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Research article

Safety Evaluation of Protective Equipment for the Forearm, Shin, Hand and Foot in Taekwondo

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Abstract
The objective of the study was to evaluate and compare different brands of forearm, shin, hand and foot protective equipment used in Taekwondo. The most popular brands of large forearm, shin, hand and foot protectors (D®, A®, K ®), approved by the World Taekwondo and Korean Taekwondo Association, were examined. A drop test was used to test the protective equipment using impact levels of 3J, 9J, 12J and 15J for the forearm and shin guards, and 3J and 9J for the hand and foot protectors. The protective equipment was hit ten times from each of the designated drop heights. The drop test is described in the European standards manual of protective equipment for martial arts (SRPS EN 13277-2). The maximum force (MF) and impulse were lowest for brand K® (2610.3 ± 1474.1 N), and brand A® (9.6 ± 3.1 Ns), respectively, for the forearm guards; for brand A® (2053.4 ± 1267.1 N) and brand K® (9.8 ± 3.5 Ns), respectively, for the shin guards; for brand K® (4486.5 ± 1718.4 N), and brand A® (6.3 ± 1.1 Ns), respectively for the hand protectors; and for brand A® (3733.7 ± 2465.3 N), and brand D® (6.8 ± 0.6 Ns), respectively, for the foot protectors. For the forearm guard brand and impact level, there was a significant interaction effect for the MF ($F=42.44$, $\eta^2=.677$, $p < 0.001$) and impulse ($F = 33.97$, $\eta^2 = 0.626$, $p < 0.001$). Based on the MF, brand K® performed the best for the forearm guards and hand protectors, and brand A®, for the shin guards and foot protectors. The best results for the impulse were for brand A® (forearm guards and hand protectors), brand K® (shin guards) and brand D® (foot protectors).

Key words Injury prevention, protectors, PSS, safety, Taekwondo rules

Introduction

Taekwondo is a popular combat sport at the summer Olympic Games (Caine et al., 2009). At the 2016 Rio Olympic games, the competition rules were changed and a refined protector and scoring system (PSS) was introduced (WT, 2016). Sparring at the Olympics takes place in an area measuring 8-metres squared or an octagon of similar size (WT, 2018b). For safety, each of the competitors has to wear a trunk protector, head protector, forearm guards, hand protectors (gloves), shin guards, foot protectors (socks), a mouthpiece, and a groin cup. The majority of tournaments sanctioned by national governing bodies or World Taekwondo (WT), including the Olympics and World Championships, must use an electronic trunk protector, electronic foot protectors, and an electronic head protector to register and determine scoring techniques. Judges then assess and add scores for techniques (i.e., spinning) and punches (WT, 2018b). Since upgrading at the Rio Olympics, the PSS (using electronic headgear), has been implemented at the 2017 World Taekwondo Championships, the 2017-2018 World Taekwondo Grand Prix, the 2018 World Taekwondo Junior Championships, and each of the National Taekwondo Championships (WT, 2018a).

Previous studies have reported that participants in Taekwondo had the highest risk of injury in the 2012 London Olympics, and the second and fourth highest risk in the 2008 Beijing and 2016 Rio Olympic games, respectively. Thus, the International Olympic Committee raised concerns about the safety of Taekwondo athletes worldwide (Engebretsen et al., 2013; Junge et al., 2009; Soligard et al., 2017). Similarly, in a literature review of eight studies (5856 males, 2126 females), the injury rate per 1000 athlete exposures (AEs), showed that the knee and ankle were most commonly injured (21.7/1000 AEs for males, 26.6/1000 AEs for females). This was followed by injuries to the face, head, and trunk (17.5/1000 AEs for males, 17.3/1000 AEs for females), and the fingers and wrist in the upper extremity (9.4/1000 AEs for males, 7.3/1000 AEs for females) (Thomas et al., 2017). Likewise in a literature review of nine studies (7509 males, 2852 females), the injury rate per 1000 AEs was highest for contusions/abrasions/lacerations (37.5/1000 AEs for males, 27.9/1000 AEs for females), followed by sprains/strains (10.3/1000 AEs for males, 8.7/1000 AEs for females), and fractures (5.9/1000 AEs for males, 3.8/1000 AEs for females) (Thomas et al., 2017). Since the main objective of sparring in Taekwondo is to either knock out the opponent or hit the person the most amount of times to gain points, it is unsurprising that most injuries are contact injuries. There were many contact injuries due to kicks to the face (including to the eyes, ears, nose), head and trunk. Other common injuries occurred to the fingers, wrist, and forearm during blocking or avoiding a kick or a punch. The major cause of non-contact injury was when the athlete was stepping away to avoid an attack (Park and Song, 2017; Pieter et al., 2012; Thomas et al., 2017).

With the majority of injuries caused by impacts between athletes, it is clear that improvements in the current Taekwondo protective equipment are needed. With the high severity of head injury in Taekwondo, the majority of Taekwondo injury research has focused on concussion, with recommendations for improvements in headgear (Fife et al., 2013a; Fife et al., 2013b; Koh and Cassidy, 2004; Koh et al., 2003; O'Sullivan and Fife, 2016, 2017; O'Sulli-

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an et al 2013). Considering the high frequency of impact injuries, the use of different protective equipment (i.e., PSS), and the changes to the Taekwondo rules, there is a dearth of research focusing on improving and evaluating the forearm, lower leg, hand and foot protectors (Ramazanoglu, 2012).

In Korea, protective equipment is approved by the Korean Taekwondo Association (KTA) or WT, which have different approval rules and regulations. Our injury research from the latest World Taekwondo Championships at Muju in Korea, shows that the equipment that is currently used and approved is not providing adequate protection for athletes (Lee et al., 2017). Since Taekwondo is a combat sport, it is necessary to provide clear standards for the protective equipment of athletes regarding safety and functionality during training and competition (Thomas et al., 2017). However, no published study or data provides details about the safety performance of current equipment, except for head and trunk protectors (Bae, 2013; O'Sullivan and Fife, 2016; O'Sullivan et al., 2013).

This study aims to evaluate the safety of forearm, shin, hand and foot protectors. Furthermore, the importance of upgrading current Taekwondo protective equipment to fully adhere to the new rules and regulations will be highlighted.

Methods

Materials and equipment

Testing material: The most popular forearm, shin, hand and foot protectors, in the large size, from brands Daedo (D®), Adidas (A®), KSD (K®) were selected for this study. These were approved by either WT or the KTA. The basic information for each brand of protective equipment is shown in the Table 1. The weight, length, width, and thickness of protective equipment were measured using Vernier Calipers (Standard, Mitutoyo Ltd, Japan) and Digital Weight Scale (CAS EC-II, CAS Scales New Zealand Ltd, New Zealand). The average stiffness of protector sponge was measured using stiffness test equipment (Omni Test 5.0, ELS 2500N, VectorPro MT, Mecmeshin Ltd, UK).

Testing equipment: The testing equipment was constructed based on the European standards manual of protective equipment for martial arts (SRPS EN 13277-1, 2) (ECN, 2008a, 2008b). It was 300 mm wide, 300 mm long and 1200 mm high. The iron block striker (2.5 kg) was placed inside a transparent cylindrical acrylic tube and hung at specific levels using a hook and wire (Figure 1). The reliability and validity of the maximum force and impulse measurements were verified using force platform (ORG-6 AMTI, Watertown, MA, USA) data collected and analysed using VICON Nexus software. Reliability and validity were calculated using Cronbach's alpha coefficient (0.851) and Pearson's correlation coefficient (0.810).

Procedure

The procedure was based on the European standards manual of protective equipment for martial arts (SRPS EN 13277-1, 2). An impact location in the centre of the thickest part of the forearm, shin, hand and foot protectors was selected. The protectors were then fixed to the aluminium plate at the bottom of the striker.

As recommended by the European standards manual, an impact level of 3 J had to result in an impact force of less than 2000 N; this corresponded to a drop height of 12 cm. According to the literature, bone fractures and ligament/tendon tears and/or ruptures occur between 8-15 J; therefore the resulting impact force should be less than 5000 N (Beumer et al., 2003; Martinet al., 2015; Race and Amis, 1994). Consequently, we tested multiples of 3 J (9 J

Table 1. The basic information for each brand of forearm, shin, hand and foot protector.

Guard parts	Quality	D®	A®	K®
Forearm	Weight(g)	122.7	55.2	60.9
	Width (mm)	175-195	145-185	130-180
	Length (mm)	235-240	225-260	220-230
	Thick (mm)	10-14	13.5-14	11-16
	Sponge average stiffness (N)	18.0	12.6	14.2
	Sponge layer	third	single	double
Shin	Weight(g)	167.4	70	68.7
	Width (mm)	194-225	105-140	100-135
	Length (mm)	285-295	300-335	310-320
	Thick (mm)	12-16	10-23	10.5-22
	Sponge average stiffness (N)	22.0	15.3	17.5
	Sponge layer	third	double	double
Hand	Weight(g)	47.1	46.9	46.9
	Width (mm)	81-95	80-95	77-95
	Length (mm)	169-195	170-195	167-193
	Thick (mm)	5.8-7.4	5.5-8.0	4.5-7.5
	Sponge average stiffness (N)	13.7	13.0	15.3
	Sponge layer	single	single	single
Foot	Weight(g)	61.5	63.9	52.2
	Width (mm)	80-93	85-95	77-95
	Length (mm)	235-258	235-260	235-245
	Thick (mm)	5.7-8.5	5.5-9.5	4.5-9.5
	Sponge average stiffness (N)	19.4	14.3	16.4
	Sponge layer	single	single	single

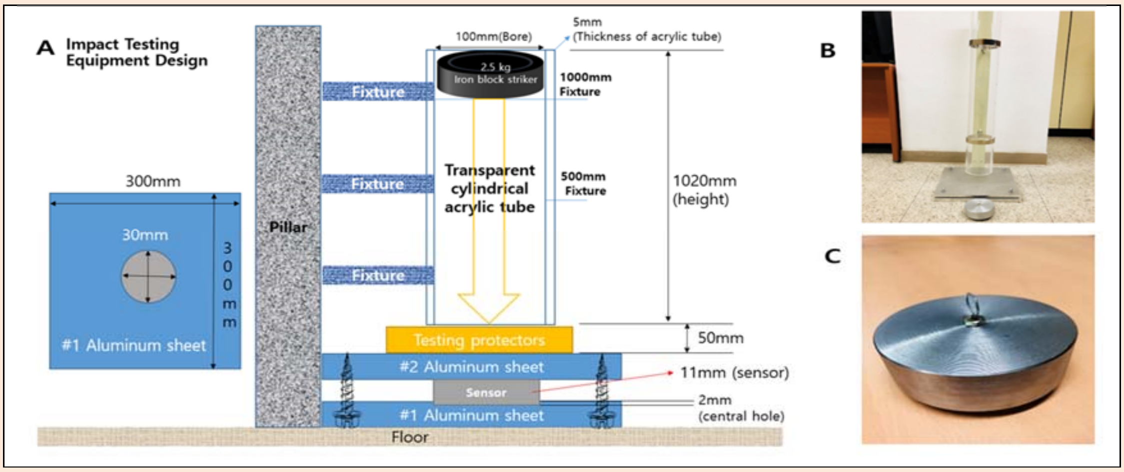

Figure 1. Impact testing equipment for the modified SRPS EN 13277-2. The schematic of the equipment design (A), the picture of the equipment (B), the close-up picture of the striker (C).

at 36 cm, 12 J at 48 cm, and 15 J at 60 cm), for a more comprehensive understanding of how the protective equipment would perform at varying impact levels. Ten impacts were performed for each of the levels tested (Beumer et al., 2003; Martinet al., 2015; Race and Amis, 1994). A bone fracture has been recorded with a force of 5000 N (Martin et al., 2015). This is above the impact force (4000-5300 N) recorded for the front kick, roundhouse kick and turning kick (Bae, 2013).

The forearm guards were tested using drop heights of 12 cm, 36 cm and 48 cm; and the shin guards were tested using drop heights of 12 cm, 48 cm and 60 cm. Ten impacts were performed for each drop height (a total of 30 impacts for each guard). Both the hand and foot protectors were tested using drop heights of 12 cm and 36 cm. Ten impacts were performed for each drop height (a total of 20 impacts for each protector). As recommended by the European standards for testing materials, an interim time of 60 seconds separated each impact. According to previous research, the lower the resulting maximum force during the impact tests, the safer the protectors are deemed to be (Lee, 2014).

Data acquisition and processing

A uniaxial vertical load sensor (9031a, Kistler, Switzerland), was mounted at the centre of the impact block at the bottom of the striker. The sensor recorded the impact force at 10 000 Hz and data were passed through a channel frequency class 1000 filter (as recommended for impact testing), using a customised Labview programme (LABVIEW 2015, National Instruments, USA). The customised programme was used to record, process, and calculate the maximum force (N) and the impulse (Ns) for all the impacts. A customised data processing programme (LABVIEW 2015, National Instruments, USA), was used to record, filter, and process the impulse sensor data. Impulse data acquisition was performed using a universal serial bus (USB) connected to a Compact data acquisition (DAQ) chassis (cDAQ-9174, National Instruments, USA), fitted with a 24-Bit National Instruments 9234 module (National Instruments, USA). The USB-connected data acquisition system was connected to a Samsung desktop computer, and all data were then exported to Microsoft Excel for processing.

Statistical analysis

A two-way analysis of variance and post hoc (Tukey and Duncan) tests were used to identify differences in maximum force and impulse across impact levels and protector brands. The level of significance was set to an effect size (η^2: eta squared) of 0.20 (Hopkins, 2002). Comparisons between each brand of protective equipment were confirmed using the mean difference and 95% confidence interval (CI). All statistical analyses were performed using IBM SPSS 24.0 (IBM Corp, New York, USA). Differences were regarded as significant if the two-tailed p-values were <0.05.

Results

The maximum impact forces for the forearm, shin, hand and foot protectors

The maximum impact force for the forearm guards was significantly different between protector brands (F = 108.99, η^2 = 0.729, p < 0.001) and impact levels (F = 2470.26, η^2 = 0.984, p < 0.001). The highest maximum force was recorded for brand D®, followed by brands A® and K® (Table 2). There were significant mean differences between brands D® and A® (281.3 N, p < 0.001, 95% CI: 124.0 to 438.7 N), between brands D® and K® (947.4 N, p < 0.001, 95% CI: 790.0 to 1104.7 N), and between brands A® and K® (666.0 N, p < 0.001, 95% CI: 508.7 to 823.4 N).

The maximum impact force for the shin guards was significantly different between protector brands (F = 176.43, η^2 = 0.813, p < 0.001) and impact levels (F=562.06, η^2=.933, p < 0.001). The highest maximum force was recorded for brand D®, followed by brands K® and A® (Table 2). There were significant mean differences between brands D® and A® (1810.2 N, p < 0.001, 95% CI: 1546.0 to 2074.5 N), brands D® and K® (1790.6 N, p < 0.001, 95% CI: 1526.4 to 2054.9 N), and brands A® and K® (-19.6 N, p < 0.001, 95% CI: -283.9 to 244.6 N).

Table 2. The maximum force for each brand of forearm, shin, hand and foot protector at each impact level

Guard parts	Impact level (Joule)	Max Force (N)		
		D®	A®	K®
Forearm	3	827.9±37.5	793.6±54.3	907.6±34.8
	9	3714.1±137.5	3114.3±290.1	2548.7±123.2
	15	6130.9±8.2	5921.0±401.2	4375.5±549.2
Shin	3	818.6±17.0	466.1±23.9	522.0±27.6
	12	5282.4±718.1	2216.4±190.6	2064.2±190.6
	15	5490.0±835.4	3477.8±230.7	3633.0±545.6
Hand	3	3053.4±350.1	3242.3±221.5	2836.9±432.5
	9	Max limit > 6000	Max limit > 6000	Max limit > 6000
Foot	3	1457.4±124.7	1331.4±78.5	1580.9±48.2
	9	Max limit > 6000	Max limit > 6000	Max limit > 6000

Values are the mean ± standard deviation.

Table 3. The impulse for each brand of forearm, shin, hand and foot protector at each impact level.

Guard parts	Impact level (Joule)	Impulse (Ns)		
		D®	A®	K®
Forearm	3	6.3±0.1	5.5±0.2	6.7±0.2
	9	12.4±0.2	10.8±0.2	10.5±0.2
	15	14.2±0.1	12.6±0.3	13.5±0.8
Shin	3	6.6±0.1	4.6±0.1	5.3±10.9
	12	12.7±0.3	11.7±0.6	10.9±1.3
	15	14.6±1.3	13.8±0.4	13.1±1.6
Hand	3	5.3±0.2	5.3±0.1	5.5±0.4
	9	7.4±0.1	7.4±0.1	7.4±0.1
Foot	3	6.3±0.2	6.1±0.3	6.5±0.1
	9	7.4±0.1	7.7±0.9	7.7±0.9

Values are the mean ± standard deviation.

For the hand protectors, there were significant differences in the maximum force between brands ($F = 3.44$, $\eta^2 = 0.113$, $p < 0.039$) and impact levels ($F = 2398.52$, $\eta^2 = 0.978$, $p < 0.001$). The highest maximum force recorded was for brand A®, followed by brands D®, and K® (Table 2). There were significant mean differences between brands A® and K® (202.7 N, $p < 0.030$, 95% CI: 16.4 to 389.0 N).

For the foot protectors, there were significant differences in the maximum force between brands ($F = 19.43$, $\eta^2 = 0.418$, $p < 0.001$) and impact levels ($F = 8201.17$, $\eta^2 = 0.994$, $p < 0.001$). The highest maximum force recorded was for brand K®, followed by brands D® and A® (Table 2). There were significant mean differences between brands D® and A® (63.0 N, $p < 0.001$, 95% CI: 14.8 to 111.2 N), brands D® and K® (61.8 N, $p < 0.001$, 95% CI: -109.9 to -13.5 N), and brands A® and K® (124.8 N, $p < 0.001$, 95% CI: -173.0 to -76.5 N).

The impulse for the forearm, shin, hand and foot protectors

The impulse force for the forearm guards was significantly different between protector brands ($F=125.79$, $\eta^2=.756$, $p < 0.001$) and impact levels ($F = 4031.42$, $\eta^2 = 0.990$, $p < 0.001$). The highest impulse recorded was for brand D®, followed by brands K® and A® (Table 3). There were significant mean differences between brands D® and A® (1.3 Ns, $p < 0.001$, 95% CI: 1.1 to 1.5 Ns), brands D® and K® (0.8 Ns, $p < 0.001$, 95% CI: 0.6 to 1.0 Ns), and brands A® and K® (0.6 Ns, $p < 0.001$, 95% CI: -0.8 to -0.4 Ns). The mean contact time ± standard deviation (SD) was 0.0013± 0.0003 s.

The impulse force for the shin guards was significantly different between protector brands ($F = 28.63$, $\eta^2 = 0.414$, $p < 0.001$) and impact levels ($F = 806.89$, $\eta^2 = 0.952$, $p < 0.001$). The highest impulse recorded was for brand D®, followed by brands K® and A® (Table 3). There were significant mean differences between brands D® and A® (1.3 Ns, $p < 0.001$, 95% CI: 0.8 to 1.8 Ns), brands D® and K® (1.5 Ns, $p < 0.001$, 95% CI: 1.0 to 2.1 Ns). The mean contact time was 0.0015±0.0003 s.

For the hand protectors, there were significant differences in the impulse between impact levels ($F=1994.78$, $\eta^2 = 0.973$, $p < 0.001$). The highest impulse recorded was for brand K®, followed by brands D® and A® (Table 3). The mean difference was similar for all the brands. The mean contact time was 0.0005 ± 0.0002 s.

For the foot protectors, there were significant differences in the impulse between impact levels ($F = 90.72$, $\eta^2 = 0.627$, $p < 0.001$). The highest impulse recorded was for brand K®, followed by brands A®, and D® (Table 3). The mean difference was similar for all the brands. The mean contact time was 0.0010±0.0007 s. There were no significant differences in the impulse between brands for the hand and foot protectors.

Comparison of brand and impact level interaction effects

Significant interaction effects were shown between the forearm guard brand and the impact level for the maximum force ($F = 42.44$, $\eta^2 = 0.677$, $p < 0.001$) and for the impulse ($F = 33.97$, $\eta^2 = 0.626$, $p < 0.001$) (Figure 2A, B). Similarly, significant interaction effects were also present between the shin guard brand and the impact level for the maximum force ($F = 36.58$, $\eta^2 = 0.644$, $p < 0.001$) and for the impulse ($F = 2.86$, $\eta^2 = 0.124$, $p < 0.029$) (Figure 2C, D). For the hand and foot protectors, significant interaction effects between the brand and impact level were only observed for the maximum force ($F = 3.44$, $\eta^2 = 0.113$, $p < 0.039$, and $F = 19.43$, $\eta^2 = 0.418$, $p < 0.001$, respectively), (Figure 2E, G). There were no interaction effects between the brand and impact level for the impulse, for either the hand or foot protectors (Figure 2F, H).

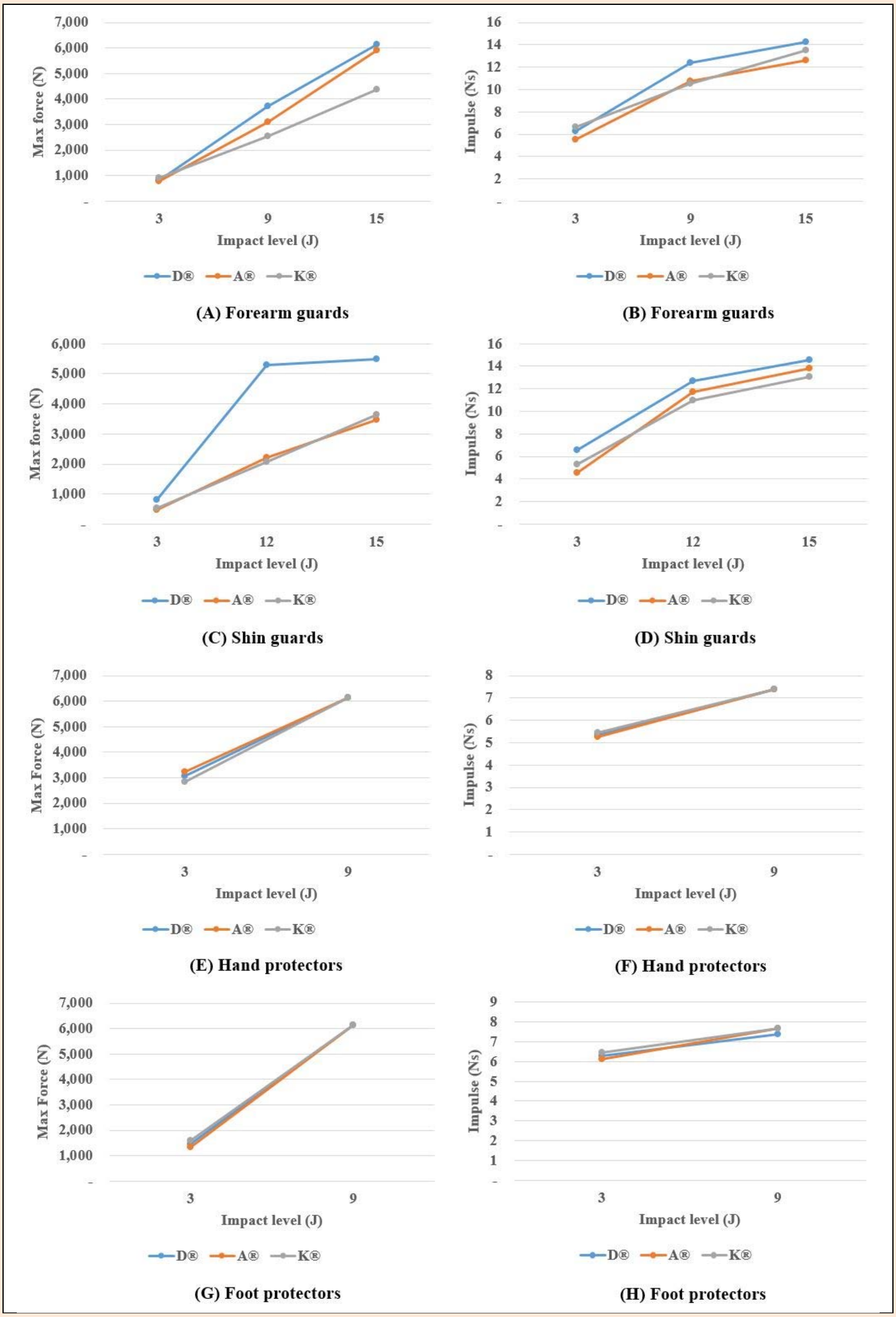

Figure 2. **Interaction effects between the protector brands and the impact levels. Maximum force for the forearm guards (A), impulse for the forearm guards (B), maximum force for the shin guards (C), impulse for the shin guards (D), maximum force for the hand protectors (E), impulse for the hand protectors (F), maximum force for the foot protectors (G), impulse for the foot protectors (H).**

Discussion

The main objective of this study was to evaluate the safety of different brands of Taekwondo forearm, shin, hand and foot protectors, by testing their impact attenuation. Brand A® were the most shock absorbent forearm guards, and brand K® were the most shock absorbent shin guards. Impact attenuation was highest for the brand A® hand protectors, and the brand D® foot protectors. There were no interaction effects between the brands and the impact levels for the impulse (for either the hand or foot protectors). The maximum force showed interaction effects between the brands and the impact levels for the hand and foot protectors. At the bone fracture and ligament and tendon tear/rupture impact level of 8-15 J, the output of the force transducer exceeded the 3000 N threshold. This means that to prevent severe injuries, the protective equipment needs to be substantially improved (the resulting impact forces need to be reduced to <2000 N).

For most protective foam materials, the thicker the material, the higher the shock absorbency. This means that there is a trade-off between thickness and comfort for the athlete. However, as shown in Table 2, the material shock absorbing properties vary according to the impact level. For example, brand A® was the best performing forearm guard at 3 J, but brand K® was the best at the higher impact levels. Similarly, brand A® was the best performing shin guard at the low impact level, and brand K® at the high impact level. Brand D® had a thick and stiff padding material. At the low impact force level of 3 J (12 cm drop height), the K® and A® brands of hand and foot protectors reduced the impact below the stated threshold of 2000 N, but at the higher impact levels, they did not perform effectively. Therefore, to protect from the high impact kicks in Taekwondo we recommend the stiffness, thickness, and weight of brands of K® and A® for the forearm, shin, hand, and foot protectors. Also, it is important that the stiffness of brand D® is reconsidered.

Impulse is defined as the integral of force concerning time (Lee, 2014). The lower the impulse, the longer the contact time, and this helps to reduce the risk of injury (Ramazanoglu, 2013). Table 3 shows that the brand A® forearm guard had the lowest overall impact values at 3J (12 cm), and brand K® resulted in the lowest impulse for the shin guards. In contrast, brand K produced the highest impulse values for the hand and foot protectors. Upon further observation, the A® and K® brands had a double layer sponge, whilst the D® brand only had a thicker, single layer sponge. Based on the data from this study, double layer sponge padding is recommended, since overall, this performed most effectively. In addition, for extra padding on the tibia, we would recommend the use of a three layer padding system with a stiffer pad surrounded by two less stiff pads to protect the athletes (as suggested in previous studies) (Bir et al., 1995; Francisco et al., 2000).

Even though the brand A® and D® hand and foot protectors passed the requirements for reducing the impact below 2000 N at the 3 J impact level, injury reports from major competitions show that more protection is needed to prevent bone fractures and tendon/ligament ruptures and tears. The PSS requires a foot sock with a sensor to be worn to record the impacts and scores, but the existing sponge pad does not seem to reduce the impact to a satisfactory level (Pieter et al., 2012; Sant'Ana et al., 2017). Furthermore, with the high frequency and severity of head injuries in Taekwondo, improvements in training methods such as avoiding and blocking (Koh and Voaklander, 2016), need to be coupled with improvements in headgear performance (O'Sullivan and Fife, 2016). Additional designs for the hand and foot protectors are required to fully protect and cover the commonly injured ulnar bone and distal phalanges.

In this study, the maximum force and impulse showed interaction effects between the brands and the impact levels for the forearm and shin guards. In contrast, the hand and foot protectors showed brand and impact level interaction effects for the maximum force only. Most customers would presume that the more expensive products manufactured by the bigger brands would perform better; however, our data did not support this assumption. On the contrary, our tests showed that the cheaper K® brand performed better than brands D® and A®. Along with the existing approval standards which stipulate the need to reduce the impact force below the 2000 N threshold, and the use of ethylene vinyl acetate, nitrile rubber or polyurethane only materials (Ramazanoglu, 2012; Woo et al., 2013); the superior performance of brand K® indicates that further standards are required.

The athletes stated that the equipment needed to be more shock absorbent, light, easy to put on and take off, and it needed to stay in place when sweating. With the high frequency of finger and wrist injuries, inclusion of a double layer sponge to the ulnar shaft portion of the forearm guards is recommended (Bromley et al., 2018; Pieter et al., 2012; Thomas et al., 2017). The distal ulnar is the part of the forearm that tends to block most of the kicks, and so it is particularly injury prone. Similarly, for the shin guards, the tibial shaft part should have a double layer sponge to increase shock absorption during the impact from kicking and blocking the opponent. One of the main complaints and suggested reasons for injury to the forearm and shin was that the protectors move when the athletes sweat. This may be reduced by adding a sticky material to the inside of the protector (Lampropoulos, 1996; Palmer and Baxter, 1999). For the hand, the fifth metacarpal and phalanges need to be more protected by adding more padding (Arthur, 1982). Likewise, for the foot protector, the medial malleolus and dorsum of the foot need more padding as these parts are regularly injured due to impact during kicking (Arthur, 1982). For the hand and foot protectors, the wrist and ankle parts should have a double-layered velcro strap that could add support and fix the ankle or wrist joint to prevent strains and sprains.

Strength and limitations

As far as known, this is one of the first published studies based on the European standards for the testing of martial arts protective equipment. The data is meaningful for martial arts practitioners and equipment manufacturers to promote safety and prevent injury. The study provides quantitative data on the safety performance of the most popular guards/protectors which can be used to improve protective equipment designs.

One limitation is that the guards/protectors were compared using data obtained from impact testing equipment, and therefore the findings cannot be extrapolated to safety performance in the field. Another limitation is the lack of information supplied by manufacturers regarding material properties, protector sizes, padding thickness and stiffness. Even though the temperature of the laboratory was maintained between 21-24°C, the humidity could not be controlled. In addition, only data for the three most popular brands were presented, which may not be representative of all of the available brands.

For the protective equipment tested in this study, the lowest maximum force and impulse for the forearm guards were produced by brand K® and A®, respectively. When testing the shin guards, brand A® produced the lowest maximum force and brand K® produced the lowest impulse. For the hand protectors, brand K® created the lowest maximum force and brand A® created the lowest impulse; whereas for the foot protectors, the lowest maximum force was obtained for brand A®, and the lowest impulse was obtained for brand D®. With the substantial differences in safety performance between the brands recorded in this study, we recommend the development of more stringent protective equipment standards to ensure the safety of athletes. Furthermore, continued research investigating injury mechanisms and the effects of the new PSS equipment and competition rule changes is warranted.

Conclusion

For the protective equipment tested in this study, the lowest maximum force and impulse for the forearm guards were produced by brand K® and A®, respectively. When testing the shin guards, brand A® produced the lowest maximum force and brand K® produced the lowest impulse. For the hand protectors, brand K® created the lowest maximum force and brand A® created the lowest impulse; whereas for the foot protectors, the lowest maximum force was obtained for brand A®, and the lowest impulse was obtained for brand D®. With the substantial differences in safety performance between the brands recorded in this study, we recommend the development of more stringent protective equipment standards to ensure the safety of athletes. Furthermore, continued research investigating injury mechanisms and the effects of the new PSS equipment and competition rule changes is warranted.

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Key points

- The best results for the maximum force were for brand K® (forearm guards and hand protectors), and brand A® (shin guards and foot protectors).
- The best results for the impulse were for brand A® (forearm guards and hand protectors), brand K® (shin guards) and brand D® (foot protectors)
- To prevent severe injuries, the protective equipment needs to be substantially improved (Even if the impact level is increasingly more than 3J, the resulting impact forces need to be reduced to <2000 N).
- It recommend the development of more stringent protective equipment standards criteria to ensure the safety of Taekwondo athletes.

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