ACCELERATIONS OF A HYBRID III DUMMY HEAD RESULTING FROM ROUNDHOUSE KICK IMPACTS AND THEIR IMPLICATIONS FOR CONCUSSIONS IN BOYS AND GIRLS

By

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ABSTRACT

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The purposes of this study were to determine the magnitudes of linear acceleration of the center of gravity and angular acceleration about the center of gravity on a Hybrid III dummy head, as a result of being impacted with roundhouse kicks performed by children and to compare these values with the same variables that are known in general to cause concussions. The potential for roundhouse kicks performed by children to cause a concussion was examined. Differences by age, gender and levels of expertise were also studied. Anthropometric data (body mass index, flexibility, sitting height, standing height, weight, biacromial and bicristal widths were also measured to study their effects on linear and angular accelerations.

Results indicated that children can exceed linear and angular acceleration thresholds for concussions that have been established for NFL players. There are no known linear or angular acceleration thresholds for children, but these may be smaller than those used for comparisons in this study.

Results also showed that female participants generated higher linear and angular acceleration values than male participants. Analyses revealed differences in linear and angular accelerations by age group where older participants generated higher acceleration values than

younger participants. Skilled participants also generated greater maximal linear and angular accelerations than beginners. Months of practice, standing height, weight, and flexibility provided some explanation to the differences observed by age, gender, and skill level.

It is necessary to educate parents, martial arts instructors, and governing bodies about the intrinsic risk for traumatic brain injuries, which has been reported to be similar to other contact sports such as American football, boxing, and ice hockey. The use of head gear and mouth guards is strongly recommended in practice and competition to reduce linear and angular accelerations that the brain experiences as a result of an impact to the head to eliminate concussions. The long term effects of single/multiple concussions in children are not known at this time; however recent studies are identifying its negative effects on cognitive functions, thus, it is suggested to reduce children exposure to these possible risks.

DEDICATION

I dedicate this work to my wife Xóchitl and my children Miguel, Marco and Michelle for their love and support throughout these years. To my parents and siblings Ulises and Iskra whom without them I would not be who I am. To all my friends, particularly Tony and Carmen Benavides, and David and Karen Mota for their encouragement and guidance.

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KEY TO SYMBOLS OR ABBREVIATIONS

g gravitational force

gr gram

kg kilogram

kgm^2 kilogram meter squared

m meter

m^2 square meter

m/s meter per second

m/s^2 meters per second squared

N Newton

Nm Newton meter

Ns Newton per second

rad/s^2 radians per second squared

s seconds

CHAPTER I

Introduction

Martial arts had their origins within many ancient cultures; some records indicate their existence as far back as 5000 years ago (Goldman, 1997). They were created as self-defense systems against animals and assailants (World Taekwondo Federation, n.d.), and included unique skills influenced by the local environment where they developed. In countries such as Japan, karate, judo, and aikido flourished; in Korea, taekwondo and hapkido are commonly practiced, while China's wushu and tai chi are among the most known martial arts (Goldman, 1997; Goodman, 2004). Some of these martial arts have transformed into competitive sports, and have even been included as official sports in the Olympic program, such as judo in Tokyo in 1964, and taekwondo in Sydney in 2000.

The popularity of martial arts around the world can be attributed to films, but also to intrinsic benefits associated with their practice. As an example of this popularity, taekwondo has a worldwide presence in over 182 countries (World Taekwondo Federation, n.d.). It is recognized among the martial arts by its emphasis on the use of kicking over punching which makes upwards to 70% of its basic techniques (Buschbacher & Shay, 1999; Kim, Chung, & Lee, 1999; Park & Seabourne, 1997; Zetaruk, Violan, Zurakowski, & Micheli, 2005). All martial arts curricula include basic movements (stances, displacements, kicks, blocks, and punches), forms (pre-established movement patterns), sparring (step and free style), and breaking (wooden boards, tiles, and bricks) (Goldman, 1997; Goodman, 2004; Kim, 1995). A colored belt system is used to classify its practitioners based on their skill proficiency. In this system, novices wear white belts and black belts are reserved for advance practitioners (Goodman, 2004; Kim, 1995).

Some systems have a strong emphasis on kicking techniques, which has lead to the development of a variety of kicks. Among the basic kicks are front, side, crescent or axe, roundhouse, hook, and back (Goldman, 1997; Goodman, 2004; Kim, 1995; Kim, Chung, & Lee 1999; Park & Seabourne, 1997). Their complexity can be increased by combining different kicks, and by adding turns and even jumps. Regardless of the nature of the kicks (individually or in a combination), kicks can be classified based on their mechanics as circular or linear (Serina & Lieu, 1991). Research on kicking technique usage in competition has shown a predominance of circular techniques due to their quickness of execution and possibility to their ability to deliver a powerful blow (Pieter & Pieter, 1995). Linear techniques have been reported to be slower and less powerful, but still effective in specific situations, where they can decide a match by a knockout (Kim, 1995; Kim, Chung, & Lee, 1999; World Taekwondo Federation (WTF), 2004).

Practitioners of different ages, gender, and physical abilities are attracted to martial arts for various reasons. Park and Seabourne (1997) identify physical challenge, to learn self-defense, to be physically active, and to have fun or socialize among these reasons. Similarly, research has also provided evidence of other benefits associated with martial arts and taekwondo practice. These include improvement of self-esteem, self-discipline, and confidence (Birrer, 1984; Finkenberg, 1990; Konzak & Boudreau, 1984; Richman & Rehberg, 1986; Trulson, 1986; Weiss & Petlichkoff, 1989). Furthermore, studies of fitness levels of martial arts practitioners have also shown improvements in cardiovascular conditioning, anaerobic power, flexibility, and balance (Bridge & Jones, 2005; Markovic, Misigoj-Durakovic, & Trninic, 2005; Melhim, 2001; Pieter, 1991). As a result of a combination of benefits attributed to taekwondo, along with media exposure, participation in martial arts in the U.S. has been reported to be one million (Birrer & Halbrook, 1988), one and a half million (Oler, Tomson, Pepe, Yoon, Branoff, & Branch, 1991), two million (Wilkerson, 1997), and even eight million (Zetaruk, Violan, Zurakowski, & Micheli, 2005). With the significant level of development and popularity of martial arts, the U.S. has had several Olympic and world champions throughout the years. Furthermore, it was indicated that the majority of these participants are children, with females representing 20% of the practicing population.

The wide age range of participants has favored the organization of free sparring championships for different age categories and gender in all martial arts. In many martial arts' free sparring competitions, full contact kicking and punching, with some restrictions, is allowed between contestants (WTF, 2004; Goodman, 2004). In spite of these regulations, injuries are common in martial arts competitions where protective equipment is minimal.

The most commonly reported injuries in martial arts are contusions, sprains, and strains (Birrer, 1984; Birrer & Halbrock, 1988; Buschbacher & Shay, 1999; Wilkerson, 1997). However, serious injuries such as concussions, paralysis, visceral rupture, and even fatalities have also been recorded (Oler et al., 1991; Pieter, 1991; Powell, 2001; Quintana-Diaz & Giralt-Lopez, 1998; Siana, Borum, & Kryger, 1986; Wilkerson, 1997; Zetaruk, et al., 2005).

The number of head injuries reported by several researchers (Birrer, 1984; Jui-Chia, Lin, & Esposito, 2006; Koh & Watkinson, 2002a; Siana et al., 1986) highlights the potential for serious neurologic damage associated with these injuries. This finding is significant since children make up a high percentage of the martial arts practicing population. Burke, Barfoot, Bryant, Schneider, Kim, and Levin (2003) reported in their study that nearly 50% of the injuries in a taekwondo tournament were to the head and neck region in spite of the fact that tournament rules forbid blows to the face. Pieter and Zemper (1997a) have reported concussions to be the second most common injury in their study on injuries sustained by children in a taekwondo competition. Although a concise definition of concussion can be difficult, Powell (2001) defined it as a “trauma induced alteration in mental status that may or may not involve a loss of consciousness” (p. 307). The Congress of Neurologic Surgeons definition states that a concussion is “a clinical syndrome characterized by the immediate and transient post-traumatic impairment of neural function such as alteration of consciousness, disturbance of vision or equilibrium due to brainstem involvement” (Powell & Barber-Foss, 1999, p.958). Regardless of who provides the definition, a concussion is associated with a disruption of brain function and an alteration of consciousness to some degree.

Zemper and Pieter (1994) reported that cerebral concussions are the most serious injuries observed in taekwondo competition. They estimated a concussion rate of 5.2/1000 athlete-exposures, which is 3.1 times higher than the rate seen in college football games based on number of exposures. In another study (Pieter & Zemper, 1998) it was noted that concussions to female athletes were all of a mild nature, whereas 16.7% of concussions in males were considered severe, because these male athletes lost an average of 21 days or more of training and/or competition per occurrence.

Koh and Watkinson (2002b) reported that in an international competition (where 32 male and 32 female high skill level athletes participated, with an age range from 15 to 38 years) the most dominant techniques that caused a head blow were the axe kick (51.4%), roundhouse and turning-roundhouse kicks (31.4%), 360 spinning kick (11.4%), and back kick (5.7%). In another study by Koh, Watkinson, and Yoon (2004), with a sample size of 2328 athletes (676 females and 1652 males between the ages of 11 to 19 years, with advanced skill level), it was reported that among concussed competitors who experienced ringing in the ear (1009 cases), 61% of the impacts were made on the side of the head and face, 16% on the lower jaw, 13% on the back of the head, and 10% on the center of the face; and the kicks that caused it were in 50% of cases roundhouse kicks, 33% axe kicks, 8% back kicks, and 6% spinning kicks. Research conducted by Koh and Watkinson (2002a) in a Canadian championship (which included 139 males and 73 females, with age ranging from 14 to 24 years) and in Korea by Koh and Cassidy (2004) (with 2328 competitors, where 391 male and 171 female studied at high school level and 810 male and 301 female did so at the middle level; their ages ranging between 11 and 19 years and classified as possessing advanced skill levels) using the same methodology also showed similar findings among these three studies.

Aside from the acute symptoms, concussions have been known to have long term effects on the individuals that suffer them, regardless of their number and severity. Powell (2001); Wojtys, Hovda, Landry, Boland, Lovell, McCrea, and Minkoff (1999); and Zemper and Pieter (1994) recognized the cumulative effects of concussion and cited reductions of memory function and information processing capacity when subjects suffered a concussion, even without losing consciousness. Johnston, McCrory, Mohtadi, and Meeuwisse (2001) also identified memory; and the abilities to learn new things, plan, and switch mental “set”; as being affected after a mild concussion. Similarly, they reported a reduction of information processing speed and reduced attention as other effects of this type of injury.

In spite of the known potential risks for long term effects on the central nervous system of concussive injuries in martial arts; the high incidence of these injuries in the activity; and the availability of studies that have described the kinetics, kinematics, and impact forces of the kicks; no studies have addressed the direct effects of contact accelerations of the most common martial arts kicks on the risk of suffering a concussion.

Statement of the Problem

Injuries are an intrinsic factor of sports participation and their effects range from being brief and non-relevant to permanent conditions and career ending, and in extreme cases even death. Contact sports such as martial arts expose their participants to competitive situations where severe injuries to the head can occur, and the long term effects of these injuries should not be ignored, especially when participants are exposed to these situations at early ages where the risk of sustaining these injuries and their long term effects may be even greater.

In martial arts, there is a paucity of information regarding the mechanisms of injuries to the head, effects of impacts on the cognitive and motor abilities of individuals after receiving kicks or punches to the head, impact mechanics of techniques, and/or advantages of requiring the use of head gear in competition. Thus, there is a need to investigate and compare selected kinematic variables and the response of the body to these stressors. An approach to this is to study the kinematic variables resulting from basic kicking techniques. The roundhouse kick is a technique that may provide an understanding of how a model head (from a humanoid model with multi-directional biofidelity) responds to this type of impact and may provide insight into the relationships between impact responses with known parameter values that are generally associated with the appearance of symptoms of concussion.

Purpose of the Study

The purposes of this study were to determine the magnitudes of linear acceleration of the center of gravity and angular acceleration about the center of gravity on a Hybrid III dummy head, as a result of being impacted with a roundhouse kick, and to compare these values with the same variables that are known in general to cause concussions. Thus, the potential for roundhouse kicks to cause a concussion was examined, and recommendations to reduce the incidence of this type of injury were made. Secondly, the roundhouse kicks to a Hybrid III dummy head by martial arts practitioners of different ages, levels of expertise, and gender were studied. Body mass index, flexibility, sitting to standing height, and biacromial to bicristal ratios were also used to study their effects on linear and angular accelerations.

Significance of the Study

Several biomechanics studies have been conducted to analyze techniques in martial arts, and in particular in taekwondo. Most of these studies have focused on the kinematics and kinetics of kicking and the differences in performances of individuals with various skill levels. Variations of the front kick, and mostly its kinematic variables, have been studied by Bercades and Pieter (2006); Kim (1993); Park (1989); Sorensen, Zacho, Simonsen, Dyhre-Poulsen, and Klausen (1996); Tsai and Huang (2000); and Yates (2005). More complex kicking techniques such as the roundhouse kick, side kick, back kick, and hook kick have also been studied by Joon, Guk, Jong, and Kyu (1987); Kim, Yamaguchi, and Hinrichs (2004); Kong, Luk, and Hong (2000); Lan, Wang, Wang, Ko, and Huang (2000); Liu, Tan, An, and Wang (2000); Luk and Hong (2000); Shiang and Chou (1998); and Wohlin (1989). Kinetic variables have been the focus of the studies by Lee and Lee (1999); Lee, Jung, Shin, and Lee (2001); Neal and Landeo (1998); Pieter and Pieter (1995); Serina and Lieu (1991); Tsai, and Huang (2000); and Sidthilaw (1996).

Studies that have focused on the dynamics of general kicking tasks as well as computer simulations have been conducted by Barfield, Kirkendall, and Yu (2002); Choi, Kim, So, Yi, and Kim (2002); Kim, Yamaguchi, and Hinrichs (2004); Lindbeck (1983); and Putnam (1991).

Biomechanical studies that addressed the impact of kicks and their risk of imparting injuries have not been found in the literature. Only a few studies attempted to assess the risk of head injuries in martial arts: Moffitt (1995) evaluated the impact response of martial arts headgear to simulated kicks and falls, Hrysomallis and McLaughlin (1999) assessed the risk of head injuries from falls on taekwondo mats, and Chi (2005) proposed the use of wearable force sensors in martial arts.

In general, all of these studies had small sample sizes; most of them included only male practitioners with high skill levels, and data collection was based on videography. There has not been any studies that attempted to estimate the contact force to the head generated by a kick of a martial arts practitioner and evaluate its risk of injury to the central nervous system, much less as a result of a roundhouse kick, which is one of the most commonly used kicks in the martial arts curriculum. The roundhouse is the most frequently used kick in competition, and it has been reported to cause concussions in taekwondo and martial arts competition. By understanding the potential for martial arts kicks to cause concussions, adequate measures may be taken to reduce the risks of this type of injuries in competition and practice, and may make the participation of athletes safer.

Hypotheses

To address the stated research problems, the following hypotheses were investigated:

1) There will be no difference between maximum impact linear accelerations of the dummy head generated via roundhouse kicks and acceleration values known to cause concussions in humans.

2) There will be no difference between maximum impact angular accelerations of the dummy head generated via roundhouse kicks and acceleration values known to cause concussions in humans.

3) Roundhouse kicks by male participants will not generate greater maximum impact linear accelerations of the dummy head than female participants.

4) Roundhouse kicks by male participants will not generate greater maximum impact angular accelerations of the dummy head than female participants.

5) Older participants' roundhouse kicks will not generate greater maximum impact linear accelerations of the dummy head than younger participants.

6) Older participants' roundhouse kicks will not generate greater maximum impact angular accelerations of the dummy head than younger participants.

7) Skilled participants' roundhouse kicks will not generate greater maximum impact linear accelerations of the dummy head than less skilled participants.

8) Skilled participants' roundhouse kicks will not generate greater maximum impact angular accelerations of the dummy head than less skilled participants.

Limitations

Martial arts practitioners were recruited from local gymnasia and may not represent the whole martial arts population.

Participants from martial arts which emphasize kicking over punching may have performed differently than those that use hands techniques more often.

Accelerometer measurements may be affected by the fact that the Hybrid III female head model has a metal core, and is covered by a hard rubber-like material, thus making it a hard surface to kick, and may cause some discomfort in some participants potentially resulting in less than maximum velocity kicks. However it is designed to react to external forces as a human head would under the same circumstances.

No linear or angular accelerations on thresholds known to cause concussion are available to assess the risk of impacts in children; thresholds used in this study were obtained from adult

NFL players. It may be possible that linear and angular thresholds for children be lower than these values.

The automotive industry has been developing and using various humanoid models throughout the years to understand the responses of humans in car collisions as an alternative for using human cadavers. Kinematic data such as linear and angular accelerations have been measured and calculated to establish safety guidelines that rule automotive design, but are not extensive to other fields that relate to human injuries. It was not until the creation of the National Operating Committee on Standards for Athletic Equipment (NOCSAE) (Overland Park, Kansas, 1969) and its initial testing of football helmets, that data on the head behavior during and after an impact in sports and recreational activities were available. In spite of these efforts to understand the mechanisms of injury to the head, and particularly the effects of impacts to the head, there have been no studies on the effects of punching and/or kicking in martial arts that can relate acceleration values of the head with their potential for concussion. Thus, data collected in the current research will provide the first data under this perspective.

The testing position of the dummy (see CHAPTER III: Methods) can be considered a limitation because it will not fall back as a person would as a result of the impact. The setup used was considered adequate to hold the dummy head in place (Nathan Dau, personal communication, March 2009), to allow as much movement as possible of the head and neck after impact, and reduce the chances of injury to the participants if the dummy were not movable at all. When a person is struck in the head, regardless of the direction of the impact (front, back, or side), the head tends to rotate about the neck as a result of the impact. Thus, a system for the dummy head where support is simulated by the neck is more natural than holding the head from the top, where an impact to the head would result in a rotation about the top of the head.

Additionally, the sample size, the small number of female participants, the small number of advanced level participants, and possible negative effects related to the setup on participants' willingness to exert maximal kicking impact against a padded metal device contribute to the limitations.

CHAPTER II

Literature Review

Kinematic and Kinetic Studies on Martial Arts Techniques

Park (1989) investigated kinematic and kinetic parameters of front kicks by taekwondo practitioners with their trunk in three different positions (slightly forward, vertical, and slightly back). There were 18 male black belt taekwondo participants with a mean age of 29.5 years. Subjects were filmed with a 16 mm camera at a 100 frames per second while each kicked with the right foot and maintained his supporting foot on an AMTI force platform. Quadrant markers were positioned on the lateral side of the right toe, ankle, knee, and hip joints. Digitizing was done via a Sonic Digitizer interfaced to an XT-type computer. Nineteen landmarks were digitized. Linear and angular kinematics were calculated from the digitized data. Muscle moments at the right ankle, knee, and hip joints were computed, and ground reaction forces were also stored in the computer system. The results pointed to a reduction in movement time of the kicks as a result of positioning the trunk backward immediately before the kick. In practice situations, the use of this kick variation is emphasized in order to prevent counter-attacks from opponents. Maximum resultant linear velocities of the kicking foot were between 11.03 to 11.28 m/s in all kicks, indicating that there was no significant difference observed in the front kicks with the three different trunk positions. Mean maximal horizontal acceleration of the kicking foot for the three kicks ranged from 66.51 to 68.21 m/s^2. The mean maximal vertical acceleration values were between 94.64 to 108.29 m/s^2. Although there were no significant differences in vertical acceleration among kicks, it was observed that there was a difference for the mean maximal vertical acceleration favoring the trunk backward position. There was no significant difference in the peak muscle moments at the hip, knee, and ankle joints among the kicks. The mean values ranged from 156.82 to 169.63 Nm for the hip, 26.68 to 33.61 Nm for the knee, and 5.72 to 6.76 Nm for the ankle. No significant differences were observed in the mean maximum vertical ground reaction forces of the supporting foot during the three kicks. These values were between 934.1 to 986 N.

Kim (1993) analyzed the kinematics and kinetics of the front thrust kick. Five novice and five expert male practitioners participated in the study. The age of the participants ranged from 19 to 22 years, and their height ranged from 1.55 to 1.78 m. Their weight ranged from 43.6 to 74.2 kg. Data were collected via high-speed camera at 200 frames per second. Impulse was measured via Kynar Piezo film mounted on a Lexan plastic sheet as a target. Ten joint markers were placed on the right side of the subjects, but only the heel, ankle, 5th metatarso-phalangeal joint, knee, and hip were used in the study. Anthropometric measurements of height and weight, and length of the foot, shank, thigh, and trunk were taken.

Linear kinematic peak resultant variables were studied for the metatarso-phalangeal marker, as well as linear displacement of the hip marker. Angular kinematics were analyzed for the trunk, shank, and thigh. There was no significant difference in the total kicking time between novices (0.223 s) and experts (0.230 s). This time was calculated from the film, and was measured from the moment the kicking foot left the ground to the moment the foot made contact with the target. There was also no significant difference when comparing both groups in total impulse of the kicking leg before the foot left the ground; experts' mean was 19.29 Ns and novices' mean was 18.68 Ns. Mean peak resultant linear velocities of the kicking foot were also not significantly different with values of 10.6 m/s for novices and 11.28 m/s for experts. Similarly maximum resultant linear accelerations of the kicking foot also did not show a significant difference between groups, where experts exhibited a mean of 632.97 m/s^2 and novices a mean of 592.48 m/s^2. Overall, the study showed that there were no differences in the kinematic variables and impulses between novice and expert practitioners.

Lan and colleagues (2000) studied the kinematics of three taekwondo kicking movements. The kicks included were the roundhouse, back round, and back. The participants were five highly skilled female practitioners with a mean age of 21 years, height of 1.62 m, weight of 52.4 kg, and practice experience of ten years. Two high speed video cameras filming at 120 Hz were used to record the performances of the kicks. Digitizing was done using a peak Motus system, and parameters from Dempster and Gaughran's (1967) data were used to estimate centers of masses. Their results indicated the following: the maximum resultant foot velocity was observed on the roundhouse kick (mean maximum foot velocity for all three types of kicks was 37.67 m/s); movement time was shorter for the back round kick (mean movement time for all three types of kicks was 0.1985 seconds), and the smallest knee angle of the kicking leg was observed on the back kick during the preparation phase (mean minimum knee angle for all three kicks was 36.21 degrees). There was no significant differences among the three kicks when measuring the foot velocities at the moment of impact with the target (mean of 2.66 m/s for all three types of kicks). It was also observed that the roundhouse kick was a whip-like movement; whereas the back round and back kicks do not follow this pattern. It was inferred that shorter movement time explains the more frequent use of a particular kicking technique in competition.

Kong and colleagues (2000) compared kinematic variables of roundhouse kicks being performed alternately with the front and back positioned extremities while maintaining a sparring stance. Eight male subjects with a mean age of 26.1 years, height of 1.69 m, and weight of 60.68

kg participated in the study. Their training experience mean was 6.6 years. Two high speed cameras recorded the kicks at 120 Hz. Four reflective markers were placed on the major joints of the lower extremity (hip, knee, ankle, and fifth metatarsal). A start signal was given and an accelerometer recorded the moment of impact with the target. Significant differences were observed in movement time, maximum resultant linear velocity of the ankle, and maximum resultant linear velocity of the knee (mean maximum linear velocity of the ankle for the front positioned leg was 18.83 m/s; whereas, the mean maximum linear velocity of the back positioned leg was 14.56 m/s; the mean maximum linear velocity of the knee was 9 m/s for the front positioned leg and 14.56 m/s for the back positioned leg). Movement time for the front positioned leg was an average 0.73 s; whereas the back positioned leg took 0.83 s for the foot to reach its target. They concluded that having a fast kick may be convenient to score points due to the fast movement time, but also acknowledged that a powerful kick associated with a greater momentum such as kicking with the back positioned leg may be also useful in competition; thus, they recommended developing strategies that included the use of both techniques.

Wohlin's (1989) study focused on the kinematics and kinetics of the whole body of a practitioner performing a hook kick. There were two male and one female participants in the study; all were highly skilled and ranged in age from 25 to 31 years. Data were collected via two high speed cameras sampling at 150 fields per second. Joint markers were placed on the right side of the subjects' upper and lower extremities. Anthropometric data (height, weight, and segmental lengths) were also collected. Video fields were digitized using a FILMADATA motion analysis program and linear and angular kinematic and kinetic data were generated. The rotational inertia of the body at the end of the push-off phase ranged from 5.61 kgm^2 to 7.69 kgm^2; when normalized for subjects' masses, ranged from 0.078 m^2 to 0.09 m^2. Anterior-posterior dimensions of the base of support during the push-off phase also varied (0.57 to 0.82m) from participant to participant but did not seem to be related to the height of the subjects. Total peak resultant velocities of the metatarso-phalangeal joint at target contact ranged from 12.4 to 15.5 m/s. Total movement times for the kick for all participants ranged from 0.63 to 0.71 s; it was noted that participants tended to keep the upper body segments as close as possible to the trunk which allowed them to increase the velocity of the rotational movement, thus generating faster kicks. The analyses also provided insight into the acceleration sequence of the thigh and shank; and it appeared to be similar to those found in other kicking techniques, where the thigh reached its maximum acceleration before the shank, and occurred before contact with the target. Once maximum acceleration is achieved by the thigh, it started to decelerate, and the shank followed in reaching its maximum acceleration, also prior to contact with the target.

The study by Tsai and Huang (2000) focused on the kinetic analysis of the taekwondo axe kick. There were 20 male participants, with a mean experience of 6.6 years and a mean age of 17.1 years; their mean height was 168.8 cm, and their mean weight was 59.9 kg. Participants' data were collected from one foot on each of two Kistler force platforms with a sampling frequency of 600 Hz. The mean of the total movement time of the axe kick was 0.88 s with a range between 0.795 and 1.06 s. For the kicking leg the mean peak vertical ground reaction force normalized to body weight was 1.46 with a range between 2.20 and 0.96. Mean vertical impulse of the kicking leg prior to the kick was 227.7 Ns, while the horizontal impulse was 69.1 Ns. For the support leg the mean peak vertical ground reaction force normalized to body weight was 1.79 with a range between 2.18 and 1.39. Mean vertical impulse of the kicking leg was 104 Ns with a range between 155.9 and 70.6 Ns. No relationship was established between ground reaction forces at the moment the kicking foot left the ground and contact force at the target. However, findings indicate a negative correlation between peak anterior-posterior force of the kicking foot and movement time.

Waliko, Viano, and Bir (2005) studied the risk of head injury from translational and rotational acceleration from punches to the jaw of a Hybrid III dummy. There were seven participants, all Olympic level boxers from five different weight categories. The results indicated a correlation between punch force and weight class (r = 0.0539). The mean force applied was 876 N. Translational and angular accelerations also were found to correlate to weight class (r = 0.432) and (r = 0.524), respectively. Mean linear acceleration was 58 g's with a standard deviation of 13 and mean angular acceleration was 6343 rad/sec^2 with a standard deviation of 1789. The mean HIC from all punches was 71 with a standard deviation of 49, similarly this showed a positive correlation with boxers' weight (r = 0.672). The researchers concluded that "the acceleration levels may be sufficient to cause some level of head injury if multiple punches are landed". They also suggested that rotational accelerations may be the most important factor for concussions, indicating that findings were consistent with levels found in concussed professional football players.

Concussions

Koh, Cassidy, and Watkinson (2003) studied the incidence of concussion in contact sports, and conducted a systematic review of evidence. The authors' purpose was to estimate the incidence of concussion in contact sports, through an analysis of data contained in the literature available between 1985 and 2000. The researchers' inclusion criteria was based on documented incidence of concussions in the sports of American football, boxing, ice hockey, judo, karate, taekwondo, rugby, and soccer, all being defined as contact sports either by the possibility of colliding with other players or making contact with other implements, such as balls (e.g., heading the ball in soccer). The review included data from male and female athletes of all competitive levels and ages, and also included information as to whether or not the injury occurred during practice or competition situations. Additional criteria included evidence of the incidence of injury to the head or brain, and relevant reports on concussion and mild traumatic brain injury or diagnostic criteria used for concussion. Studies related to whiplash or spinal cord injury, facial bone fracture, and soft tissue injuries were not included. Similarly, articles reporting only prevalence, unique cases, or did not include risk ratios were also excluded. A total of 23 articles were used in this review from an initial set of 127. Their findings indicated that, on the selected team sports, ice hockey showed the highest incidence of concussion in male athletes at the high school, college, and amateur adult levels, and American football had the second highest incidence. Among the individual sports, boxing was found to exhibit the highest frequency of concussion. However, the authors identify an issue with over estimating cases in this sport due to a fact that in boxing a knockout and a technical knockout are defined as concussion. The researchers were only able to identify a limited number of studies on female athletes, but were able to identify that taekwondo shows the highest frequency of concussion regardless of age.

Schulz, Marshall, Mueller, Yang, Weaver, Kalsbeek, and Bowling (2004) studied the incidence and risk factors for concussion in high school athletes in North Carolina. The purpose of this study was to examine the incidence rate of sports-related concussions and to estimate the association between history of previous concussion and concussion rate. The researchers used a stratified cluster sample of 15802 athletes from the North Carolina High School Athletic Association, representing 12 sports. The sample included football (boys), cheerleading (girls), wrestling (boys), volleyball (girls), baseball (boys), softball (girls), basketball (boys and girls), soccer (boys and girls), and track (boys and girls), and the selected teams were followed for a period of three years. The functional definition of concussion for the study was a “clinical syndrome characterized by immediate and transient post-traumatic impairment of neural functions, such as alteration of consciousness, disturbance of vision, equilibrium, etc., due to brain stem involvement” (p. 938). A concussion report was a two-step process; one provided information on the type of injury, and the second, provided information about signs and symptoms associated with a concussion. Concussion incidence rates were defined for athlete-game, athlete-practice, and athlete-exposure. A regression model included sport, body mass index (BMI), year in school, calendar time, school size, and highest educational level attainment by the head coach. Sports were classified as contact, limited contact, and non-contact. An alternate classification grouped these sports as collision and non-collision.

From the 2750 injuries reported, only 206 were properly documented concussions, and only 8% of them resulted in loss of consciousness. There were 124 more concussions that were identified after reviewing injury forms. The results indicated the highest concussion rate overall and during competition was observed in football. Conversely, cheerleading had the highest rate in practice. Previous concussions were also a strong predictor for concussion rate in addition to participation in contact sports, being in the bottom quintile of body mass indexes, and being in 9^{th} grade.

Wojtys, Hovda, Landry, Boland, Lovell, McCrea, and Minkoff (1999) reported their findings on concussion in sports. The authors acknowledge that a concussion is a form of traumatic brain injury and defined it as:

“Any alteration in cerebral function caused by a direct or indirect (rotation) force transmitted to the head resulting in one or more of the following signs or symptoms: a brief loss of consciousness, light-headedness, vertigo, cognitive and memory dysfunction, tinnitus, blurred vision, difficulty concentrating, amnesia, headache, nausea, vomiting, photophobia, or a balance disturbance" (p. 677).

They also recognize that there may be delayed signs and symptoms such as "sleep irregularities, fatigue, personality changes, inability to perform daily activities, depression, or lethargy" (p. 677). They pointed out that there was a lack of a uniform consensus on how to classify concussions. However, it was agreed that an early diagnosis will be helpful in determining the time needed to recover, the effect of the second impact syndrome, and also the cumulative effects of concussions over time. The authors explained some neurophysiologic responses of the brain after a concussion, citing among these the "injury-induced vulnerability" that describes the vulnerability of the neurons after a head injury to minor changes in cerebral blood flow, intracranial pressure, and apnea that may lead to cellular death. They also commented on the evidence of a metabolic dysfunction post-concussion that maintains this state characterized by an increase in the demand for glucose, and a reduction in cerebral blood flow. This response has also been observed in studies on mildly concussed animals; and in humans that have experienced severe head injuries. The duration of this condition is not known in humans, but in other species (i.e., rodents) it has been observed to last as long as ten days. Among their recommendations for diagnosis were evaluations on the field, and on the bench, with a neurologic and neuropsychologic approach. As a complement to these evaluations, it was also recommended to have a baseline neuropsychologic assessment of the athlete so it can be used to compare performances after the injury. Criteria for return to play was also discussed and it was recommended that only when there were no signs and symptoms after 15 minutes of the collision or impact, and there was a normal neurologic evaluation and no loss of consciousness, then return to play the same day may be possible. However, if there was a loss of consciousness, headaches were present, there was memory loss or other impairments; the player should not return to play.

Covassin, Swanik, and Sachs (2003a) explored the topic of epidemiological considerations of concussions among intercollegiate athletes. In this study the authors compared the incidence of concussions among 15 different collegiate sports. They used data from the National Collegiate Athletic Association (NCAA) Injury Surveillance System (ISS), and considered data from 3535 team-seasons in a three year period. It is important to mention that all the data in this system were recorded by certified athletic trainers from the participating institutions throughout each sport season. The authors highlight the lack of agreement on the definition of a concussion. However, they cite two definitions that are commonly accepted. One by the American Medical Association and the Committee of Head Injury Nomenclature of the Congress of Neurological Surgeons that states “a concussion as a clinical syndrome characterized by the immediate and transient post-traumatic impairment of neurological function (such as alteration of consciousness, disturbance of vision and equilibrium), due to brainstem involvement” (p.13). The second, by the Quality Standards Subcommittee of the American Academy of Neurology, indicates that “cerebral concussions are altered mental states that may or may not include loss of consciousness” (p.13), and agreeing that amnesia and confusion are symptoms of concussions. After analyzing the data, their findings indicate that, from a total of 40547 injuries suffered by men and women, 6.2% of them were concussions. Five percent of the concussions (1224/24480) occurred during practice and 8% (1278/15975) during games. The breakdown by gender indicated that female occurrences were 3.3% during practices and 8.9% during games, whereas for males, the percentages were 5.5% and 7.7%, respectively. Sports like football, soccer, ice hockey, lacrosse, wrestling, baseball, and basketball showed higher incidence of concussions in game situations compared with practice. The same trend was observed for females in soccer, basketball, and field hockey. It was concluded that overall athletes participating in football, ice hockey, wrestling, soccer (male and female), and lacrosse (male and female) are at the highest risk of suffering a concussion.

In another work by Covassin, Swanik, and Sachs (2003b), they compared sex differences associated with the incidence of concussions among collegiate athletes in a three-year period, using data from the NCAA ISS. The sports included in the study were soccer, lacrosse, basketball, softball, baseball, and gymnastics. The authors recognized the cumulative effects of concussions, and their long term negative consequences, and stressed the need to identify groups of athletes at risk at every level of competition. In their paper, the authors suggested that an increase in number of participants and anatomical differences (e.g., size, overall muscular strength, greater ball-to-head size ratio in females, and weaker neck muscles in females) between male and female athletes may be factors for the observed increase in number of concussion cases in sports, thus the importance of conducting these types of studies.

The operational definition of concussion in this study (Covassin, Swanik, and Sachs, 2003b) was based on the NCAA ISS, which follows a grading scale. Grade 1 was characterized by no loss of consciousness and short duration of post-traumatic amnesia. Grade 2 subjects experienced loss of consciousness (for less than five minutes) and amnesia up to 30 minutes. For grade 3, there was a loss of consciousness for more than five minutes and extended amnesia. The researchers also defined injury rate as the ratio of the number of injuries in a specific sport to the number of athlete-exposures in the same sport multiplied by a reference population of 1000 athlete-exposures. Their results indicated that concussions during practices represented 4.2% (315 cases) of the total injuries observed during the three-year period the study was conducted and in game situations this number was 7.8% (558 cases). A breakdown of the total number of injuries by gender indicated that female athletes sustained 167 (3.6%) concussions during practices and 304 (9.5%) during games. For males the numbers were 148 (5.2%) and 254 (6.4%), respectively. Results also indicated that those sports considered contact sports presented a greater risk for concussion, regardless of gender; thus lacrosse, soccer, and female basketball were identified as sports with higher incidences. Similarly, those sports where there was no direct contact between competitors presented the lowest risks for concussion. However, this may be associated with the use of more protective equipment in these sports.

Female athletes suffered more concussions than males in soccer, basketball, lacrosse, softball, and gymnastics. Some of these differences were associated with differences in the rules of competition (lacrosse, softball) and the type of exercises (gymnastics), but others can be directly associated with the morphology of the female athlete such as size, overall muscular strength, and neck muscle strength.

Koh and Watkinson (2002a) studied the incidence and characteristics of head blows and concussions in a Canadian national taekwondo championship. They analyzed videotapes of head blows that had a potential for causing a mild traumatic brain injury. Their study included 139 male and 73 female competitors, ranging in ages from 14 to 24 years. They used the Mild Traumatic Brain Injury Committee's definition of concussion, which states "a traumatically induced physiological disruption of brain function with a short period of altered or loss of consciousness" (p.80). Their case definition of potential concussion included any athlete who had experienced a direct blow to the head or face region which may have induced a physiological disruption of the brain function. This disruption included loss of consciousness, loss of memory, disorientation, and/or confusion. When there was a fracture to the face or skull as a result of a direct blow, the case was excluded. The inclusion criteria considered 1) rapid movement of the head as a result of the impact, 2) being stunned or dazed, 3) referee giving a standing eight-count, 4) opponent being awarded a point, 5) exhibiting gait unsteadiness, 6) hitting the head as a result of falling; and 7) any loss of consciousness. There were observers on site during the tournament that identified possible subjects, which were referred to the researchers to be evaluated. Videotapes were observed later to code the cases.

After all the injuries where quantified by reviewing all the videos, injury incidence rates were calculated using the number of injuries divided by the number of athlete-exposures (i.e., number of injuries divided by the number of minutes of exposure), as described by Zemper and Pieter (1994). Inter-observer agreement was calculated and differences between groups of concussed versus non-concussed were calculated. Six participants were characterized as having experienced a concussion within the last 12 months. The rates for concussion were 53 per 1000 athlete-exposures, and 9 per 1000 minute-exposures. The highest frequencies were observed in the lightest weight groups.

Researchers reported that 22 concussions occurred due to a direct kick to the head, which represents a high incidence for the sport. A probable cause of these concussions was suggested to be the rules granting a higher score (i.e., three points awarded for a kick to the head). When these results were compared with other contact sports (i.e., soccer, football), it was observed that taekwondo incidences of concussions were much higher.

Among the techniques used to cause a concussion were the roundhouse kick which was used in 43% of the cases, axe kick in 29%, spinning kick in 14%, and back kick in 10%. The offensive action proved to be the situation where the risk of a concussion was higher as compared to defensive actions.

Guskievicz and Mihalik (2006) studied the biomechanics and pathomechanics of sport-related concussions. The authors were aware that the term cerebral concussion is used interchangeably with mild head injury, and that it is also the result of an:

"acceleration-deceleration mechanism in which a blow to the head or the head striking an object results in one or more of the following conditions: headache, nausea, vomiting, dizziness, balance problems, fatigue, trouble sleeping, drowsiness, sensitivity to light or noise, loss of consciousness, blurred vision, difficulty remembering, or difficulty concentrating" (p.66).

The authors also made a reference to Hugenholtz and Richard's (1982) work which reported that a "linear acceleration of 80 to 90 g's acting for more than four milliseconds can result in a concussion" (p. 67). They further made references to other studies that indicated the basic concussion mechanism was the acceleration and deceleration and/or rotation of the skull, thus leading to categorize the mechanisms into head-contact injuries and head-movement injuries. Furthermore, they also explained that mild traumatic head injury can result from a focal injury or a diffuse injury. The authors also recognized several events that follow head trauma, which included physiological, vascular, and biochemical changes that lead to irreversible brain damage. Among these changes are the formation of oxygen-free radicals and lipid peroxidation, and changes in neuropeptides and neurotransmitters, ischemia, and brain swelling; also a reduction of intracellular pH, an increased cerebrospinal fluid, and even glycolytic increases, and reduction of cerebral blood flow.

Zemper (2003) conducted a two year prospective study of relative risk of a second cerebral concussion. The author pointed to the common presumption that an individual who has incurred a cerebral concussion was at greater risk for sustaining another one, and also underscored the lack of a risk ratio that could describe this relationship. He used the American

Academy of Neurology's definition of concussion, which states that it is "a traumatically induced alteration in mental status (e.g., confusion, amnesia) that may or may not involve loss of consciousness" (p.654), and also considered the Concussion in Sport Group's definition proposed in 2001 as "a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces" (p.654). The author highlighted the importance of studying the risk of concussion in individuals who have a history of concussion, and its association with amount of playing time and exposure time. His study included data from two high school football and college seasons taken from a large national sample. Data from 89 high schools and 85 colleges from the 1997 and 1998 football seasons were collected from the Athletic Injury Monitoring System (AIMS). The information included number of players that had a history of concussion during the previous five years, any reports of injuries during practice and games, and the severity of them. Concussions were reported following the aforementioned definition, and also used the American Academy of Neurology scale, which ranges from "grade 1 indicating transient confusion that resolves in less than 15 minutes; grade 2 indicating symptoms that last longer than 15 minutes but there is no loss of consciousness; and grade 3 for any concussion involving loss of consciousness" (p.655).

During the study period, there were 572 concussions, 240 in high school athletes and 332 in college athletes representing 4.1% of the sample population. Injury rates were calculated based on total athlete-exposures considering the following equation:

Injury rate per 1000 athlete-exposures = (number of injuries reported/number of exposures) x 1000.

The concussion rates were 0.5 concussions per 1000 athlete-exposures for high school and 0.57 for college, which translates to 3.33 concussions per 1000 high school players per seasons and 4.1 per 1000 college players per season.

Considering the information collected at the beginning of the season and the two season data sets, it was observed that among those high school players with a history of concussion 18% sustained a new concussion, and less than 3% of those with no history sustained one. For the high school level, the relative risk was calculated by considering 7197 player-seasons and the number of concussion in the season; the players who had a history of concussion during the previous five years (296 player-seasons) experienced 53 new cases; the group of players who had no history of concussions (95.9% of all the player-seasons healthy cases) and sustained one during the season had 187 cases. Thus, the relative risk was calculated ((53/296)/(187/6901)) indicating that a player that has had a concussion is 6.6 times more likely to sustain another one in comparison with a player that has not experienced one. At the college level, there were 8107 player-seasons. Six hundred and seventy nine player-seasons had sustained a concussion within the previous five years. Of the total 332 concussions, 108 were sustained by players with a history, and 224 were new cases. The relative risk was calculated ((108/679)/(224/7428)), indicating a risk of 5.3 for those who already had a concussion. When the results from high school and college were combined, the relative risk was 5.8, still indicating a greater risk for those players who had sustained a concussion. Based on these findings, the author concluded that a history of concussion does have an impact on new occurrences but does not seem to have an impact on the severity of a new concussion. It was inferred that a longer participation in the sport (particularly if it is a contact sport) will increase the chances of sustaining a concussion.

Macciocchi, Barth, Littlefield, and Cantu (2001) studied multiple concussions and neuropsychological functioning in collegiate football players. The authors indicated that concussive injuries in American football can cause time-limited neuropsychological and neurobehavioral problems. They recognized that there is not much evidence of the effects of multiple concussions. Their study focused on cognitive deficiencies presented after a second concussion and how they compare with the same measurements after sustaining the first one. Twenty-four division I-A football athletes from a population of 2300 that participated in a previous concussive injury study were selected to participate in this study. Players sustaining one concussion were matched on age, education, years of experience, and prior concussion history with players sustaining two concussions. Players in the one concussion group had an average age of 19.5 years, and a mean of 8.4 years of playing experience, while the two concussions group had a mean age of 19.1 years and 9.1 years of experience playing football. All participants were assessed during the preseason to establish baseline data. The Paced Auditory Serial Addition Task (Gronwall, 1977), the Trail-Making Tests A and B for the Halstead-Reitan Neuropsychological Test Battery (Retain & Wolfson, 1985), and the Symbol Digit Test (Smith, 1982), in addition to a history questionnaire and a symptom checklist were administered to the participants. Players who were suspected of sustaining head injuries during practices or games were examined by athletic trainers and physicians using standardized medical and mental status procedures. All the cases were consistent with a grade one concussion using the American Academy of Neurology standards. The results indicated that two grade 1 concussions sustained at least two weeks apart do not result in more neurocognitive impairment than a single concussion. Players who sustained 2 concussions performed as well or better on all neuropsychological tests after their first and second concussions when compared with those that only experienced one concussion. There was no evidence of a decrement in test performance relative to the performance observed after players' first concussions. Players who sustained two concussions performed better on post-season assessments than on preseason examinations. Among the limitations of the study, the authors recognized the small sample size, the fact that all of the concussions were grade 1 does not allow any inference related to more severe injuries, and the timing of the injuries, which in some cases occurred within 12 to 24 months.

Janda, Bir, and Cheney (2002) studied the presence of cumulative concussive effects of soccer heading in a youth population by quantifying the number of times a player headed the ball throughout two years either in practices or games. Cognitive function was assessed at the beginning of the fall and at the end of the spring season (approximately nine months between measurements). Verbal learning was assessed with the Wide Range of Assessment Memory and Learning (WRAML) (Western Psychological Services, Los Angeles, CA), attention ability was assessed using the Wechsler Intelligence Scale for Children – III (WISC-III) (The Psychological Corporation, San Antonio, TX) tracking and information processing speed was assessed with the Symbol Digits Modality Test (SDMT), and verbal learning was assessed with a delay test. Participants also completed a subjective assessment by answering questions at the end of the spring season about experiencing any symptoms associated to concussions. The age range of the participants was 10 to 13.7 years of age, with a mean of 11.55. Data from 57 participants (37 males and 20 females) were used for analysis. The average heading in season one was 33.75 and 131.78 headers per female and male players respectively, with a minimum of 1 and a maximum of 450. Season two had only 1 team participating and was composed by 18 male participants with a mean age of 13.25 and a range of 12.6 to 14.5 years. The average number of headers in the second year was 129.6.

No significant differences were observed in any of the cognitive function components tested in the first year. However, results for the second year indicate a marginal significant difference for verbal learning ($p = 0917$). These findings support previous research recognizing negative effects of head impacts on cognitive function. Additionally, they are also in accordance with previous findings on the inverse relationship between cognitive function decline and players' maturation, explained by having experienced more repetitive head trauma as they aged.

Forstl, Haass, Hemmer, Meyer, and Halle (2010) completed a review of acute, subacute, and chronic neuropsychiatric consequences of boxing. They identify fist speeds of 10 m/s or greater upon impact, forces of 5000 N (and correlations of this force with weight class), that lead to translational accelerations of 50 g. Rotational accelerations were also identified as a critical factor, because they generate shearing forces causing lesions in the upper brainstem.

It was reported that in Olympic and amateur World Championships up to 1984, 13.6% of the matches had to be stopped due to knockout or other injuries. After introducing the use of head guards, the percentage was 9.5 (up to 1996), and when the duration of the matches was reduced from three 3-minute rounds to four 2-minute rounds the percentage was 2.2. Modifications to the rules, such as the "outclassed rule" reduced the knockouts and other injuries to zero up to 2004. Boxer's age and number of matches fought were identified as risk factors for injuries.

These authors also identified potential risk factors for increased mortality, such as age, pre-existing brain changes, somatic disease (chronic), medication, dehydration, pronounced weight loss, large number of punches striking the head during the match, and "second impact syndrome" with incomplete recovery after a recent injury.

Subacute consequences included symptoms present 24 hours after the knockout, such as headaches, tinnitus, forgetfulness, impaired hearing, dizziness, nausea, and impaired gait. Cognitive deficit was reported to affect immediate recall, working memory, and reaction time. Performance in visual-spatial and mathematical exercises was also diminished in those participating in a study exploring the effects of knockouts even 48 hours after the event. The authors also reported studies highlighting impaired performance in information processing and verbal fluency one month after a knockout.

Biochemical changes associated with traumatic brain injury have also been reported in the literature, particularly identifying the presence of tau, neurofilament light, and glial fibrillary acidic proteins in higher concentrations as a response to more frequent and harder punches.

Among the chronic consequences, Forstl and colleagues (2010) also found that professional boxers with longer careers are more susceptible to tremors, dysarthria, Parkinson's disease, ataxia, and spasticity. On cognition they experience lower processing, loss of memory, and dementia. Behaviorally, they suffered more depression, irritability, aggression, criminality, and addiction.

Rabadi and Jordan's (2001) review on the cumulative effect of repetitive concussion in sports, included sports such as soccer, football, ice hockey, and martial arts. They recognized the prevalence of chronic traumatic brain injury (CTBI) in professional boxing and identified boxing longer than ten years, participation in over 150 bouts, and retiring after the age of 28 years as factors for CTBI. The signs and symptoms of CTBI in boxers were more manifest after the age of 50 and included motor and cognitive impairments as well as behavioral changes. Radiological imaging has shown structural changes and lesions in the frontal and temporal lobes.

CTBI has been associated with soccer, and possible risk factors are increased exposure to the sport, duration of participation, and increased level of competition. Among the potential mechanisms of injury were direct forces resulting from collisions with the ground, other players, or cumulative impacts associated with heading the ball. CTBI in soccer is mostly associated with a decrease in cognitive function, such as memory, attention, concentration, and judgment.

In football CTBI is associated with repetitive impacts, and a history of concussions. Neurological impairment manifestations are memory loss, confusion, information processing speed, attention, and speech difficulties. In ice hockey the incidence of concussions increased with the level of play through the professional level. Additionally, it was reported that using protective equipment may help to mitigate the occurrences of concussions. In martial arts information on CTBI is limited. However case studies have identified cerebella ataxia, seizures, and dementia, associating these to repeated blows to the head. Recommended preventive measures include “reducing the exposure of high-risk athletes using protective equipment, enforcing strict rule adherence, training and supervising athletes, and increasing medical surveillance”.

Pellman, Viano, Tucker, Casson, and Waeckerle (2003) reproduced game impacts and injuries that produced concussions in professional football. The authors pointed out the start of the National Operating Committee on Standards for Athletic Equipment (NOCSAE) in 1973 to establish standards for the impact performance of football helmets, limiting the Severity Index (SI), which was based on resultant head acceleration. Adoption of these standards by the helmet manufacturers by 1980 showed “significant reductions” in injuries observed in youth football (i.e., a 51% reduction in fatal head injuries, 35% reduction in concussions, and 65% reduction in cranial fractures). In spite of rule changes implemented later, the reduction of injuries was still considered to be associated to helmet design improvement, and was explained by the increase of neck injury rates, which is indicative of the occurrence of head impacts.

Hodgson and Thomas (1985) reported an average SI of 1064 for helmets meeting NOCSAE standards. It is recognized that improvements continue to be made on helmet performance, and the attention was focusing on the incidence of concussion in sports. The summative effect of multiple concussions and their long term effects were also noted.

It was reported that in 1994 the NFL formed a committee to study mild traumatic brain injuries (MTBI) in football (Pellman, 2003), with the mission to scientifically investigate MTBI's in the NFL. Thus, MTBI cases in professional football were systematically recorded between 1996 and 2001, generating approximately 90 MTBI cases that were studied by evaluating video tapes of events when a MTBI was suspected. MTBI were reported by a physician and a trainer, as well as the engineering group responsible of analyzing and reconstructing the game impacts. Reconstructions were made using videotapes of the games. Location of the impact and the striking objects were identified. These reconstructions determined impact velocities, orientations, and helmet kinematics. These variables were later used in the laboratory to replicate the impacts. The lab reconstructions involved the use of a Hybrid II male anthropometric test device (crash test dummy) with a football helmet strapped to it. A mechanical device impacted the helmet at various velocities and angles. Velocities and accelerations were measured 3-dimensionally at the center of gravity of the head. Nine accelerometers were placed to record linear and rotational acceleration. Two high speed cameras recorded head kinematics in the lab. The authors identified two categories of potential errors in their measurements: position of the accelerometers and data-processing techniques to determine accelerations and use of broadcast video as the bases to determine collisions. They reported that translational acceleration of the head's center of gravity was determined from three orthogonal accelerations measured in the dummy, and was expressed in g's (1g = 9.8 m/s^2). The use of Lissner, Lebow, and Evans (1960) Concussion Tolerance Curve was cited to estimate the tolerable peak translational acceleration of the head. Various works were cited providing a range between 42 to 80 g's as the limits of tolerance in humans.

The Severity Index (SI) was calculated by using Gadd's (1966) method:

$$SI = \int_{0}^{T} a(t)^{2.5} dt$$

where,

a(t) = the resultant translational acceleration at the head center of gravity and

T = duration of the acceleration pulse.

SI cannot exceed 1200 to be acceptable.

The Head Injury Criterion (HIC) used by the National Highway Traffic Safety Administration considers a SI variation, and was reported as:

$$HIC = \{(t_2 - t_1)[\int_{t1}^{t2} a(t)dt/(t_2 - t_1)]^{2.5}\}\max$$

where,

a(t) = resultant translational acceleration at the head center of gravity and

$t_2 - t_1$ = T = 15 ms (used to determine maximal value).

The analyses included 174 cases with 29% of the impacts on the facemask, and the remaining on the helmet shell. There were 25 concussions, 16 on the offense, five on the defense, and the rest on special teams. Thirty one videos were analyzed which included those where concussions were reported. The peak head acceleration for concussed players averaged 98 ± 28 g, with 15 ms duration, and was significantly greater than the 60 ± 24 g experienced for uninjured players. Concussion was primarily related to translational head acceleration resulting from helmet impact to the face mask at an oblique or lateral angle, and falling hitting the back of the head. Concussion was strongly correlated with SI, HIC, peak translational acceleration, and head velocity change. Nominal tolerance levels for concussion were SI of 300 and HIC of 250 for helmet impacts. There was a low correlation with rotational acceleration.

Hodgson’s (1990) study tested several types of helmets using a child size humanoid headform (6 5/8” in diameter), and provided evidence of the effectiveness of the use of helmets in reducing head injuries. A small size humanoid head was instrumented with a triaxial accelerometer to measure the linear acceleration experienced at the center of gravity of the head. These values were used to calculate the Severity Index (SI). Drop tests were conducted from the following heights: 1, 1.5, and 2m.

$$(SI)^2 = \int_o^T A dt$$

where, T is the effective impact duration, A is the instantaneous acceleration (g), and dt is time increment of integration.

The risk of injury was evaluated according to the Severity Index and use of a risk chart, which was constructed from the data obtained from experiments of head impacts received by adult cadavers in controlled falls. The author recognized that the values of the chart may be affected negatively by age of the subjects, and also by the rotational motion at impact that may lower the impact tolerance of an individual. The overall results indicated a decrease of acceleration associated with the use of helmets. While falling from 1 m without head protection may result in a serious head injury in 70-99 % of the population, the use of helmets reduced this to 1 %. When the height was increased to 2 m, the risk varied from 6-35% depending on the type of helmet. Caution must be exerted when using this data, because it was observed that there were differences on the protective behaviors of the helmets if the forces were not uniform and helmets could not be kept in place. When the results were analyzed to evaluate the stress in the neck, there was a difference between shell and no-shell helmets, where the later produced greater neck flexion, axial loading, and head angular acceleration. Neither helmet was able to prevent injuries to the facial region.

Dau, Chien, Sherman, and Bir (2006) studied the effectiveness of boxing headgear for limiting injury. In their research they used a Hybrid III dummy. There were 27 amateur boxers who participated in the study. They were asked to punch the dummy's head. The variables measured were linear and angular accelerations of the head, head injury criteria (HIC), and punch force. The Hybrid III head had nine linear and three angular accelerometers, the neck had six-axis load cells, and the boxers' gloves had three accelerometers. Sampling rate was 20 KHz. The dummy head, with and without headgear, was struck.

A decrease of all variables with the headgear in place, was reported. Peak rotational acceleration decreased from 9164.1 to 5534.78 rad/s^2 with the use of the headgear, punch force also decreased from 4260.51 to 2815.59 N, the HIC decreased from 79.23 to 47.34, and the peak resultant acceleration fell from 78.04 to 51.79 g. Punch velocity was also reduced from 9.57 to 8.43 m/s.

In King's (2000) review on the fundamentals of impact biomechanics, the author identified two injury mechanisms for the brain, and pointed out that diffuse axonal injury can be produced by angular or linear acceleration, because both can generate shear stress in the brain.

However, he also cautioned that in spite of a body of knowledge related to linear and angular accelerations as injury mechanisms, there was not enough evidence to support the idea of shear stress. When head injury mechanisms were explained with more detail, the author listed them as "positive pressure, negative pressure, and shear due to pressure gradients or relative motion of the brain with respect to the skull"(p.58), suggesting that movement of the brain after impact has a direct effect on the cellular structure, particularly on the axons, which respond with swelling. This particular observation provided some evidence that diffuse axonal injury (DAI), which takes several hours to develop, was a result of the impact and not secondary to ischemia or increased intracranial pressure, as it has been suggested by other authors. He also indicated that most of the testing done in the car industry to evaluate injury risk from impact in humans is based on a criteria that defines "reasonably safe" levels, as meaning that injuries sustained by a car occupant should not be life-threatening. Along with this criteria, others have also been develop, among these, the Abbreviated Injury Scale (AIS), developed by emergency room physicians (Committee on Medical Aspects of Automotive Safety, 1971), where severity is defined as a "threat to life and is not based on disability or impairment"(p.57). In this scale, a life-threatening injury will receive a value of four. In spite of these efforts, there is still a void on how to express in quantitative terms the agent(s) that cause these injuries. (Table 1).

Table 1
Abbreviated Injury Scale (AIS)

AIS	Severity
0	No injury
1	Minor
2	Moderate
3	Serious
4	Severe
5	Life threatening
6	Maximum
9	Unknown

Note. Adapted from "Fundamentals of impact biomechanics: Part I – Biomechanics of the head, neck and thorax" by A.I. King, 2000, *Annual Review of Biomedical Engineering,* Copyright 2000 by Annual Reviews.

On head injury tolerance, the author recognized that several models have been used, and identified the Gadd Severity Index (GSI) (Gadd, 1966) as the one with confirmed validity (tested on subhuman primates) and built upon the contributions of the previous indexes. This index considers the acceleration of the head center of mass (a(t)), time (t), and the duration of the impact pulse(T).

$$GSI = \int_{o}^{T} a(t)^{2.5} dt \leq 1000$$

The GSI has been re-named the Head Injury Criterion (HIC), and redefined to be considered the current standard for the US federal government for automotive and other safety legislation. It is defined as follows:

$$HIC = \left[\int_{T1}^{T2} a(t) dt \right]^{2.5} / (T2 - T1) \leq 1000$$

It is important to note that this criterion is valid for linear acceleration impacts only; does not consider angular accelerations, even though they are present during impacts, but no criterion is available for angular accelerations.

King, Yang, Zhang, and Hardy (2003) explored the causal relationship between head injury and linear and angular acceleration. The authors indicated that based on the automotive industry data on injuries, there were approximately 1.5 million traumatic brain injuries per year in the US, and 2% of the US population lives with disabilities resulting from a traumatic brain injury. The current literature indicates that the principal cause of injury is brain deformation or strain during head impacts. However, it is not possible to measure this variable in vivo. Thus, head acceleration is used as an alternate parameter. These authors recognized linear and angular accelerations as the two major mechanisms of head injury. Rotational acceleration was thought to produce focal and diffuse brain injuries, while linear acceleration was associated with focal brain injuries.

King et al. (2003) listed various injury mechanisms that have been proposed to explain concussion mechanisms, among them were the shear strains generated by rotation and cited in Holbourn's (1943) work; extent of relative displacement due to impact from different directions, supported by Pudenz and Sheldon's (1946) work; and the coup/countercoup cavitation associated with the relative displacement between the brain and the skull, reported by Gross in (1958). Other mechanisms include the shear stress, distortion or mass movement in the brain stem resulting from impact loading, and its linear acceleration, as presented by Gurdjian, Webster, and Lissner (1955); Gurdjian, Lissner, and Evans (1961); Gurdjian, Lissner, and Patrick (1963); and Hodgson, Thomas, and Gurdjian (1969); the pressure waves traveling through the brain proposed by Goldsmith (1972); strains affecting the brain in a centripetal sequence, as described by Ommaya and Gennarelli (1974); and the impact pulses containing frequencies that are close to the nodal frequencies of the skull/brain which are capable of producing injury due to resonance, a theory proposed by Willinger, Taleb, and Kopp (1996). The authors also cited the results of

Hardy, Foster, Mason, Yang, King, and Tashman (2001) where relative motion data between brain and skull were studied using cadaver heads. Linear acceleration peak was in excess of 60 g and the angular acceleration was above 200 rad/s^2. Additional tests were carried out at linear accelerations in excess of 200 g and 10000 rad/s^2. It was reported that linear acceleration created a 1mm displacement of the brain at most, while angular acceleration produced displacements of 5mm regardless of the direction of impact.

After reviewing studies on helmets that indicated a reduction on linear acceleration in all the helmet models tested, and in some cases showed an increase of the angular component, King et al. (2003) concluded that because the results support the idea that the helmet reduces the occurrence of concussions, and that there was a reduction in the linear component, even though the rotational component may have even increased, then there may not be a link between concussions and the angular component.

In a more recent study by Zhang, Dwarampudi, Yang, and King (2003), also cited by the authors, and conducted in 2001 on NFL players, showed that an average linear acceleration of 94±27 g was known to cause a concussion, as well as angular accelerations of 6398 ±1978 rad/s^2. These accelerations produced a strain over 10% in the midbrain, upper brain stem, and most of the diencephalon, in addition to the frontal lobe. This rate of strain was hypothesized to be the key biomechanical parameter to explain the cause of brain injury and concussion.

The guidelines for rating injury measures, developed by the Insurance Institute for Highway Safety (2009) were created to provide uniform criteria for rating injuries. The data were "obtained from an instrumented 50th percentile male Hybrid III dummy seated in the driver seat" (p.2). Twenty eight measures were recorded from the following body regions: head and neck, chest, left leg and foot, and right leg and foot. Four injury parameters were used to evaluate protection for the head and neck. The injury protection ratings went from good, to acceptable, to marginal or poor based on the injury parameters. The rating criteria indicated that the whole region would receive the same rating as the lowest of the parameters of that particular region. Thus, if any body parameter had a poor result, then the whole region was to receive a poor rating. The authors emphasized that the data presented are guidelines that in no way include all the possible circumstances that may be present in any particular event. Thus, caution must be exercised. When evaluating the risk of injury in the head, a 5 percent risk of a severe injury is estimated to be a HIC-15 (Head Injury Criteria evaluated over a period of 15 ms) of 700, equivalent to a score of 4+ on the Abbreviated Injury Scale (AIS). When these values are considered as multiples of acceleration, a value of 70 g is critical, because depending on the timing of this value with respect to the HIC-15, the injury projection rating can be given a lower evaluation (higher risk of injury). A range of accelerations of 15-90 g experienced by a Hybrid III dummy head results in forces that represent 670 to 4000 N, which are enough to cause face and skull fractures. Aside from the evaluation of the head, the neck was also evaluated, but mostly on the tension experienced axially and the bending moment about a lateral axis passing through the dummy's occipital condyle. These values have been reported to be 6806 N for the neck axial force during tension/flexion, and 6160 N under compression/extension conditions. Similarly, the bending moments have been observed to be 310 to 135 Nm, respectively.

Definitions of Injuries in Martial Arts

The definition of injury is difficult due to the differences in perspective and criteria as to what is considered an injury and how severe it is. The perspective from an epidemiologist is quite different from that of a physician or an engineer. To exemplify these differences, several definitions are presented.

Birrer and Halbrook (1988) based their definition on medical judgment of expected physical impact as well as life threat and potential for permanent impairment; thus, all non fatal injuries were classified on a six point scale with injury classifications ranging from minor to most severe. Scale values increased by 1 point if the patient was admitted for inpatient hospital care.

Hung (1997) defined a sports injury as one suffered from being engaged in sports activities. He also indicated that participation in a sport placed persons at risk for incurring sports related injuries. However, there was no mention on severity, but Hung recognized that the occurrence and frequency of an injury can impair performance, lead to lost competitiveness, disability, and, in some severe cases, even death.

Van Mechelen, Hlobil, and Kemper (1992) define a sport injury as any injury occurring as a result of sports activity and causing one or more of the following: the subject had to stop sports activity and/or could not fully participate in the next planned sports activity, and/or could not go to work the next day, and/or needed medical attention. In addition, a fifth characteristic defined an overuse injury as suffering from pain or stiffness during ten subsequent days while doing sports.

Pieter (1991) defined serious injuries as those that lead to time-loss from participation of one day or more; furthermore, Pieter and Zemper (1998) consider an injury as any circumstance for which assistance was sought from medical personnel.

Injury Mechanisms in Martial Arts

There are many factors that contribute to injuries in martial arts. Kannus, Niittymaki, and Jarvinen (1988) indicated that overuse in systematically trained children and adolescents tends to increase epiphyseal injuries and avulsion fractures, acute characteristic injuries, and long bone fractures. Abrasion, laceration, dislocation, contusion, and fracture are common terms to injuries that have their origin in sports (see definitions section). When studying these factors in competition, the following has been observed:

Table 2 identifies the distribution of injuries by mechanism per 1000 Athlete-Exposures (A-E) of two different round robin tournaments - one restricted for adults and the other exclusively for adolescents (Pieter, Van Ryssegem, Lufting, & Heijmans, 1995) and (Pieter & Zemper, 1997a).

Table 2

Injury Mechanisms per 1000 Athlete-Exposures (A-E)

	A-E men = 258 and women = 114 Pieter et al. 1995				A-E boys = 6068 and girls = 1538 Pieter & Zemper, 1997a			
	Men		Women		Boys		Girls	
	N=67		N=30		N= 3341		N= 917	
Injury Mechanism	No.	Injury Rate	No.	Injury Rate	No.	Injury Rate	No.	Injury Rate
Delivering round kick	12	46.51	2	17.54				
Receiving round kick	11	42.64	4	35.09				
Receiving punch	3	11.63						
Receiving spinning back kick	3	11.63	4	35.09				
Delivering punch	2	7.75						
Receiving spinning hook kick	1	3.88						
Receiving axe kick	1	3.88						
Simultaneously round kicks	1	3.88	1	8.77				
No evidence of contact	1	3.88			2	.33	2	1.3
Receiving a blow					212	34.77	46	29.91
Delivering a blow					90	14.83	17	11.05
Impact with surface					21	3.46	9	5.85
Simultaneous blows					9	1.48	4	2.6
Overuse/gradual onset					5	.82	2	1.3
Other					16	2.64	7	4.55
Total	36	139.54	11	96.49	354	58.34	87	56.57

The number and mechanisms of injuries severe enough to require the player to retire from the competition and miss at least one practice session after the injury are illustrated in Table 3. The injury mechanism of concussions in taekwondo events are illustrated in Table 4.

Table 3
Injury mechanism of time-loss injuries per 1000 Athlete-Exposures (A-E) (Pieter et al. 1995)

Men Injury Mechanism	Number	Injury Rate	Women Injury Mechanism	Number	Injury Rate
Receiving round kick	3	11.63	Receiving spinning back kick	1	8.77
Receiving punch	1	3.88			
Receiving spinning hook kick	1	3.88			
Delivering round kick	1	3.88			
No evidence of contact	1	3.88			
Total	7	27.13	Total	1	8.77

Table 4
Injury mechanism of cerebral concussions per 1000 Athlete-Exposures (A-E)

Men	Study by Pieter et al., 1995		Study by Pieter & Zemper, 1998		Women	Study by Pieter et al., 1995		Study by Pieter & Zemper, 1998	
Injury Mechanism	No.	Injury Rate	No.	Injury Rate	Injury Mechanism	No.	Injury Rate	No.	Injury Rate
Receiving round kick	3	11.63			Receiving spinning back kick	1	8.77		
Receiving punch	1	3.88							
Receiving a blow			22	6.46				4	2.42
Impact with surface			2	.59					
Total	4	15.50	24	7.04	Total	1	8.77	4	2.42

CHAPTER III

Methods

Participants

Participants were recruited from two gymnasia in the Detroit, Michigan area after making arrangements in advance with the instructors at each site. Site A was made available by the Grand Master exclusively for the research data collection session. He invited all students interested in participating in the project to come to the gymnasia on a set date. A data collection session was also hosted at Site B on a date during which classes were being taught. Students interested in participating were allowed to step out of class to have their data collected. The research was approved by the Michigan State University Institutional Review Board (IRB) and the Wayne State University Human Investigation Committee (HIC). Verbal assent (see Appendix C) was obtained from each participant younger than 13 years of age and written assent (see Appendix D) was obtained from those participants older than 13 years of age. Written assent (see Appendices A and B) was obtained from one parent of each youth who assented to participate. A questionnaire was administered to collect demographic data (Appendix E). Anthropometric data were collected using a data sheet (Appendix F).

There were 18 participants (three female and fifteen male) with a mean age of 10.7 (1.7) years (range 7-14 years of age). Only one male participant reported left foot predominance. Participants were categorized into three age groups, where pre-pubescent participants were included in the youngest age group (under 9 years); the second group (10-13 years) was set considering the possibility that children in this age range may experience the initiation of the adolescent growth spurt during this time. The final group (older than 14) was set considering that by this age most of the participants would have reached adolescence. Additionally, these age groups are commonly used to set up competition categories in martial arts events. (Table 5).

Table 5

Age Groups and Number of Kicks

n	Participant ID #	Age (yrs.)	Age Group (yrs.)	Gender	Skill Level	Height (m)	Weight (kg)	Body mass index (kg/ m^2)	# of Kicks
4	M1	7	Under 9	male	beginner	1.23	27.0	17.8	9
	M2	9		male	advanced	1.35	44.5	24.2	11
	M3	9		male	beginner	1.39	37.8	19.4	11
	M4	9		male	beginner	1.40	43.0	21.7	11
12	M5	10	10 to 13	male	beginner	1.46	59.1	27.4	12
	M6	10		male	beginner	1.54	86.6	36.4	7
	M7	10		male	beginner	1.48	38.9	17.6	4
	M8	10		male	beginner	1.42	37.8	18.7	8
	M9	10		male	advanced	1.49	60.6	27.3	10
	F1	11		female	beginner	1.31	29.2	16.8	10
	F2	11		female	beginner	1.32	29.2	16.7	10
	M10	11		male	beginner	1.51	57.4	24.8	5
	M11	11		male	advanced	1.59	48.6	19.1	12
	F3	12		female	beginner	1.53	57.2	24.1	10
	M12	12		male	beginner	1.46	49.8	23.2	10
	M13	12		male	beginner	1.54	49.5	20.7	14
2	M14	14	14 and older	male	beginner	1.62	50.5	19.2	10
	M15	14		male	advanced	1.7	59.6	20.6	7

Participants' experience in martial arts ranged from 1 to 96 months of practice with a mean of 26 months (Figure 1). Fourteen participants were classified as beginners (colored belts) and four males (M2, M9, M11, and M15) as advanced (black belts) (Figure 1). Most of the participants (n=15, 83%) expressed an interest in full-contact sparring competition, and more than 60% in forms competition (n=11). Ten participants (55%) reported to participate in one or more sports in addition to their martial art.

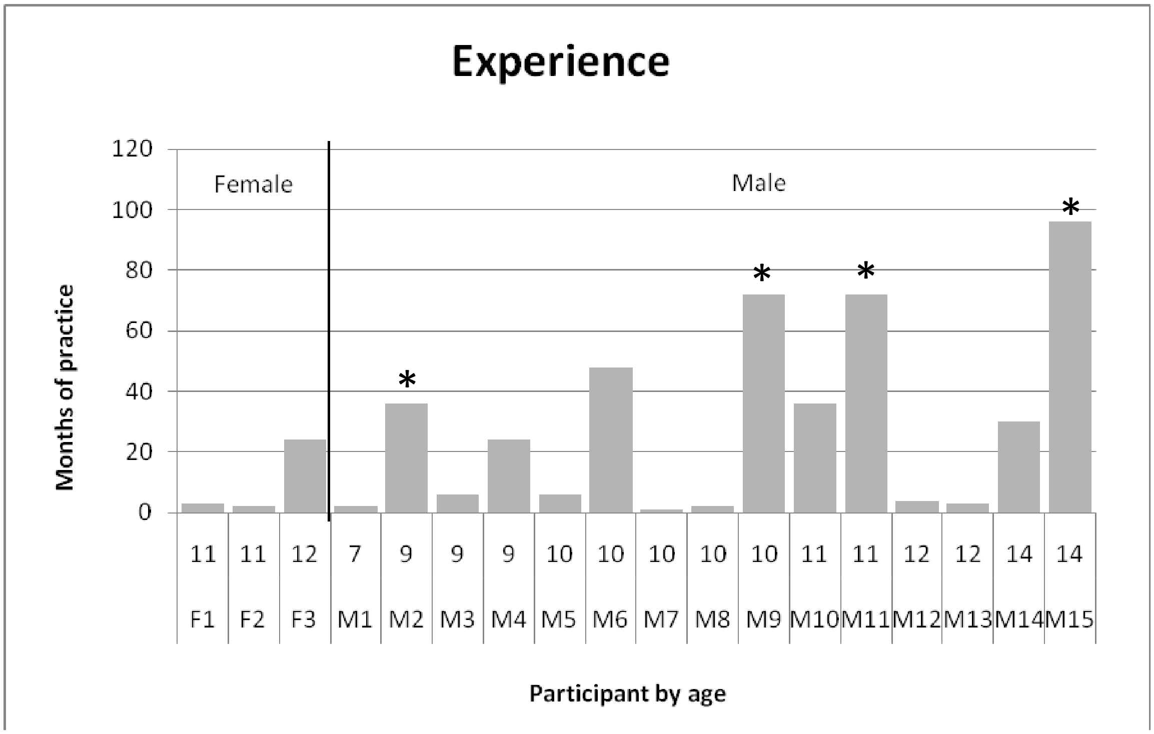


Figure 1. Experience of participants by age and gender (* indicates a black belt participant).

Procedures

Instrumentation and Setup

A 5th percentile Hybrid III female dummy head was mounted on a support base (Figure 2). This head size (3.7 kg, 0.53 m in diameter) was used due to its similarities to the participants' anthropometric characteristics. The support base was stabilized with 100 pounds of sand to prevent excessive movement, thus reducing the risk of injuries.

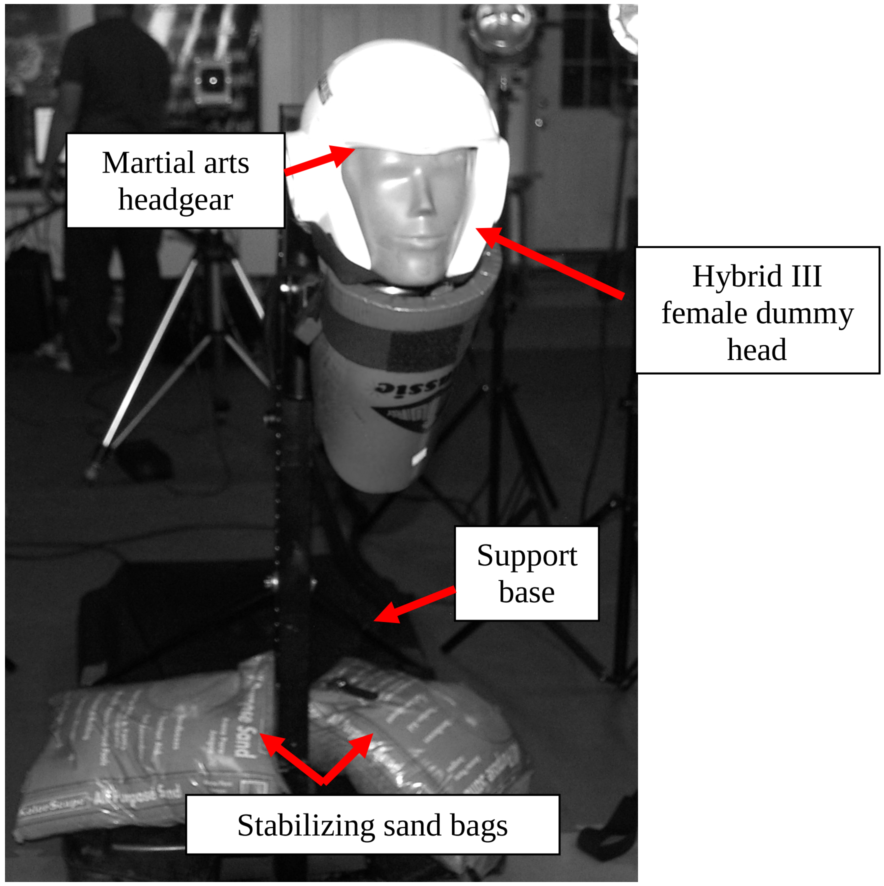


Figure 2. Testing setup.

The coordinate system established for the head followed SAE J211-1 recommendations (Society of Automotive Engineers, 1995) resulting in +X toward the front of the head in an anterior-posterior axis, +Y to the right of the head in a medio-lateral axis, and +Z toward the neck in the longitudinal (vertical) axis (Figure 3).

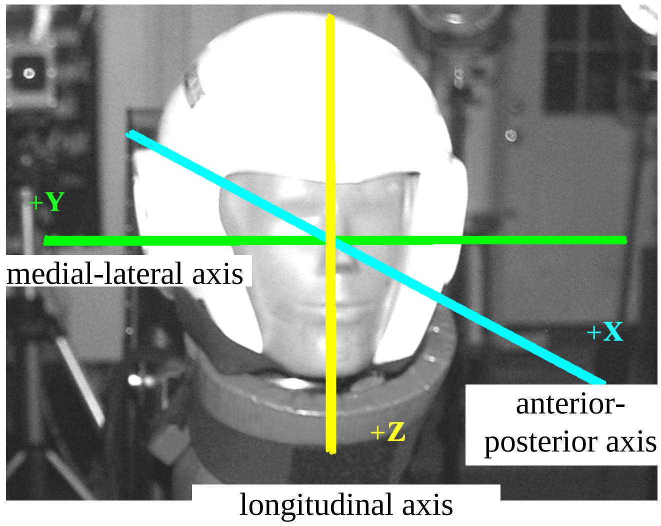


Figure 3. Orientation of standardized dummy coordinate system. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this dissertation.

A 3/4 inch thick vinyl covered foam, medium size, protective martial arts headgear (Proforce Lightning, Proforce Inc., USA) was placed on the dummy head to reduce the exposure to its hard surface by the feet in kicking, thus minimizing the risk of injuries (Figure 4).

Figure 4. Headgear.

All participants wore 5/8 inch dipped foam foot pads by Century (Century LLC. Oklahoma City, OK, USA) provided by the research team during their trials as an additional measure to reduce the risk of injury (Figure 5). Each participant selected the size of foot pad that he/she felt most comfortable using.

Figure 5. Foot pad used by participants to reduce the risk of injury during testing.

For each participant, the dummy head was adjusted to the same height as the head of each participant during his/her stance (Figure 6).

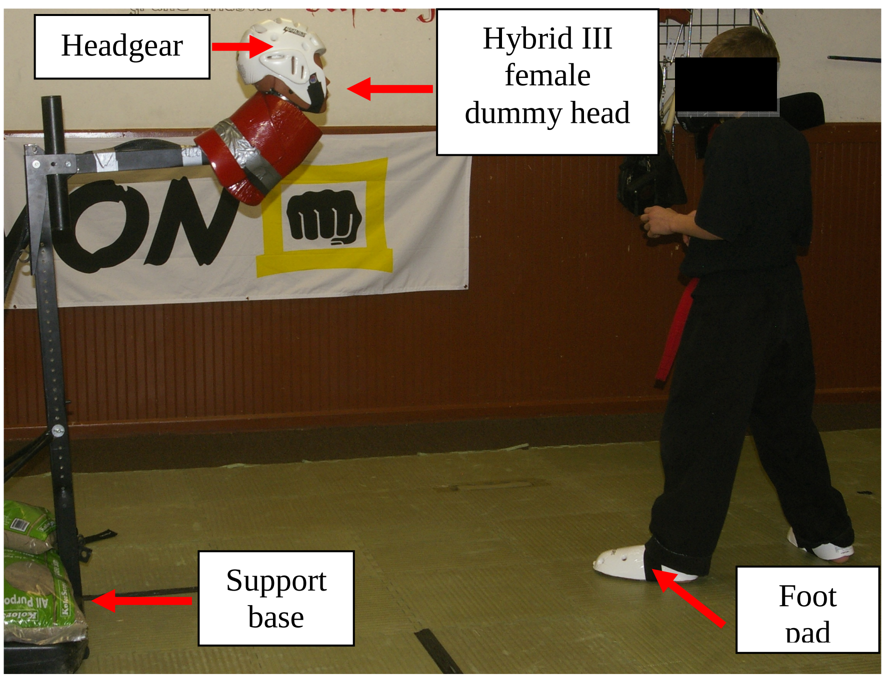


Figure 6. Dummy head set at participant's stance head height.

Three 2000 g's accelerometers (Endevco 7264, ENDEVCO Corp. San Juan Capistrano, CA, USA) were placed in the mounting plate in the Hybrid III female dummy head perpendicular to each other following manufacturer's recommendations (Figure 7). These devices are lightweight (1 gr) piezoresistive accelerometers designed for applications requiring minimal mass loading and meet SAEJ2570 (Society of Automotive Engineers, 2009) specifications for anthromorphic testing. Three angular rate sensors (DTS ARS-12K, Diversified Technical Systems, Inc. Seal Beach, CA, USA) were also placed in the mounting plate (Figure 7). These devices are designed for high rate dummy impact and vehicle component testing for precise measurements of head rotation and other biodynamic measurements. They weigh less than 3 gr, have a SAE class 100 response and a range of ±12000 degrees/sec.

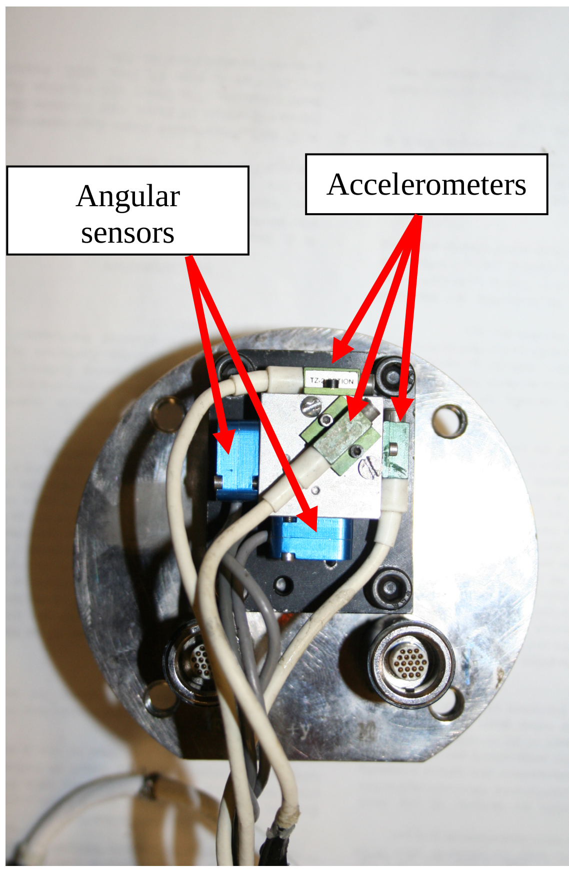


Figure 7. Accelerometers and angular sensors mount.

A TDAS PRO Sensor Input Module (SIM) (Diversified Technical Systems Inc. Seal Beach, CA, USA) data system was used to collect data from the accelerometers and angular sensors. This system has eight fully-programmable sensor input channels with isolated excitation that can integrate various modules (Figure 8) to increase its data collection capability. The system is controlled by its TDAS Control software which allows automatic sensor assignment, detailed channel diagnostics, and real-time data display (Figure 9). TDAS PRO functions were set-up using an IBM-compatible computer. Data were stored in each module and, after testing was complete, it was downloaded to the PC hard drive in binary format. Once on the hard drive, the binary data files were then unpacked for viewing and post-processing. It is certified to NHTSA, FAA, ISO 6487 and SAE J211 (Society of Automotive Engineers, 1995) data acquisition practices. Sampling was done at 10 KHz for each channel, and recorded for 30 seconds to allow participants to complete ten or more kick trials during this period of time. The data were filtered with a CFC1000 filter (-3dB point of 1650 Hz) as specified by SAE J211 standard for head accelerometers.

Figure 8. TDAS PRO modules.

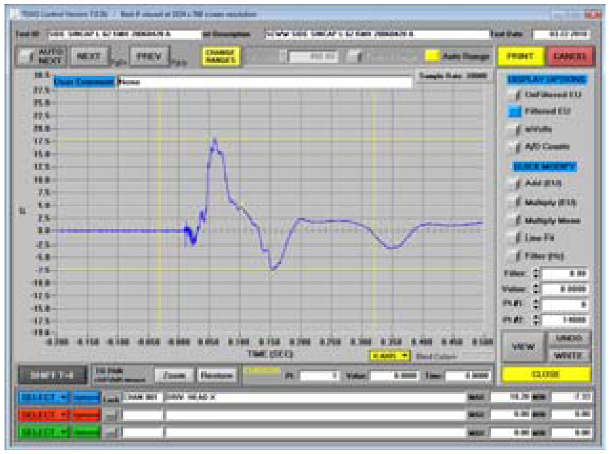


Figure 9. TDAS software screen snapshot.

Each participant was asked to consecutively kick the side of the dummy head with a roundhouse kick five times with one foot as hard as possible and then to repeat the process with the opposite foot within a 30 second period. Participants were asked to assume a right ready stance (staggered foot position with right foot farthest from the target) and, at an indication by a member of the research team, to kick the head assuming a ready stance before each kick. Once these trials were completed, the participant switched to the opposite stance and began kicking with the left foot until the completion of the five additional trials (Figure 10), again, assuming a ready stance before each kick. If there were collection time left after the ten trials, the participant was asked to continue kicking with his/her preferred foot until the collection time expired. Allowing continued kicking resulted in a total of 171 attempts available for analysis.

Figure 10. Participant roundhouse kick trial.

Anthropometric Measurements

A SECA portable digital scale (SECA model Alpha 770, Hamburg, Germany) was used to measure weight in kilograms to the closest 0.1 kilogram. Participants wore their martial arts uniform while being weighed and were barefoot. A SECA portable stadiometer (SECA model 214, Hamburg, Germany) was used to measure standing, sitting, and shoulder heights to the closest 0.1 centimeter. Participants were barefoot.

A GPM 101 anthropometer (Siber & Hegner, Zurich, Switzerland) was used to measure biacromial and bicristal widths to the closest 0.1 centimeter. Participants wore their martial arts uniform during measurements, and were barefoot. A Sit and Reach Flex Tester (Power-Systems, Inc. Knoxville, TN, USA) was used to measure flexibility of the shoulder joints and shoulder girdle, and lower back and hip regions to the closest 0.5 centimeter.

CHAPTER IV

Results and Statistical Analysis

Anthropometry

These data were collected to provide descriptive information on participants' anthropomorphic characteristics and explore their effect on linear and angular accelerations. There are differences by age and gender in height, weight, flexibility, biacromial and bicristal widths, thus, these measurements provided an understanding of the effects of maturation on linear and angular accelerations. Table 6 shows anthropometric data and flexibility scores. Participants' mean standing height was 146.7 centimeters (range from 123 to 170 centimeters) and mean weight was 48.15 kilograms (range from 27.0 to 86.6 kilograms). Mean Body Mass Index (BMI) was 22.0 kg/ m^2 (range from 16.8 to 36.4 kg/ m^2). Sit and reach flexibility ranged from -7.5 to 14 centimeters, with a mean of -0.1cm.

When examined by gender, mean standing heights were 139.2 cm for females and 148.21 cm for males (Figure 11). Mean weight was 38.55 kg for females and 50.07 kg for males (Figure 12). Mean flexibility for the sit and reach test was 6.5 cm for females and -1.2 cm for males (Figure 13). Mean BMI was 19.2 kg/ m^2 for females and 22.6 kg/ m^2 for males (Figure 14).

Table 6

Sample Anthropometric Data and Flexibility Scores

	Mean	SD	Min	Max
Age (yrs.)	10.7	1.7	7	14
Height (cm)	146.7	11.8	123	170
Weight (kg)	48.1	14.5	27	86.65
Sit and Reach (cm)	-.1	6.1	-7.5	14
Body Mass Index (kg/ m^2)	22.0	4.9	16.78	36.44

Figure 11. Participants' height by age and gender.

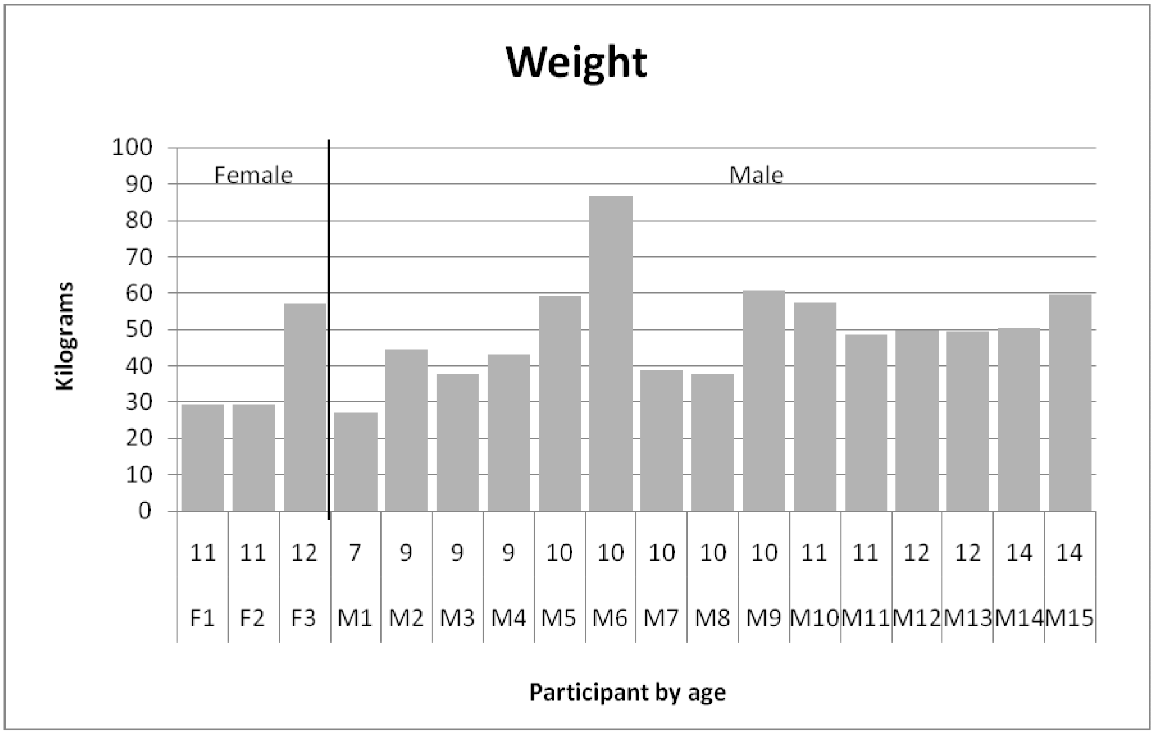


Figure 12. Participants' weight by age and gender.

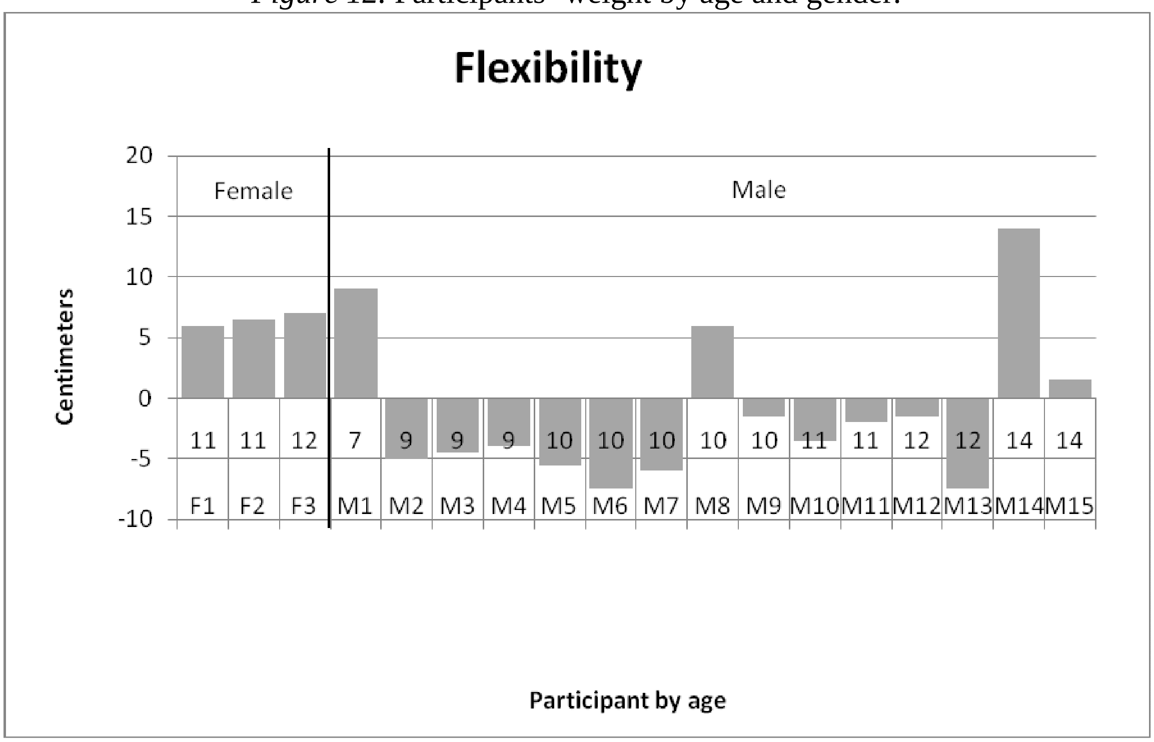


Figure 13. Participants' sit and reach flexibility by age and gender.

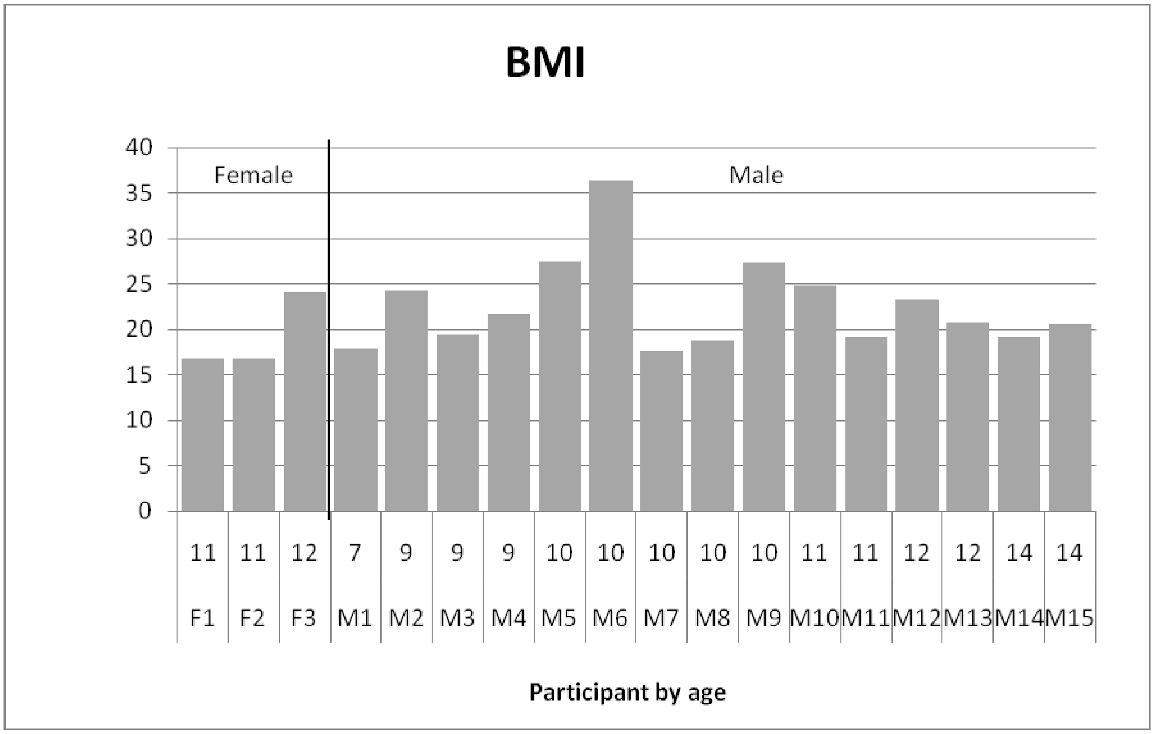


Figure 14. Participants' body mass index by age and gender.

The overall mean of the sitting height to standing height ratio was 0.51 with a range from 0.48 to 0.53 (Figure 15). Biacromial to bicristal ratio ranged from 0.8 to 1.4 with an overall mean of 1.2 (Figure 16). Grouped by gender, mean sitting height to Standing height ratio was 0.51 for both groups. Mean Biacromial to Bicristal ratio was 1.27 for females and 1.23 for males. When participants were grouped by skill level, Sitting height to Standing height ratio mean for each groups was 0.5 (Figure 17). The Mean Biacromial to Bicristal ratio for beginners was 1.26 and 1.13 for advanced participants (Figure 18). Mean BMI for beginners was 21.8 and 22.8 for advanced participants (Figure 19).

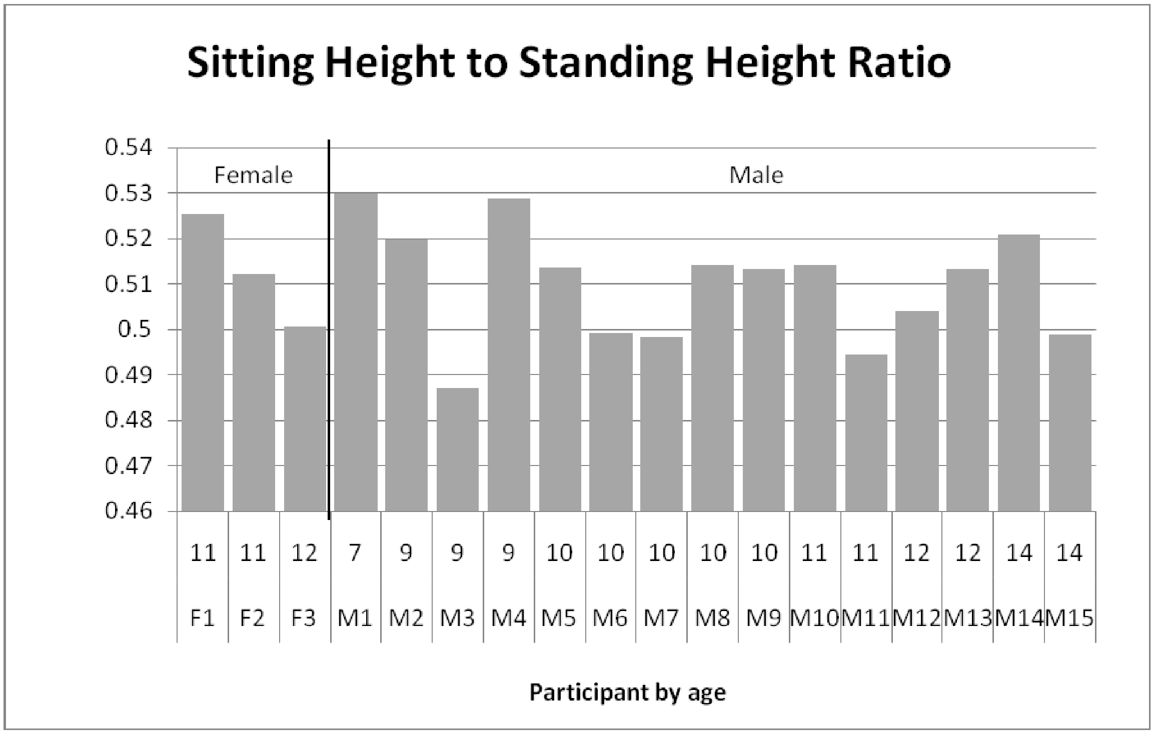


Figure 15. Participants' sitting height to standing height ratio by age and gender.

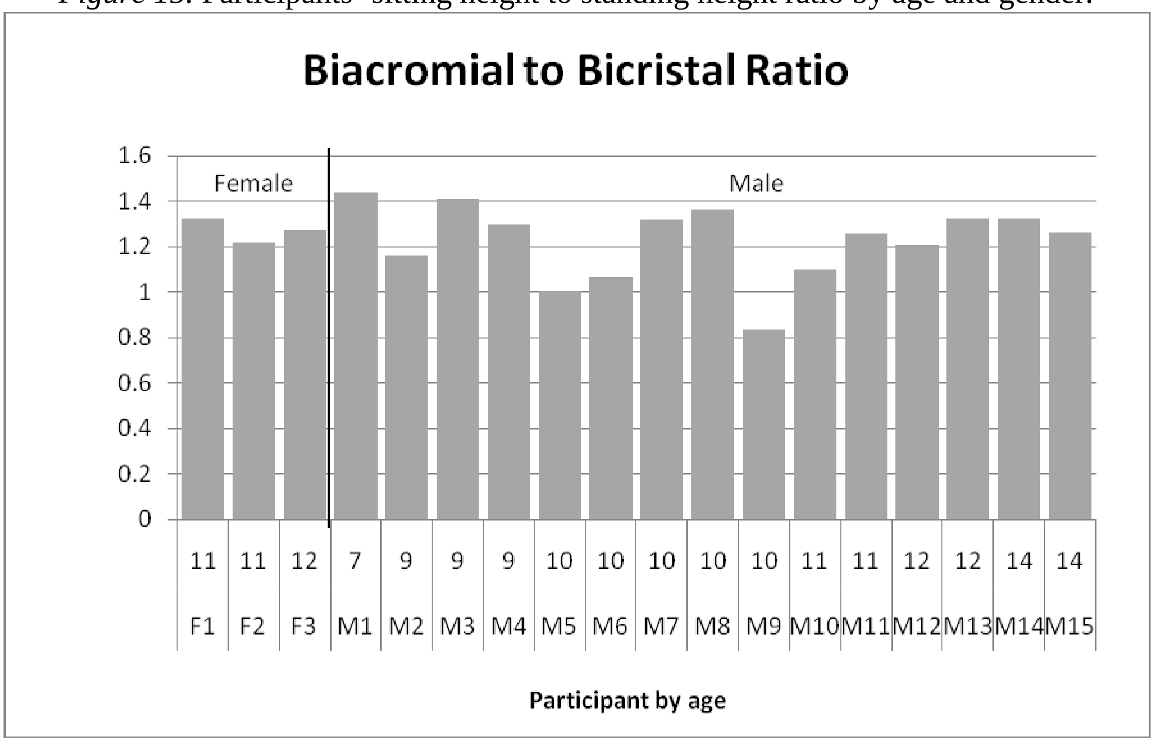


Figure 16. Participants' biacromial to bicristal ratio by age and gender.

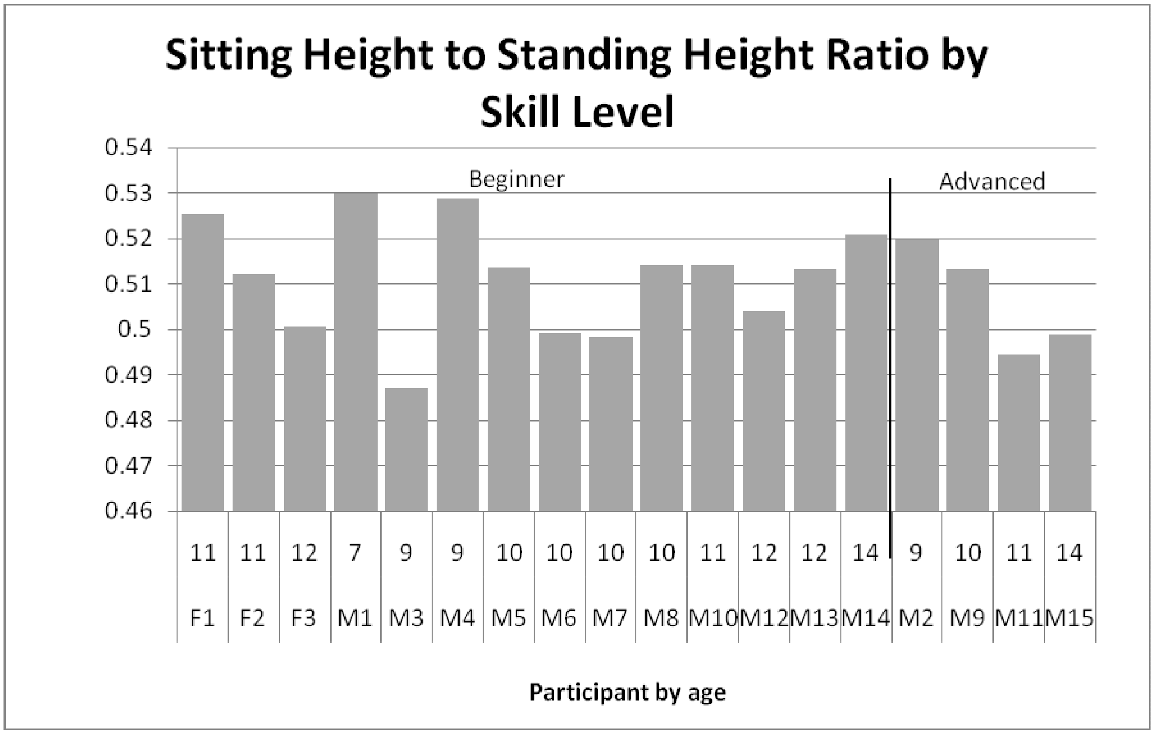


Figure 17. Participants' sitting height to standing height ratio by skill level.

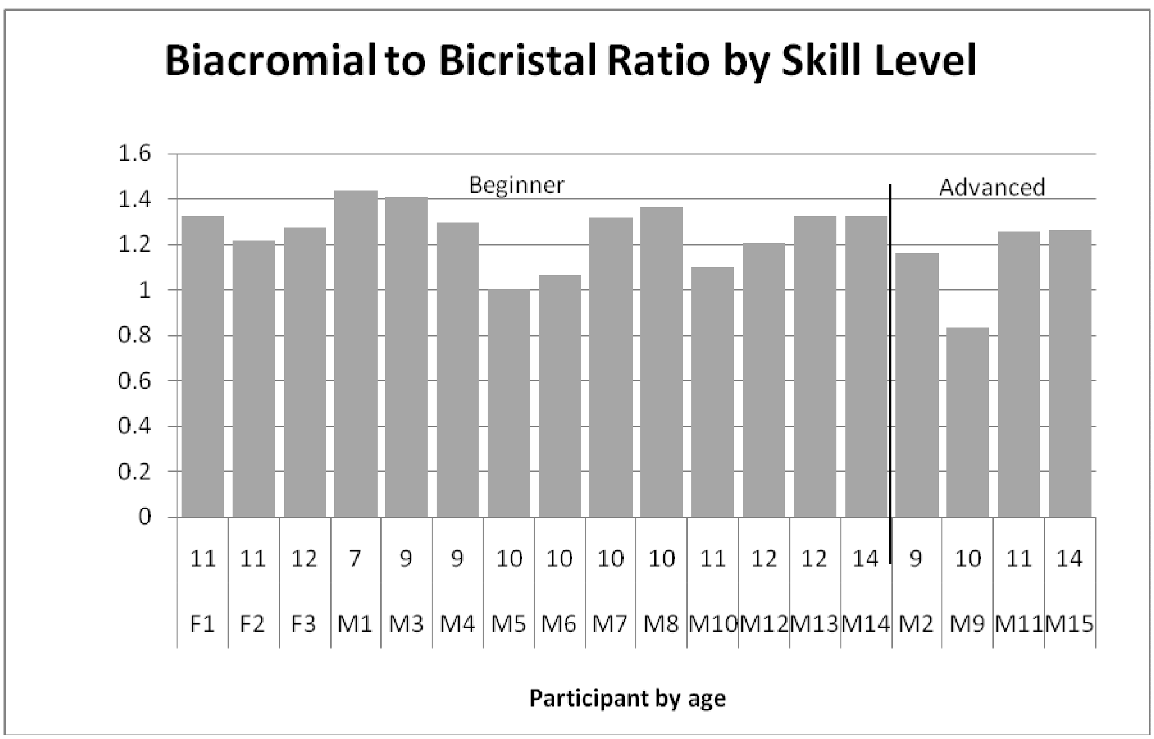


Figure 18. Participants' biacromial to bicristal ratio by skill level.

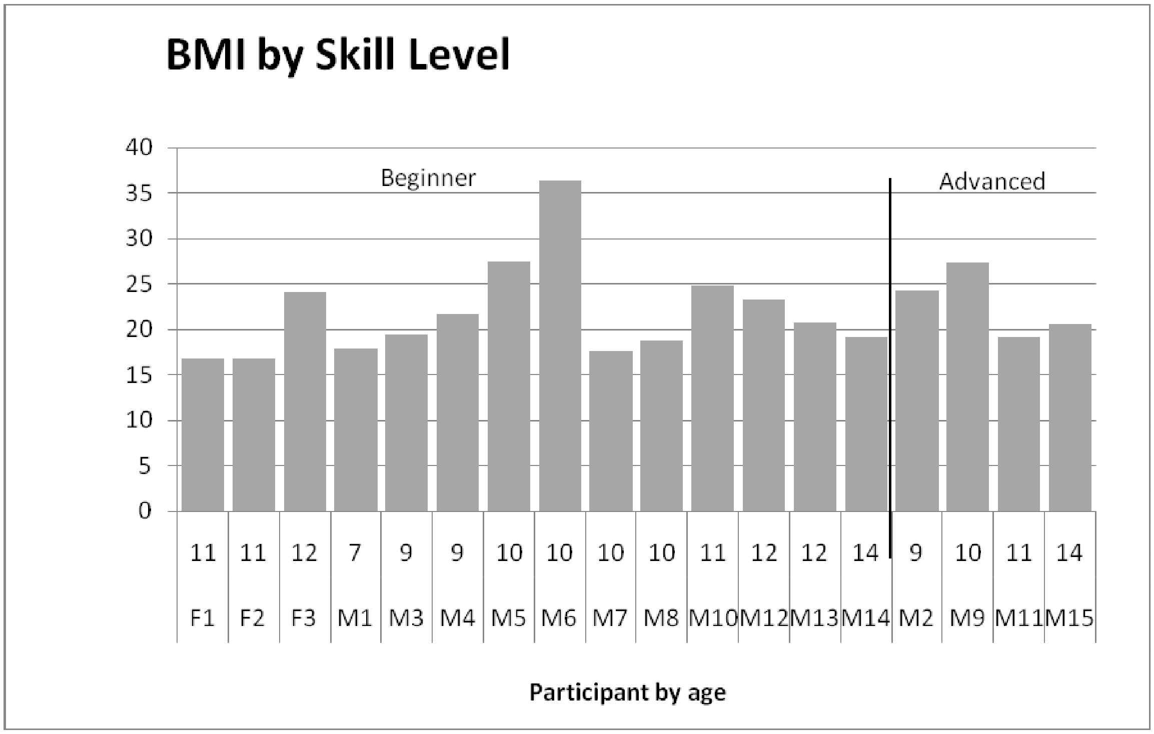


Figure 19. Participants' Body Mass Index by skill level.

Performance Data

Table 7 shows the number of successful data collection trials (number of roundhouse kicks to the head recorded) from each participant and the corresponding averages per participant for Mean Linear Acceleration (MeanMaxLinAcc), Mean Angular Acceleration (MeanMaxAngAcc), Mean Gadd Severity Index (SI), which according to Pellman, Viano, Tucker, Casson, and Waeckerle (2003) is calculated by integrating the resultant translational acceleration at the head center of gravity over the duration of the acceleration pulse and cannot exceed 1200 to be acceptable, thus indicating a football helmet's ability to absorb forces, and protect its user, and the Mean Head Injury Criteria (HIC) (considered as a SI variation used by the National Highway Traffic Safety Administration, and reported by Pellman et al. (2003). Figure 20 compares linear acceleration values from all trials by participants to low and high thresholds known to cause concussions. Figure 21 shows minimum, maximum and means of linear accelerations generated by each participant. Figure 22 compares angular acceleration values from all trials by participants to thresholds known to cause concussions. Figure 23 shows minimum, maximum and means of angular accelerations generated by each participant.

Table 7

Mean Values for Linear and Angular Accelerations, HIC, and SI by Participant

Age	Gender	Skill level	Participant ID	# Kicks	MeanMaxLinAcc (g)	MeanMaxAngAcc (rad/sec^2)	Mean SI	Mean HIC
11	female	beginner	F1	10	2.73	357.8	0.24	0.13
11	female	beginner	F2	10	5.29	554.4	1.78	0.61
12	female	beginner	F3	10	83.76	3181.7	127.85	102.42
7	male	beginner	M1	9	8.88	1585.7	2.12	1.17
9	male	advanced	M2	11	11.83	2089.4	4.83	2.67
9	male	beginner	M3	11	15.26	1247.6	9.16	6.12
9	male	beginner	M4	11	10.44	895.8	2.86	2.14
10	male	beginner	M5	12	7.15	1454.8	2.11	0.76
10	male	beginner	M6	7	16.59	1210.3	8.43	6.22
10	male	beginner	M7	4	22.26	2161.8	16.62	12.06
10	male	beginner	M8	8	35.08	3426.3	28.34	21.72
10	male	advanced	M9	10	26.71	1262.2	21.22	14.36
11	male	beginner	M10	5	19.23	1143.1	16.26	12.95
11	male	advanced	M11	12	25.03	4230.7	17.98	8.43
12	male	beginner	M12	10	9.42	907.9	3.77	2.78
12	male	beginner	M13	14	14.61	1025.2	6.88	4.31
14	male	beginner	M14	10	15.5	3203.9	13.26	5.84
14	male	advanced	M15	7	41.45	4154	57.36	47.1

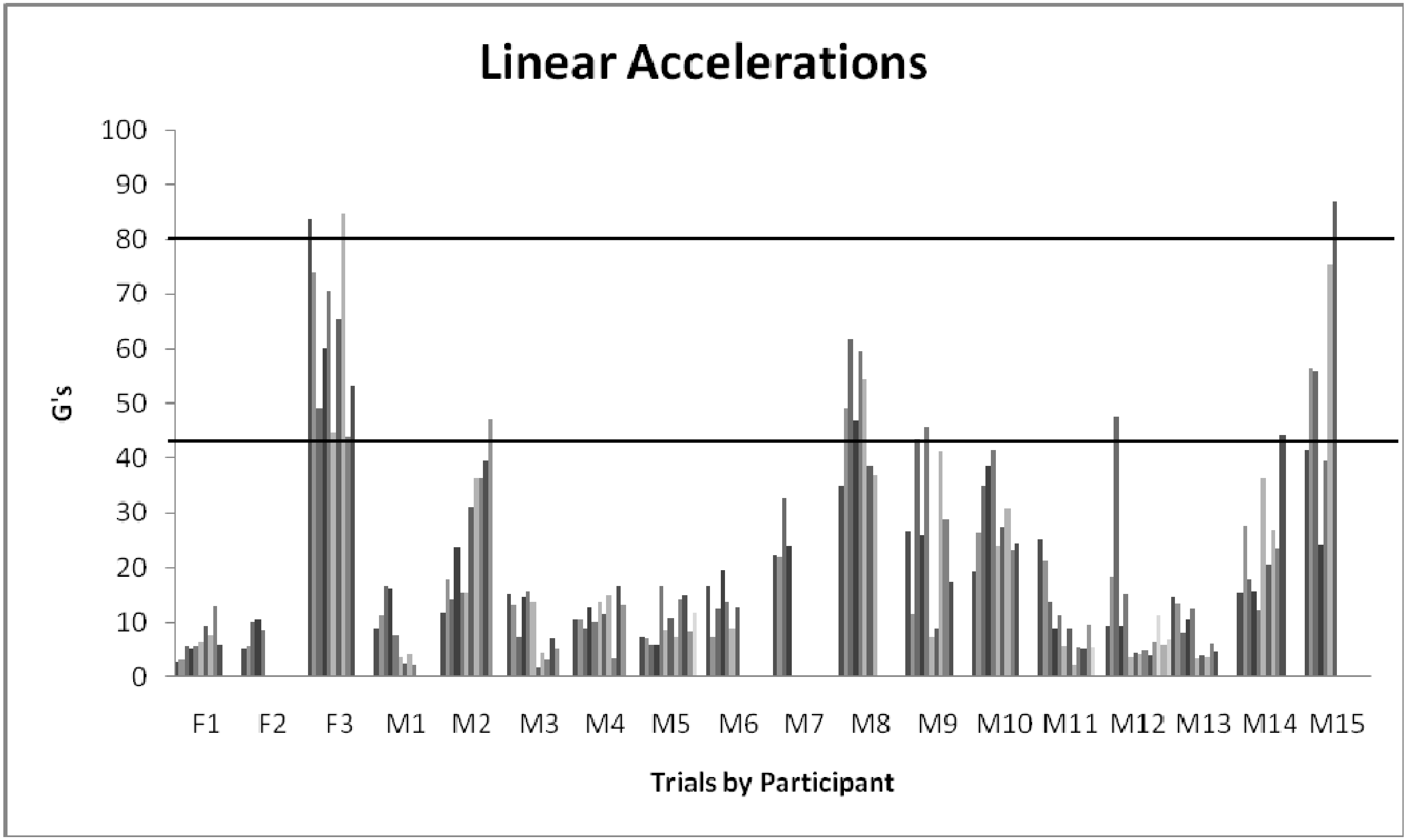
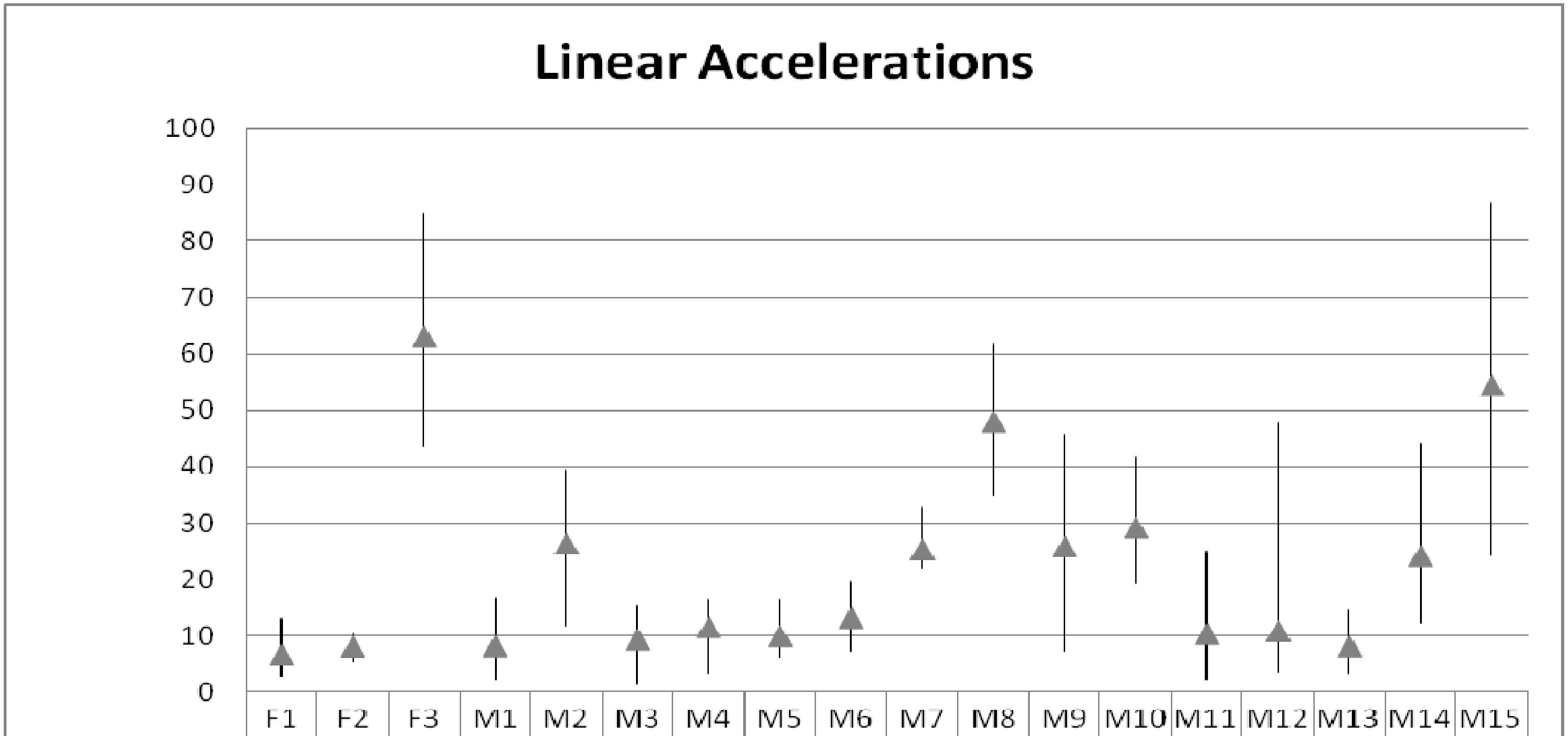


Figure 20. Linear acceleration values per trial by participant, low and high thresholds from Pellman et al. (2003).



	F1	F2	F3	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15
Minimum	2.73	5.29	43.8	2.35	11.8	1.66	3.29	5.95	7.3	22	35.1	7.4	19.2	2.38	3.64	3.4	12.3	24.3
Maximum	13.1	10.4	84.8	16.7	39.4	15.6	16.6	16.6	19.6	32.7	61.7	45.7	41.7	25	47.6	14.6	44.1	86.7
▲ Mean	6.52	8.03	63	8.13	26.2	9.22	11.4	9.87	13.1	25.3	47.8	25.7	29.1	10.2	10.8	8.09	24.1	54.3

Figure 21. Mean, minimum and maximum linear acceleration values by participant.

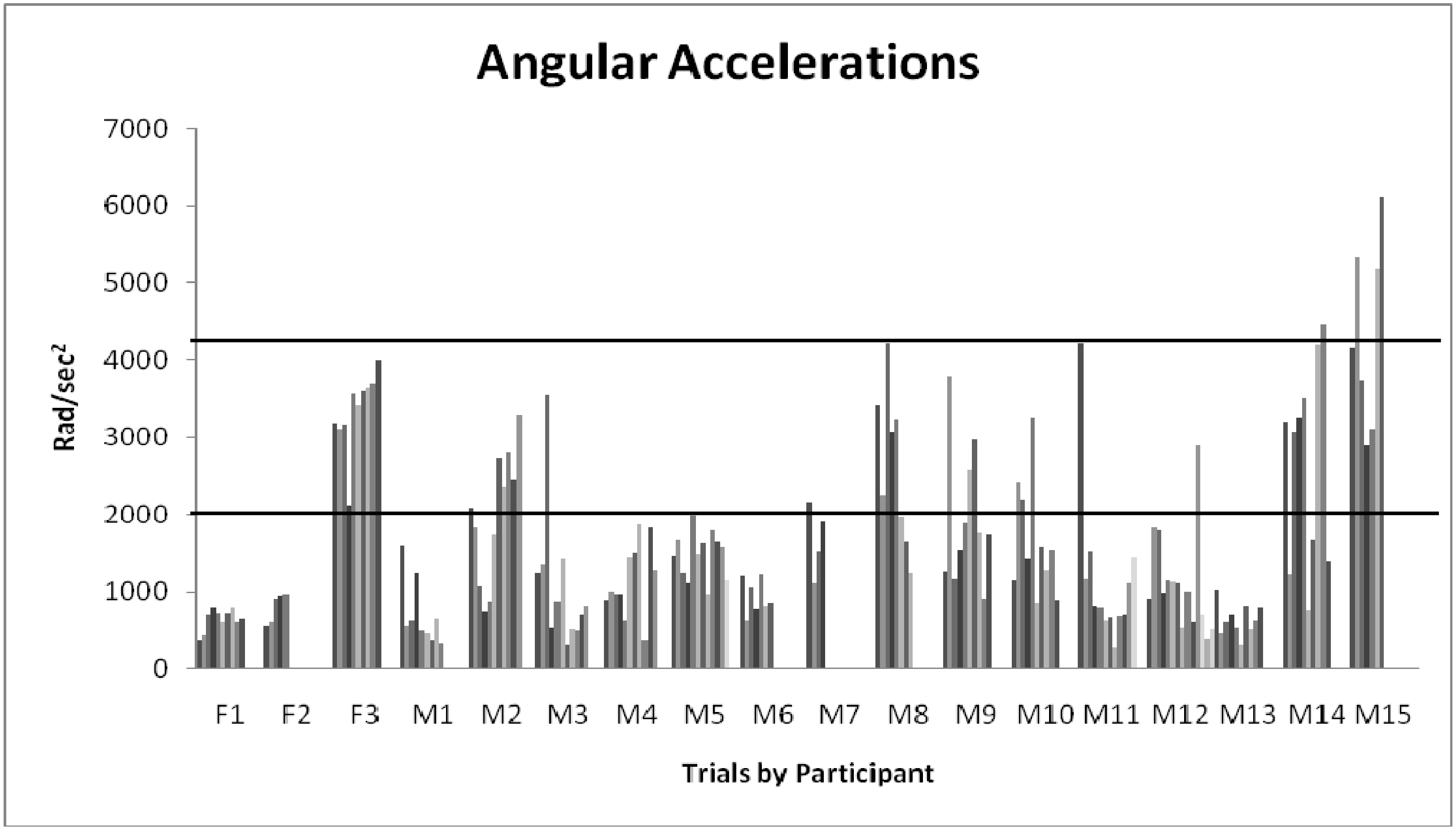
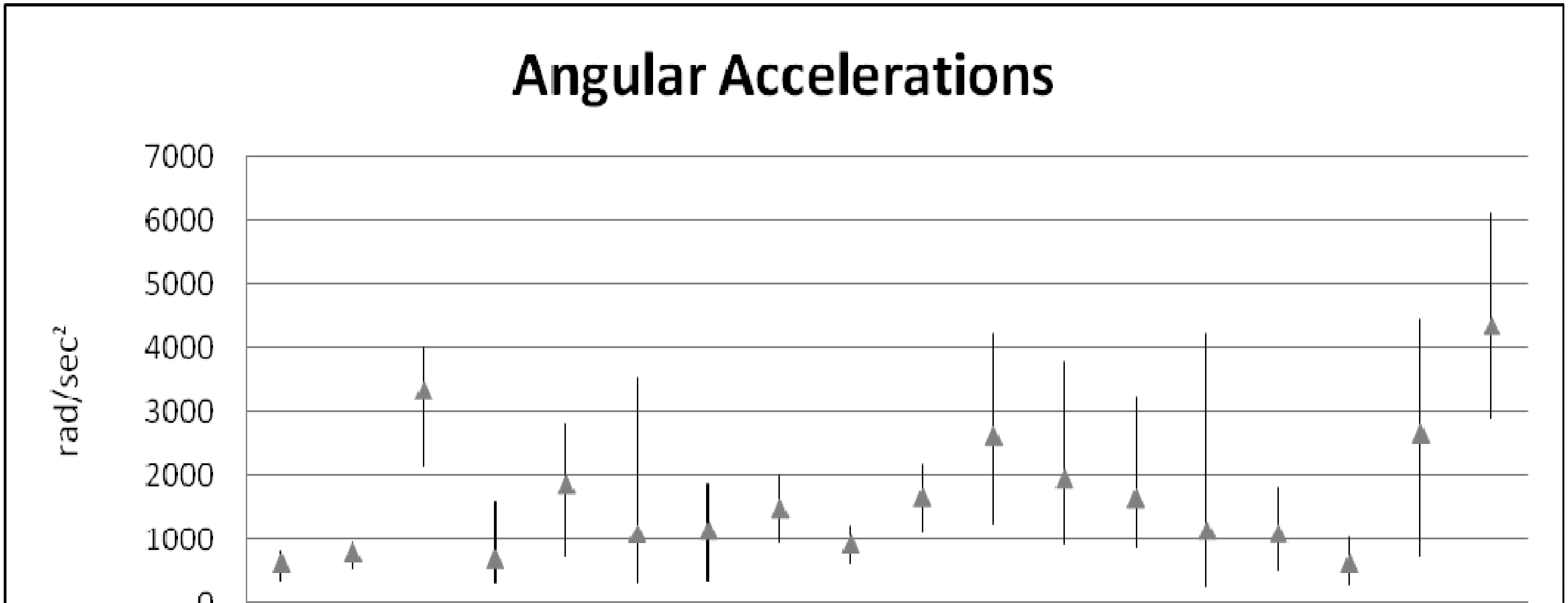


Figure 22. Angular acceleration values per trial by participant. Low threshold from King et al., (2003), high threshold from Zhang, Dwarampudi, Yang, and King (2003).



	F1	F2	F3	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15
Minimum	358	554	2126	327	732	316	364	962	615	1117	1251	915	864	275	521	311	739	2893
Maximum	804	961	3992	1586	2805	3556	1869	1992	1215	2162	4229	3787	3251	4231	1823	1025	4472	6109
▲ Mean	634	799	3351	696	1870	1097	1144	1496	936	1674	2637	1959	1655	1145	1102	635	2672	4362

Figure 23. Mean, minimum and maximum angular acceleration values by participant. Low threshold from King et al., (2003), high threshold from Zhang, Dwarampudi, Yang, and King (2003).

Female F1 was 11 years old and had practiced for 3 months, F2 was 11 years old and had practiced for 2 months; F3 was 12 years old and had practiced for 24 months. Table 8 provides overall and by gender descriptive data of linear and angular accelerations, HIC, SI and number of kicks. Descriptive data of linear and angular accelerations, HIC and SIC by skill level are found in Table 9. Pellman, Viano, Tucker, Casson, and Waeckerle (2003) reported nominal tolerance levels for concussion of 300 for SI and 250 for HIC, observed in helmet impacts. These authors also reported linear accelerations between 42 to 80 g's as the limits of tolerance in humans.

Table 8

Descriptive Statistics for Linear and Angular Acceleration, HIC and SI Overall and by Gender

Gender		LinAcc (g's)	AngAcc (rad/s^2)	HIC	SI
Female *(n=25 roundhouse kicks)*	Mean	29.39 (SD 29.56)	1753.82 (SD 1374.23)	30.47 (SD 41.06)	39.87 (SD 53.34)
	Minimum - Maximum	2.73-84.81	357.80-3991.90	0.13-141.17	0.24-183.13
Male *(n=146 roundhouse kicks)*	Mean	19.21 (SD 15.86)	1603.09 (SD 1145.38)	12.94 (SD 23.02)	17.26 (SD 28.49)
	Minimum - Maximum	1.66-86.72	274.50-6109.20	0.03-177.00	0.06-219.88
Overall *(n=171 roundhouse kicks)*	Mean	20.70 (SD 18.73)	1625.12 (SD 1178.31)	15.50 (SD 26.99)	20.56 (SD 34.02)
	Minimum - Maximum	1.66-86.72	274.50-6109.20	.03-177.00	.06-219.88

Table 9

Descriptive Statistics for Linear and Angular Acceleration, HIC and SI by Skill Level

Skill Level		MaxLinAcc (g's)	MaxAngAcc (rad/s^2)	HIC	SI
Beginner *(n=131 roundhouse kicks)*	Mean	19.02 (SD 18.16)	1463.94 (SD 1038.55)	12.96 (SD 22.77)	17.51 (SD 29.25)
	Minimum - Maximum	1.66-84.81	311.10-4472.20	141.17	183.13
Advanced *(n=40 roundhouse kicks)*	Mean	26.21 (SD 19.77)	2153.02 (SD 1443.52)	23.81 (SD 36.80)	30.58 (SD 45.40)
	Minimum-Maximum	2.38-86.72	274.50-6109.20	0.09-177.00	0.35-219.88

Tests of Null Hypotheses

Correlational analyses were performed for age, months of practice, standing height, weight, flexibility, BMI, Linear Acceleration (LinAcc), Angular Acceleration (AngAcc), Severity Index (SI), and Head Injury Criteria (HIC). Results of the correlational analyses for 171 kick trials were presented in Tables 10 and 11.

Table 10
Sample Pearson Correlation Coefficients (2-Tailed) Among Performance Parameters and Injury Factors (n=171 roundhouse kicks)

	Linear Acceleration of Hybrid III Dummy Head (LinAcc)	Angular Acceleration of Hybrid III Dummy Head (AngAcc)	Severity Index (SI)	Head Injury Criteria (HIC)
LinAcc		.714**	.932**	.930**
AngAcc			.705**	.697**
SI				.998**
HIC				

*** Indicates significance at the 0.01 level.*

Table 11
Sample Pearson Correlation Coefficients (2-Tailed) for Mean Values, Among Age, Experience, Anthropometry, Performance Parameters, and Injury Factors (n=171 roundhouse kicks)

	Age	Months of Practice	Standing Height	Weight	Sit and Reach Flexibility	BMI
LinAcc	.307** (r^2 = .09)	.293** (r^2 = .08)	.349** (r^2 = .12)	.232** (r^2 = .05)	.282** (r^2 = .07)	.078 (r^2 = .01)
AngAcc	.389** (r^2 = .15)	.376** (r^2 = .14)	.434** (r^2 = .18)	.249** (r^2 = .06)	.281** (r^2 = .07)	.052 (r^2 = .00)
SI	.360** (r^2 = .12)	.314** (r^2 = .09)	.376** (r^2 = .14)	.225** (r^2 = .05)	.264** (r^2 = .06)	.041 (r^2 = .00)
HIC	.354** (r^2 = .12)	.319** (r^2 = .10)	.369** (r^2 = .13)	.219** (r^2 = .04)	.258** (r^2 = .06)	.038 (r^2 = .00)

*** Indicates significance at the 0.01 level.*

The high correlation values observed between Linear Acceleration (LinAcc) and Head Injury Criteria (HIC), and Linear Acceleration (LinAcc) and Severity Index (SI) can be explained by the dependence of HIC and SI calculations on Linear Acceleration. A high correlation (r=.714) was also observed between Linear Acceleration (LinAcc) and Angular Acceleration (AngAcc) (Table 10).

Low but significant, correlations for Linear Acceleration (LinAcc) and age (r=0.307), months of practice (r=0.293), standing height (r=0.349), weight (r=0.232), and sit and reach flexibility (r=0.282) (Table 11) were found.

Low, but significant, correlations were observed between Angular Acceleration (LinAcc) and age (r=0.389), months of practice (r=0.376), weight (r=0.249), and sit and reach flexibility (r=0.281). A moderate and significant correlation was observed between Angular Acceleration (LinAcc) and standing height (r=0.434).

Also, low, but significant, correlations were found between Severity Index (SI) and age (r=0.36), months of practice (r=0.314), standing height (r=0.376), weight (r=0.225), and sit and reach flexibility (r=0.264).

Low, but significant, correlations for Head Injury Criteria (HIC) and age (r=0.354), months of practice (r=0.319), standing height (r=0.369), weight (r=0.219), and sit and reach flexibility (r=0.258) were observed. No significant correlations were observed for BMI and Linear Acceleration, Angular Acceleration, Head Injury Criteria and Severity Index.

Correlational analyses were performed for age, height, weight, flexibility, BMI and months of practice. Results of the correlational analyses for 171 kick trials were presented in Table 12.

Table 12
Sample Pearson Correlation Coefficients (2-Tailed) Among Age, Experience, and Anthropometry (n=171 kicks)

	Height	Weight	Flexibility	BMI	Months of Practice
Age	.769**	.333**	.285**	-.069	.264**
Height		.680**	-.076	.250**	.610**
Weight			-.380**	.876**	.515**
Flexibility				-.494**	-.096
BMI					.277**

** *Indicates significance at the 0.01 level*

Low correlations significant at the 0.01 were observed for age and weight (.333), flexibility (.285) and months of practice (.264). Moderate correlations were observed for age and height (.769). Low correlations were observed for height and BMI (.250). Moderate correlations were observed for height and weight (.680) and months of practice (.610). Low correlations were observed for weight and flexibility (-.380). Moderate correlations were observed for weight and months of practice (.515). A high correlation was observed between weight and BMI (.876). A moderate correlation was observed between flexibility and BMI (-.494). A low correlation was also observed for BMI and months of practice (.277) (Table 12).

Correlational analyses were performed for age, months of practice, standing height, weight, flexibility, BMI, considering only maximal values of linear acceleration (MaxLinAcc), angular acceleration (MaxAngAcc), SI and HIC. Results of the correlational analyses for 18 participants were presented in Table 13.

Table 13

Pearson Correlation Coefficients (2-Tailed) for Maximum Values per Participant, Among Age, Experience, Anthropometry, Performance Parameters, and Injury Factors (n=18 participants)

	Age	Months of Practice	Standing Height	Weight	Sit and Reach Flexibility	BMI
MaxLinAcc	.496* (r^2 = .25)	.454 (r^2 = .21)	.517* (r^2 = .27)	.293 (r^2 = .09)	.270 (r^2 = .07)	.077 (r^2 = .00)
MaxAngAcc	.445 (r^2 = .20)	.633** (r^2 = .40)	.601** (r^2 = .36)	.230 (r^2 = .05)	.227 (r^2 = .05)	-.045 (r^2 = .00)
SI	.554* (r^2 = .31)	.499* (r^2 = .25)	.556* (r^2 = .31)	.284 (r^2 = .08)	.269 (r^2 = .07)	.021 (r^2 = .00)
HIC	.527* (r^2 = .28)	.436 (r^2 = .19)	.517* (r^2 = .27)	.279 (r^2 = .08)	.303 (r^2 = .09)	.045 (r^2 = .00)

** Indicates significance at the 0.05 level.*
*** Indicates significance at the 0.01 level.*

Moderate correlations were observed at the 0.05 level for maximal linear accelerations, age (r=.496) and standing height (r=.517). Also moderate correlations were observed at the 0.05 level with SI, age (.554), months of practice (.499) and standing height (.556). Similarly, moderate correlations were observed for HIC and age (.527), and standing height (.517) (Table 13). Moderate correlations were observed at the 0.01 level for maximal angular accelerations, months of practice (r=.663) and standing height (r=.601) (Table 13).

Results indicated that, only two participants were able to generate dummy head accelerations greater than 80 g's in three trials (see Chapter V). Using a more conservative criteria there were a total of 24 trials by six different participants that exceeded 42 g's (see Chapter V). Overall, the results indicated that participants did not consistently generate linear accelerations close to concussion values failing to reject the null hypothesis of no difference between maximum impact linear accelerations of the dummy head generated via roundhouse kicks and acceleration values known to cause concussions in humans.

Testing the hypothesis of no difference between maximum impact angular accelerations of the dummy head generated via roundhouse kicks and acceleration values known to cause concussions in humans, there were 44 trials exceeding 2000 rad/s^2 and only two participants exceeding the 4420 rad/s^2 threshold (see Chapter V). The results indicated that the 2000 rad/s^2 threshold was exceeded in 25 percent of the cases, thus presenting a relatively high risk for concussions. This hypothesis was rejected.

To test the null hypothesis of no difference in Linear Acceleration values based on gender, an Independent-Samples T-Test analysis was performed on LinAcc. The results ($t(169) = 2.55$, $p<.05$) supported the rejection of the null hypothesis and recognize that there is a difference in Linear Acceleration values associated with gender. Specifically, female participants showed greater Linear Acceleration than males (Table 14). However, it is important to note that results should not be generalized, due to the small number of female participants. Additionally, standard deviations were large, compared to the mean; thus, the spread of the data is significant and indicated a high level of variability within the sample.

Table 14
Statistics for Maximum Linear Acceleration by Gender

	Female	Male
Mean	29.39	19.21
Std. Deviation	29.56	15.86
# of Kicks	25	146

To test the null hypothesis of no difference in Angular Acceleration values based on gender, an Independent-Samples T-Test was performed. No difference in Angular Acceleration values was found (t (169) = 0.59, p>.05). Thus, the null hypothesis was supported (Table 15).

Table 15
Means and Standard Deviations for Maximum Angular Acceleration by Gender

	Female	Male
Mean	1753.82	1603.09
Std. Deviation	1374.23	1145.37
# of Kicks	25	146

A one-way ANOVA was conducted to determine age differences in Maximum Linear Acceleration among the three age groups. Age differences were found, F (2, 168) = 9.6, p<.01. A Tukey Post Hoc test revealed the following differences. The "9 and under" group showed less acceleration than the "14 and older" group. The "10 to 13" group exhibited less acceleration than the "14 and older" group. The "9 and under" group did not differ from the "10 to 13" group (Table 16). The results supported the rejection of the null hypothesis, indicating that there was a difference in linear acceleration among age groups with the 14 and older group generating the highest linear accelerations.

Table 16
Linear Acceleration (LinAcc) and Age Group Descriptive Statistics

Age Group (yrs.)	N	Minimum	Maximum	Mean	Std. Deviation	Variance
9 and under	42	1.66	47.09	14.01	10.40	108.24
10 to 13	112	2.38	84.81	20.81	19.37	375.27
14 and older	17	12.30	86.72	36.49	21.60	466.65

A One-way ANOVA was conducted to analyze differences in Angular Acceleration among the three age groups. Significant differences were found, $F(2, 168) = 28.067$, $p < .01$. A Tukey Post Hoc test revealed the following differences. The “9 and under” group showed less angular acceleration than the “14 and older” group. The “10 to 13” group exhibited less angular acceleration than the “14 and older” group. The “9 and under” group did not differ from the “10 to 13” group (Table 17). The results supported the rejection of the null hypothesis, indicating that there was a difference in linear acceleration among age groups with the 14 and older group generating the highest angular accelerations.

Table 17
Angular Acceleration (AngAcc) and Age Group Descriptive Statistics

Age Group (yrs.)	N	Range	Min	Max	Mean	Std. Dev.	Variance
9 and under	42	3240.20	316.20	3556.40	1256.67	831.29	691057.65
10 to 13	112	3956.20	274.50	4230.70	1498.79	1006.52	1013097.51
14 and older	17	5370.60	738.60	6109.20	3367.74	1502.75	2258279.47

To test the null hypothesis of no differences in linear acceleration values based on skill level, an Independent-Samples T-Test was performed. Significant differences were found ($t(169) = -2.147$, $p<.05$) with advanced performers having greater linear acceleration than beginners. Thus, the null hypothesis was rejected (Table 18).

Table 18
Means and Standard Deviations for Linear Acceleration by Skill Level

	Skill Level	# of Kicks	Mean	Std. Deviation	Std. Error Mean
LinAcc	Beginner	131	19.02	18.15	1.58
	Advanced	40	26.21	19.77	3.12

To test the null hypothesis of no differences in Angular Acceleration values based on skill level, an Independent-Samples T-Test was performed. Advanced participants had greater angular acceleration than beginner participants ($t\ (169) = -3.332$, $p < .01$). Thus, the null hypothesis was rejected (Table 19).

Table 19
Means and Standard Deviations for Maximum Angular Acceleration by Skill Level

	Skill Level	# of Kicks	Mean	Std. Deviation	Std. Error Mean
AngAcc	Beginner	131	1463.93	1038.55	90.73
	Advanced	40	2153.02	1443.51	228.24

Multiple regressions analyses for linear and angular accelerations were conducted, and multicollinearity of variables was also evaluated. The analysis for linear acceleration included age, height, weight, flexibility, and months of practice as predictors. The results $F\ (6, 170) = 10.055$, $p < .05$, and $R = .519$ indicated the model was significant. The significant predictors were flexibility ($\beta=.502$, $p<.05$), height ($\beta=.403$, $p<.05$) and weight ($\beta=.285$, $p<.05$). These predictors accounted for 26.9% of the variability. Low partial correlations were observed for all the predictors. Using the criterion of tolerance values less than .3 and variance inflation factor (VIF) greater than 3, age, height, months of practice and skill level indicate multicollinearity among these predictors (Table 20). A more conventional criteria of VIF >10 indicated no multicollinearity among predictors.

Table 20

Linear Acceleration Regression Coefficients and Collinearity

Model		Unstandardized Coefficients (B)	Std. Error	Standardized Coefficients (Beta)	Partial Correlation	Tolerance	VIF
1	(Constant)	-76.330	30.654				
	Age	-2.027	1.592	-.183	-.099	.217	4.613
	Height	68.157	31.807	.403	.165	.126	7.935
	Weight	.414	.170	.285	.187	.326	3.066
	Flexibility	1.532	.292	.502	.380	.488	2.049
	Months of practice	-.167	.135	-.245	-.096	.113	8.832
	Skill Level	13.168	6.842	.298	.149	.185	5.391

The analysis for angular acceleration included age, height, weight, flexibility, and months of practice as predictors. The results F (6, 170) = 14.203, p < .05, and R = .585 indicated the model was significant. The significant predictors were flexibility (β=.470, p<.05), height (β=.451, p<.05) and skill level (β=.363, p<.05). These predictors accounted for 34.2% of the variability. Low partial correlations were observed for all the predictors. Using the criterion of tolerance values less than .3 and variance inflation factor (VIF) >3, age, height, months of practice and skill level indicate multicollinearity among these predictors (Table 21). A more conventional criteria of VIF >10 indicates no multicollinearity among predictors.

Table 21

Angular Acceleration Regression Coefficients and Collinearity

Model		Unstandardized Coefficients (B)	Std. Error	Standardized Coefficients (Beta)	Partial Correlation	Tolerance	VIF
1	(Constant)	-5514.217	1828.989				
	Age	-76.510	94.976	-.110	-.063	.217	4.613
	Height	4798.556	1897.787	.451	.194	.126	7.935
	Weight	19.495	10.137	.213	.149	.326	3.066
	Flexibility	90.172	17.394	.470	.375	.488	2.049
	Months of practice	-9.827	8.074	-.229	-.095	.113	8.832
	Skill Level	1006.464	408.209	.363	.189	.185	5.391

In summary, several participants (F3, M2, M7, M8, M9, M12, M14 and M15) were able to generate linear accelerations of the center of gravity of the Hybrid III dummy head above the threshold of 42 g's known to cause concussions in adults. Similarly, there were several participants (F3, M2, M3, M7, M8, M9, M10, M11, M12, M14 and M15) able to exceed the 2000 rad/s^2 threshold for angular accelerations about the center of gravity of the Hybrid III dummy head known to cause concussions. Furthermore, two participants (M14 and M15) exceeded the more stringent threshold of 4420 rad/s^2. None of the participants' trials in the current study exceeded either the SI=300 or the HIC=250 thresholds.

High correlation values were observed between linear and angular accelerations. Low, but significant, correlations were observed for linear acceleration and age, months of practice, standing height, weight and flexibility. Similarly, low, but significant, correlations were observed for angular acceleration and age, months of practice, weight and flexibility. A moderate and significant correlation was observed between angular acceleration and standing height.

Results showed that there is a difference in linear acceleration values associated with gender. Specifically, female participants generated greater linear accelerations than males. No differences in angular accelerations were observed for gender.

Differences in linear accelerations among age groups were observed, and results indicated the 14 and older group as the one that generated the highest linear accelerations. Differences were also observed for skill level, and advanced performers were identified as the group that generated the highest linear accelerations.

Results showed a difference in angular accelerations among age groups, identifying the 14 and older group as the one that generated the highest angular accelerations. Differences by skill level indicated that advanced performers also generated the highest angular accelerations.

Analysis of multicollinearity of predictors of linear acceleration (age, height, weight, flexibility, and months of practice) indicated moderate values among these predictors. Similarly, analysis of predictors of angular acceleration (age, height, weight, flexibility, and months of practice) also indicated moderate values.

CHAPTER V

Discussion and Conclusions

Linear Acceleration

A linear acceleration of 80 to 90 g's acting for more than four milliseconds can lead to concussions (Guskievicz and Mihalik, 2006). Based only on the linear acceleration criterion, results of the current study indicated that only two participants using a roundhouse kick were able to achieve an acceleration greater than 80 g's to the head of the dummy. One of these participants was 12 year old female beginner (F3) who achieved values of 83.76 and 84.81 g's. The other participant was an advanced 14 year old male (M15) who reached a value of 86.72 (Table 19). Pellman, Viano, Tucker, Casson, and Waeckerle (2003) reported more stringent values (42-80 g's) as the limits of tolerable translational acceleration of the head in humans. These authors also reported that values greater than 60 g's have been considered critical to cause concussions. Under this range (42-80 g's) there were ten trials by one female (F3) and 14 total trials by a combination of six beginning (M2, M7, M8, M9, M12, M14) and one advanced (M15) male participants that exceeded 42 g's (Table 22).

Overall, the results indicated that participants did not consistently generate linear accelerations close to concussion values, but nevertheless are capable of doing so. Low g values may be explained by the inability of participants to consistently hit the target (as it was observed during data collection), either by the lack of familiarity with the testing setup or by a limited kicking ability. Analyses indicated that female participants' values were greater than males, in spite of being beginners. Possible explanations for this can be associated with female participants reaching puberty earlier than male participants (resulting in higher weight associated with an increase in muscle and fat mass) (Malina, Bouchard, & Bar-Or, 2004), and also exhibiting greater flexibility of the lower extremities, which may facilitate the generation of velocity in the lower extremity and greater ability to kick targets at head level.

When examining the sitting height to standing height ratios, the three female participants (F1, F2, F3) had a ratio greater than 0.5; thus this cannot be considered a significant factor to explain the difference in linear accelerations because ten of the male participants (M1, M2, M4, M5, M8, M9, M10, M12, M13, M14) had a ratio greater than 0.5. Furthermore, the average female participant was shorter (mean 139.2 cm for females and 148.21 cm for males) and lighter (mean weight was 38.55 kg for females and 50.07 kg for males) than the average male. When compared with the corresponding female Body Mass Indices (BMI) for age percentiles, the two 11 year olds (F1, F2) had a BMI below the 50^{th} percentile for their age group (16.7), while the 12 year old (F3) was classified in the 90^{th} percentile for her age group. Mean sit and reach flexibility was 6.5 cm for the females and -1.2 cm for the males, indicating that female participants were more flexible than their male counterparts. Based on these observations, BMI may not explain the differences in linear accelerations. However, a wider range of motion of the lower back and lower extremities may explain some of these variations.

Table 22

Linear Acceleration (Participants Exceeding 42 g's)

Participant ID	Gender	Age (yrs.)	Skill Level	Linear Acceleration (g)
F3	Female	12	Beginner	83.76
				74.03
				49.11
				60.13
				70.55
				44.66
				65.42
				84.81
				43.79
				53.24
M2	Male	9	Advanced	47.09
M8		10	Beginner	49.17
				61.68
				46.68
				59.73
				54.36
M9		10	advanced	43.41
				45.73
M12		12	beginner	47.61
M14		14	beginner	44.14
M15		14	advanced	56.44
				56.08
				75.49
				86.72

Angular Acceleration

Guskievicz and Mihalik (2006) identified linear acceleration and deceleration and/or rotation of the skull as the basic concussion mechanisms and categorized these mechanisms into head-contact injuries and head-movement injuries. Several thresholds for angular accelerations to cause concussions have been identified by Hardy, Foster, Mason, Yang, King, and Tashman's (2001) (2000 rad/s^2), Zhang, Dwarampudi, Yang, and King's (2003) (6398 ±1978 rad/s^2), Ommaya, Goldsmith, and Thibault (2002) (4500 rad/s^2) and Pellman, Viano, Tucker, Casson, and Waeckerle (2003) (6596 ±1866 rad/s^2). There were ten female (F3) and 34 male (M2, M3, M7, M8, M9, M10, M11, M12, M14, M15) trials exceeding the 2000 rad/s^2 values (Table 23). No female participants reached the threshold of 4420 rad/s^{2}cited by Zhang, Dwarampudi, Yang, and King (2003) and only one male beginner (M14) with one kick and one advanced participant (M15) with three kicks exceeding the 4420 rad/s^2 threshold, and Pellman's et al. (2003) lowest value of 4730 rad/s^2. Using the first criteria of 2000 rad/s^2, the results indicated that this threshold was exceeded in 25 percent of the cases, thus presenting a relatively high risk for concussions to participants receiving a roundhouse kick, regardless of age, gender, or skill level. Most of the participants did not reach the threshold obtained by Zhang and colleagues of 6398 ±1978 rad/s^2. However, it is likely for some participants who are older and more skilled to reach these values and cause a concussion to their opponents from their roundhouse kicks.

Being older is associated with an advanced mature physical state that manifests itself in a greater muscle mass (particularly in males), and thus a greater ability to generate force that can be transmitted through kicks (faster movements and greater momentum of the kicking segment). In a study of adult boxers, Waliko, Viano, and Bir (2005) reported a linear correlation between weight class, and rotational accelerations, thus providing an insight on the relationships between weight, force of impact and the resulting head accelerations.

Skill proficiency of participants particularly those with advanced levels, provides another explanation for the results observed. Theorists in motor development recognize that advanced level participants will be more efficient, faster, and demonstrate more control of the motor skills required for a sport (Schmidt & Wrisberg, 2008), thus in this project, advanced participants were able to transmit more force through their kicks.

Table 23

Angular Acceleration (Participants Exceeding 2000 rad/sec^2)

Participant ID	Gender	Age (yrs.)	Skill Level	Angular Acceleration (rad/s^2)
F3	female	12	beginner	3181.7
				3105.7
				3158.4
				2125.5
				3570.9
				3429.7
				3598.5
				3649.9
				3698.1
				3991.9
M2	male	9	beginner	3556.4
				4154.0
M3		9	advanced	2089.4
				2730.7
				2365.4
				2805.4
				2448.0
				3300.9
M7		10	beginner	2161.8
M8		10	beginner	3426.3
				2258.1
				4229.4
				3070.2
				3240.3
M9		10	advanced	3787.4
				2586.2
				2971.2
M10		11	beginner	4230.7

Table 23 (cont'd)

M11	11	beginner	2418.8
			2187.1
			3251.4
M12	12	beginner	2899.4
M14	14	beginner	3203.9
			3072.4
			3260.9
			3507.8
			4185.8
			4472.2
M15	14	advanced	5351.8
			3726.0
			2892.7
			3115.4
			5181.8
			6109.2

Severity Index (SI) and Head Injury Criteria (HIC)

Pellman, Viano, Tucker, Casson, and Waeckerle (2003) reproduced game impacts and injuries that produced concussions in professional football players and identified values of 300 for SI and 250 HIC as nominal values for concussions (for helmet impacts). King (2000) reported values ≤ 1000 for SI and HIC as acceptable (under the automotive safety industry standards). Under the Abbreviated Injury Scale (AIS) for rating injuries by the Insurance Institute of Highway Safety (2009), a HIC-15 (Head Injury Criteria evaluated over a period of 15 ms) of 700 can indicate a higher risk of injury. None of the participants' trials in the current study exceeded either the SI=300 or the HIC=250.

The aforementioned HIC and SI thresholds have been developed by and for the automotive industry where the nature of the impacts is a result of an interaction (direct or indirect) of humans and vehicles. They were not created to assess impacts between humans. However, they provided models that can be modified to consider these conditions. At this point, the results did not meet the criteria to consider the impact to the dummy head as significant for a high risk of injury. More research is needed to effectively adapt these scales to assess the potential for concussions.

Conclusions

Results provided insight on the ability of children to generate linear and angular accelerations on a Hybrid III female dummy head and the risk of concussion. It may be possible that the linear and angular acceleration thresholds for concussions for children be smaller than those used for comparisons in this study (collected from concussions in NFL players) thus the results must be observed with caution because no data are available for children.

The results indicated that participants were capable of reaching thresholds for linear and angular accelerations known to cause concussions, although not consistently. Thus, further research is needed to explain the risks of concussion in martial arts from kicks to the head in this population.

Results also showed that female participants did generate higher linear acceleration values than male participants. Analyses showed differences by age group where older participants generated higher maximal linear and angular accelerations. Skilled participants also generated greater maximal linear and angular accelerations than beginners.

Some participants were able, with their roundhouse kicks, to reach the threshold known to cause concussions in humans. Age, months of practice, standing height, weight, and sit and reach flexibility showed low, but significant, correlations with maximum linear and angular accelerations of the dummy head suggesting that these variables may not be related to these accelerations. However, significant differences between skill levels, suggested that advanced performers generated greater maximum linear and angular accelerations than beginners. Gender differences in maximum linear and angular accelerations of the dummy head generated via roundhouse kicks did show differences, but results were limited by the small sample size.

Practical Implications

Martial arts are a popular choice as a physical activity for children. However, it is necessary to educate parents, instructors, and governing bodies about the intrinsic risk for traumatic brain injuries, which has been reported to be similar to other contact sports such as American football, boxing, and ice hockey. Thus, providing parents with more evidence to make decisions when selecting a martial arts program, and providing instructors and organizations insight into potentially offering better services to their communities.

Martial arts programs can benefit by promoting non-contact sparring programs, particularly for children. Safer environments can translate into more participants and even participation extending over a period of several years, impacting not only self-esteem, socialization, and fitness of participants, but an increased income for studio owners.

Children are capable of generating linear and angular accelerations high enough to cause concussion with their roundhouse kicks to the head. Thus, it is suggested to reduce the number of practice sessions or tournaments that encourage kicks to the head.

The use of head gear and mouth guards is strongly recommended in practice and competition, but is important to recognize that this gear only reduces the risk of fractures of the skull and may not sufficiently reduce the linear and angular accelerations that the brain experiences as a result of an impact to the head to eliminate concussions. These accelerations are the contributing factors to concussions, thus the use of head gear may give a false sense of protection against concussions.

The long term effects of single/multiple concussions in children are not known at this time; however recent studies on contact sports, particularly American football, are pointing to negative effects on cognition, memory, irritability, sudden bursts of rage, and number of cases of depression (Rabadi and Jordan, 2001). Thus, it is suggested to reduce children exposure to these risks. In martial arts this can be accomplished by reducing the exposure to kicks to the head in practice and competition. By modifying competition rules, promoting controlled (low impact) kicks to the head or discouraging the use of competition systems that award higher scores for full force impacts, not promoting knockout of an opponent, and/or having a differential scoring system in place where more points are not awarded when complex kicks (adding jumps and body turns) are used to impact the head of an opponent. These complex kicks typically have a greater moment of inertia that may contribute to higher accelerations of the brain after an impact, and may cause a more serious injury.

It is also recommended that safety training modules for athletes, parents, and instructors be developed on the health risks associated with concussions, the possible negative long term effects of concussion, and how to identify them in competition or practice. Furthermore, becoming familiar with guidelines that dictate when a participant can go back to the activity and developing a surveillance system to monitor the incidence of this type of injury will contribute to a safer participation in martial arts.

Recommendations for Further Study

It is important to continue exploring the effects of these variables on concussion by conducting similar studies that focus on increasing the number of participants by gender, age, skill level, and control for martial art style. Including participants from martial arts that emphasize kicking over punching such as taekwondo and muay thai, may provide a better understanding of high injury rates reported by Pieter et al. (1995), and Pieter and Zemper (1998). These styles promote the use of kicking techniques to the head, and knocking out an opponent is one of the goals of the competition.

The accelerations resulting from other kicking techniques need to be studied. Among these are front and crescent kicks (for the simplicity), and particularly those that include whole body rotations along the longitudinal axis of the kicker, such as back and reverse hook kicks. These kicks have been reported to be not as fast or popular as roundhouse, but are used effectively in competition, due to their devastating effects if the head is impacted.

Although the results of this study of the roundhouse kick to the Hybrid III female dummy head showed most linear and angular accelerations lower than the thresholds known to cause concussions, the effects of receiving one or several kicks to the head during martial arts competitions or practice settings need to be studied further, because there may be cumulative effects on the brain even at lower acceleration levels, which may predispose participants to concussions, or more severe brain injuries. Further understanding is also needed for “second impact syndrome”, which can occur when a practitioner receives an impact to the head and falls uncontrolled or unconscious to the ground, thus exposing him/her to a second impact, this time against the floor (which could be padded or not), potentially contributing to a more serious outcome.

APPENDICES

Appendix A

Parental Consent Form Michigan State University

“Accelerations of a Hybrid III Dummy Head Resulting From Roundhouse Kick Impacts and Their Relation to the Risks of Concussions in Boys and Girls”

Your child is being asked to participate in a research study. The purposes of this study are to compare the magnitudes of impacts by a roundhouse kick, measured on a Hybrid III head dummy, to those that are known to cause concussions. This study will attempt to identify differences in performances of practitioners with various skill levels, ages, and gender.

Your child is being asked to participate in this study because s/he has been participating in martial arts for 4 or more weeks (or at least 8 hrs). Your child’s participation is totally voluntary, and s/he may refuse to participate in certain procedures or answer certain questions as well as to discontinue participation at any time without any explanation. There is no direct economic benefit to you or your child from your child’s participation. By allowing your child to participate in this study you agree that the materials and data generated (pictures, video and measurements) may be used for research and academic purposes. Please note that your child cannot be in the study without being taped. Only the research team members, the Human Investigation Committee at Wayne State University and the Michigan State University’s Human Research Protection Program will have access to the research data. Your child’s confidentiality will be protected to the maximum extent allowable by law. We will keep your child’s records private unless we are required by law to share any information. Any films or pictures shown in research presentations will be deidentified with faces not visible. After completion of the project, all research data will be stored securely for a period of 3 years under the supervision of Dr. Marty Ewing at the Department of Kinesiology at Michigan State University. When this research is completed, an abstract of the results will be mailed to you.

The participants must be free of any orthopedic condition that may hinder their ability to perform roundhouse kicks, the data collection session will last approximately 1 hour and participants will be asked to participate in only one data collection session. Data collection will have the following stages:

1. General information.

Your child will be asked to complete a questionnaire in order to provide general information about himself/herself such as name, date of birth, gender, martial arts experience, leg predominance, practice time, competition experience and overall physical activity.

2. Anthropometrical measurements and flexibility.

All anthropometric data will be collected in private (parents or guardians may be present) in the Sports Injury Biomechanics Lab at Wayne State University's Department of Biomedical Engineering.

- Weight will be assessed on a standard weight balance while your child wearing only shorts and
t-shirt.
- Height will be assessed with a standard stadiometer.
- Sitting height will be assessed with a standard stadiometer while you are seated on a bench.
- Segmental lengths will be assessed with the use of standard body calipers. Thigh, shank, and foot lengths will be taken.
- Biacromial and bicristal widths will also be measured with a body caliper.
    - Flexibility will be measured with the sit-and-reach test.

3. Kinetic data collection

Kinetic data collection (data related to velocities and accelerations experienced by a dummy head) will involve the use of a Hybrid III dummy and the BAF system will collect kinematic data through your child's kick attempts; a backup high-speed video system will be used to record performances. The following protocol will be used:

- Your child will be asked to warm up as if you were about to participate in one of your standard
Martial arts practice sessions.
- Following your child's overall warm up, your child will be asked to perform 5 roundhouse kicks according to
how your child would normally perform them. (Note that there is no correct or incorrect performance. We only want to record your child's style of performance.) Your child will be asked to
assume a "ready sparring position" prior to kicking the side of a Hybrid III crash dummy head that has been adjusted to your child's height.
- Your child will be asked to do 5 trials of the technique with each foot. Each trial will be recorded.

There will be no direct benefit to your child from participating in this study. However, the study will help to identify differences that may lead to improve teaching techniques, reduction of injuries, and promote safer martial arts.

Risks associated with your child's participation in this study may include bruises on your child's feet as a result of kicking the dummy head (even though your child will be wearing protective equipment on his/her feet, and the head will be fitted with protective gear too), or "pulling a muscle" while kicking, however, this risk is no different from a normal martial arts practice session. No other serious risks are identified at this time.

In the event that this research related activity results in an injury, treatment will be available including first aid, emergency treatment and follow-up care as needed. Care for such will be billed in the ordinary manner to you or your insurance company. No reimbursement, compensation or free medical care is offered by Wayne State University or Michigan State University. This does not mean that you are giving up any legal right you may have. If you think that your child may have suffered a research related injury you may contact Dr. Cynthia Bir ☎no. (313)577-3830, Dr. Marty Ewing ☎no. (517)353-4652, or Miguel Narvaez ☎no. (716)372-2233.

If you have questions or concerns about your child's role and rights as a research participant, would like to obtain information or offer input, or would like to register a complaint about this study, you may contact, anonymously if you wish, the Michigan State University's Human Research Protection Program by phone: (517)355-2180, fax: (517) 432-4503, e-mail: irb@msu.edu, or regular mail at 207 Olds Hall, MSU, East Lansing, MI 48824, or the Chair of the Human Investigation Committee at Wayne State University ☎no.(313) 577-1628. If you are unable to contact the research staff, or if you want to talk to someone other than the research staff, you may also call ☎no. (313) 577-1628.

Name of participant:___________________________________ Date:___________
Date of birth:____________

Name of parent/guardian:____
I voluntarily agree to allow my child to participate in the study. (Signature of parent/guardian): _________________________

Mailing address:____
Phone:_______________ e-mail address:_____________________________________

Appendix B

Research Consent Form Wayne State University

Title of the Study: Accelerations of a Hybrid III Dummy Head Resulting From Roundhouse Kick Impacts and Their Relation to the Risks of Concussions in Boys and Girls**.**

Principal Investigator (PI): Cynthia Bir
Department of Biomedical Engineering
(313)577-3830

When we say "you" in this consent form, we mean you or your child; "we" means the researchers and other staff.

Purpose

The purposes of this study are to compare the magnitudes of linear acceleration of the center of gravity of the head and angular acceleration about the center of gravity from a hybrid III head dummy as a result of being impacted with a roundhouse kick, to values of these same variables that are known in general to cause concussions as a result of direct contact with the head. It will attempt to identify differences in performances of practitioners with various skill levels, ages, and gender. The roundhouse kick is considered a simple kick in the martial arts, and the study will help to identify performance differences that may lead to the improvement of teaching techniques, reduction of risk of injury, and promotion of a safer activity.

The data collection session will last approximately 1 hour and participants will be asked to participate in only one data collection session, also participants must be free of any orthopedic condition that may hinder their ability to perform kicks. It is estimated to have 60 participants in the project. Data collection will have the following stages:

Study Procedures

1. General information.

You will be asked to complete a questionnaire in order to provide general information about yourself such as name, date of birth, gender, martial arts experience, leg predominance, practice time, competition experience and overall physical activity.

2. Anthropometrical measurements.

All anthropometric data will be collected in private (parents or guardians may accompany you) in the Sports Injury Biomechanics Lab at Wayne State University's Department of Biomedical Engineering.

- **Weight** will be assessed on a standard weight balance while you are wearing only shorts and
t-shirt.
- **Height** will be assessed with a standard stadiometer.

- **Sitting height** will be assessed with a standard stadiometer while you are seated on a bench.
- **Segmental lengths** will be assessed with the use of standard body calipers. **Thigh**, **shank**, and **foot** lengths will be taken.

3. Kinetic data collection

Kinetic data collection will involve the use of a Hybrid III dummy and the BAF system will collect kinematic data through your kick attempts. A high-speed video system will also be used as a backup for the BAF system. The following protocol will be used:

- You will be asked to warm up as if you were about to participate in one of your standard
Martial arts practice sessions.
- Following your overall warm up, you will be asked to perform 5 roundhouse kicks according to
how you would normally perform them. (Note that there is no correct or incorrect performance. We only want to record your style of performance.) You will be asked to assume a "ready sparring position" prior to kicking the side of a Hybrid III crash dummy head that has been adjusted to your height.
- You will be asked to do 5 trials of the technique with each foot. Each trial will be recorded.

Benefits

You are being asked to participate in this study because of you have been participating in martial arts for 4 or more weeks (or at least 8 hrs). As a participant in this research study, there will be no direct benefit for you; however, information from this study may benefit other people now or in the future.

Risks

There are no known risks at this time to participation in this study.

Study Costs

Participation in this study will be of no cost to you.

Research Related Injuries

In the event that this research related activity results in an injury, treatment will be made available including first aid, emergency treatment, and follow-up care as needed. Care for such will be billed in the ordinary manner to you or your insurance company. No reimbursement, compensation, or free medical care is offered by Wayne State University. You may contact Dr. Cynthia Bir ☎no. (313)577-3830, Dr. Marty Ewing ☎no. (517)353-4652, or Miguel Narvaez ☎no. (716)372-2233 with any questions or to report an injury.

Confidentiality

All information collected about you during the course of this study will be kept confidential to the extent permitted by law. You will be identified in the research records by a code name or number. Information that identifies you personally will not be released without your written permission. However, the study sponsor, the Human Investigation Committee (HIC) at Wayne State University, or federal agencies with appropriate regulatory oversight [e.g., Food and Drug Administration (FDA), Office for Human Research Protections (OHRP), Office of Civil Rights (OCR), etc.) may review your records.

When the results of this research are published or discussed in conferences, no information will be included that would reveal your identity.

If photographs, or video recordings of you will be used for research or educational purposes, your identity will be protected or disguised. All the materials will be kept in a locked cabinet under the supervision of the PI, and will be destroyed after three years. Only coded information will be used for analysis and it will not be possible to identify you or your data.

Voluntary Participation/Withdrawal

Taking part in this study is voluntary. You have the right to choose not to take part in this study. You are free to only answer questions that you want to answer. You are free to withdraw from participation in this study at any time. Your decisions will not change any present or future relationship with Wayne State University or its affiliates, or other services you are entitled to receive.

The PI may stop your participation in this study without your consent. The PI will make the decision and let you know if it is not possible for you to continue. The decision that is made is to protect your health and safety, or because you did not follow the instructions to take part in the study

Questions

If you have concerns or any questions about this study, such as scientific issues, how to do any part of it, or to report an injury, please contact the researchers Dr. Marty Ewing ☎no. (517)353-4652, email: mewing@msu.edu at the Department of Kinesiology at Michigan State University, or Miguel Narvaez ☎no. (716)372-2233, email: narvaezm@sbu.edu at the Department of Physical Education at Saint Bonaventure University. If you have questions or concerns about your role and rights as a research participant, would you like to obtain information or offer input, or would you like to register a complaint about this study, you may contact, anonymously if you wish, the Michigan State University's Human Research Protection Program by phone: (517)355-2180, fax: (517) 432-4503, e-mail: irb@msu.edu, or regular mail at 207 Olds Hall, MSU, East Lansing, MI 48824, the Chair of the Human Investigation Committee at Wayne State University ☎no.(313) 577-1628. If you are unable to contact the research staff, or if you want to talk to someone other than the research staff, you may also call ☎no. (313) 577-1628 to ask questions or voice concerns or complaints.

.**Consent to Participate in a Research Study**

To voluntarily agree to take part in this study, you must sign on the line below. If you choose to take part in this study you may withdraw at any time. You are not giving up any of your legal rights by signing this form. Your signature below indicates that you have read, or had read to you, this entire consent form, including the risks and benefits, and have had all of your questions answered. You will be given a copy of this consent form.

______________________________	____________
Signature of participant	Date
______________________________	____________
Printed name of participant	Time
______________________________	____________
Signature of witness**	Date
______________________________	____________
Printed of witness**	Time
______________________________	____________
Signature of person obtaining consent	Date
______________________________	____________
Printed name of person obtaining consent	Time

Appendix C

Verbal Assent Script Wayne State University

Project Title: "Accelerations of a Hybrid III Dummy Head Resulting From Roundhouse Kick Impacts and Their Relation to the Risks of Concussions in Boys and Girls"

Principal Investigators:
Cynthia Bir Ph.D.
Marty Ewing Ph.D.
Miguel Narvaez

My name is Miguel Narvaez.

We want to tell you about a research study we are doing. A research study is usually done to find a better way to treat people or to understand how things work. In this study, we want to find out more about how a head moves and reacts after being hit with a roundhouse kick. You are being asked to be in this study because you have been practicing a martial art for at least 8 hours, you are between 5 and 17 years of age and can perform a roundhouse kick without any problems. In any study, only people who want to take part are allowed to do so. You do not have to be in this study if you do not want to do so.

If it is okay with you and you agree to join this study, you will be asked to complete a questionnaire about your age, your martial arts experience and overall physical activity. You can ask for help from your parent(s).
You height, weight and length of your arms and legs will be also measured.
Some sensors will be placed in your trunk, arms and legs that will allow us to record the movement of these parts of your body while you are asked to use a roundhouse kick to hit a special dummy head. We will also use high-speed video cameras to record your performance.
You will be asked to kick the dummy head 5 times with each leg.
You only need to come here once, and all these measurements will take about an hour to complete.

As a result of kicking the dummy head you may get a bruise on your kicking foot (note that you will be wearing protective equipment on your feet), or "pull a muscle" while kicking, however, this risk is no different from a normal martial arts practice session. No other serious risks can be identified.
If anything hurts or you are uncomfortable with some of the questions, please let us know, you can stop to participate at any time.

We do not know if you will be helped by being in this study however the study will help to identify differences that may lead to improve teaching techniques, reduction of injuries, and promote safer martial arts.

You do not have to be in this study. It is up to you. You can say no now or you can change your mind later. All you have to do is tell us. No one will be mad at you if you change your mind.

Your parents/guardian say it is okay for you to be in this study. If you have questions, please ask them now or at anytime.

We will make every reasonable to keep your information confidential. But we do have to let some people look at your study records. We will keep your records private unless we are required by law to share any information. The law says we have to tell someone if you might hurt yourself or someone else. The study researchers can use the study results as long as you cannot be identified. Any films or pictures shown in research presentations will be deidentified with faces not visible. Information that identifies you personally will not be released without you written permission. However, the Human Investigation Committee (HIC) at Wayne State University, The Institutional Review Board (IRB) at Michigan State University or federal agencies with appropriate regulatory oversight, may review your records.

If you are not happy with this study and want to talk to someone else other than the research personnel please call Dr. Cynthia Bir at (313)577-3830, Dr. Marty Ewing at (517)353-4652 or Miguel Narvaez (716)372-2233 with any questions or to report an injury. If you have questions or concerns about your rights as a research participant contact the Wayne State University Chair of the Human Investigation Committee at (313)577-1628 or Michigan State University Human Research Protection Program at (517)355-2180.

Do you understand this study and are you willing to be in it?

To be completed by person obtaining verbal assent from the child/subject:
Child's/Subject's response**:** ☐Yes ☐No

Check which applies below:

☐The child/Subject is capable of understanding the study
☐The child/Subject is not capable of understanding the study

____
Child's/Subject's Name (printed)

____ __________________
Signature of Person Obtaining Verbal Assent Date

Appendix D

Adolescent Assent Form Wayne State University

Title: "Accelerations of a Hybrid III Dummy Head Resulting From Roundhouse Kick Impacts and Their Relation to the Risks of Concussions in Boys and Girls"

Study Investigators:
Cynthia Bir Ph.D.
Marty Ewing Ph.D.
Miguel Narvaez

Why am I here?

This is a research study. Only people who choose to take part are included in research studies. You are being asked to take part in this study because you have been an active martial arts participant in the last four weeks, have accumulated at least eight hours of practice during this time frame, are between five and 17 years of age, and you are healthy, without any abnormalities or injuries that may adversely affect performance of the roundhouse kick. Please take time to make your decision. Talk to your family about it and be sure to ask questions about anything you don't understand.

Why are they doing this study?

This study is being done to find out how a hybrid III head dummy responds (its velocities and accelerations will be estimated) after being kicked with a roundhouse kick and compare them with known values that can cause concussions. It will attempt to identify differences among practitioners of various skill levels, age, and gender.

What will happen to me?

You will complete a questionnaire about your age, your martial arts experience and overall physical activity. You can ask for help from your parent(s).
You height, weight and length of your arms and legs will be also measured.
Some sensors will be placed in your trunk, arms and legs that will allow us to record the movement of these parts of your body while you are asked to use a roundhouse kick to hit a special dummy head. We will record your performance with high speed video cameras.
You will be asked to kick the dummy head 5 times with each leg.

How long will I be in the study?

You will be in the study for only one hour, and only need to visit once.

Will the study help me?

We cannot promise you that being in this research study will help you, however the study will help to identify differences that may lead to improve teaching techniques, reduction of injuries, and promote safer martial arts.

Will the study hurt?
As a result of kicking the dummy head you may get a bruise on your kicking foot (note that you will be wearing protective equipment on your feet), or "pull a muscle" while kicking, however, this risk is no different from a normal martial arts practice session. No other serious risks can be identified.

Research Related Injuries:
In the event that this research related activity results in an injury, treatment will be available including first aid, emergency treatment and follow-up care as needed. Care for such will be billed in the ordinary manner to you or your insurance company. No reimbursement, compensation or free medical care is offered by Wayne State University or Michigan State University. If you think that you have suffered a research related injury, let the investigator know right away.

Do my parents or guardians know about this?
This study was explained to your parents/guardian and they said that you could be in it. You can talk this over with them before you decide.

What about confidentiality?
Every reasonable effort will be made to keep your medical records confidential. But we do have to let some people look at your study records. We will keep your records private unless we are required by law to share any information. The law says we have to tell someone if you might hurt yourself or someone else. The study researchers can use the study results as long as you cannot be identified. Any films or pictures shown in research presentations will be deidentified with faces not visible. Information that identifies you personally will not be released without you written permission. However, the Human Investigation Committee (HIC) at Wayne State University, The Institutional Review Board (IRB) at Michigan State University or federal agencies with appropriate regulatory oversight, may review your records.

What if I have any questions?
For questions about the study please call Dr. Cynthia Bir at (313)577-3830, or Dr. Marty Ewing at (517)353-4652 or Miguel Narvaez (716)372-2233 with any questions or to report an injury. If you have questions or concerns about your rights as a research participant contact the Wayne State University Chair of the Human Investigation Committee at (313)577-1628 or Michigan State University Human Research Protection Program at (517)355-2180.

Do I have to be in the study?
You don't have to be in this study if you don't want to or you can stop being in the study at any time. Please discuss your decision with your parents and the researchers. No one will be angry if you decide to stop being in the study.

AGREEMENT TO BE IN THE STUDY

Your signature below means that you have read the above information about the study and have had a chance to ask questions to help you understand what you will do in this study. Your signature also means that you have been told that you can change your mind later and withdraw if you want to. By signing this assent form you are not giving up any of your legal rights. You will be given a copy of this form.

_________________________________ _______________
Signature of Participant (13 yrs & older) Date

____
Printed name of Participant (13 yrs & older)

___________________________________ __________________
**Signature of Witness (When applicable) Date

____
Printed Name of Witness

___________________________________ ______________
Signature of Person who explained this form Date

____
Printed Name of Person who explained form

** Use when participant has had consent form read to them (i.e., illiterate, legally blind, translated into foreign language).

Appendix E

Data Collection Form (Demographics)

Date:________________ ID No.:_________

Name:____ Date of Birth:__________

Gender:___________Rank (Kup/Dan):___________ Belt Color:____________

Leg predominance: ___________________________

How many months have you been practicing martial arts? __________

In the last month, how many hours per week have you practiced martial arts? __________

In the last week, how many hours have you practiced martial arts? __________

Using the following table, tell us how many competitions you participated in during the past year, and what was the nature of each competition. Also indicate if you finished in the top ten participants in each contest.

	martial arts Only			Mixed Martial Arts
	Full-contact sparring	Non-Contact sparring	Forms	Describe
Weight/skill division				
Approx. # participants in your category				
Approx. # of matches you participated				
Final placement				
Did you suffer any injuries that require you to miss at least one practice session? (describe)				

How many hours per week do you invest in preparing/practicing for free-sparring competitions? ______________________________________

How many hours per week do you invest in preparing/practicing for form competitions? ____

Use the following table to tell us about any other physical activities that you may do during your week.

List any other sport(s) of physical activities that you participate in	For each sport/activity indicate the frequency and number of hours you practice it per week	If you compete in any of these, please indicate the level of participation (school clubs, community clubs, junior varsity, varsity sports, etc.)	Please number these activities in your favorite order of preference, starting with 1 as being the most favorite.	Have you suffer any injuries in these activities that required you to miss at least one practice session? (describe)

Appendix F

Data Sheet

Date:__________________________ ID No.:________________________

Name	
DOB mm/dd/yy	
Gender	
ID number (ddmmyygbddmmyy)	
Sitting height (m): (measure to the closest mm)	
Standing height (m): (measure to the closest mm)	
Shoulder height (m): (measure to the closest mm)	
Trochanteric height (m): (measure to the closest mm)	
Leg length (m): (measure to the closest mm)	
Weight (kg): (measure to the closest hundredth)	
Flexibility (cm): (measure to the closest mm)	
Biacromial width (cm): (measure to the closest mm)	
Bicristal width (cm): (measure to the closest mm)	

Appendix G

Glossary

To understand concepts presented throughout this document, the following definitions are provided:

Abrasion: Minor wound in which the surface of the skin or mucous membrane is worn away by rubbing or scraping.

Abbreviated Injury Scale (AIS): The AIS was originally designed to stratify victims of motor vehicle crashes. The AIS injury severity values are consensus-derived and range from 1 (minor) to 6 (fatal).

Accelerometer: An instrument used to measure acceleration.

Angular acceleration: The rate of change of angular velocity over time.

Angular velocity: The rate of change of the angular position of a rotating body over time.

Anthropometry: The measurement of the structures and proportions of the human body.

Apnea: Transient cessation of respiration.

Ataxia: An inability to coordinate voluntary muscular movements that is symptomatic of some central nervous system disorders and injuries and not due to muscle weakness.

Athlete-Exposure (A-E): An epidemiologic concept of person-time at risk, thus describing the time or times an athlete is at risk of an injury by participating in his/her sport.

Athlete-game: An injury incidence density rate that considers one-athlete participation in a game.

Athlete-practice: An injury incidence density rate that considers one-athlete participation in a practice.

Athletic Injury Monitoring System (AIMS): An injury surveillance system established by the NCAA to provide data on injury rates, patterns, and risk factors of various sports.

Avulsion: Tearing or forcible separation of part of a structure.

Body Mass Index (BMI): Is an index for relating a person's body weight to their height.

Chronic Traumatic Brain Injury (CTBI): A condition characterized by persistent brain damage or dysfunction as sequelae of cranial trauma.

Collision sports: A sport in which the athletes purposely hit or collide with each other or inanimate objects, including the ground, with great force.

Contact sports: A sport in which body contact either is an integral component of the sport or commonly occurs while engaged in the sport.

Contusion (bruise): An area of skin discoloration caused by the escape of blood from ruptured underlying vessels following injury.

Coup/counter coup cavitation: Injury to the brain occurring directly beneath the area of impact.

Diencephalon: The posterior part of the forebrain, consisting of the hypothalamus, thalamus, metathalamus, and epithalamus.

Diffuse Axonal Injury (DAI): A relatively common sequela of blunt head injury, characterized by a global disruption of axons throughout the brain.

Dislocation: Displacement from the normal position of bones meeting at a joint.

Dysarthria: Difficulty in articulating words due to emotional stress or to paralysis, lack of coordination, or spasticity of the muscles used in speaking.

Excoriation: A circumscribed removal of the epidermis of skin or mucous membrane.

Flexibility: Represents the relative ranges of motion allowed at a joint.

Focal injury: Acute and/or chronic injuries to the brain, including the cerebral hemispheres, cerebellum, and brain stem.

Force: A push or a pull; the product of mass and acceleration.

Fracture: Breakage of a bone, either complete or incomplete.

Gadd Severity Index (GSI): An index developed to quantifying the severity of an injury sustained in an automobile accident.

Glial fibrillary acidic protein: Is a cell-specific marker that, during the development of the central nervous system, distinguishes astrocytes from other glial cells.

Halstead-Reitan Neuropsychological Test Battery: Consists of a series of individual neuropsychological measures that, in combination, permit a skilled examiner to make detailed inferences about the integrity of the cerebral hemispheres.

Head-contact injuries: An injury associated with direct trauma to the head.

Head Injury Criteria (HIC): Is a measure of the likelihood of head injury arising from an impact.

Head-movement injuries: An injury associated with sudden changes in direction, resulting in indirect trauma to the head.

Impact height: In the current study, defined as the height of the lateral malleolus of the kicking foot when the foot makes contact with the Hybrid III female dummy head target.

Injury criteria: A mathematical relationship between some measurable physical parameter interacting with a test subject and the occurrence of injury that directly results from that interaction.

Injury rate: The incidence of injury per unit of athlete time.

Injury: Damage, wound, trauma.

Inverse dynamics: Use of link-segment models to represent mechanical behavior of connected pendulums, or more concretely, body segments of humans.

Ischemia: is a condition that occurs when blood flow and oxygen are kept from a particular part of the body.

Kinematics: The branch of mechanics concerned with motion without reference to force or mass.

Kinetics: The branch of mechanics concerned with forces that cause motions of bodies.

Laceration: A tear in the flesh producing a wound with irregular edges.

Limited contact sports: A sport in which the rules are designed to prevent intentional or unintentional contact between players which, if it occurs, carries strong penalties.

Linear acceleration: The rate of change in linear velocity over time.

Linear velocity: The rate of change in position over time.

Lipid peroxidation: Is a mechanism of cellular injury in plants and animals, used as an indicator of oxidative stress in cells and tissues.

Neurofilament light polypeptide: Is a gene that provides instructions for making the smallest protein component (the light subunit) of neurofilaments.

Non-contact sports: A sport in which the players are physically separated such as to make it nearly impossible for them to make physical contact during the course of a game.

Non-collision sports: A sport in which the athletes are not permitted to hit or collide with each other.

Outclassed rule: A referee in an amateur boxing has the responsibility to stop a fight at any time one fighter seems in danger due to being clearly outmatched.

Pace auditory serial addition task: Is a test often used to measure attention, concentration, working memory, and speed of information processing.

Pathomechanics: The study of mechanical forces that are applied to a living organism and adversely change the body's structure and function.

Player-seasons: An injury incidence density rate that considers one-athlete participation in a season.

Severity Index (SI): See Gadd Severity Index.

Second Impact Syndrome (SIS): Results from an acute, usually fatal brain swelling that occurs when a second concussion is sustained before complete recovery from a previous concussion.

Sitting height: Height of the participant while sitting on a bench with hips and back against a wall, measured from the bench to the vertex of the head.

Shoulder height: Height of participant's right shoulder while standing erect.

Skill level (colored belt, black belt): Individual skill levels in martial arts that follows a colored belt system, where a light color belt indicates beginner/intermediate levels, and a black belt is recognized as an advanced level. A participant that has not achieved a black belt typically has a level of experience in martial arts less than 6 months to approximately 2 years. A black belt requires years of training, and it is usually reached within 2 years of practice.

Sparring ready stance: Stance assumed by martial arts competitors during a free sparring contest, characterized by a staggered anterior-posterior placement of the feet, with the body weight evenly distributed on both feet, and a relatively high center of gravity.

Sprain: Ligamentous injury to a joint with possible rupture, but without dislocation or fracture.

Standing height: Height of a participant when standing erect.

Strain: Excessive stretching or working of a muscle resulting in pain and swelling of the tissue.

Symbol Digits Modality Test (SDMT): Detects cognitive impairment. The test involves a simple substitution task that normal children and adults can easily perform.

Tau: Is a protein used as a serum marker of brain damage in mild traumatic brain injury.

Total kicking time: Starts from the moment the kicking foot leaves the ground, through the contact with the target, and ends when the foot touches the ground again.

Trochanteric height: Height of a participant's right trochanter from the ground while standing.

Leg length: Measurement from the ground to the lateral condyle of the tibia while the participant stands erect.

Wechler Intelligence Scale for Children III (WISC-III): A test developed to measure intelligence in children ages 6-0 to 16-11.

Wide Range of Assessment Memory and Learning (WRAML): A test designed to assess memory and learning functions across the school years.

Wound: An injury to the body (as from violence, accident, or surgery) that typically involves laceration or breaking of a membrane (as the skin) and usually damage to underlying tissues.

Appendix H

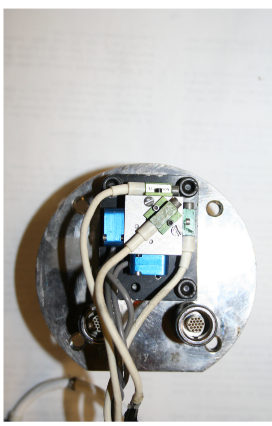
Permission Letter to Use Figure 7

April 26, 2011

Nate Dau
818 W. Hancock
Detroit, MI 48201USA

Dear Nate:

I am completing a doctoral dissertation at Michigan State University entitled "Accelerations of a Hybrid III Dummy Head Resulting from Roundhouse Kick Impacts and their Implications for Concussions in Boys and Girls". I would like your permission to reprint in my dissertation the following picture:



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If these arrangements meet with your approval, I would appreciate your assistance by signing the letter where indicated below and return it to me via fax, email or regular mail.

Thank you very much.

Sincerely,

Miguel Narvaez
1C Butler Gym
Saint Bonaventure University
Saint Bonaventure, NY 14778
Telephone (716)375-2233
Fax (716)375-2360
Email: mnarvaez@sbu.edu

PERMISSION GRANTED FOR THE USE REQUESTED ABOVE:

____
[Type name of addressee below signature line]

Date:____________________________

Appendix I

Permission Letter to Use Figures 8 & 9

April 26, 2011

Diversified Technical Systems, Inc.
909 Electric Avenue, Suite 206
Seal Beach, CA 90740 USA

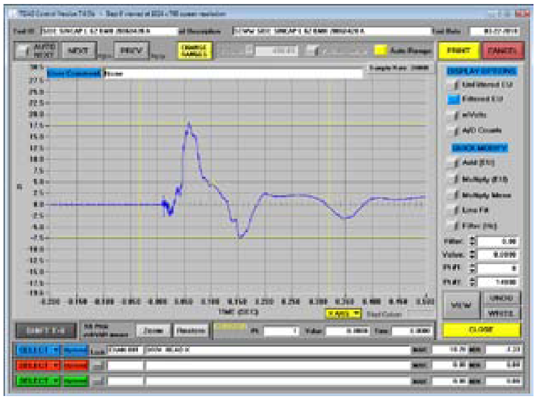
Dear Sir/Madame:

I am completing a doctoral dissertation at Michigan State University entitled "Accelerations of a Hybrid III Dummy Head Resulting from Roundhouse Kick Impacts and their Implications for Concussions in Boys and Girls". I would like your permission to reprint in my dissertation the following pictures:

a) TDAS PRO sensor input module, included in the TDAS PRO manual, downloaded from:

http://dtsweb.com/library/tdas/DTS%20Datasheet%20TDAS%20PRO%20SIM-6.2010.pdf

b) TDAS control software screen shot, included in the TDAS PRO manual, downloaded from: http://dtsweb.com/library/tdas/DTS%20Datasheet%20TDAS%20PRO%20SIM-6.2010.pdf



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If these arrangements meet with your approval, I would appreciate your assistance by signing the letter where indicated below and return it to me via fax, email or regular mail.

Thank you very much.

Sincerely,

Miguel Narvaez
1C Butler Gym
Saint Bonaventure University
Saint Bonaventure, NY 14778
Telephone (716)375-2233
Fax (716)375-2360
Email: mnarvaez@sbu.edu

PERMISSION GRANTED FOR THE USE REQUESTED ABOVE:

____
[Type name of addressee below signature line]

Date:___________________________

REFERENCES

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