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Review of Standards for Evaluating Polo Helmet Performance

Introduction

Polo is a unique contact sport involving two teams of players mounted on horseback. The playing surface, or pitch, may consist of an outdoor field (300 x 160 yards) or indoor arena (300 x 150 feet). The objective of the game is to score the most goals by driving the ball between the opponent's goal posts. Players advance the ball by striking it with a specialized mallet composed of a bamboo shaft and hardwood head. The game is broken down into periods, or chukkers, that last seven and a half minutes each. A typical polo game comprises four to six chukkers depending on tournament guidelines. At the highest level, players at the amateur and professional levels may play on the same team at the same time.

The U.S. Polo Association (USPA) was established in 1890 to govern the sport of polo in the United States. However, polo is an international sport that is played in over 50 countries. In Great Britain, players are required to become members of the Hurlingham Polo Association (HPA), which serves as the country's governing body for the sport. In 2015, nearly 3000 players and 13,000 horses were registered under the HPA [1].

Polo is considered a high-risk sport with injuries occurring due to falls, equipment failures, collisions, or impacts from mallets and balls. The injury rate in polo is approximately 7.8/1000 hours of play, which is lower compared to other contact sports such as soccer (16.9/1000 hours of play) and rugby (44.9/1000 hours of play). However, 64% of injuries sustained by polo players are considered severe with injuries that include bone fractures, ligament tears, and concussion [2]. While previous studies characterized injuries in a variety of equestrian sports [3-14], very few studies have focused specifically on polo-related injuries [1, 2]. Another major issue for polo and other equestrian sports is the lower concern for head protection compared to other contact sports. Although helmets decrease the risk of head injury by 40-50% in equestrian sports, the rate of helmet use is only 9-25% [15]. When asked to identify factors that influence helmet selection, 49% of polo players considered appearance as the primary factor while only 29% considered safety as the primary factor [1]. Given the severity of polo-related head injuries and the variety of polo helmet certification criteria, the objectives of this work were: (1) to identify differences in current polo helmet standards and (2) to outline a roadmap to inform the advancement of next-generation polo helmets.

Helmet Standards Assessment

Polo helmets must undergo laboratory evaluations before they are certified and approved for use by consumers. In the United States, helmet standards for polo and equestrian sports were developed by organizations such as the National Operating Committee on Standards for Athletic Equipment (NOCSAE), American Society for Testing & Materials (ASTM), and the Snell Memorial Foundation. Similar standards were developed internationally through the Products Approval Specification (PAS) in Great Britain, the Joint Standards Australia/Standards New Zealand Committee, and the European Committee for Standardization (CEN).

Each polo helmet should possess one or more labels indicating the helmet standard(s) applied (Table 1). The British Standards Institute (BSI) gives the BSI Kitemark if the helmet conforms to the PAS 015:2011 standard. Acquisition of this label requires helmet manufacturers to give BSI unrestricted access to company facilities so that BSI personnel can perform batch testing of randomly selected helmets. Compliance to these strict guidelines is intended to prevent a product recall. The BSI Kitemark is also used for VG1 01.040-2014, an interim standard for (BS) EN 1384 when it was withdrawn in 2014. However, (BS) EN 1384 was recently reinstated in 2017. Helmets that conform to (BS) EN 1384 may also have the CE mark to show compliance with European laws such as the Personal Protective Equipment Directive. Another common label is the SAI Global mark, which indicates that a helmet conforms to the Australian/New Zealand standard. In the United States, the Safety Equipment Institute (SEI) functions similarly to BSI and provides the SEI Kitemark for helmets that comply with either ASTM or NOCSAE standards. The Snell Memorial Foundation also provides labeling to show compliance with Snell standards [16-18].

Table 1. Comparison of safety marks in polo helmets.

Standard	Labeling
PAS 015: 2011 with BSI Kitemark	
VG1 01.040-2014 with BSI Kitemark	
(BS) EN 1384:2017 with CE mark	CE BSEN1384
AS/NZS 3838: 2006	Australian Standard Certified Product
ASTM F1163	SEI Certified by SEI to ASTM F1163
NOCSAE 050	SEI Certified MEETS NOCSAE STANDARD ®
Snell E2001	E2001 SNELL

Helmet evaluations are performed in a laboratory by dropping a headform/helmet combination from a predetermined height onto a rigidly mounted anvil using a wire or rail guided apparatus

(Figure 1). While this test procedure assesses impact energy absorption, other procedures can be used to assess retention strength (Figure 2) and helmet stability (Figure 3). However, it should be noted that alternative forms of testing may be applied and that pass/fail criteria could vary based on the country and standards organization involved in the certification of a particular helmet model. Table 2 provides a summary of six standards from the United States (US), Great Britain (GB), Australian and New Zealand (AU/NZ), and European Union (EU).

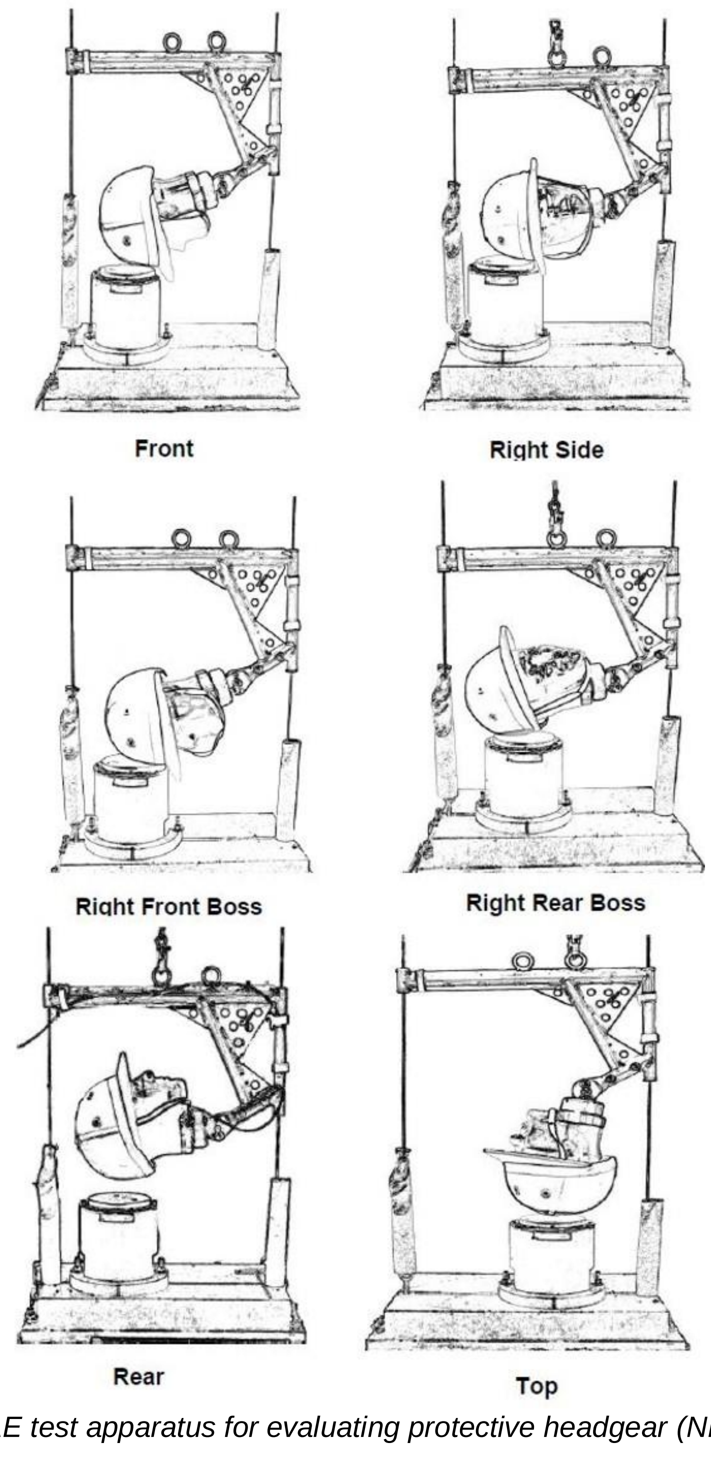

Figure 1: NOCSAE test apparatus for evaluating protective headgear (ND 050 – 11m15).

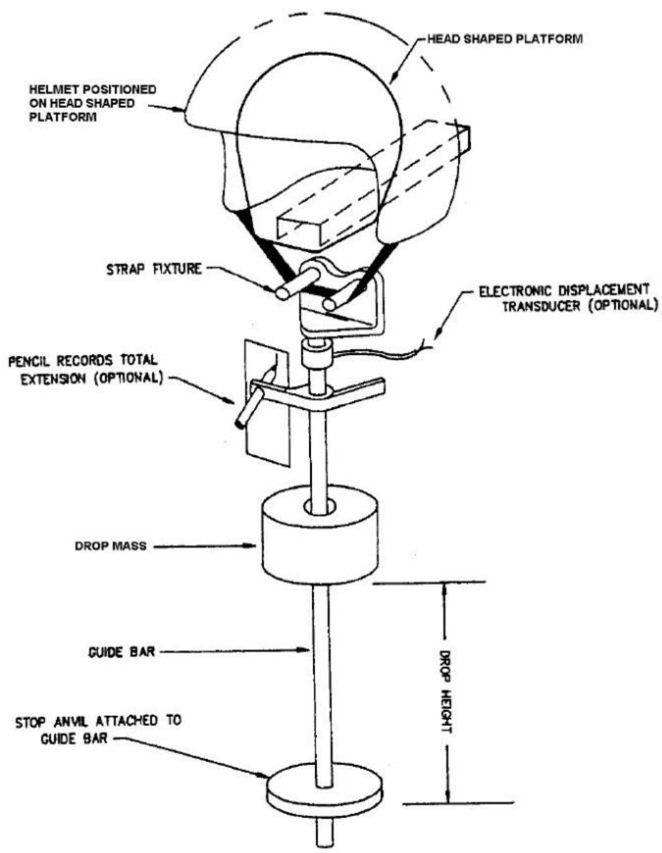

Figure 2: NOCSAE test apparatus for evaluating retention strength (ND 050 – 11m15).

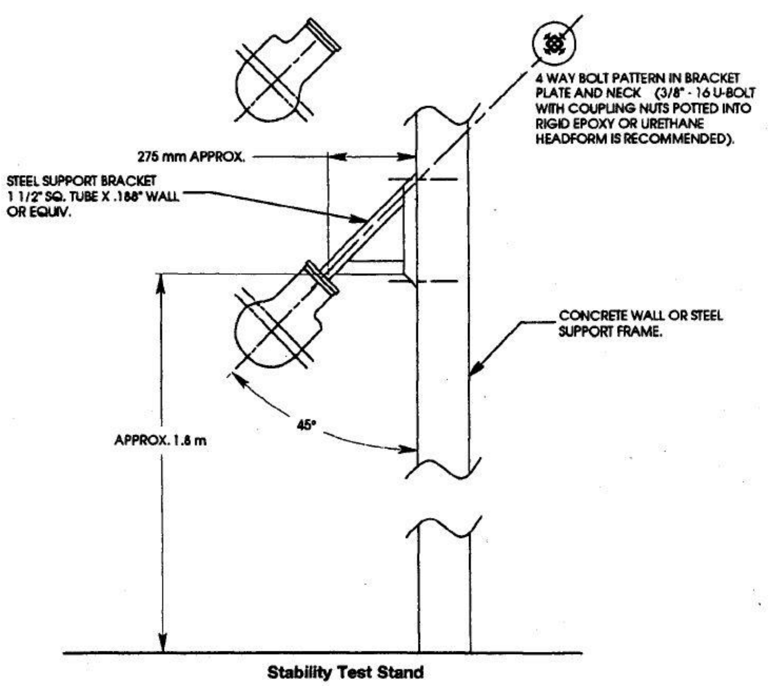

Figure 3: NOCSAE test apparatus for evaluating helmet stability (ND 050 – 11m15).

Table 2. Comparison of polo helmet standards.

Helmet Standard Features	NOCSAE 050 (US)	ASTM F1163-15 (US)	Snell E2016 (US)	PAS 015:2011 (GB)	AS/NZS 3838:2006 (AU/NZ)	EN 1384:2017 (EU)
Testing Envs	Ambient, high temps	Ambient, low, high temps; Humid	Ambient, low, high temps; Humid	Ambient, low, high temps; Humid	Ambient, low, high temps; Humid	Ambient, low, high temps; Humid
Headform	NOCSAE	ISO A, C, E, J, M, O	ISO A, C, E, J, M, O	ISO A, E, J, M, O	ISO AA, A, E, J, M, O	ISO A, E, J, M, O
Drop mass	5.0 kg	3.1-6.1 kg	3.1-6.1 kg	3.1-6.1 kg	2.5-6.1 kg	3.1-6.1 kg
Impact Anvils	Hemi; EH; MEP pad	Flat; EH	Flat; Hemi; EH	Flat; EH	Flat; EH	Flat
Impact Locations	Front; side; front boss; rear boss; rear; top; random	Sites above test line; Front, rear, or side	Sites above test line	Sites above test line; Vent; Retention attachment; Temple; Peak	Sites above test line	Sites above test line; Temporal; Frontal; Crown; Rear; Vent; Retention attachment
Impact Velocities	5.4 m/s (Hemi, EH); 3.4 m/s and 5.4 m/s (MEP)	6.0 m/s (Flat); 5.0 m/s (EH)	5.6-6.0 m/s (Flat); 5.0-5.4 m/s (Hemi); 4.7-5.1 m/s (EH)	5.9 m/s (Flat); 5.0 m/s (EH)	5.4 m/s (Flat); 5.0 m/s (EH)	5.94 m/s
Impact Energy	74.5 J (Hemi, EH); 28.9 J and 72.9 J (MEP)	55.8-109 J (Flat); 38.8-76.3 J (EH)	56.9-98.7 J (Flat); 45.5-79.0 J (Hemi); 39.8-69.1 J (EH)	54.0-106 J (Flat); 39.5-77.8 J (EH)	36.8-89.7 J (Flat); 31.9-77.8 J (EH)	54.0-106 J
Impact Test Criteria	SI<1200 (Any impact); SI<300 (3.4 m/s impacts)	PLA<300 g (Flat anvil, any size); PLA<300 g (EH anvil, any size)	PLA<275 g (A, C, E, J); PLA<264 g (M); PLA<243 g (O)	PLA<250 g (Flat anvil, any test); Average PLA<225 g (Flat anvil); PLA<200 g (EH anvil)	PLA<300 g (Flat anvil); PLA<300 g (EH anvil)	PLA<250 g (Any impact)
Impact Duration Criteria	N/A	N/A	N/A	<5 ms if PLA>150 g	<3 ms if PLA>200 g; <6 ms if PLA>150 g	<5 ms if PLA>150 g

Abbreviations: Environments (Envs), temperatures (temps), Hemispherical (Hemi), Equestrian Hazard (EH), Modular Elastomer Programmer (MEP) Peak Linear Acceleration (PLA), Gadd Severity Index (SI)

Table 2 (continued). Comparison of polo helmet standards.

Helmet Standard Features	**NOCSAE 050 (US)**	**ASTM F1163-15 (US)**	**Snell E2016 (US)**	**PAS 015:2011 (GB)**	**AS/NZS 3838:2006 (AU/NZ)**	**EN 1384:2017 (EU)**
Retention System Criteria	Elongation <31.75 mm	Elongation <30 mm	Elongation <30 mm	Elongation <35 mm (dynamic); Elongation <25 mm (residual)	Elongation <25 mm	Elongation <35 mm (dynamic); Elongation <25 mm (residual)
Helmet Stability	Remains on headform during roll-over test	Remains on headform during roll-over test	Remains on headform during roll-over test	Remains on headform during roll-over test; Vertical motion of liner edge <15 mm	Remains on headform during roll-over test	Remains on headform during roll-over test
Lateral Deform	N/A	N/A	N/A	<30 mm (dynamic); <10 mm (residual)	N/A	<30 mm (maximum); <10 mm (residual)
Peak Deflect	N/A	N/A	N/A	Peak Deflect >6 mm	Peak Deflect >6 mm	Peak Deflect >6 mm
Eye Protector Criteria	Protector fully intact during test; No contact with ocular region	N/A	N/A	N/A	N/A	N/A
Chin Bar Test Criterion	N/A	N/A	Def < 60 mm	N/A	N/A	N/A
Rigidity Test Criterion	N/A	N/A	Ext < 30 mm	N/A	N/A	N/A
Shell Pen Criterion	N/A	N/A	No pen with 60 HRC tip	No pen with 45-50 HRC tip	N/A	N/A

Abbreviations: Penetration (Pen), Deflection (Deflect), Extension (Ext), Deformation (Deform), Hardness – Rockwell C scale (HRC).

NOCSAE Standards

The NOCSAE 050 standard possesses notable differences compared to other polo helmet standards. Some of these differences are relatively minor. For instance, NOCSAE testing of polo helmets occurs under ambient and high temperatures while other standards require testing under ambient, low, and high temperatures as well as a more humid environment. In addition, NOCSAE 050 includes testing with a modular elastomer programmer (MEP) pad while other standards specify flat, equestrian hazard, and/or hemispherical anvils. However, major differences between the NOCSAE 050 standard and other standards include the headform, impact test criteria, and supplementary standard (NOCSAE 055) used for evaluating polo helmet performance.

The NOCSAE headform consists of a polyurethane skin, a polyethylene skull, and glycerin for simulating the brain [19]. Other polo helmet standards specify a rigid headform composed of a low-resonance magnesium alloy. Compared to other traditional headforms such as the Hybrid III, the NOCSAE headform possesses shape characteristics that facilitate a better helmet fit [20].

Given the severity of head injuries in polo, it is understandable that the impact test criteria for U.S. and international helmet standards consist of a peak linear acceleration threshold. However, it should be noted that the NOCSAE 050 standard specifies an injury metric known as the Severity Index (SI), which accounts for the resultant head acceleration and its duration [21, 22]. While some standards also account for duration (PAS 015:2011, AS/NZS 3838:2006, EN 1384:2017), other standards do not (ASTM F1163-15 and Snell E2016).

Another distinction between NOCSAE and other polo helmet standards is that NOCSAE 055 provides a standard specific to the eye protectors used in polo. These tests simulate a direct impact from a polo ball traveling at 40.2 m/s (90 mph). This velocity is based on 2001 field data in which 100 polo balls were struck by offside forehand shots from a distance of 60 yards while horses travelled at 5.3 m/s (12 mph). To pass NOCSAE 055, eye protectors must remain intact during testing and prevent ball contact with the ocular region (Figure 5) [23].

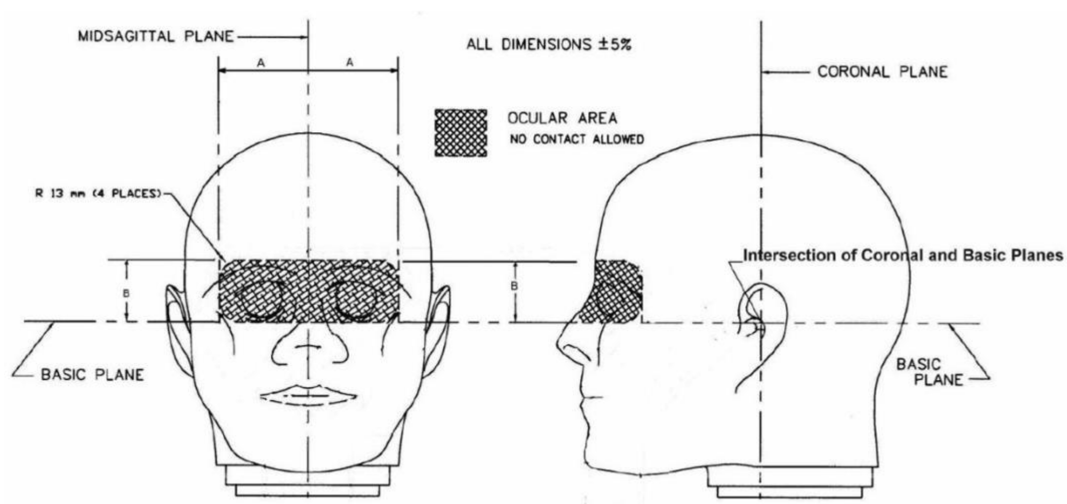

Figure 5: No contact zone specified in the NOCSAE 055 standard for eye protectors.

In the United States, polo helmets are certified mainly by the Snell Memorial Foundation and/or the American Society for Testing and Materials (ASTM). Interestingly, various polo helmets do not possess some form of safety labeling from the National Operating Committee on Standards for Safety Equipment (NOCSAE) despite the organization's development of polo-specific standards. However, a June 1, 2020 update to the United States Polo Association (USPA) rules will eventually require players to wear protective headgear that are NOCSAE-approved [24]. A comprehensive understanding of how NOCSAE standards compare with U.S. and international standards will facilitate the general public's understanding of polo helmet performance.

Snell Standards

The Snell E2001 standard for polo helmets has been in use for nearly two decades, but the Snell Memorial Foundation recently updated the standard in 2016. The previous E2001 standard required the same headform mass of 5.0 kg regardless of headform circumference while the new E2016 standard specifies a ranged of headform masses from 3.1 kg (Size A) to 6.2 kg (Size O). This update was based on previous work, which showed that head mass had a stronger correlation to circumference than length or width [25]. Due to variation in headform mass and prescribed velocity, Snell E2016 specified acceleration thresholds of 243 g for the smallest headform (Size O), 264 g for the second smallest headform (Size M), and 275 g for the remaining headform sizes. Impact energies range from 56.9 to 98.7 J for the flat anvil, 45.5 to 79.0 J for the hemispherical anvil, and 39.8 to 69.1 J for the equestrian hazard anvil (Table 2) [18].

Comparison of Impact Test Conditions

Polo helmet impact locations vary based on the standard specified. For instance, Snell E2016 and AS/NZS 3838:2006 only specify that the impact site is located above the headform test line and that subsequent impacts are outside a predefined damage zone, which takes into account the helmet geometry and impact surface. Meanwhile, NOCSAE 050 specifies more specific impact sites such as the front, side, and rear surfaces of the helmet along with off-axis sites including the front boss and rear boss sites. For ASTM F1163-15, impacts must occur above the headform test line but also include specific locations such as the front, side, and rear of the helmet. Similarly, PAS 015:2011 and EN 1384:2017 require impacts to be located not only above the headform test line, but also at specific sites. Common impact locations between the two aforementioned standards include the vent and retention attachment region. However, the PAS standard also specifies impact sites located at the temple and peak whereas the EN standard specifies temporal, frontal, and crown impact locations.

Impact energy was considered a suitable parameter for comparing different standards given the variability in drop masses, heights, velocities, and anvils. It should be noted that the NOCSAE standard specifies a drop mass of 5.0 kg while the other standards utilize a variable mass approach with drop masses as low as 3.1 kg and as high as 6.1 kg. A comparison of impact energies on the flat anvil showed that the ASTM, PAS, Snell, and EN standards had similar ranges of maximum impact energies with Snell allowing the lowest at 98.7 J while ASTM allowed the highest at 109 J. Compared to those four standards, the AS/NZS standard allowed a lower range of impact energies with the maximum at 89.7 J. Although NOCSAE does not utilize a flat anvil, the organization uses a flat MEP pad that generates impact energies of 28.9 J or 72.9 J depending on the velocity specified. The MEP is a less rigid surface compared to the other anvils. Another anvil used by multiple standards is the equestrian hazard anvil. A comparison of the corresponding impact energies revealed that NOCSAE, ASTM, PAS, and AS/NZS generate a similar range of impact energies with maximum values of 74-77 J. However, the Snell standard allows a slight lower maximum impact energy at 69.1 for the equestrian hazard anvil. Lastly, the hemispherical anvil is employed in only two standards with Snell generating a maximum impact energy up to 79 J and NOCSAE generating 74.5 J.

A comparison of the impact testing pass/fail thresholds revealed further differences among the six polo helmet standards. Both the ASTM and AS/NZS standards specify the highest peak linear acceleration thresholds (300 g) compared to the other standards such as the EN standard (250 g). Interestingly, the Snell and PAS standards provide multiple thresholds based on headform size and anvil selected. Finally, direct comparisons between NOCSAE pass/fail impact criteria and those of other standards may be challenging due to the differences in injury metrics selected and the duration of headform responses, which may or may not have to fall within certain ranges.

Comparison of Alternative Test Criteria

Additional testing may be performed to assess other polo helmet features aside from impact attenuation. Based on the standard specified, tests could be conducted to evaluate the performance of helmet structures such as the retention system, peak, chin bar, and eye protector as well as helmet characteristics including deformation, penetration, and rigidity (Table 1). For all polo helmet standards specified in Table 2, the criteria for retention strength varies between 25 and 35 mm. While NOCSAE 050, ASTM F1163-15, Snell E2016, and AS/NZS 3838:2006 specify a single threshold for retention strength, both PAS 015:2011 and EN 1384:2017 specify two thresholds for dynamic and residual retention strength.

Helmet stability is assessed using a roll-over test to ensure that the helmet stays on the player's head during regular use. Each of the six standards in Table 1 specifies this condition for helmet stability. However, PAS 015:2011 also limits vertical displacement of the liner edge by no more than 15 mm. In contrast to other standards, PAS 015:2011 and EN 1384:2017 also provide limits for lateral deformation, which are divided further into dynamic and residual deformation thresholds.

When comparing the deformation thresholds for the helmet peak, it was determined that the three international standards set deformation limits while the three U.S. standards had none. Meanwhile, NOCSAE was the only standard with criteria for eye protectors while Snell was the only standard with criteria for the chin bar and helmet rigidity. Finally, the Snell and PAS standards each specified a shell penetration threshold although the Rockwell hardness values vary from 60 HRC for the Snell standard to 45-50 HRC for the PAS standard.

Previous Evaluations of Polo Helmets

In 2008, the Transportation Research Laboratory (TRL) was contracted by the Hurlingham Polo Association (HPA) to evaluate polo helmet performance under the Equestrian New Helmet Assessment Programme (ENHAP). The ENHAP test protocol comprised pull-off, impact, and dynamic crush tests on multiple helmets and headform sizes. A rating system was also implemented with helmets receiving no more than two stars if peak headform accelerations exceeded 330 g, or one star if peak headform accelerations exceeded 300 g and energy absorption was less than 69 J. Evaluations by TRL revealed two distinct groups of helmets within the nine total that were tested. During impact and crush testing, four helmets that employed a modern design (i.e., energy absorption layer) outperformed the five helmets without absorption layers. Furthermore, helmets with 3-point harnesses outperformed helmets with a traditional single-strap design [26].

In 2016 and 2017, the USPA contracted Southern Impact Research Center (SIRC) to assess the performance of several polo helmet models. Evaluations were conducted in accordance with both NOCSAE and ASTM standard testing procedures with the exception that NOCSAE tests were performed only under ambient and elevated temperatures. Based on findings by the SIRC, only six of the eleven helmets tested had complied with ASTM F1163 while none complied with NOCSAE 050 [27, 28].

In 2018, Swedish insurance company Folksam and the Research Institutes of Sweden (RISE) evaluated fifteen adult and youth-sized equestrian helmets. Traditional drop tests were conducted using an ISO headform while oblique impact tests were conducted using a Hybrid III 50th percentile male headform. The oblique impact tests were designed to replicate typical equestrian accidents. In addition, a Hybrid III headform was used to gather rotational head kinematics data, which was used as inputs for the KTH finite element (FE) model to assess concussion risk based on the strain generated in the model. Based on previous studies, strains above 26% correlated with a 50% risk of concussion [29, 30]. Experimental results showed that several of the fifteen helmets generated a peak linear acceleration below 200 g while the two helmets fitted with the Multi-directional Impact Protection System (MIPS) received the highest ratings, which accounted for performance under normal and oblique impacts. Furthermore, computational results showed that the gray matter region of the KTH model produced strains in the range of 16-51%. The Swedish researchers also noted that more expensive helmets did not necessarily offer better head protection [31].

The Virginia Tech Helmet Lab has also conducted studies in recent years to evaluate the performance of equestrian helmets. In one study, drop tests were conducted on equestrian, cycling, lacrosse, and American football helmets in accordance with ASTM standards to assess the variation in impact attenuation based on helmet type (Figure 6). Although each of the six equestrian helmets passed the ASTM standard, four helmets generated peak linear accelerations (206-230 g) that were higher than the cycling helmets (155-192 g), the lacrosse helmet (149 g), and the American football helmets (109-130 g) [32]. In another study, multiple polo helmet models were tested according to ASTM and NOCSAE standards. None of the polo helmets passed the ASTM standard because one of the impacts resulted in a peak linear acceleration that exceeded the 300 g threshold (Figure 7). Furthermore, none of the polo helmets passed the NOCSAE standard because one of the impacts on the MEP pad resulted in a Severity Index (SI) that exceeded the threshold of 1200 for any impact (Figure 8) [33]. These studies further highlight the variability in the impact attenuation of polo helmets despite conforming to other standards.

Sport	Helmet Model	Impact Surface	Average Peak Linear Acceleration (g)
Equestrian	Charles Owen Ayr8	Equestrian	122
		Flat	189
	Charles Owen GR8	Equestrian	107
		Flat	196
	GPA First Lady	Equestrian	132
		Flat	**206**
	GPA Speed Air	Equestrian	135
		Flat	**223**
	KASK Dogma Lite	Equestrian	132
		Flat	**231**
	Troxel Liberty	Equestrian	131
		Flat	**231**
Cycling	Bell Chicane	Equestrian	142
		Flat	192
	Schwinn Chic	Equestrian	103
		Flat	156
Lacrosse	Cascade PVR	Equestrian	**95**
		Flat	149
American Football	Riddell Speed	Equestrian	**81**
		Flat	109
	Xenith X2E	Equestrian	**86**
		Flat	131

< 100 g   100-200 g   > 200 g

Figure 6: Impacts to the equestrian anvil consistently generated lower accelerations.

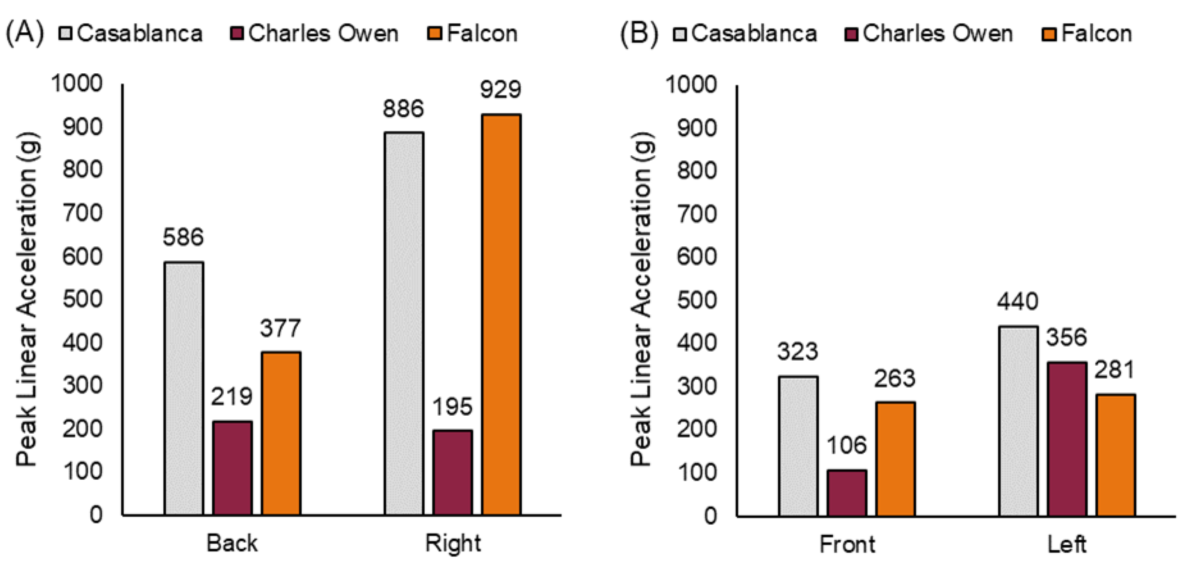

Figure 7: Each polo helmet failed the ASTM standard because one of the impacts to either the (A) flat anvil or (B) equestrian anvil produced a peak linear acceleration above 300 g. For most test cases, accelerations were higher due to helmet impacts on the side versus the back/front.

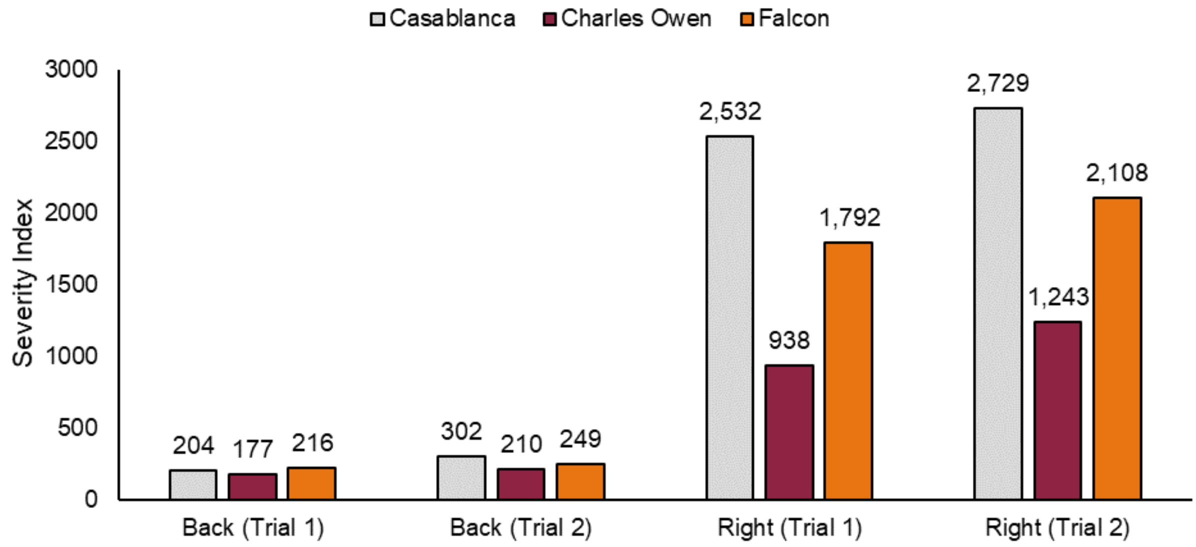

Figure 8: Each polo helmet failed the NOCSAE standard because one of the impacts to the MEP pad from a 1.8 m drop height produced a Severity Index above 1200. Values for Severity Index were higher due to helmet impacts on the side versus the back.

Polo Helmet Standard Recommendation

We recommend use of the NOCSAE polo helmet standard. There are key features of the NOCSAE polo helmet standard that differentiate it from other existing polo standards. First, the NOCSAE standard uses a headform with a more realistic shape while other polo standards use a headform that lacks features such as a chin and nape. A headform with more human-like features is likely to produce a more secure helmet fit during laboratory testing and more realistically simulate the head impacts that occur on the pitch during a polo match. Another notable feature of the NOCSAE standard is the use of high and low impact velocities. While most standards specify higher impact velocities between 5.0 and 6.0 m/s, the NOCSAE standard specifies a high velocity of 5.4 m/s and a low velocity of 3.4 m/s, each with its own pass/fail criterion. A polo helmet designed to pass the NOCSAE standard would be stiff enough to manage impact energy during a high velocity impact without bottoming out and compliant enough to manage impact forces through compression during lower velocity impacts. Finally, the NOCSAE standard specifies that polo helmet samples must attenuate multiple impacts to the same location with varying impact surfaces, a feature that is not strongly emphasized by the other standards. This is an important feature of the standard because it is feasible that a helmet could be impacted in the same location multiple times. Players do not replace their helmets each time they fall or experience an impact in-match, which creates the multiple impact possibility. Furthermore, the NOCSAE standard includes flat, hemispherical, and equestrian hazard impacts that are likely most representative of potential on-field head impact conditions. To achieve advancements in helmet performance, polo organizations should adopt the NOCSAE standard for the immediate future. Given that the NOCSAE standard is more comprehensive and challenging than existing standards, a helmet that passes NOCSAE should also pass other existing standards. Long-term, an investment in developing an advanced testing protocol that considers the rotational forces causing brain injury should be considered.

Engineering Roadmap

The roadmap for achieving advancements in polo helmet protection consists of three phases. Phase 1 involves an updated assessment of polo-specific injury exposure because current helmet standards are designed to assess the risk of severe head injury. Phase 2 involves the development of a comprehensive helmet testing methodology based on injury risk and the real-world data collected during Phase 1. Phase 3 involves the use of computational tools to characterize brain injury responses under simulated real-world (Phase 1) and laboratory (Phase 2) environments (Figure 9).

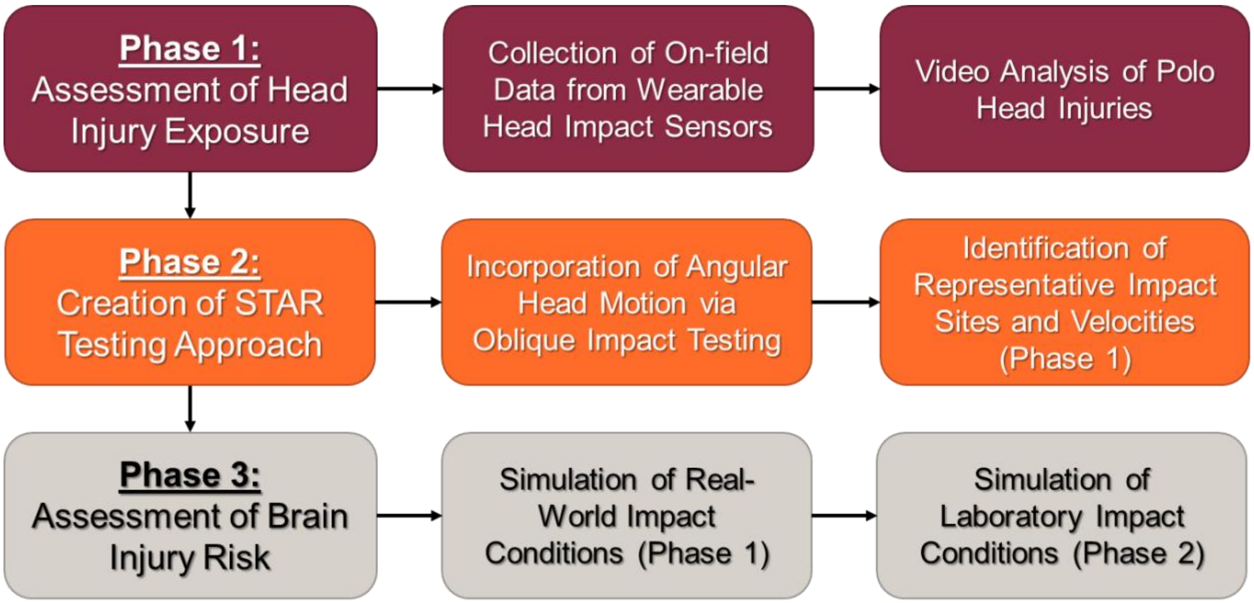

Figure 9: Engineering roadmap for advancing polo helmet performance.

Wearable head impact sensors have been used extensively in recent years to measure the head kinematics of American football players at the collegiate [34-37] and youth levels [38, 39]. Although polo helmets differ from those used in American football and other contact sports, head impact sensors can be implemented via non-helmeted versions such as instrumented mouth guards [40-45]. Using the real-time data from these sensors, researchers can pair impact data with clinical outcome to quantify injury risk [46-48]. If wearable head impact sensors are considered to be a costly and time consuming endeavor, then alternative routes should be explored. One recommended approach involves laboratory recreation of helmet damage based on samples collected from polo players who sustained head injuries. Another recommended approach involves video analysis of footage collected from polo matches to define the impact parameters to replicate in a laboratory setting. Collectively, these efforts constitute Phase 1 and should occur in parallel as a comprehensive approach to quantifying the boundary conditions of head impact and injury in polo.

For Phase 2, current protocols for evaluating polo helmets will be modified so that laboratory testing conditions account for head impact exposure and concussion risk. This helmet testing approach has been implemented previously through the Summation of Tests for the Analysis of Risk (STAR) methodology, which correlates on-field impact exposure with laboratory parameters such as impact location and energy level [49, 50]. Data from Phase 1 should be used to develop laboratory testing protocols that account for polo-specific head impact and injury. Risk of severe and mild brain injury should be evaluated in future testing protocols by implementing real-world impact conditions for polo players that induce rotational motion of the head. Recent studies on bicycle helmets have shown substantial differences in their protective capabilities when evaluated under standard laboratory conditions that focused on linear head motion versus simulated real-world conditions that also accounted for angular head motion [51, 52]. The approach developed under Phase 2 has been used previously to develop sport-specific protocols for protective headgear in football, hockey, soccer, and cycling.

During Phase 3, polo helmet performance will be evaluated further using finite element (FE) models because they serve as valuable tools for understanding the underlying brain response. Previous research has demonstrated the advantages of using FE models to identify relevant impact parameters in equestrian activities such as impact location and velocity [53]. Data collected from Phases 1 and 2 will inform the simulations completed during Phase 3. Representative on-field simulations will be guided by sensor data and/or video analysis from Phase 1 while representative helmet testing simulations will be guided by laboratory data collected during Phase 2. Overall, the framework could be used for each of the three phases as they address critical knowledge gaps that will lead to the advancement of polo helmets to reduce the frequency and severity of brain injury.

Due to the variety of U.S. and international standards adopted by polo helmet manufacturers, it would be beneficial for consumers, players, and organizations to have access to a comprehensive breakdown of the differences in their specifications. A broader understanding of these differences would also be advantageous for helmet manufacturers who must balance design features that optimize safety versus aesthetics. Advancements in polo helmets are achievable provided that a multi-phase approach is taken to assess injury risk, account for rotational head kinematics, and examine the underlying brain injury response.

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