ORIGINAL SCIENTIFIC PAPER

Assessing the Effect of Head and Neck Orientation on Head Injury Parameters in Taekwondo

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Abstract

Background: Brain injuries may be caused by the linear and rotational acceleration of the head and neck; in fact, head and neck orientation are one of the factors determining the type and severity of brain injury when the impact delivered to head is a less important consideration. This investigation has analyzed the effect of head and neck orientation on linear and rotational acceleration in Taekwondo. Methods: The ADAMS software model has been used to determine the linear and rotational acceleration in the taekwondo roundhouse kick in various orientations. Results: The results revealed that the maximum linear and rotational acceleration was related to neck 0° were 99g, and 4576$\frac{rad}{s^2}$, respectively. The head and neck orientation did not affect the magnitude of the linear and rotational acceleration in the sagittal plane. However, as the angle of the head and neck orientation increased in the frontal plane, the magnitude of the linear and rotational acceleration decreased. Conclusion: In general, the results indicate that only rotational acceleration was the cause of brain injury in taekwondo. Increasing the angle of orientation of the head and neck in frontal plane would lead to a reduction in intensity.

Keywords: *ADAMS software model, Brain injuries, Taekwondo, Orientation, Roundhouse kick*

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Introduction

In combat sports like taekwondo and boxing, intense head injuries have been the primary concern of sports administrators. Athletes are exposed to severe and repeated impacts to the head (Pieter, Fife, & O'Sullivan, 2012; Walilko, Viano, & Bir, 2005). Rider stated that the occurrence of head and neck injuries is 21.4 per 1000 athlete exposures among male taekwondo athletes and even among females it is 16.9 per 1000 (Pieter et al., 2012).Moreover, Kooh and Cassidy have reported that the concussion incidence in taekwondo competition is approximately four times greater than American football (Koh & Cassidy, 2004). The roundhouse kick is most commonly associated with mild traumatic brain injury in taekwondo competition (Pieter et al., 2012).

A concussion is known as a pathophysiological process leading to disorders of neurological function. It occurs due to

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severe biomechanical effects on the head, neck or face (Pieter et al., 2012). A few modern studies associated with the biomechanics of head injury and sport-relevant concussion in combat sports and martial arts have provided insights into the mechanisms of head injuries (Fife, 2010). It has been found that brain injuries are caused by the linear and rotational acceleration of the head and neck (Schmitt, Niederer, Muser, & Walz, 2019). Moreover, it has been determined that the impact force parameter is the cause of skull damage7. Rotational acceleration is considered to produce both focal and diffuse brain injuries, while linear acceleration produces focal brain injuries (Schmitt et al., 2019).The nature of most head injuries, as displayed in HIC and the Wayne State Tolerance Curve, are explained by these accelerations (Schmitt et al., 2019). Boroushak et.al has stated that rotational acceleration and linear acceleration in $4656\frac{rad}{s^2}$, and 104.4 g respectively resulting from a roundhouse kick to the head causes injury in taekwondo (Boroushak, Eslami, Kazemi, Daneshmandy, & Johnson, 2018). O'Sullivan et.al in his investigation entitled; "Biomechanical head impact characteristics in taekwondo", has indicated that of 461 (66.9%) impacts delivered to the head, rotational acceleration is less than $4600\frac{rad}{s^2}$,, and that of 121 (17.1%) are between 4600 and $7900\frac{rad}{s^2}$, and of 107 impacts (15.5%) are greater than $7900\frac{rad}{s^2}$. furthermore, they have noted that linear acceleration (87.1%) ranging between 10g and 39g, 66 (9.6%) impacts ranging between 40g and 69g, and 23 (3.3%) above 70g (O'Sullivan & Fife, 2016). Due to the unpleasant nature of brain injury and its irreversible symptoms and effects, examination of the mechanism of brain injury in humans remains a critical issue.

Furthermore, an accurate understanding of the parameters associated with brain injury, necessitates a rigorous investigation of the factors affecting these parameters. With regards to the head impact, the effective mass of the impact, the material of the impactor and its velocity, the locations, and direction of the impact, as well as the orientation of the head and neck to the body, are all important factors affecting the biomechanical parameters of the head injury (Green & Angelaki, 2004; Leonardi et al., 2012; Williams & Kirsch, 2008). Despite numerous investigations on the biomechanics of head injury, there are still many uncertainties about the effect of some factors upon brain injury, especially in martial arts.

Among a variety of parameters, the head and neck orientation are the most important factors in determining the type and severity of brain injury when an impact delivered to head. Unfortunately, it has been almost totally ignored. In previous research, diverse angles of the head and neck about an axis perpendicular to the impact plane when impact applied to head were discussed as well as their effects on acceleration (Green & Angelaki, 2004; Leonardi et al., 2012; Walsh, Rousseau, & Hoshizaki, 2011; Williams & Kirsch, 2008). This orientation has been covered in research on the effects of explosions on head and brain injury factors as well (Leonardi et al., 2012). Some studies also have examined the direction and severity of a head collision with the ground in falls (Wright & Laing, 2012). The conclusions of all the researchers confirm the massive influence of the head and neck orientation on the probability and severity of brain injury.

Consideration of the importance of brain injuries in the popular sport of taekwondo, the effects of head and neck orientation during impact should be study. The changes in the athlete's head and neck orientations during foot impacts in competitions, and the relationship of significant head injury to acceleration magnitude will be addressed in this paper. The impact of the roundhouse kick's foot to the head in various orientations of the athlete's head and neck will be studied, and then effect of this orientation on the linear and rotational acceleration magnitude will be discussed. In this way, it is possible to obtain better information about the amount of head and neck injuries of athletes in the field of competition in order to prevent these injuries by making the right decisions and making the right equipment.

Materials and Methods

In the present research, a computer simulation method has been used. Except for conditions and mechanical parameters of the athlete's foot strike, the other requirements for the head and neck impact were simulated in Mechanical Dynamics Incorporation (MSC) Automated Dynamic Analysis of Mechanical Systems (ADAMS) software (MSC Software Corporation, 2013 version). For the simulation target, an appropriate model of the head and neck was required. Head attributes like hardness, material, the properties of the impact (i.e., modulus of

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

Body part	Physical parameters	Parameter dimensions
Neck and body	Equivalent length	30 cm
	Equivalent material	Steel
	Equivalent diameter	1 cm
Head	Diameter	25 cm
	Stiffness	200 N/m
	Damping coefficient	12
	Penetration depth in impact	4 cm
	Mass	5 kg
Leg	Length	95 cm
	Mass	12.4 kg
	Moment of inertia around the hip	3 kg.m^2
	Rotation angle for impact	270°
	Spring coefficient at hip joint	900 Nm/degree (for 13 m/s) 1350 Nm/degree (for 16 m/s)
	Pre-loading angle	20°

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elasticity of skin and skull), damping factor in the impact, and other elements were examined. Neck attributes contained equivalent flexibility, damping coefficient, mass, and length, to simulate a roundhouse kick's impact, Foot specifications subjected length, mass, rotational inertia, and foot end velocity at the time of impact. These attributes were derived from former studies and the outcome confirmed by this research (Boroushak et al., 2018). In this model, the dynamical and mechanical properties of head, neck and foot of human in a sport impact are presented (Table 1). This dynamic model of multi-body system is used for simulating Roundhouse kick impact in taekwondo.

For verifying this model, the peak of impact force in visual Nastran simulation and MSC ADAMS software are compared (Table 2) and results indicate the accuracy of the proposed model.

Table 2. Comparison of simulation results in the MSC ADAMS study with previous study (Boroushak et al., 2018)

velocity of foot (m/s)	time of impact (ms)	Peak of Impact Force (N)	
		simulation in MSC ADAMS	simulation in visual Nastran (Tsui & Pain, 2012)
12	25	5282	5620
14	20	6048	6380
16	18	7129	6810

For more insurance to validity of this model, the incline-sled apparatus test (Sato et al., 2014a) is simulated in ADAMS software and the proposed model is compare by the results of experimental test. This test is analyzed the dynamic of cervical vertebral motion during low-speed rear impact.

The anthropometry properties of head and neck are obtained from anthropometric table (Schmitt, Niederer, Cronin, Muser, & Walz, 2014) for average of height and weight of volunteers in (Sato et al., 2014a) and model of software are adopted by these properties. Some markers are posited in the locations as experiment are (Ono & Kaneoka, 1999) and used for Extract the results. Then, the conditions of incline-sled apparatus test are get ready in software and the sled from the top of the rails is released. It moved in effect of gravity force and a hydraulic damper decelerated the sled in the end of rails. Displacements and the linear and rotational velocity and acceleration of model are obtained from markers. The results are shown good accuracy by comparison the experimental test (Table 3).

Table 3. Comparison of simulation by experimental results

	Impact velocity= 4 km/h		Impact velocity= 6.2 km/h	
	Computer simulation	Experimental test (Ono & Kaneoka, 1999)	Computer simulation	Experimental test (Sato et al., 2014b)
Time of sled acceleration peak (s)	50	50	45	46
Time of head (C.G.) acceleration peak (s)	102.5	110	84.3	80
sled acceleration peak (m/s^2)	20	22	30	27
head (C.G.) acceleration peak (m/s^2)	34.7	32	53	50
Maximum of head rotational angle (degree)	22	20	42	35

Description: seatback angle from the vertical= 20 degree, sled angle from the horizontal= 10 degree and incline rail length= 4 m

So, the proposed model is ready to use in other orientation of head and neck relative to human body.

To explore the orientation of the head and neck, three main axes that determine its angles relative to the reference position were considered (fig. 1).

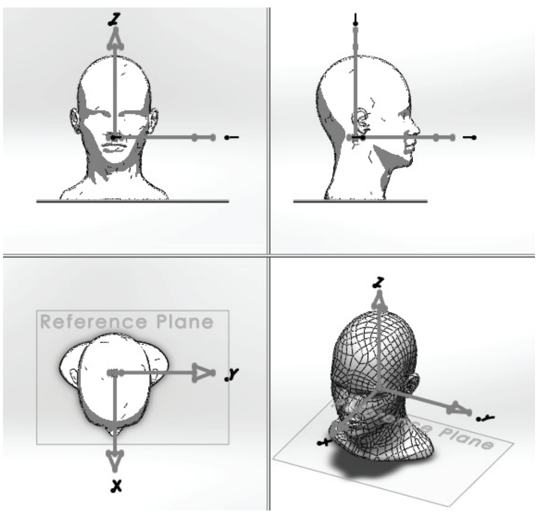

Figure 1. Three main axes of the head to determine the angles of orientation in impact moment

Euler ZXZ angles were used to rotate the head and neck set. The set rotates around the Z-axis, then by β about the X ‘axis and eventually by У about the Z” axis respectively to achieve the desired orientation in space (equation 1).

$$R_{ZX'Z''}(\alpha,\beta,\gamma)=\begin{bmatrix} -s\alpha c\beta s\gamma + c\alpha c\gamma & -s\alpha c\beta c\gamma - c\alpha s\gamma & s\alpha s\beta \\ c\alpha c\beta s\gamma + s\alpha c\gamma & c\alpha c\beta c\gamma - s\alpha s\gamma & -c\alpha s\beta \\ s\beta s\gamma & s\beta c\gamma & c\beta \end{bmatrix}$$

If the rotation matrix is expressed by equation 2;

$$R_{ZX'Z''}(\alpha,\beta,\gamma)=\begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

Applying inverse kinematics, and comparing 1 and 2 equations, arbitrary angles in the workspace could be converted to joint angles. Euler angles were obtained according to equation 3.

$$\beta = A\tan 2(\sqrt{r_{31}^2 + r_{32}^2},\, r_{33})$$
$$\alpha = A\tan 2(r_{13}/s\beta,\, -r_{23}/s\beta)$$
$$\gamma = A\tan 2(r_{31}/s\beta,\, r_{32}/s\beta)$$

Found Euler angles suitable for different orientations as follows:

State 1: Bending the head to the sides or rotating around the X-axis by the angle θ (positive angle for right and negative for left):

$$R_X(\theta)=\begin{bmatrix} 1 & 0 & 0 \\ 0 & c\theta & -s\theta \\ 0 & s\theta & c\theta \end{bmatrix} \Rightarrow (\alpha,\beta,\gamma)=(0,\theta,0)$$

State 2: Bending the head to the anterior and posterior or rotating around the y-axis by the angle φ (positive angle for anterior and negative for Posterior):

$$R_Y(\varphi)=\begin{bmatrix} c\varphi & 0 & s\varphi \\ 0 & 1 & 0 \\ -s\varphi & 0 & c\varphi \end{bmatrix} \Rightarrow (\alpha,\beta,\gamma)=(-\pi/2,\varphi,\pi/2)$$

State 3: rotation around the X-axis by the angle θ and then rotation of around the Y-axis by the φ angle:

$$R=R_X(\theta)R_Y(\varphi)=\begin{bmatrix} 1 & 0 & 0 \\ 0 & c\theta & -s\theta \\ 0 & s\theta & c\theta \end{bmatrix}\begin{bmatrix} c\varphi & 0 & s\varphi \\ 0 & 1 & 0 \\ -s\varphi & 0 & c\varphi \end{bmatrix}=\begin{bmatrix} c\varphi & 0 & s\varphi \\ s\theta s\varphi & c\theta & -s\theta c\varphi \\ -c\theta s\varphi & s\theta & c\theta c\varphi \end{bmatrix}$$

Then, the inverse kinematics in the built mechanism was calculated (table 4). Finally, using the established model, the roundhouse kick impact was applied on the head at 0°, 5°, 10° and 15° degrees of rotation towards left and right, anterior and posterior at 13 m/s velocity, and then translational and rotational accelerations were obtained. Outcomes were compared with the threshold tolerances of head injury and then analyzed.

Table 4. Inverse kinematic Angles for different orientations

		θ (degree)			
		0	5	10	15
φ (degree)	0	(0,0,0)	(0,5,0)	(0,10,0)	(0,15,0)
	5	(-90,5,90)	(45,7,-45)	(-153,11/2,154)	(-161,16,162)
	10	(-90,10,90)	(-116, 11, 117)	(45,14,-45)	(-146,18,147)
	15	(-90,15,90)	(-108,16,109)	(-123,18,124)	(46,21,-44)
	20	(-90,20,90)	(77,21,-76)	(-116,22,117)	(-125,25,128)
	25	(-90,25,90)	(79,26,-78)	(70,27,-67)	(-120,29,122)

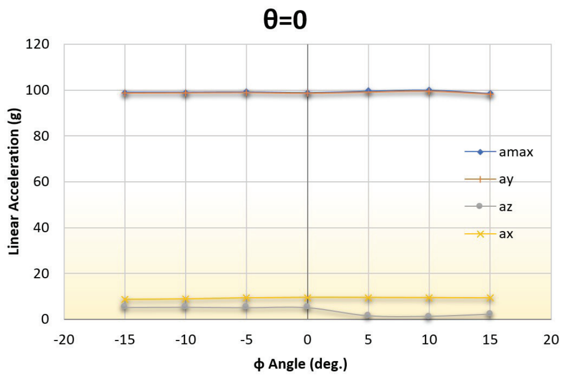

Figure 2. Linear acceleration of the head vs. φ angle

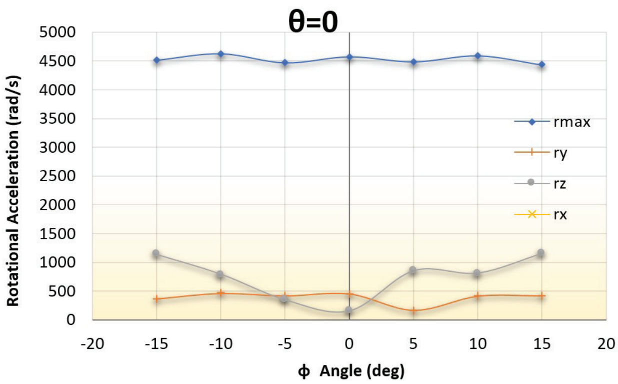

Figure 3. Rotational acceleration of the head vs. φ angle

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Results

Table 3 indicates Euler angles for different orientations of head and neck. Fig.s 2 and 3 illustrate the orientation of the head and neck in the sagittal plane. Moreover, Fig.s 4 and 5 depict the orientation of the head and neck in the frontal plane.

a_{max}, and r_{max} display linear and angular acceleration measures respectively. furthermore, a_x, r_x, a_y, r_y, a_z and r_z indicate a linear acceleration component along the x- axis, the rotational acceleration component around the anterior-posterior axis, a linear acceleration component along the y- axis, the rotational acceleration component around the lateral axis, a linear acceleration component along the z-axis, and the rotational acceleration component around the neck axis respectively.

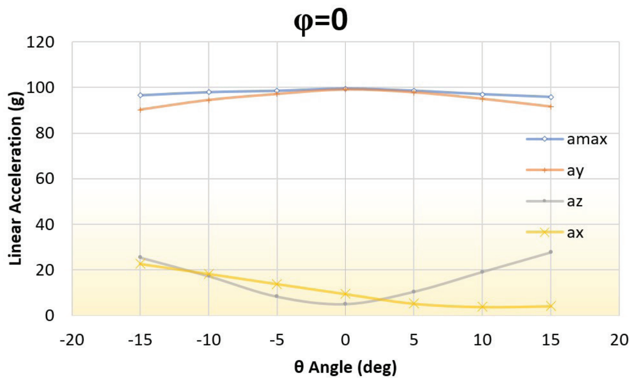

Figure 4. Linear acceleration of the head vs. θ angle

the present study has captured the peak of the linear acceleration of 99 g and a peak of rotational accelerations of 4576$\frac{rad}{s^2}$, in angle 0° of head and neck in reference condition. By comparing the linear acceleration with the threshold tolerance of the head in the Wayne State Tolerance Curve (Gurdjian, Roberts, & Thomas, 1966), it can be stated that the linear acceleration at 99 g is below the threshold of head injury. However the comparison of the rotational acceleration wi$\frac{rad}{s^2}$ the rotational acceleration threshold values of the head (1800 , concussion) expresses that the obtained values were within the head injury threshold (Ommaya, Goldsmith, & Thibault, 2002).

Fig. 2 presents that linear acceleration measured alteration and

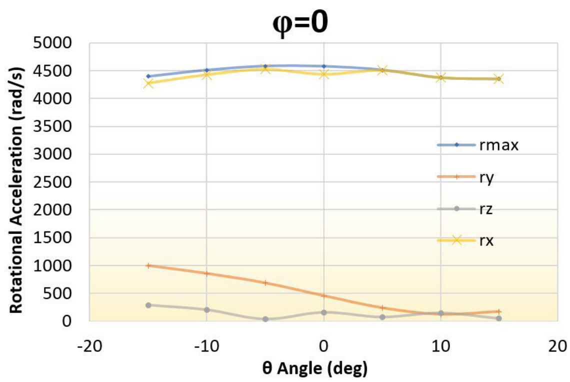

Figure 5. Rotational acceleration of the head vs. θ angle

its components, which are similar for diverse orientations of the head and neck on the sagittal plane. Fig. 3 indicates the same rotational acceleration measured alteration in all orientations. It is clear that the rotational acceleration component reduced with increasing of φ angle slightly, while the rotational acceleration component went up with increasing φ angle at the angle of 15°, 628.85% (Table 5). However, the rotational acceleration component remained almost constant in the head and neck orientation shift.

Table 5. Percentage of rotational acceleration changes relative to the reference state with orientation changes in the sagittal and coronal plane.

Degree of rotation		5	10	15	-5	-10	-15
φ=0	r_{max}	-1.39	-4.40	-4.88	0.062	-1.47	-3.94
	r_x	1.62	-1.37	-1.94	2.075	-0.16	-3.68
	r_y	-47.41	-72.95	-61.71	50.28	87.55	118.34
	r_z	-52.74	-5.96	-69.65	-75.55	30.05	83.23
θ=0	r_{max}	-1.44	-1.66	-3.16	-0.56	-1.00	-1.32
	r_x	-1.76	-2.64	-6.04	-1.54	-2.87	-4.18
	r_y	-10.77	-8.56	-7.61	-7.54	1.77	-19.22
	r_z	413.69	413.69	628.85	121.02	-19.22	617.31

Fig. 4 illustrates a_{max}, and major acceleration component (a_y) which decrease with increasing θ angle in the frontal plane. The linear acceleration component has shown an increase in the trend at an angle of 15°, 441.84% (Table 6). Furthermore, there is an asymmetry of the component in that the left and right sides of diagrams have an increasing and decreasing trend respectively.

Fig.5 demonstrates a decreasing trend for r_{max} and r_x. Besides, it has shown a slight increasing trend on the right side of the diagram, and slightly decreasing trend on the left side of the diagram, whereas, the opposite is true for the component.

Table 6. Percentage of linear acceleration changes relative to the reference state with orientation changes in sagittal and coronal plane

Degree of rotation		5	10	15	-5	-10	-15
φ=0	a_{max}	-0.91	-2.45	-3.64	-0.98	-1.58	-2.97
	a_x	-44.32	-59.39	-55.81	46.42	93.48	139.41
	a_y	-1.22	-4.06	-7.48	-1.97	-4.60	-8.85
	a_z	105.39	274.68	441.84	63.80	63.80	398.00
θ=0	a_{max}	0.18	-0.11	-0.51	0.27	-0.13	0.02
	a_x	-0.81	-1.52	-2.73	-2.56	-7.13	-9.12
	a_y	0.51	0.931	-0.41	0.31	0.20	0.10
	a_z	-2.34	1.562	-0.39	0.07	3.76	1.93

Discussion and Conclusions

The present investigation simulated the taekwondo roundhouse kick using MSC ADAMS software and assessing the linear and rotational acceleration responses of the head in the various orientations of the head and neck.

The results demonstrated that the peak of linear and rotational accelerations occurred at 99g and 4576$\frac{rad}{s^2}$, on the reference condition respectively. The research outcome exhibits φ angle variations do not affect the magnitude of linear and rotational accelerations on the sagittal plane. While the magnitude of linear and rotational accelerations decreased with increases of θ angle on the frontal plane. In other words, the magnitudes of accelerations remain constant when the roundhouse kick is delivered to head at different angles of neck flexion-extension. However, linear acceleration reduced by 3.64% (Table 5) and rotational acceleration decreased by 4.88% (Table 6). With increasing the angle in lateral bending, although these values are insignificant, or fairly low, they might decrease rotational acceleration under the injury threshold of the bridging veins in the brain (4500$\frac{rad}{s^2}$) (Löwenhielm, 1975).Therefore, it may be concluded that neck angle variation on the frontal plane of taekwondo fighters when an impact is delivered to the head may affect the type and severity of brain injury. Likewise, related studies suggest that there is a relationship between frontal plane movements and the severity of damage.

When an impact is delivered to the head in bending of the lateral neck, the angle of the F vector varies along the y-axis parse force into two vertical (f_n) and tangent (f_t) components with θ angle. f_n Creates acceleration, however, f_t is compensated for by the neck muscles (fig. 6). Therefore, the vertical component of the force is reduced and as a result, the linear acceleration decreases on the frontal plane. Such torque, which is a function of the force components, is reduced by the same proportion; consequently, it seems that torque component variations with θ angle change are the main reason for reducing rotational acceleration on the frontal plane. The Asymmetry of Inertial Moment Matrix is another reason.

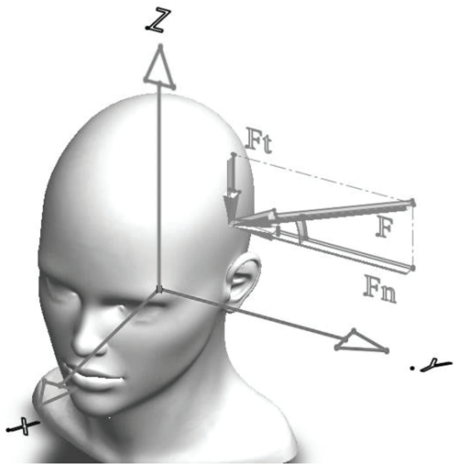

Figure 6. Impact force and its components

Among the acceleration components, the rz component had the most increase on the sagittal plane from 155$\frac{rad}{s^2}$ to 1155 $\frac{rad}{s^2}$. However, this is below the threshold for a head injury except that the rate of increase of this component could occur above the threshold of damage with a slight increase in φ angle, more than 15 degrees. Walsh et al have stated that changes in vector angles that are applied to head, alternates with acceleration component. They also found that acceleration magni-

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tudes alone have not been sufficient for rigorous investigation of the dynamic response of head (Walsh et al., 2011). Therefore, in addition to the magnitude of acceleration, its components are likely to influence the severity of the head injury too. Further research is necessary to obtain more precise results.

Due to the obtained results in the present and comparing it with a threshold of head injury tolerance, rotational acceleration is risk factor for head injury in taekwondo athletes, while linear acceleration does not play a significant role. Because linear acceleration can be countered by neck muscles, greater muscle strength may increase its resistance against impact force and linear acceleration. Linear acceleration is produced when resistance force or the neck force is lower than impact force. Although, the reaction that the neck has against the impact force would cause the impulse transmission through the neck to the brain. Translational acceleration commonly results in focal brain injury, while rotational acceleration also causes diffuse brain injury (Schmitt et al., 2019). Although neck resistance can protect the head against focal injury, it can, through rotating the head, can transmit the momentum to the brain. The structure and physical features of brain tissue are such, that demonstrate great resistance through tensile and pressure forces are applied to head Hence, the threshold of head injury tolerance for linear acceleration is more; however, the threshold of head injury tolerance for rotational acceleration is much lower due to the resistance of brain tissue layers against the shearing force. This leads to rotation and the creation of shearing in brain tissue.

Techniques to prevent and diminish the risk of head injury have been described in Rousseau's researches(Rousseau, 2008). Athletes familiar with an impending collision are able to protect themselves through a compound of the muscle tensioning and impact deflection techniques. Increasing neck compliance decreases stiffness, lessens linear acceleration and raises rotational acceleration; whereas a decrease in neck compliance (increased stiffness) increases linear acceleration and decreases rotational acceleration (Rousseau, 2008). The mechanical features of compliance provided by neck muscles in six degrees of freedom through location-specific impacts affects the dynamic response across all anatomical planes (Zhang, Yang, & King, 2004). The neck remains an ambiguous variable with regards to its contribution towards the dynamic impact response at various locations and orientations. Hence, to clarify, in addition to the head and neck model, we need to use a convenient neck muscle model. In addition to the orientation variable, a three-dimensional protocol for head injury and the threshold is required to determine more factors affecting the dynamic parameters associated with head injury and the development in helmet technology to reduce the risk of injuries as well. Therefore, this suggestion should be considered in future researches.

The results of this investigation indicate that the head and neck orientation during an impact influences its dynamic response. Generally, increasing the head and neck orientation angle is associated with a decrease in the magnitude of acceleration on the frontal plane. However, the head and neck orientation angle do not appear to have a visible effect in the magnitude of acceleration on the sagittal plane. The results reveal that only rotational acceleration causes brain injury in taekwondo, the severity of which is decreased with increasing the head and neck orientation in taekwondo fighters.

In order to assess helmet performance in this sport properly, it will be necessary to identify the most dangerous parameters of head injury, as well as the factors affecting them. These will need to be considered in helmet manufacturing industry.

At this moment, it is impossible to determine whether the additional knowledge of head and neck orientation during impact could ameliorate the assessment of helmet performance; however, according to the results of this study, it seems that such a protocol would require a more thorough helmet evaluation.

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