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BIOMECHANICS & HEALTH

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The dynamic response of the taekwondo roundhouse kick to head using computer simulation

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Key words: linear acceleration, rotational acceleration, head injury, concussion, Wayne State University Cerebral Concussion Tolerance Curve (WSTC)

Abstract

Background, Problem and Aim. Investigations into head injuries in combat sports have utilized a linear acceleration parameter only. Utilization of computer simulation techniques may provide more accurate and reliable information. Thus, this study analyzed the linear and rotational acceleration of the taekwondo roundhouse kick using Automated Dynamic Analysis of Mechanical Systems (ADAMS) software.

Methods. The ADAMS software model was used to determine the linear and rotational acceleration of the taekwondo roundhouse kick.

Results. The analysis of linear and rotational acceleration curves showed that peak linear acceleration, average linear acceleration, peak rotational acceleration, and average rotational acceleration resulted from the roundhouse kick to head at a foot velocity of 13 m/s were 99g, 25g, 4346 rads/s^2, 1465 rads/s^2, respectively. At foot velocity of 16 m/s, these accelerations were 136 g, 33 g, 5908 rads/s^2, and 2539 rads/s^2, respectively. Also, impact time at velocities of 13 m/s and 16 m/s were 23 ms and 18 ms, respectively

Conclusions. It is biomechanically improbable that the head would be displaced translationally or rotationally as a result of a taekwondo roundhouse kick. Nevertheless, both accelerations should be considered and also the comparison between the results of this study and acceleration tolerance thresholds of head injury indicated that only rotational acceleration causes an injury to head. Especially at high foot speeds, rotational acceleration can lead to cerebral concussion and brain surface shearing.

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Background, Problem, and Aim

There has been an increased interest in studying traumatic brain injuries as a result of blows to the head in recent years [Chen 2011: 51]. These injuries range from no apparent brain damage to severe cerebral damage, unconsciousness, and death. In combative sports like taekwondo, karate, and boxing, athletes are exposed to severe and repeated blows to head [Tanbakoosaz *et al*. 2015]. Among these sports, taekwondo is considered to be one of the most popular [Feehan, Waller 1995]. The risk of head injury may be more in taekwondo due to the sport assigning more points for kicks delivered to the head [Falco *et al*. 2009]. A recent review of taekwondo injuries highlighted a concussion incidence of 9.4 per 1000 athlete exposures among male taekwondo athletes compared to 4.6 per 1000 among females [Pieter *et al*. 2012]. The concussion incidence is approximately four times higher in taekwondo competition than American football [O'Sullivan, Fife 2016; Viano *et al*. 2005]. The roundhouse kick is most commonly associated with mild traumatic brain injury in taekwondo competition

[Tanbakoosaz *et al.* 2015].

A number of recent issues related to the biomechanics of head injury and sport-related concussion in contact sports and martial arts have provided insights into the mechanisms of head injury [Fife *et al.* 2013]. However, the exact mechanism of head injuries has not been known yet. Early experiments using impact forces on cadaver heads suggested that skull deformation and changes in intracranial pressure were key factors. Brown and Russell suggested that head movement and rotation may be important factors [Brown, Russell 1941]. Yet, it has still not been fully elucidated how external forces are transmitted internally, nor is it fully understood what the underlying mechanism of neurological damage is, but the prevailing thought is that head acceleration produces axonal twisting and shearing injuries [Kis *et al.* 2013; Rowson *et al.* 2009]. Impacts to the head (predominantly linear acceleration) and inertial loading of the head (predominantly rotational acceleration) have been postulated as the two major mechanisms of head injury [Clark *et al.* 2015: 168-179]. Rotational acceleration is considered to produce both focal and diffuse brain injuries, while linear acceleration produces focal brain injuries [Schmitt *et al.* 2014; Hoshizaki *et al.* 2014].

Studies on the mechanism of head injury in taekwondo are very limited. These experimental studies have only addressed linear acceleration [Fife *et al.* 2013; Fife 2010: 64; Fife, O'Sullivan 2012]. The first known study on head impacts in kicking-oriented martial arts was by Schwartz et al. They used a Hybrid II crash test dummy created by General Motors for car crash tests, where the head and neck were mounted to an immovable concrete post. Karate practitioners were instructed to strike the Hybrid II with various techniques (i.e., kicks and hand strikes), and the peak resultant linear acceleration (RLA) was reported to be 120 g (the technique was unspecified) [Schwartz *et al.*1986].

In two different studies, Fife et al. obtained the average linear acceleration caused by a roundhouse kick to head as 130.1 g [Fife 2010: 64; Fife, O'Sullivan 2012]. They used a Hybrid II head and neck equipped with accelerometer. Similarly, Fife et al. studied the biomechanics of head injuries in Olympic taekwondo [Fife *et al.* 2013]. To simulate head impact in their 2013 study, a Hybrid II was equipped with a tri-axial accelerometer mounted inside the dummy's head. They reported the RLA acceleration of a roundhouse kick to head to be 130 g and a peak foot velocity of 11.9 m/s [Fife *et al.* 2013]. Thus far, research has investigated head injuries in combat sports using only a linear acceleration parameter.

Drawbacks and limitations of these kinds of experimental methods are their time-consuming nature, cost, time limited availability potential for participant injury, and inherent equipment and experimenter's error. However, utilization of computer simulation techniques may not only reduce or eliminate these limitations but may also provide more accurate and reliable information. Hence, the aim of this study was to analyze the effect of the taekwondo roundhouse kick to the head in terms of dynamic variables such as linear and rotational acceleration through computer simulation technique.

Methods

Applied impact forces to the head can lead to various reactions and injuries to the head and neck depending on the intensity, complexity, location, and direction of the forces. These injuries can target a wide range of layers such as skin, bone, brain layers, brain vessels, and structures (e.g., the eyes, nose, ears, and mouth). Various methods are used to study these effects on the human body [Motherway *et al.* 2009]. Among these, computer simulations have made significant contributions to medical, engineering, and sports science.

For simulation purposes, an appropriate model of the head and neck was required (Figure 1). Except for conditions and mechanical parameters of the athlete's foot strike, other requirements for head and neck impact were simulated in Mechanical Dynamics Incorporation (MSC) Automated Dynamic Analysis of Mechanical Systems (ADAMS) software (MSC Software Corporation, 2013 version), which has not been used in previous studies [Grujicic, Arakere 2010; Canavese 2004: 190]. It is worth noting that simulations conducted in earlier studies used finite element software, such as visual Nastran and Abaqus [Chen 2011: 51; Tanbakoosaz *et al.* 2015; Clark *et al.* 2015: 168-179], but from the perspective of multi-body dynamic analysis, notable research has been done. The current study used the ADAMS software model to determine the linear and rotational acceleration of the taekwondo roundhouse kick.

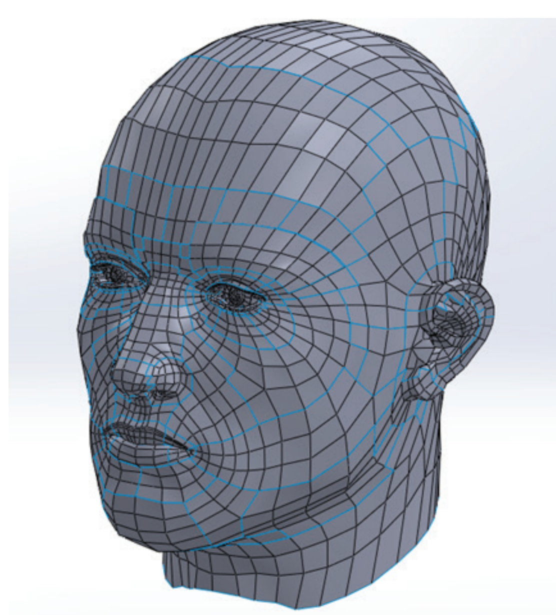

Figure 1. Model used for head and neck

Head properties such as hardness, material, the properties of hit (i.e., modulus of elasticity of skin and skull), damping factor in the impact, and other parameters are variables related to contact. Thus, accurate modeling of the neck and body is vital to understanding the impact of the taekwondo roundhouse kick. Modeling must respond to the actual conditions of the neck and the body in a state of shock. As noted above, because of the head’s connection to the neck and body, rotational acceleration is caused when impacts to the head occur. The behavior of the neck must therefore be determined when studying taekwondo roundhouse kicks to the head. To create a realistic model, the current study simulated neck and body characteristics and behavior with a clamped-free beam. Neck properties included equivalent flexibility, damping coefficient, mass, and length to simulate a roundhouse kick’s impact on the whole body.

Foot characteristics included effective length, rotational inertia, and foot end velocity at time of impact. The length, mass, and rotational inertia of foot were considered from athletes’ anthropometric data [Winter 2009: 384], which applies to approximately 50% of all men [Winter 2009: 384; Dempster 1955: 155-159]. Toe speed at contact time was considered to be between 13 and 16 m/s.

After determining the mechanical properties, system motion constraints were established. Leg rotation was calculated around the thigh axis with a rotational spring that had a coefficient of kθ. This design satisfied all actual conditions of the impact of a high taekwondo roundhouse kick during competition.

Table 1. Physical and mechanical parameters of organs simulated with the MSC ADAMS software model

Body part	Physical parameters
Neck and body	Equivalent length
	Equivalent material
	Equivalent diameter
Head and helmet	Diameter
	Stiffness
	Damping coefficient
	Penetration depth in impact
	Mass
Leg	Length
	Mass
	Moment of inertia around the hip
	Rotation angle for impact
	Spring coefficient at hip joint
	Pre-loading angle

MSC: Mechanical Dynamics Incorporation, ADAMS: Automated Dynamic Analysis of Mechanical Systems

The foot conditions and the force-time graph output were set at the same parameters as previous studies. Mechanical characteristics of head and neck impacts from roundhouse kick were thus reverse engineered and obtained. Table 1 presents the mechanical and dynamic properties of different components of the current study’s simulation. In fact, for this reason, these parameter values are changed in a logical bounds for a frictionless contact to adapted results with previous studies. The greatest impact force values obtained from this model are compared with previous models [Tsui, Pain 2012], as shown in Table 2, and indicate the accuracy of the current model.

Table 2. Comparison of simulation results in the current study using MSC ADAMS study with previous studies

Velocity (m/s)	Time of impact (ms)	Peak of impact force (N)
		Simulation in MSC ADAMS
12	25	5282
14	20	6048
16	18	7129

MSC: Mechanical Dynamics Incorporation, ADAMS: Automated Dynamic Analysis of Mechanical Systems

Finally, using the resulting model, the dynamic outputs, such as translational acceleration, rotational acceleration, and impact duration for desire condition and speed were obtained for this study. Results were compared and analyzed with the thresholds tolerance of head injury.

Results

Figure 2 illustrates that roundhouse kicks to head with a speed of 13 m/s produce a mean and peak of linear acceleration of 25 g and 99 g, respectively. Figure 3 shows that the average and peak of rotational accelerations of the head caused by these kicks was 1465 rad/s^2 and 4346 rad/s^2, respectively. The impact duration was specified as 23 ms due to the acceleration-time curve.

Figure 4 shows that if a roundhouse kick hits the head at 16 m/s, the head’s mean linear acceleration and peak linear acceleration are 33 g and 136 g, respectively. Also, Figure 5 illustrates that the average and peak rotational acceleration of the head are 2539 rad/s^2 and 5908 rad/s^2, respectively. The impact duration was specified as 18 ms due to the acceleration-time curve.

Linear and rotational acceleration that are generated in the head at 16 m/s were greater than them at 13 m/s, but the impact duration at 16 m/s was less than the impact duration at 13 m/s. By comparing the linear acceleration curves with the threshold tolerance curve of the head at these speeds, it can be stated that the acceleration created will be located below the linear acceleration threshold. Also, a comparison of the rotational acceleration-time curve to the rotational acceleration threshold values of the head concluded that the values obtained were within the head injury threshold.

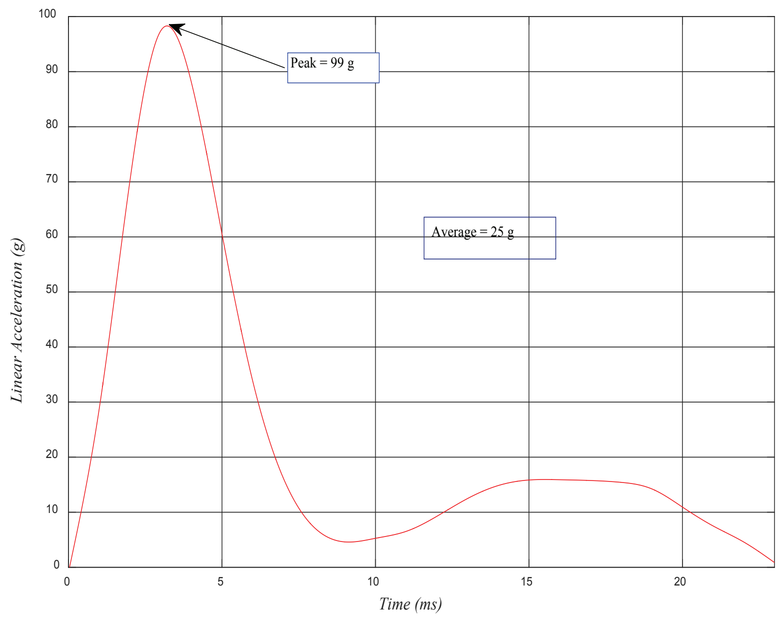

Figure 2. Linear acceleration of the head vs. time for 13 m/s impact velocity

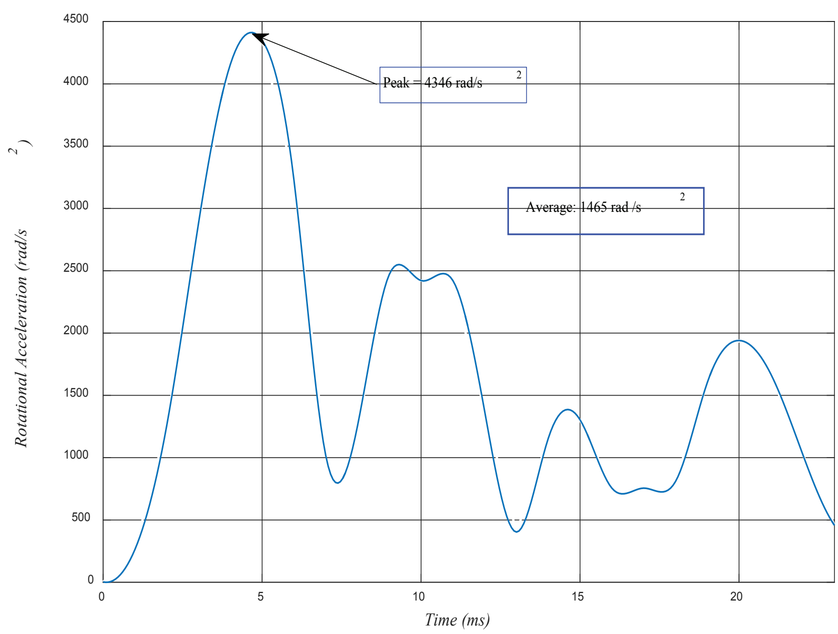

Figure 3. Rotational acceleration of the head vs. time for 13 m/s impact velocity

Discussion

The present study simulated the taekwondo roundhouse kick by using MSC ADAMS software and evaluating the linear and rotational acceleration responses on the head. The results showed that if a roundhouse kick impacts the head at 13 m/s, the average linear acceleration is 25 g per 23 ms (Figure 2).

As a result of extensive cadaver tests focusing on head acceleration, the Wayne State University Cerebral Concussion Tolerance Curve (WSTC) was established. Acceleration created in the head is located at the bottom of the curve. The WSTC indicates a relationship between the duration and the average anterior-posterior translational acceleration level that accounts for similar head injury severity in head contact impacts. Combinations of acceleration level and pulse duration that lie above the curve are thought to exceed the human tolerance; i.e., they cause severe, irreversible brain injury. Combinations below the curve do not exceed human tolerance, but may result in reversible injury. Therefore, the results of this study show the acceleration created in the head per 23 ms is located at the below of the curve, and therefore they cannot lead to damage [Gurdjian *et al.* 1955, Gurdjian *et al.* 1966].

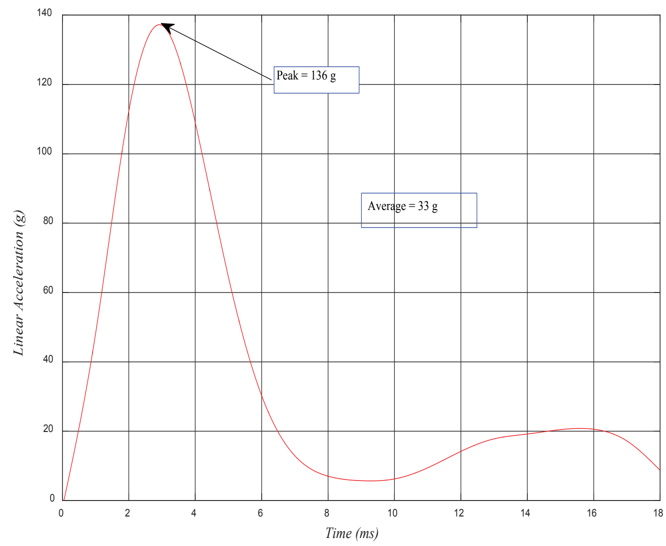

Figure 4. Linear acceleration of the head vs. time for 16 *m/s* impact velocity

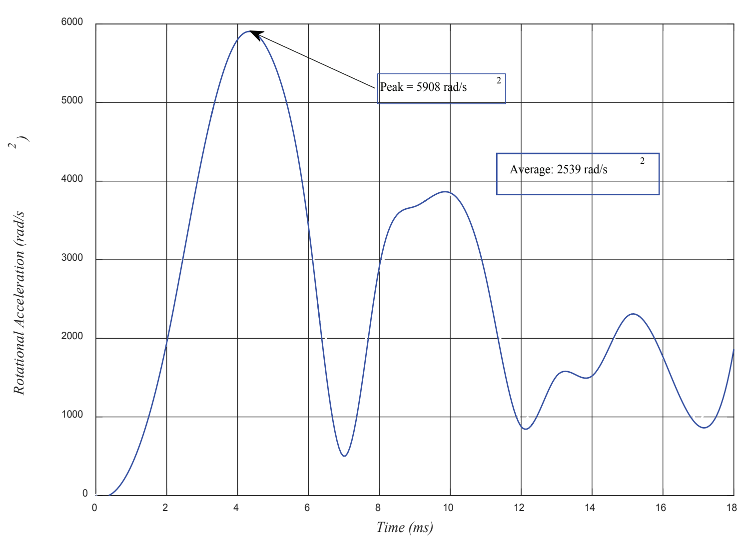

Figure 5. Rotational acceleration of the head vs. time for 16 *m/s* impact velocity

It should be noted that as a result of one blow, this type of acceleration is caused in the head. If the head is accelerated at this velocity frequently, it causes changes in brain tissue. The taekwondo roundhouse kick delivered at 13m/s produces a peak linear acceleration of 99 g per 2ms (Figure 2). According to the WSTC, irreversible damage is incurred with impacts to the head delivered to the head at 4 ms. Furthermore, analysis of linear acceleration-time (Figure 4) revealed that kicks with a velocity of 16 m/s produce an average linear acceleration and peak linear acceleration of head are 33 g and 136 g, with 18 ms and 1 ms respectively. As such, these accelerations are located at the below of the WSTC curve. Fife indicated that a mean linear acceleration of head produced by a roundhouse kick with a velocity of 11.9 m/s was 130.1 g [Fife 2010: 64]. Fife et al. also reported the mean linear acceleration resulting from a roundhouse kick to the head to be 130.11 g [Fife *et al.* 2013].

Gupta showed that the mean linear accelerations due to roundhouse kick delivered to a punching bag by men and women were 61.5 g and 53 g, respectively [Gupta 2011]. O'Sullivan *et al.* obtained a mean linear acceleration for taekwondo roundhouse and spinning back kicks of 95 g and 64 g, respectively [O'Sullivan *et al.* 2013]. The gained linear accelerations from the present study do not correspond to these previous studies, however. This might be due to the fact that previous studies used laboratory methods that are not free of subject and device errors. Further, previous studies have not reported on the duration of head acceleration, a very important role in the severity of injuries. In addition, mechanical properties of the head and roundhouse kick are not mentioned in these studies. On the other hand, the current study not only accounted for these variables but utilized computer simulation to further reduce errors of laboratory methodologies as well. Hence, the values reported in the present study should be more accurate.

The current study also showed that at speeds of 13 m/s produce average and peak rotational accelerations of the head at 1465 rad/s^2 and 4346 rad/s^2, respectively, whereas a speed 16 m/s kick changes the head acceleration to 2539 rad/s^2 and 5908 rad/s^2 (Figure 5), respectively. Currently, there are no standards for tolerance thresholds of head injuries based on rotational acceleration-time. This study analyzed rotational acceleration-time based on two values. According to Advani *et al.*, heads in angular acceleration between 2000 and 3000 rad/s^2 would result in brain surface shearing [Advani *et al.* 1982: 562]. According to Löwenhielm, head acceleration of 4500 rad/s^2 causes rupture of the bridging veins in the brain [Löwenhielm 1973]. Brain damage occurs at rotational acceleration peaks of 13-16 m/s, but brain damage only occurs if the average rotational acceleration is 16 m/s. O'Sullivan and Fife's investigation of rotational head acceleration in taekwondo and boxing showed that the average rotational acceleration from an impact to the side of the head covered with an Adidas helmet was 3554 rad/s^2 and to the front was 14010 rad/s^2 [O'Sullivan, Fife 2016]. These amounts were compared to the average rotational acceleration caused by boxing strikes to the head while wearing an Adidas helmet. That study found that boxing strikes to the side of the head were 7997 rad/s^2, while strikes to the front of the head were 5197 rad/s^2. The difference between the results of that study and the current research might be due to different measuring methods. The present study, for instance, calculated the delivered head acceleration whereas O'Sullivan and Fife estimated the value.

Conclusions

The WSTC only shows the translational acceleration tolerance, and a few studies have only considered the threshold of rotational acceleration. However, it is biomechanically improbable that the head would only be displaced translationally or rotationally as a result of a taekwondo roundhouse kick. In analyzing head injury mechanisms in sport, both transitional and rotational accelerations should be considered. The combination of these showed a lower threshold that it has not been noted in other studies. Hence, we recommend that future studies investigate both translational and rotational acceleration thresholds for head injuries. Other authors reported rotational acceleration leading to cerebral concussion [Ommaya *et al.* 2002], rupture of vessel junctions [Löwenhielm 1975], and shear the brain surface [Advani *et al.* 1982: 562]. Our data as well as current thresholds for head injury [Margulies, Thibault 1992] suggest that rotational acceleration is more important than translational acceleration when understanding the causes of brain injuries in taekwondo athletes [Advani *et al.* 1982: 562; Löwenhielm 1975; Ommaya *et al.* 2002]. The structure and physical properties of brain tissue are more resilient to direct and linear forces (compressive and tensile forces) than rotational and shearing forces. As such, the translational acceleration injury threshold is higher than the rotational acceleration threshold.

Meanwhile, to decrease the risk of brain injuries in taekwondo athletes, we recommend proper defensive techniques to be practiced and employed. We also recommend that taekwondo helmets should be designed to absorb more force and decrease the rotational acceleration.

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Dynamiczna reakcja na kopnięcie okrężne w głowę w czasie walki Taekwondo dokonana za pomocą symulacji komputerowej

Słowa kluczowe: przyspieszenie liniowe, przyspieszenie rotacyjne, uraz głowy, wstrząs mózgu, krzywa wstrząsów mózgowych wg Wayne State University (TST)

Streszczenie

Tło, problem i cel. W badaniach nad urazami głowy w sportach walki wykorzystano jedynie parametr przyspieszenia liniowego. Zastosowanie technik symulacji komputerowych może zapewnić dokładniejsze i bardziej wiarygodne informacje. W niniejszym badaniu przeanalizowano liniowe i rotacyjne przyspieszenie w czasie kopnięcia okrężnego w *taekwondo* za pomocą oprogramowania automatycznej analizy dynamicznej systemów mechanicznych (ADAMS).

Metody. Model oprogramowania ADAMS został wykorzystany do określenia liniowego i rotacyjnego przyspieszenia w trakcie kopnięcia okrężnego w *taekwondo*.

Wyniki. Analiza krzywych przyspieszenia liniowego i rotacyjnego wykazała, że szczytowe przyspieszenie liniowe, średnie przyspieszenie liniowe, maksymalne przyspieszenie obrotowe i średnie przyspieszenie obrotowe wynikające z kopnięcia okrężnego głowy przy prędkości stopy wynoszącej 13 m/s to odpowiednio 99 g, 25 g, 4346 radów/s^2 i 1465 radów/s^2. Przy prędkości stopy 16 m/s przyspieszenia te wynosiły odpowiednio 136 g, 33 g, 5908 rad/s^2 i 2539 radów/s^2. Również czas uderzenia przy prędkościach 13 m/s i 16 m/s wynosił odpowiednio 23 ms i 18 ms.

Wnioski. Jest biomechanicznie nieprawdopodobne, żeby głowa została przemieszczona translacyjnie lub obrotowo w wyniku kopnięcia w *taekwondo*. Niemniej jednak należy rozważyć oba przyspieszenia. Także porównanie wyników tego badania z progami tolerancji przyspieszenia przy urazach głowy wskazuje, że tylko przyspieszenie rotacyjne może powodować uraz głowy. Zwłaszcza przy wysokich prędkościach stóp przyspieszenie rotacyjne może doprowadzić do wstrząsu mózgu i naruszenia powierzchni mózgu.