The HIC measure has been widely used in American football. Pellman et al. conducted a study involving re-enacted collisions from professional football games using two instrumented H3Ds.[23] It was concluded that an HIC of 250 represented a threshold for concussion.[23] however a study[46] using accelerometer-instrumented helmets reported 55 head-to-head impacts with HICs greater than 200 but no concussions were diagnosed. A common finding in concussion incidence investigations is that athletes are often reluctant to report concussion symptoms to medical personnel in fear of being excluded from sport participation.[3] Although Duma et al.[17] observed head collisions with HICs greater than 200, this phenomenon of the underreporting of concussions in sport may explain this anomaly.

A criticism of these head injury measurements is the disregard for other injurious forces acting on the head. Head injury results from a complex sequence of events that cannot simply be represented from resultant translational forces. Even as early as these injury criterions were developed an understanding of potential effects of rotational accelerations, not considered in the HIC or SI, were established.[46] Although rotational forces that are often responsible for more serious head injuries (e.g., diffuse axonal injury, hematomas[10,11]) should be considered in this study, financial limitations will only allow for more simple measures in head injury by considering only RLA and HIC values.

7.8 Summary

Concussion has been identified as a problem within sports, including the Olympic sport of TKD. Biomechanical studies on head injury measurements using karate black belts and Olympic boxers provide an understanding of expected outcomes and methodology when observing head impacts from combative strikes of expert participants (boxing punches and martial art head kicks). It is important to understand how ATDs are used for the measurement of impact related injury and that there are limitations to be considered when estimating head injury in sport. To this date there has been no study concerned with the concussive blows as experienced by TKD athletes. However, biomechanical investigations on TKD kick impact force illustrate the potential to induce severe head injury as TKD kicks have been reported to produce greater impact forces when compared to Olympic boxing punches.

Appendix A: Individual results by weight division

S1: Weight Class: <58 kg				
Trial	**RLA (g)**	**HIC (15 ms)**	**HVEL (m/s)**	**FVEL (m/s)**
1	111.43663	471.2	4.872966	10.24348
2	66.239418	186.1	5.068141	9.008014
3	89.768829	307	4.341278	9.497951
4	84.092468	278.6	4.849755	9.269642
5	97.001602	343.2	4.637665	10.149144
Average	89.7077894	317.22	4.753961	9.6336462
Minimum	66.239418	186.1	4.341278	9.008014
Maximum	111.43663	471.2	5.068141	10.24348
SD	16.6406297	103.890818	0.27653199	0.54313054

S2: Weight Class: <68 kg				
1	155.535202	852.2	3.29468	10.84842
2	168.993668	842.3	4.071031	11.696797
3	126.726173	511.8	4.02986	10.886348
4	99.534592	319.6	4.071349	10.021758
5	128.587784	588.1	4.340577	10.451054
Average	135.875484	622.8	3.9614994	10.7808754
Minimum	99.534592	319.6	3.29468	10.021758
Maximum	168.993668	852.2	4.340577	11.696797
SD	27.1145695	227.079248	0.39277386	0.62041126

S3: Wt. Class >80 kg				
1	192.462051	1413.2	4.472089	12.041923
2	191.638046	1438.7	6.172177	12.251163
3	226.153976	2210.3	5.4828	12.507929
4	173.327225	1369.8	4.723257	11.919784
5	254.627304	2544.1	4.692869	12.37007
Average	207.64172	1795.22	5.1086384	12.2181738
Minimum	173.327225	1369.8	4.472089	11.919784
Maximum	254.627304	2544.1	6.172177	12.507929
SD	32.4591021	544.779916	0.70669821	0.23886169

S7: Weight Class: <68 kg				
Trial	**RLA (g)**	**HIC (15 ms)**	**HVEL (m/s)**	**FVEL (m/s)**
1	129.442139	485.6	4.160375	8.868453
2	113.255013	407.8	4.180005	10.975
3	116.345299	436.2	3.264447	10.462068
4	121.401306	499.5	4.150904	10.894715
5	143.434448	698	3.394921	11.927319
Average	124.775641	505.42	3.8301304	10.625511
Minimum	113.255013	407.8	3.264447	8.868453
Maximum	143.434448	698	4.180005	11.927319
SD	12.0945128	113.837612	0.45928596	1.11840107

S8: Wt. Class <80 kg				
1	485.911316	5781.2	4.643936	15.18679
2	245.178726	2200.9	5.526348	19.022913
3	217.327408	1608.7	5.33864	14.584724
4	173.760605	1211.7	4.239244	18.232189
5	185.291275	1058.2	5.620115	15.193102
Average	261.493866	2372.14	5.0736566	16.4439436
Minimum	173.760605	1058.2	4.239244	14.584724
Maximum	485.911316	5781.2	5.620115	19.022913
SD	128.534053	1956.20252	0.60304782	2.02796956

S9: Wt. Class <58 kg				
1	129.54628	497.7	3.332798	15.171
2	146.623581	577.6	2.946271	15.383247
3	101.504395	323.7	3.858662	11.75738
4	127.578842	513.2	3.481519	11.75597
5	182.621506	428	3.404488	11.500342
Average	137.574921	468.04	3.4047476	13.1135878
Minimum	101.504395	323.7	2.946271	11.500342
Maximum	182.621506	577.6	3.858662	15.383247
SD	29.902076	96.6433805	0.32684466	1.97922242

S10: Wt. Class <68 kg				
1	86.707184	283.5	3.287192	10.406013
2	101.844696	378.6	2.568318	10.475547
3	82.64782	182.7	3.493306	10.874188
4	75.005104	270.8	3.541534	10.94085
5	145.22052	277.2	4.306415	10.104555
Average	98.2850648	278.56	3.439353	10.5602306
Minimum	75.005104	182.7	2.568318	10.104555
Maximum	145.22052	378.6	4.306415	10.94085
SD	28.0006038	69.4327228	0.62189294	0.34714371

S11: Wt. Class <68 kg				
1	93.433144	337.9	4.502743	11.618915
2	82.405548	259.2	3.989655	10.244402
3	95.871696	324.5	4.166553	10.606605
4	138.287415	705.7	4.799377	11.48385
5	159.64386	880.5	4.973957	11.983434
Average	113.928333	501.56	4.486457	11.1874412
Minimum	82.405548	259.2	3.989655	10.244402
Maximum	159.64386	880.5	4.973957	11.983434
SD	33.2530268	274.837166	0.41382098	0.73046663

S12: Wt. Class <58 kg				
1	45.35857	110	3.272369	9.91727
2	60.497654	128.4	3.708759	10.097114
3	47.664425	98.1	3.824532	10.595551
4	165.700882	330.3	4.028521	10.600507
5	79.72773	220.4	6.022828	10.539386
Average	79.7898522	177.44	4.1714018	10.3499656
Minimum	45.35857	98.1	3.272369	9.91727
Maximum	165.700882	330.3	6.022828	10.600507
SD	49.9260806	98.0556628	1.07130888	0.32020411

APPENDIX B: IRB INFORMED CONSENT

University of Delaware Human Subjects
Informed Consent Form

RESEARCH STUDY TITLE: Examining the Concussion Dilemma in Taekwondo: An Initial Look at Impact Forces to the Head

INVESTIGATORS: Gabriel P. Fife, B.S. and Dr. Thomas W. Kaminski, PhD (Dept. of Health, Nutrition & Exercise Sciences), ***Coral Falcó PhD (Catholic University of Valencia), David P. Cook PhD (London South Bank University), Manfred Vieten PhD (University of Konstanz), David M. O'Sullivan MS (Seoul National University), Willy Pieter PhD (University of Asia and the Pacific)***

PURPOSE OF STUDY AND INTRODUCTION
The purpose of this study is to observe impacts to the helmet and head of a ***Hybrid II crash test dummy (H2D)*** from various kicks involving expert taekwondo (TKD) athletes. You are being asked to participate because you are an expert taekwondo athlete. You must be 18 years or older to participate in this study. You will be asked to perform a series of TKD kicks to the ***H2D***. Kicks will occur to the head of the ***H2D*** fitted TKD protective headgear. Your participation is voluntary and you are in no way obligated to take part in this project.

PROCEDURES
Questionnaires: In order to determine your eligibility to participate in the study you will be asked to complete two questionnaires used to evaluate your readiness level (PAR-Q) and TKD experience. Based on your answers on the questionnaires, the investigators will inform you immediately as to whether or not you will qualify to participate.

The testing will take approximately *15-20 minutes* to complete. All testing will take place in a biomechanics laboratory ***within your country of residence (London South Bank University in Great Britain, University of Konstanz in Germany or at the 2010 Murcia Spanish Taekwondo Federation Summer Training Camp)***. You will wear suitable clothing to allow for unrestricted movements to perform the TKD kicks.

Warm-up: You will be provided with a short warm-up consisting of TKD specific movements plus lower body stretching activities before testing begins.

Familiarization Period: After the warm-up period, you will be asked to perform a series of light TKD kicks into a small hand-held kicking pad. This will be followed by a familiarization session of kicking techniques that will include the round kick, axe kick, *clench* ***axe-kick***, jump hook kick, and jump back kick, to the ***H2D*** (see figures). The ***H2D***

will be suspended and adjusted to a height needed for you to execute each kicking technique.

Figure 1. Height Adjustable ***H2D***

Figure 2. ***H2D*** mounted head

Test Period: Following a brief rest period (2-3 minutes) the test kicks will be performed. You will perform 5 trials of each of the five kicks done during the familiarization period. The type of kick will be randomized.

Cool-down: At the conclusion of testing you be allowed to go through your personal cool-down and stretching program.

CONDITIONS OF SUBJECT PARTICIPATION

All of the data will be kept confidential. Your information will be assigned a code number. The list connecting your name to the code number will be kept in a locked file. When the study is completed and the data have been analyzed, that list will be destroyed, but the coded data will be kept indefinitely on a secured electronic file device. Your name will not be used in conjunction with this study. In the event of physical injury during participation, you will receive first aid. If you require additional medical treatment, you will be responsible for the cost. You will be removed from the study if you experience any injury that interferes with the results or prevents you from completing it. There are no consequences for withdrawing from the study and you can do so at any time.

RISKS AND BENEFITS

Potential risks in this project are minimal. As with any exercise or challenging movements, risks include fatigue, localized muscle soreness, and the potential for strains and sprains of muscles and joints of the lower leg. There is a slight risk to you of suffering bone, muscle, or joint injuries during the exercise protocol. In the event of an acute injury, you will receive immediate first aid. Follow-up care will be at your own expense. If you become too fatigued or uncomfortable, you may stop the test at any time. Potential benefits include the better understanding of concussion related to TKD and improvements in participant safety. In addition, this study may lead to developing a safer design of the protective headgear worn in TKD.

FINANCIAL CONSIDERATIONS

There will be no compensation for participating in this study. There will be no cost to you, the subject, for participating in the study and all materials will be provided by the researcher.

CONTACTS

Gabriel P. Fife (302) 831-8222 or fifeg@udel.edu, Dr. Thomas W. Kaminski (302) 831-6402 or kaminski@udel.edu, **Dr. Manfred Vieten (manfred.vieten@uni-konstanz.de), or Dr. Coral Falcó (coral.falco@ucv.es), or Dr. Dave P. Cook (cookdp@lsbu.ac.uk)**. ***Questions regarding the research study can be directed to the above email addresses.***

For questions of concerns about the rights to the individuals who agree to participate in the study: Human Subjects Review Board, University of Delaware (302) 831-2137.

ASSURANCE

Participation in this study is completely voluntary. You may stop at any time during the testing without penalty. Refusal or choosing to discontinue participation in this study is the right of the individual, with no loss of benefits to which the subject is otherwise entitled.

CONSENT SIGNATURES (signed forms will be retained by the researchers for 3 years after the study is completed)

____

Subject Consent Signature Date

____

Principal Investigator Signature Date

APPENDIX C: HUMAN SUBJECTS PROTOCOL

HUMAN SUBJECTS PROTOCOL
University of Delaware

Protocol Title: **Examining the Concussion Dilemma in Taekwondo: An Initial Look at Impact Forces to the Head**

Principal Investigator
Name: **Gabriel P. Fife**
Contact Phone Number: **302-831-8222**
Email Address: **fife@udel.edu**

Advisor (if student PI):
Name: **Thomas W. Kaminski**
Contact Phone Number: **302-831-6402**
Email Address: **kaminski@udel.edu**

Other Investigators:

Type of Review:
Exempt Expedited Full board

Exemption Category: 1 2 3 4 5 6

Minimal Risk: ______ yes ______ no

Submission Date: **10/07/2009**

HSRB Approval Signature	Approval Date
HS Number	Approval Next Expires

Investigator Assurance:

By submitting this protocol, I acknowledge that this project will be conducted in strict accordance with the procedures described. I will not make any modifications to this protocol without prior approval by the HSRB. Should any unanticipated problems involving risk to subjects, including breaches of guaranteed confidentiality occur during this project, I will report such events to the Chair, Human Subjects Review Board immediately.

Signature of Investigator:

Date: 10/07/09

1. **Is this project externally funded?**

No

2. **Project Staff**

Please list personnel, including students, who will be working with human subjects on this protocol (insert additional rows as needed):

NAME	ROLE	HS TRAINING COMPLETE?
Gabriel P. Fife	PI	Yes
Thomas W. Kaminski	PI	Yes

3. **Special Populations**

Does this project involve any of the following?

Research on Children?

No

Research with Prisoners?

No

Research with any other vulnerable population (please describe)?

No

4. **RESEARCH ABSTRACT** Please provide a brief description in LAY language (understandable to an 8th grade student) of the aims of this project.

The history of taekwondo (TKD), a Korean martial art, dates back 2000 years and has since developed into a modern sport. TKD has been a participating sport in the Olympic Games since 1988 where it first debuted as a demonstration sport and later gained full medal status for the 2000 Olympic Games (Sydney). Competitions include the full contact combative

display like that seen in Olympic style boxing however kicking to the chest and head is predominant. Due to the full contact nature of the sport, incidence of concussion in TKD has been reported to be three times greater than that of American football. Kicks aimed to the head, especially pose a risk for the more serious damage as they possess a rotational element that is associated with loss of consciousness, brain bleeding, and even death. The minimally protective headgear worn in TKD competition has not been modified or improved upon in over 30 years. The purpose of this study is to observe impact location characteristics and calculate the linear and rotational accelerations acted on the helmet and head of a Hybrid II crash test dummy (H2D) subjected to various kicks from expert taekwondo athletes. Data will be collected in a Biomechanics Laboratory at the London South Bank University (United Kingdom), Spanish Taekwondo Federation Summer Training Camp in Murcia Spain, Konstanz University (Konstanz, Germany) under the supervision of the PI (GPF), who is an expert black belt and experienced competitor. Expert TKD athletes from competitive teams will be recruited and asked to perform a series of kicks to the H2D. The H2D, fitted with protective head gear and instrumented with an array of accelerometers will be used to compare forces acting on the helmet and H2D. The forces then will be compared across various genders, types of kicks, and weight classes. The specific aim of this study is to gain a better understanding of the forces involved in Olympic style TKD kicks to the head and subsequently learn more about concussion injury mechanics. Additionally, the location and magnitude of the force impacts will be examined.

5. **PROCEDURES** Describe all procedures involving human subjects for this protocol. Include copies of all surveys and research measures.

Male and female expert TKD athletes from competitive teams will be recruited to participate in this study. Expert TKD athletes must be 18 years or older to participate. Pre-participation screening will consist of completing the Physical Activity Readiness Questionnaire (PAR-Q) to assess cardiovascular fitness along with the completion of brief demographic and injury history questionnaire concerning their TKD competition experience and other demographic information (age, height, weight, gender, competition weight category). Subjects who qualify (see exclusionary criteria below) will be asked to report to the biomechanics laboratory within their respective country of residence for testing. Each subject will complete the UD IRB approved informed consent document translated in their native language. Prior to data collection, the subjects will be orally briefed on the testing procedures. Participants will wear suitable TKD clothing to allow for unrestricted movements common in the sport.

Figure 1. Height adjustable H2D Head Figure 2. Hybrid III Crash Dummy Head/Neck

Prior to testing the subjects will warm-up by performing a series of routine movements specific to the sport of TKD (upward knee motions followed by light stretching). After the warm-up period, subjects will be asked to perform a series of light kicking techniques, into a small hand held kicking pad (Figure 3). These same kicking patterns will be used in the testing. The athletes will be asked to begin a familiarization session of a random set of kicking techniques including the round kick, axe-kick, hook kick, clench axe-kick, and back kick. The purpose of the familiarization trials is to allow the TKD experts an opportunity to "ramp up" their kicking speed and accuracy of kicks to the H2D (See figures 1 & 2). Following the familiarization period and brief 5' rest period, the subject will be asked to stand near the H2D that will be suspended at an appropriate height for kicking. Each kick will be performed a total of five times. The type of kick order will be randomized across all trials. At the conclusion of testing the TKD athletes will participant in their normal cool-down program that consists of stretching exercises.

Figure 3 – TKD athlete warming up

6. **STUDY POPULATION AND RECRUITMENT**

Describe who and how many subjects will be invited to participate. Include age, gender and other pertinent information. Attach all recruitment fliers, letters, or other recruitment materials to be used.

Male and female expert TKD athletes from Great Britain, Spain, and Germany will be recruited to participate in this study. The goal is to recruit 136 TKD athletes (68 females and 68 males) in each of the 4 Olympic weight classes (flyweight, featherweight, lightweight, and heavyweight). Expert TKD athletes are defined as having placed in the top three of their weight category at a national TKD event. Athletes that are not over 18 years old at the time of testing will not be allowed to participate. Recruitment efforts will focus on visits and solicitations to various TKD clubs/organizations in the mid-Atlantic region.

Describe what exclusionary criteria, if any will be applied.

Exclusion criteria for all participants will include: (1) any recent injury (head, limbs, etc..) within the past six months that might affect their ability to perform TKD head kicks to the H2D; (2) any "yes" responses on the PAR-Q.

Describe what (if any) conditions will result in PI termination of subject participation.

Inability of the TKD participants to execute any of the required kick maneuvers.

7. **RISKS AND BENEFITS**

Describe the risks to participants (risks listed here should be included in the consent document). If risk is more than minimal, please justify.

Risks associated with participation in this study will not extend beyond those that would normally be experienced when participating in a regular TKD practice session that involves kicking techniques and sparring. Participants are aware of these minimal risks (minor musculoskeletal injury; i.e. muscle strains or ligament sprains) involved with TKD.

As with any exercise procedure, there are minor risks for cardiac or respiratory injury, as well as leg cramps and dehydration. Subjects may also develop muscle soreness in the lower extremity 24 - 48 hours following testing.

What steps will be taken to minimize risks?

To minimize musculoskeletal injury and soreness, carefully monitored warm-up and cool down stretching periods will be provided. In the event of an acute injury, immediate first aid will be provided.

Describe any direct benefits to participants.
This study is designed to investigate the mechanics of concussion injury in TKD. Results of this study will determine location and magnitude of kicks to the head and may allow for the development of better designed protective helmets. Concussion mechanics data can also be utilized to implement the appropriate prevention and medical care procedures for health care professionals who deal with concussions. Additionally, findings from the study will provide information that we hope will make the sports safer for all participants.

Describe any future benefits to this class of participants.

In the future, we hope to use this baseline data to instrument a protective head-gear embedded with accelerometers. This protective head-gear set-up would allow for real time observations of head impacts during TKD competition. Currently within the sports of American football, hockey, boxing and even war combat in Iraq and Afghanistan, researchers have been able to observe the location and magnitude of blows experienced to the head of athletes/soldiers during real-time events. Researchers and sport medical teams are able to monitor these impacts on the sideline/battlefield allowing for the quick identification of at-risk impacts. Data from these previous studies is allowing for a better understanding of live concussive impacts in sport.

If there is a Data Monitoring Committee (PMC) in place for this project, please describe when and how often it meets.

N/A

8. **COMPENSATION**

Will participants be compensated for participation? **No**

If so, please include details.

9. **DATA**

Will subjects be anonymous to the researcher?

No

If subjects are identifiable, will their identities be kept confidential?
Yes

How and how long will data be stored?

Each subjects' information will be assigned a code number. The list of codes and the names they correspond to will be kept in a locked file. The list will be destroyed after the data has been analyzed, however, the data will be stored indefinitely via electronic files on a secured file media. Subject's names will not be used in any report whatsoever.

How will data be destroyed?

A paper shredder will be used to destroy hard copy documents.

How will data be analyzed and reported?

Data will be analyzed using SPSS statistical software. Data will be reported in all manuscripts. The identity of all participants will be protected.

10. **CONFIDENTIALITY**

Will participants be audiotaped, photographed or videotaped during this study?
No

How will subject identity be protected?
All participants will have a code number.

Is there a Certificate of Confidentiality in place for this project? (If so, please provide a copy).
No

11. **CONSENT and ASSENT**

__X__ Consent forms will be used and are attached for review.

____ Additionally, child assent forms will be used and are attached.

____ Consent forms will not be used (Justify request for waiver).

12. **Other IRB Approval**

Has this protocol been submitted to any other IRBs?
No

If so, please list along with protocol title, number, and expiration date.

APPENDIX D: PHYSICAL ACTIVITY READINESS QUESTIONNAIRE

UD Athletic Training Research Laboratory

PAR-Q Physical Activity Readiness Questionnaire

Name/ID Number: ________________ Date: _________________

For most people physical activity should not pose any problem or hazard. PAR-Q has been designed to identify the small number of adults for whom physical activity might be inappropriate or those who should have medical advice concerning the type of activity most suitable for them. Common sense is your best guide in answering these few questions. Please read them carefully and check the yes or no opposite if it applies to you.

	Yes	No	
1.	☐	☐	has your doctor ever said you have heart trouble?
2.	☐	☐	do you frequently have pains in your heart and chest?
3.	☐	☐	do you often feel feint or have spells of severe dizziness?
4.	☐	☐	has your doctor said you have high blood pressure?
5.	☐	☐	has your doctor ever told you that you have bone or joint problems such as arthritis that has been aggravated by exercise, or might be made worse with exercise?
6.	☐	☐	is there any good physical reason not mentioned why you should not follow an activity program even if you wanted to?
7.	☐	☐	Are you over the age of 65 and not accustomed to vigorous exercise?

APPENDIX E: ATHLETE DEMOGRAPHIC QUESTIONNAIRE

*Today's Date:*__________ *Subject #:*__________

Taekwondo Research Study Medical Eligibility Questionnaire

Name(last,first):____

Height (to nearest inches):__________ Weight (to nearest lb.):______________

Gender:__________ Age (years, months):________________

Contact Info: __________________________ e-mail _________________ phone______

Taekwondo Belt/Rank ____________# of Years of Taekwondo Training _____________

Competition Weight Category (Olympic) _____________________

In the space below please provide a detailed report of your recent competition record that best represents your level of expertise:

____
____
____
____

Please answer the following question to the best of your ability.

Do you have any injuries or orthopedic limitations that may affect your **FULL** participation in this study?

YES **NO**

If YES, please explain your injury and the current status of your injury:

____
____
____

If yes, please explain:

____
____
____

REFERENCES

1. National Center for Injury Prevention and Control. Report to Congress on Mild Traumatic Brain Injury in the United States: Steps to Prevent a Serious Public Health Problem. Atlanta, GA: Centers for Disease Control and Prevention; 2003.

2. McCrory PM, Johnston K, Dvorak J, et al. Consensus Statement on Concussion in Sport: The 3rd International Conference on Concussion in Sport held in Zurich, November 2008. J Clin Neurosci. 2009;16:755–63.

3. Guskiewicz KM, SL, Cantu RC, Ferrara MS, Kelly JP, McCrea M, et al. National Athletic Trainers' Association position statement: management of sport-related concussion. *J Athl Train.* 2004;39:280-297.

4. Kukkiwon: World Taekwondo Headquarters; c2008 [cited October 14, 2009] Available from: www.kukkiwon.co.kr

5. Pieter W, Zemper ED. Incidence of reported cerebral concussion in adult taekwondo athletes. *J R Soc Promot Health.*1998;118:272-279.

6. Koh JO, Cassidy JD. Incidence study of head blows and concussions in competition taekwondo. *Clin J Sport Med.* 2004;14(2):72-9.

7. Fife GP, Harter RA. Predictors of Concussion in Elite Korean Taekwondo Athletes. Proceedings of The 2nd International Symposium for Taekwondo Studies: Globalizing Taekwondo; 2009 Oct 12-13; Copenhagen, Denmark . Seoul South Korea: Kyung Hee University; 2009. P. 151-53.

8. Pieter W. Cerebral Concussions in Adult Taekwondo-in: Mechanisms and Risk Factors. Proceedings of The 2nd International Symposium for Taekwondo Studies: Globalizing Taekwondo; 2009 Oct 12-13; Copenhagen, Denmark . Seoul South Korea: Kyung Hee University; 2009 .P 145-47 p.

9. McKee AC, Cantu RC, Nowinski CJ, et al. Chronic Traumatic Encephalopathy in Athletes: Progressive Tauopathy following Repetitive Head Injury. *J Neuropathol Exp Neurol*. 2009 Jul;68(7):709-35.Review.

10. Medana M, Esiri MM. Axonal Damage: A Key Predictor of Outcome in Human CNS Diseases. *Brain*. 2003 Mar;126(Pt 3):515-30.Review.

11. Nolan S. Traumatic Brain Injury: A Review. *Crit Care Nurs Q*. 2005 Apr-Jun;28(2):188-94. Review.

12. Guskiewicz KM, Mihalik JP, Shankar V, et al. Measurement of head impacts in collegiate football players: relationship between head impact biomechanics and acute clinical outcome after concussion. *Neurosurgery*.2007:Dec;61(6):1244-52; discussion 1252-3.

13. Naunheim RS, Standeve J. Richter C, et al. Comparison of impact data in hockey, football, and soccer. *J Trauma*. 2000;May 48(5):938-41.

14. Viano DC, Pellman EJ, Bir CA, et al. Concussion in professional football: comparison with boxing head impacts – part 10. *Neurosurgery,* 2005 Dec;57(6):1154-72;discussion 1154-72.

15. Walilko TJ, Viano DC, Bir CA. Biomechanics of the head for Olympic boxer punches to the face. *Br J Sports Med,* 2005 Oct;39:710-19.

16. Stojsih S, Boitano M, Wilhelm M, et al. A prospective study of punch biomechanics and cognitive function for amateur boxers. *Br J Sports Med*. 2010 Aug;44(10):725-30. Epub 2008 Nov 19.

17. Duma SM, Manogian SJ, Bussone WR, et al. Analysis of real-time head accelerations in collegiate football players. *Clin J Sport Med*. 2005;Jan;15(1):3-8.

18. Kazemi M. Pieter W. Injuries at a Canadian national taekwondo championship: a retrospective study. *BMC Musculoskelet Disord.* 2004 Jul;27;5:22.

19. SAE. Instrumentation for impact test – part 1: electronic instrumentation. SAE paper no. J211/1. Warrendale, PA: Society of Automotive Engineers, 1995.

20. O'Sullivan D, Chung CS, Lee KK, et al. Measurement and comparison of Taekwondo and Yongmudo turning kick impact force for two target heights. *J Sci Med Sport*. 2009;8 13-16.

21. Haslegrave CM. test dummies record higher injury estimates that actually occurred in real auto collisions. Vehicle Safety Legislation: Its Engineering and Social Implications; A Conference Sponsored by the School of Automotive Studies. 1975.

22. Schwartz ML, Hudson AR, Fernie GR, et al. Biomechanical study of full-contact karate contrasted with boxing. *J Neurosurg.* 1986 Feb;64(2):248-52.

23. Pellman EJ, Viano DC, Tucker AM, et al. Concussion in professional football: location and direction of helmet impacts – part 2. *Neurosurgery*. 2003 Dec;53(6):1328-41; discussion 1340-1.

24. Broglio SP, Schnebbel B, Sosnoff JJ, et al. Biomechanical properties of concussions in high school football. *Med Sci Sports Exerc*. 2010 Nov;42(11)2064-71.

25. Marjoux et al. Head injury prediction capability of the HIC, HIP, SIMon and ULP criteria. *Accid Anal Prev*. 2008 May;40(3):1135.Epub 2008 Jan 7.

26. ASTM International. Standard specification for protective headgear used in martial arts:F2397-04. ASTM Volume 15.07. Nov 2004.

27. Leopold J. Kick Kills Taekwondo Black Belt. Los Angeles Times (USA). 1999 Jan 11 [cited 2010 Nov 10]; Available from: http:/articles.latimes.com/1999/jan/11/local/me-62448

28. Quek C. Teen dies after match. The Straits Times (Signapore). 2009 July 11 [cited 2010 Nov 10]; Available from: http://www.straightstimes.com/Breaking%2BNews/Singapore/STIStory_401727.html

29. World Taekwondo Federation News. WTF general assembly approves New Caledonia as 192nd member nation; passes new statutes, competition rules. 2010 Oct 8 [cited 2010 Nov 10]; Available from: http://www.wtf.org/wtf_eng/site/news/wtfnews.html

30. Moffitt MM. Impact response of martial arts headgear to stimulated kicks and falls [Master's Thesis]. Berkeley, CA: University of California, Berkeley; 1995.

31. Koh JO. Watkinson EJ. Video analysis of blows to the head and face at the 1999 world taekwondo championships. *J Sports Med Phys Fitness*. 2002 Sep;42(3):348-53.

32. Falco et al. Influence of the distance in a roundhouse kick’s execution time and impact force in taekwondo. J *Biomech*. 2009;42:242-48.

33. Pieter, W., Heijmans, J. Training & competition in Taekwondo. *Journal of Asian Martial Arts. 2003;*12(1):9-23.

34. Pieter W, Zemper ED. Head and neck injuries in young taekwondo athletes. *J Sports Med Phys Fitness*. 1999;39:147-53.

35. Siana J. et al. Injuries In Taekwondo. *Brit J of Sport Med*. 1986;20:165-6.

36. Pieter W, Lufting R. Injuries at the 1991 Taekwondo World Championships. *J Sports Trau Rel Res*. 1994;16:49-57.

37. Pieter W. Zemper ED. Time-loss injuries in Junior Olympic taekwondo athletes. *Sport Ex and Inj.* 1997;3:31-42.

38. Pieter F. Pieter W . Speed and force of selected taekwondo techniques . *Biol Sport* .1995;12(4):257-266.

39. Sung N. et al. An analysis of the dynamics of the basic Taekwondo kicks. *US Taekwondo Journal*. 1987;6(2):10-15.

40. Hertzberg HE. The Antrhopology of Anthropometric Crash Dummies. Society of Automotive Engineers. Proceedings of Thirteenth Stapp Car Crash Conference, Paper Number: 690805. Boston, MA. 1969.

41. Denton ATD. Hybrid II 50th Percentile Male: HII – 50M (Model SA-50-M002. website: www.dentonatd.com.

42. Spittle et al. Hybrid II and hybrid III dummy neck properties for computer modeling. *Interim rept*. Jan 1991-Feb 1992

43. Scott MW, et al. (1993): Comparison of Human and ATD Head Kinematics During Low-Speed Rearend Impacts. SAE paper no. 930094, SAE/SP-93/945, SAE Inc., Warrendale, Philadelphia, USA, ISBN 1-56091-330-4, LC 92-63144.

44. Pintar FA, et al. Biodynamics of the Total Human Cadaver Cervical Spine. Proceedings of the 34’h Stapp Car Crash Conference, Orlando, FL, 1990, pp. 55-72.

45. Backaitis SH. The Automotive Crash Test Dummy, Its Instrumentation and Testing. Journal: Realism in Environmental Testing and Control. Journal: Realism in Environmental testing and control. 1973.

46. McElhaney JH, Stalnaker RL, Robers Vl. Biomechanical Aspects of Head Injuy. Proceedings of the Symposium on Human Impact Response. Warren, MI. 1962.

47. Miller JS. Performance Evaluation of the General Motors Hybrid II Anthropometric Test Dummy. U.S. Department of Transportation National Highway Traffic Safety Administration Report No: DOT HS-800 919. April, 1973.