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BIOMECHANICS

Neda Boroushak[1(ABCDEFG)], Hasan Khoshnoodi[2(ABD)], Mansour Eslami[3(G)], Mohsen Kazemi[4(E)]
1 ORCID: 0000-0003-3953-722X
Department of sports biomechanics, Sport Science Research Institute, Tehran (Iran)
2 ORCID: 0000-0001-5035-8113
Department of Mechanical Engineering, Shoushtar Branch, Islamic Azad University, Shoushtar (Iran)
3 ORCID: 0000-0002-8050-7076
Faculty of Sports Sciences, University of Mazandaran, Babolsar (Iran)
4 ORCID: 0000-0003-0245-2281
Faculty of Graduate Studies and Research, Canadian Memorial Chiropractic College, Toronto (Canada)
Corresponding author: Neda Boroushak, Department of sports biomechanics, Sport Science Research Institute, Tehran, Iran;
e-mail: nedaboroushak@yahoo.com

Comparison of dynamic parameters related to head injuries using four common styles of commercial taekwondo headgear in a simulated protocol roundhouse kick

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Key words: impact force, linear acceleration, rotational acceleration, roundhouse kick, taekwondo, headgear

Abstract
Background, Problem and Aim. Despite the use of four types of headgear in taekwondo. A high prevalence of head injuries has been reported in competitions. It is important to ensure that headgear can effectively reduce the parameters related to head injuries. However, headgear is usually evaluated only based in linear acceleration at the moment of collision and on an unreal competition situation. The purpose of this study is to investigate and compare some selected dynamic parameters related to head injury among four types of common taekwondo headgear in a simulated protocol.
Methods. A device included an artificial head equipped with force and acceleration sensors and a lever arm to simulate roundhouse kick skill, was used. Before testing the four types of headgear, the foot force of 15 taekwondo elite male athletes with a mean weight of 77.7 ± 6.27 Kg and height of 182.1 ± 5.05 cm was obtained. The device then delivered 10 impacts to the artificial head with and without the four types of headgear. One-way repeated measures ANOVA and Bonferony were used for statistical analysis.
Results. All four headgear reduced maximum impact force and maximum linear acceleration by more than 80% ($p< 0.01$) as compared to no headgear condition. Furthermore, headgear A (density 86 kg/m^3, thickness 20 mm and mass 0.203 kg) and B (density 125 kg/m^3, thickness 37 mm and mass 0.293 kg) reduced maximum rotational acceleration about 7.47% and 23.6% respectively, while C (density 65 kg/m3, thickness 20 mm and mass 0.190 kg) and D (density 58 kg/m3, thickness 18 mm and mass 0.150 kg) increased it by 57.8 and 85%, respectively, when compared to no headgear condition ($p< 0.01$). Headgear B with the highest thickness, density and mass has the best performance in reducing impact force, and linear and rotational accelerations (23.64%, 3555 rad/s^2).
Conclusion. All Taekwondo headgear tested in this study provided sufficient protection against injuries caused by impact force and linear acceleration, but not against rotational acceleration. Only headgear B reduced the rotational acceleration by about 24%.

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Introduction

Despite the use of various types of headgear in combative sports, high prevalence of injuries resulting from repetitive blows to the head has been reported in competitions. *Taekwondo* is considered to be one of the most popular martial arts [Feehan, Waller 1995]. The risk of head injury may be more frequent in taekwondo due to the assignment of 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]. The roundhouse kick is the most commonly associated kick with mild traumatic brain injury in taekwondo competitions [Tanbakoosaz *et al.* 2015]. These statistics indicate a serious risk to the health of taekwondo athletes. One of the methods of preventing brain injuries and reducing the resulting economic costs is the utilization of proper and standard headgear.

It is necessary to know and evaluate the amount of impact absorption of headgear in taekwondo and its possible protective properties against head injuries. However, it seems that the standards and methods of examining these headgear have not been able to meet all the safety requirements of athletes in sports fields. There are currently headgear with different brands that are evaluated by the American Society for Testing and Materials (ASTM) [O'Sullivan *et al.* 2013]. In 2012, the protective quality of five types of headgear in Taekwondo was examined by the World Taekwondo Federation [Gupta 2011].

McIntosh *et al*. in a study examining the impact absorption performance of 7 types of headgear in combat sports reported the mean peak acceleration for the frontal and lateral rigid anvil impact tests to be between 32% and 40% lower for the top ten boxing model compared with the Adidas boxing model [McIntosh, Patton 2015]. Despite several studies on taekwondo headgear, their effectiveness in preventing head injuries is still unknown [Gupta 2011; McIntosh, Patton 2015; O'Sullivan *et al.* 2013].

In the investigation of dynamic parameters related to head injury, it was found that brain injury was due to linear and rotational accelerations of the head and neck [Schmitt *et al.* 2019]. Linear acceleration is used to assess focal brain injury and rotational acceleration for diffuse and severe damage such as axonal damage and bleeding vascular structures.

Traumatic head injuries are typically associated with cognitive, behavioral, and motor control impairments from 24 hours to 10 days after injury and if it is repeated, may be associated with severe impairments such as Mild Traumatic brain injury and memory impairment [Denny-Brown, Russell 1940]. These injuries usually prevent the athletes from training or competing. Therefore, the use of headgear that reduces the parameters of injury may help to prevent irreparable damage.

There are currently studies on the effect of helmets on linear acceleration to prevent head injuries [Gupta 2011; McIntosh, Patton 2015; O'Sullivan *et al.* 2013]. However, the effect of headgear on important dynamic parameters such as rotational acceleration and impact force is still unclear. With the assignment of higher points to successful kicks to the head in taekwondo the impact force may be an important factor in head injury [Viano *et al.* 2005]. On the other hand, injuries may occur due to secondary impact effects (linear acceleration and rotational acceleration). As a result, it is necessary to investigate the effect of headgear on each of the dynamic parameters associated with head injury in order to prevent injury in taekwondo. Accordingly, in the present study, the effect of using headgear in taekwondo on the dynamic parameters related to head injury was investigated.

Methods

The present study is quasi-experimental. Before performing the main test, it was necessary to know the maximum foot strength of taekwondo practitioners. For this purpose, 15 male taekwondo athletes entered the study by completing the informed consent form. Of these, 14 athletes (age range of 18-30 years) were selected according to Morgan's table [Hadavi 2011]. Inclusion criteria were having the first to third place in the selection of the country's national team. The exclusion criteria were having any postural and musculoskeletal disorders and/or deformities of the lower body such as Genu Varum and Genu Valgum, flat feet, chronic ankle sprain, fracture, dislocation, and diseases such as osteoarthritis and shin splint.

Before collecting data, this study was approved by the review board of Guilan University of Medical Sciences based on the principles of human ethics (IR.GUMS. REC.1396.284).

In this study, 4 types of common types of headgear in Taekwondo were used (table 1). The thickness, density and mass of headgear A (made in Germany) were 20 mm, 86 kg / m^2 and mass 0.203 kg, respectively. Headgear B was made in Spain and had a thickness of 37 mm, a density of 125 kg/m^3 and a mass of 0.293 kg. Headgear C was made in Iran with a thickness of 20 mm, a density of 65 kg/m^3 and a mass of 0.190 kg. Headgear D was also made in Iran, with thickness, density and mass of 18mm, 58 kg/m^3 and 0.150 kg, respectively. Prior to the tests, participants were instructed on the methods and procedures.

To investigate the effect of using headgear in taekwondo on dynamic parameters related to head injury, a device consisting of an artificial head and neck equipped with accelerometers and a mechanical arm (length 95 cm, mass 12.4 kg, moment of inertia 3 kg/m^2) representing the taekwondo foot was developed by the principle author (Figure 1). A three-axis acceleration sensor (ADXL 375, Analog Device Company, USA) was used to measure the linear acceleration of the head. A gyroscope module (MPU 6050, Invensense Company, USA) was used to measure the rotation of the head, and a flexi-force sensor (A 401, Tekscan Company, USA) was used to measure the force. MATLAB program computer system was used to evaluate, monitor and record information and the results of data analysis. In order to measure the variables simultaneously, the sensors were matched with each other and the sampling speed at the time of data collection from the device was considered to be 1000 Hz.

Table 1. Four common types of headgear used in Taekwondo

Headgear	Thickness *mm*	Density *kg/m^3*	Mass *k*
	20	86	0.203
	37	125	0.293
	20	65	0.190
	18	58	0.150

To ensure the validity of the results of the device, the model of the head and neck and striking arm was designed in SolidWorks program version 16 (System Dassault company, France) and simulated using Adams software version 2013 (MSC company, American). By applying the force of a foot strike to the head, the maximum linear and rotational accelerations caused by the device and simulation were obtained and their results were compared with each other.

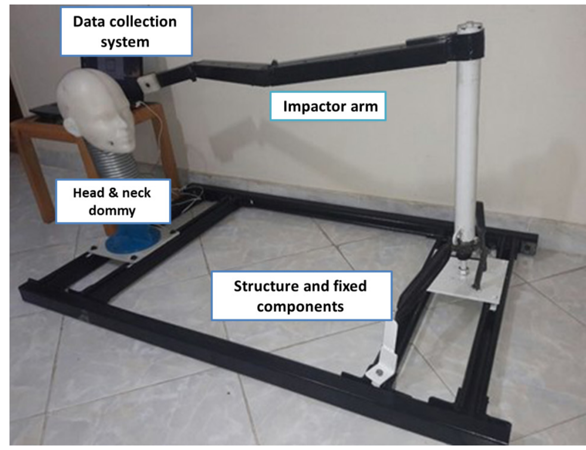

Figure 1. The test device and its components

To ensure the reliability of the device, four strikes were applied to each of the 45, 60, 75, and 90 degrees angles. The correlation coefficient was 0.7, which indicated adequate reliability of the device.

After 10-minute warm-up, the athletes performed 10 roundhouse kicks to a kicking bag equipped with a force sensor. The maximum foot force of taekwondo practitioners was obtained and the average of these values was used for the next stages of the experiment. To measure the linear and rotational accelerations resulting from the impact, the average force measured by the subjects was applied to the dummy head through the lever arm in 10 repetitions without the headgear and with each headgear [Hadavi 2011].

Descriptive statistics and inferential statistics tests were used to analyze the data. Shapirovilk test was used to normalize the data distribution. One-way repeated measures ANOVA and Bonferroni tests were used to evaluate the effect of using headgear on impact force, linear, and rotational accelerations. Data were analyzed using SPSS software version 20 (version 20, SPSS Inc., Chicago, IL). $P < 0.05$ was considered as a significant level.

Results

In this study, 14 taekwondo practitioners (mean age 27.77±1.04 years, height 182.11±5.05 m, weight 77±6.27kg) participated. The average maximum force of their kicks was 5660±300 Newtons.

The results of device validity are shown in Table 2. The average rotational acceleration error of the device compared to the simulation results was 3.4% for maximum linear acceleration and 2.2% for maximum rotational acceleration. This indicates that the device has proper accuracy. The impact force, linear acceleration and rotational acceleration were obtained by applying the pre-obtained impact force (5660 N) to the dummy head with and without headgear. There was a significant difference between the mean maximum impact force, linear acceleration and maximum rotational acceleration of the headgear compared to no headgear (p<0.001, table 3). There was no significant difference between the mean maximum impact force of headgear A, B, C, and D (P≥0.05; figure 2). Each of the headgear A, B, C, and D were able to reduce the impact force by 88.43%, 92.14%, 87.2% and 83.2% respectively; with headgear B being the most effective.

Table 2. comparison of the results in simulation and device test

Average error percentage		**Peak of rotational acceleration (rad/s²)**		Peak of linear acceleration (g)		Impact Force (N)
rotational acceleration	linear acceleration	Device	Simulation	Device	Simulation	
2.2	4.3	1367	1367	37	34	2000
		1813	1813	47	44	2500
		2352	2321	52	53	3000
		2890	2792	64	61	3500
		3416	3255	75	72	4000
		4507	4351	102	99	5600

Table 3. One-way variance analysis test with repeated measures of maximum impact force, maximum linear acceleration and maximum rotational acceleration in four types of taekwondo headgear

p value	**Peak of rotational acceleration (rad/s²)**	Peak of linear acceleration (g)	Peak of Impact Force (N)	Variable
< 0.001*	4656.22±15	104.4±5.1	5660.46±210	No headgear
	4308.31±13	8.49±1.01	655.16±30	Headgear A
	3555.81±11	6.34±0.9	432.20±19	Headgear B
	7351.38±30	11.24±1.1	725.62±32	Headgear C
	8642.19±43	13.62±1.3	954.56±44	Headgear D

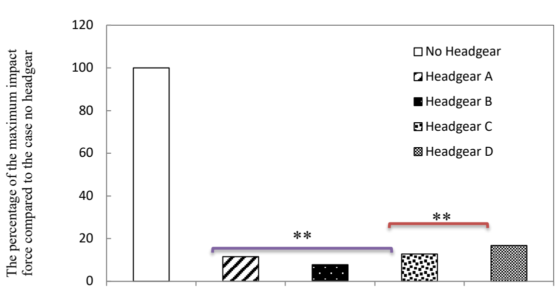

Figure 2. Histogram showing the differences in percentage of the maximum impact force compared to the case no headgear. Statistically significant value is defined at the 0.05 level. ** Absence of significant difference in columns

Figure 3 indicated no significant difference between the mean maximum linear acceleration of headgear A, B, C, and D. In addition, there was no significant difference between the mean linear maximum acceleration of headgear A, B, C, and D (P≥0.05). Each of the headgear A, B, C, and D were able to reduce the maximum linear acceleration by 91.83%, 93.90%, 89.19% and 86.90% respectively. Headgear B showed a greater decrease in maximum linear acceleration than headgear C and D as well as headgear A than headgear D. There was a significant difference (P≤0.05) between the mean maximum rotational acceleration of each headgear with the pre-headgear position and also each of headgear together (Figure 4). Headgear A and B were able to reduce the maximum rotational acceleration by 7.47% and 23.64% respectively, compared to no headgear. However, headgear C and D increased the maximal rotation acceleration by 57.88 and 85% compared to no headgear, respectively. (P=0.01)

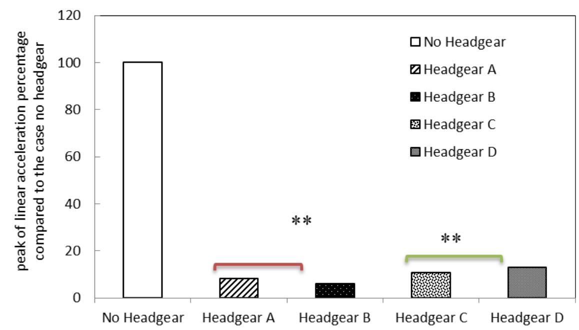

Figure 3. Results show the differences in peak of linear acceleration percentage compared to the case no headgear. Statistically significant value is defined at the 0.05 level. ** Absence of significant difference in columns

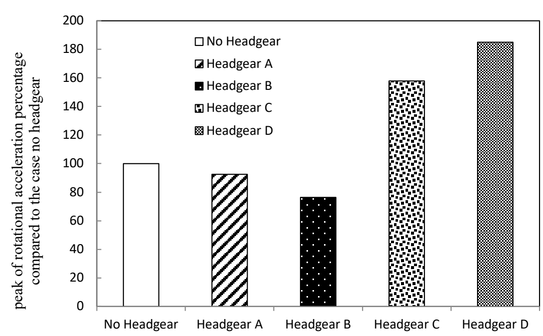

Figure 4. Results show the differences in peak of rotational acceleration percentage compared to the case no headgear. Statistically significant value is defined at the 0.05 level.

Discussion

The aim of the present study was to investigate the effects of headgear used in taekwondo on dynamic parameters related to head injury. For this purpose, a device consisting of a head and neck equipped with acceleration and force sensors and a lever arm for impact was made by the main author. We found that the headgear we tested reduced the maximum impact force by 83.2-92.4%. To the authors' knowledge, this is the first study to investigate the absorption force of the headgear impact in taekwondo. Similarly, McIntash *et al.* reported a reduction of forces in boxing helmets [McIntosh, Patton 2015].

The maximum threshold impact force of the lateral head for a skull fracture has been reported to be 3600 Newtons [Nahum *et al.* 1968]. According to the results obtained in this study, it is expected that all headgear has good protective properties against injuries caused by impact force (Table 2). Meanwhile, headgear B with the greatest thickness has the greatest effect in reducing the impact force. When the foot hits the head, the contact force is applied directly to the head, causing local injury. While placing the headgear on the head, this force is spread on the surface of the headgear and greatly reduces the possibility of local injury. On the other hand, as the thickness of the headgear increases, its surface area increases, and in this way, the amount of force absorbed by the impact force of the helmet increases, possibly resulting in a decrease in head injury.

All headgear was able to significantly reduce the maximum linear acceleration (between 86.90 % to 93.90%; table 2) to a level below the linear acceleration damage threshold [O'Sullivan, Fife 2016]. A study by O'Sullivan *et al.*, As well as O'Sullivan and Fife, stated that taekwondo headgear cannot reduce linear acceleration below the threshold of head injury, which is inconsistent with the results of our study [O'Sullivan *et al.* 2013; O'Sullivan, Fife 2016]. The reason for the discrepancy may be due to the different strengths of the subjects' neck muscles as few researchers believe that strong neck muscles could decrease head linear acceleration [Schmitt *et al.* 2019]. Another discrepancy in these results may be due to differences in the type of headgear, shape and geometry of the dummy head, and most importantly the method of testing them. The researchers used the American Testing and Materials Association standard to perform the helmet impact test which is acceptable for headgear with a linear acceleration of less than 150 g at high energies (144 j) and less than 50 g at low energies (56.25 j). Therefore, the headgear studied in their research could not reduce linear acceleration based on this criterion [O'Sullivan *et al.* 2013; O'Sullivan, Fife 2016]. Headgear B with the highest mass compared to other headgear showed a greater effect on the reduction of maximum linear acceleration [Meriam, Kraige 2007]. According to the law of inertia, the greater the mass of an object, the greater its inertia. Inertia is an inherent property of matter and is the resistance that each object exhibits in proportion to its mass to maintain its current state. Whether it is a state of stagnation or a state of uniform forward motion in a straight line. Therefore, as the headgear mass increases, it is expected that the headgear inertia against the impact force of the foot will increase, resulting in less linear acceleration. Although the results of this study show that headgear A and B reduced the rotational acceleration of the head but they have not been able to reduce the acceleration below the threshold of concussion (1800 rad/s^2) [Ommaya *et al.* 2002]. The effect of C and D headgear on the maximum rotational acceleration showed an increase compared to the state without a headgear; the use of these headgear carries the risk of serious brain damage such as ruptured communication veins [Lowenhielm 1975]. One possible reason for the increased rotational acceleration of the headgear could be that during the impact, part of the mechanical energy transferred to the head is absorbed by the headgear as internal energy and the remaining energy is converted to the sum of the linear and rotational kinetic energy of the head. Due to the significant reduction in the linear acceleration of the head by the headgear, the linear kinetic energy is significantly reduced. According to the law of conservation of energy, the mechanical energy of the foot must be equal to the energy produced in the head and headgear; As a result, with decreasing linear kinetic energy, the share of rotational kinetic energy will increase. In other words, the amount of linear kinetic energy that is reduced will be converted to the internal energy of the headgear and the rotational kinetic energy of the head. In this case, the structure of the material used in the headgear absorbs a certain amount of energy and the rest of this energy appears as a rotation of the head, thus leading to an increase in rotational acceleration.

Therefore, the use of headgear in taekwondo, most likely, does not play an effective role in preventing injuries caused by rotational acceleration. Since the present study is the first research that examined the effect of using helmets in taekwondo on maximum rotational acceleration, it is not possible to compare it with past research in this particular issue. However, in similar research on boxing headgear, the results of the present research are in line with the study of Hoshizaki *et al.* [2014]. But it is contrary to the study of McIntosh *et al.* [McIntosh, Patton 2015]. In other words, McIntosh *et al.* showed that boxing headgear can reduce the risk of concussion in boxer athletes. One of the reasons for the disagreement between the results of this study and the current research may be the difference in the type of technique, the type of headgear, or perhaps the criteria for the threshold of head rotational acceleration damage. Considering that the head in taekwondo is exposed to frequent kicks during training sessions, the lack of proper protection of headgear against rotational acceleration is considered a serious threat to the health of taekwondo athletes. The impact of repeated blows to the head, rehabilitation time and cost for head injuries and psychological consequences of inability to return to sport are devastating on athletes. As such, it is necessary to find ways to prevent these injuries. Developing a helmet with high impact absorption and reducing rotational acceleration below the head injury threshold may be one of the most effective ways to prevent brain injuries.

Conclusion

Headgear B with the highest thickness, density, and mass has the greatest effect in the reduction of impact force, linear acceleration, and rotational acceleration. However, none of the headgear was able to reduce rotational acceleration below the concussion threshold (1800 rad/s2). The design of headgear should take into account both linear and rotational acceleration parameters due to the importance of rotational acceleration in head injuries.

This is the first study to measure both linear and rotational accelerations in evaluating headgear in taekwondo. As such, our methodology can efficiently replace prior methods in evaluating any headgear in combat sports.

Authorship Statement

No potential conflict of interest exists for this study. The questionnaire and methodology for this study were approved by the Human Research Ethics committee of the Guilan University of Medical Sciences (Ethics approval number: IR.GUMS.REC.1396.284).

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Porównanie parametrów dynamicznych związanych z urazami głowy w czterech popularnych komercyjnych kaskach ochronnych do taekwondo w symulowanym protokole kopnięcia okrężnego

Słowa kluczowe: siła uderzenia, przyspieszenie liniowe, przyspieszenie rotacyjne, kopnięcie okrężne, taekwondo, nakrycie głowy/kask ochronny

Streszczenie

Tło, problem i cel. Pomimo stosowania czterech rodzajów kasków ochronnych do taekwondo, podczas zawodów odnotowano wysoką częstotliwość występowania urazów głowy. Ważne jest, aby upewnić się, że nakrycia głowy mogą skutecznie zmniejszyć parametry związane z urazami głowy. Jednak kaski są zwykle oceniane tylko na podstawie przyspieszenia liniowego w momencie zderzenia i nierealnej sytuacji podczas zawodów. Celem tego badania było zbadanie i porównanie niektórych wybranych parametrów dynamicznych związanych z urazami głowy w czterech typach popularnych kasków ochronnych do taekwondo w symulowanym protokole.

Metody. Użyto urządzenia zawierającego sztuczną głowę wyposażoną w czujniki siły i przyspieszenia oraz ramię dźwigni do symulacji umiejętności kopnięcia okrężnego. Przed przetestowaniem czterech rodzajów nakryć głowy, uzyskano siłę nacisku na stopę u 15 elitarnych zawodników taekwondo o średniej wadze 77,7 ± 6,27 kg i wzroście 182,1 ± 5,05 cm. Następnie urządzenie wykonało 10 uderzeń w sztuczną głowę z czterema rodzajami kasków ochronnych i bez nich. Do analizy statystycznej wykorzystano jednoczynnikową analizę wariancji ANOVA i Bonferony.

Wyniki. Wszystkie cztery nakrycia głowy zmniejszyły maksymalną siłę uderzenia i maksymalne przyspieszenie liniowe o ponad 80% (p<0,01) w porównaniu do sytuacji bez kasku. Co więcej, kaski A (gęstość 86 kg/m^3, grubość 20 mm i masa 0,203 kg) i kaski B (gęstość 125kg/m^3 , grubość 37 mm i masa 0,293 kg) zmniejszyły maksymalne przyspieszenie obrotowe odpowiednio o 7,47% i 23. 6%, podczas gdy C (gęstość 65 kg/m^3, grubość 20 mm i masa 0,190 kg) i D (gęstość 58 kg/m^3, grubość 18 mm i masa 0,150 kg) zwiększyły je odpowiednio o 57,8 i 85% w porównaniu do stanu bez kasku (p< 0,01). Kask B o największej grubości, gęstości i masie ma najlepszą skuteczność w zmniejszaniu siły uderzenia oraz przyspieszeń liniowych i obrotowych (23,64%, 3555 rad/s^2).

Wnioski. Wszystkie kaski ochronne do taekwondo testowane w tym badaniu zapewniały wystarczającą ochronę przed urazami spowodowanymi siłą uderzenia i przyspieszeniem liniowym, ale nie przed przyspieszeniem obrotowym. Tylko kask ochronny B zmniejszył przyspieszenie rotacyjne o około 24%.