The Most Cut-Resistant Neck Guard for Preventing Lacerations to the Neck

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Objective: To evaluate the effectiveness of a variety of neck guard brands when contacted by a sharpened hockey skate blade.

Design: Analytic experimental.

Setting: Laboratory.

Participants: Neck surrogate.

Interventions: Forty-six samples of 14 different types of neck guards were tested on a custom-made laceration machine using a neck surrogate. Closed-cell polyethylene foam was placed between the neck surrogate and the protective device.

Main Outcome Measures: The effectiveness of the neck guard was evaluated by observation of the foam after the simulated slicing action of the skate blade. Two sets of tests were performed on each device sample including low and high force. For low-force tests, initial compression loads of 100, 200, and 300 N were applied between the neck surrogate for each of 2 orientations of the blade at 45 and 90 degrees. For high-force tests, representing a more severe simulation, the applied load was increased to 600 N and a blade angle fixed at 45 degrees. All tests were performed at a blade speed of 5 m/s.

Results: Only 1 product, the Bauer N7 Nectech, failed during the 300-N compression tests. All of the neck guards failed during 600-N test condition except for the Skate Armor device and 1 of the 3 Reebok 11K devices.

Conclusions: A skate blade angle of 45 degrees increased the likelihood of a neck laceration compared with a skate blade angle of 90 degrees due to decreased contact area. Damage to the neck guard is not an indicator of the cut resistance of a neck guard. Neck protectors with Spectra fibers were the most cut resistant.

Clinical Relevance: The study provides data for the selection of neck guards and neck guard materials that can reduce lacerations to the neck.

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INTRODUCTION

Neck lacerations occur in hockey when a skate blade comes into contact with a portion of the neck, usually when a player loses their balance and errantly swings a foot into the neck of another player or from being stepped on.[1] The laceration can cause severe injury or death from damage to the airway, nerves, and blood vessels.[1,2]

Neck guards are worn with the expectation that they will prevent a laceration by providing an adequate barrier between the neck and the errant skate blade. Device design characteristics provide a cut-resistant material that covers the vulnerable structures in the neck while maintaining an acceptable level of comfort for the player. Currently, several neck guards are marketed for ice hockey,[2] but no published data exist on their effectiveness. A testing standard for these products has been developed by the Bureau de Normalisation du Québec (BNQ), but no independent analysis of neck guards, which meet this standard[3] has been published.

The purpose of this study was to compare the cut resistance of currently marketed neck guards for various loading conditions and blade angles to determine the probability of preventing a neck laceration. This study has 3 hypotheses: (1) device failure increases according to the initial applied load from the blade, (2) a skate blade oriented at 45 degrees to the neck surface will have a higher probability of laceration than 90 degrees, and (3) neck guards using Kevlar will be the most effective at preventing lacerations.

DEVELOPMENT OF A LACERATION MACHINE

A custom-made testing device laceration machine was constructed similar in design as that of the skate blade laceration machine developed for the BNQ qualifications and used for cutting resistance tests[3] (Figure 1). Design parameters of the laceration machine included a displacement rate up to 6 m/s and adjustable loading up to 900 N between the skate and neck form flexibility to adjust the blade angle.

The neck form was translated on a linear bearing past a stationary skate. Benefits of this design are translation of the neck form, which has a lower inertial mass than the skate fixture, and the obvious safety concern of a sharp skate blade traveling at a high rate. The actuator mechanism is a rodless

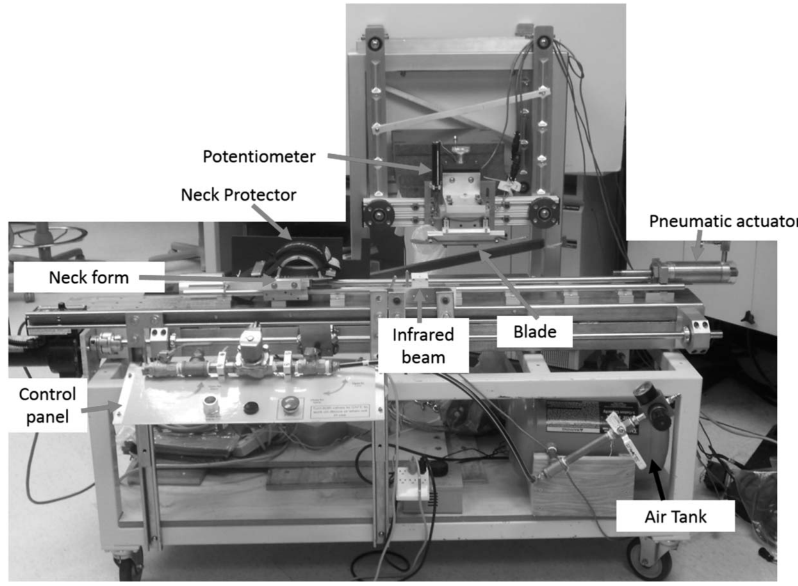

FIGURE 1. Picture of the laceration machine. The control panel controls the firing of the laceration machine and has 2 buttons for the "hold and fire" system.

pneumatic cylinder (Parker ORIGA Corporation, Inc, Richland, Michigan) coupled to a rigid base and linear slide. The linear carriage provides for the base to affix the surrogate neck form and a convenient means to attach the neck protectors (Figure 1). Velocity at which the neck form passed under the skate blade was controlled by adjustment of air pressure within a localized air reservoir. The velocity was determined by capturing the time a fixed distance centered on the neck form broke a photoelectric sensor located at the leading edge of the skate (Banner Multi-beam LV1T3, Minneapolis, Minnesota). The skate adapter was integrated to an adjustable linear slide. A linear potentiometer (Novotechnik, Southborough, Massachusetts) was used to record the vertical position of the blade relative to the neck form. The skate blade was affixed to an adapter, which integrated to 2 cantilever load cells (Interface MB-250, Scottsdale, Arizona) for measurement of the compression force of the blade on the neck form (Figure 1). Blade angle relative to the neck form could be set at 90 and 45 degrees using adapters. Blade angles were referenced from the top plane of the neck form (Figure 2). The blade could also be translated along the neck form to position over untested surfaces. The neck geometry was constructed from half of a 5mm-thick aluminum tube with a 57.5-mm radius (Figure 2).

Large bore solenoids (Getinge, Rochester, New York) were plumbed to rapidly charge the air cylinder from the pressurized volume in the air tank reservoir. To provide a measure of safety, a 2-button "hold and fire" system was designed to fire the actuator (Figure 1). To decelerate the neck, both inlet and outlet ports of the cylinder were shut immediately after the blade had passed the neck form and a pneumatic "brake" (Bimba Manufacturing, University Park, Illinois) was incorporated for dampening at the end of the stroke (Figure 1).

METHODS

Foam Selection

A specific type of foam served as an indicator of neck guard failure to protect. Foam selected was nonadhesive closed-cell polyethylene foam (SN: 8865K11; McMaster-Carr, Inc, Elmhurst, Illinois). Density of the foam was 32 kg/m^3, and vertical compression resistance was 117.3 $\pm$ 1.3 kPa. The foam, between the neck form and neck guard, was selected based on 2 criteria: density and 50% vertical compressive resistance. The density requirement was 20 kg/m^3 to 36 kg/m^3, and 50% vertical compression resistance requirement was between 72 and 120 kPa as specified by the BNQ.[3] The foam was validated directly by measuring volume and mass, and the compression test was executed in compliance with American Standard for Testing Material[4] requirements.

Skate Blade and Blade Sharpening

The skate blade was an adult-sized stainless steel Bauer TUUK Lightspeed 2 (Bauer Hockey, Exeter, New Hampshire). A blade sharpener (Model 201 A/C, Saint Paul,

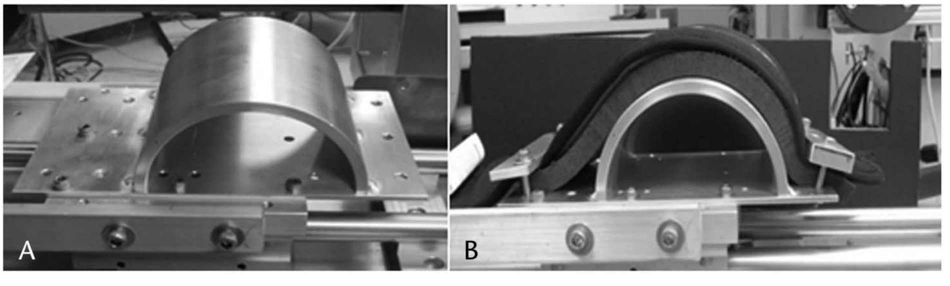

FIGURE 2. A, The aluminum neck form has a radius of 57.5 mm and 5 mm thick wall. B, The foam was placed directly onto of the neck form, and the neck guard was tightly fitted above the foam.

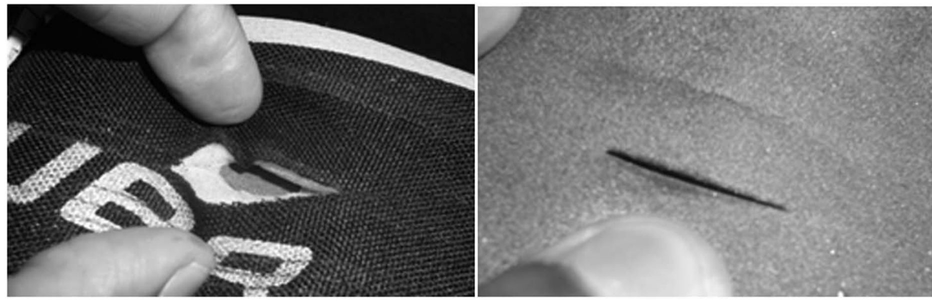

FIGURE 3. Example of a neck guard failure due to 300 N at a blade angle of 45 degrees and blade speed of 5 m/s. The figure on the left shows a Bauer N7 Nectech that failed 2 of its 4 tests. It was the only neck guard to fail low force tests. The injured foam is on the right.

Minnesota) was available for blade sharpening. A retired professional hockey player (M.B.S.) taught research staff the proper sharpening technique and is described below.

The grinding wheel was dressed with a radius set at 12.7 mm. To sharpen the blade, the contact surface of the blade was placed tangentially against the grinding wheel. Grinding progressed from front to back 5 times in the region between the screw points of the blade and 5 times front to back at each end. A hand sharpening stone was used to remove any edge burrs along the length of the blade. Two methods were used to ensure the blade hollow was even. The first was the commercially available Edge Checker (Edge Checker, Inc, Pierrefonds, QC, Canada) for an initial check, and a final validation using a bubble level. Great care was taken to maintain a consistent sharpening technique for all trials. If either technique showed that the 2 blade points were not level, the position of the blade sharpener was adjusted and the sharpening process was repeated.

Cutting Test

Each type of protector was first evaluated by an initial series of 3 load levels and 2 blade angles with forces of 100, 200, and 300 N and 45 and 90 degrees. By shifting the blade across the protector after each test, 1 protector could be used for multiple trials. The 90-degree tests were performed first, with each load being tested in ascending order. A blade speed of 100 and 200 N was set at 5 m/s for all tests. A 12.7-mm thick piece of closed-cell polyethylene foam, previously described, was placed atop the neck form. The neck guard was then placed over the foam and clamped down near the ends of the neck guard (Figure 2). The skate blade was positioned over the neck guard and slowly lowered with a precision positioning slide. Contact forces of the blade on the protector were monitored, and the relative blade to neck position noted, when the target load was observed for 3 seconds.[5] The position of the blade was documented using a linear potentiometer incorporated in the slide. The blade was then unloaded (raised), and the neck form was relocated to the beginning of the actuator. A minimum 3-minute wait time was followed to allow the polyethylene foam to recover. The blade was lowered to the previously established vertical position and the system "fired." The velocity was verified by recording the time interval recorded from the output of the photoelectric sensor. Sensors were integrated with a computer using LabVIEW (National Instruments, Austin, Texas) software designed to monitor both the load transducers and record digital events of the photoelectric sensor.

TABLE 1. Results of the Low-Force Neck Guard Tests

	90 Degrees						45 Degrees					
	100 N		200 N		300 N		100 N		200 N		300 N	
Name Brand and Type	Damaged	Failed	Damaged	Failed	Damaged	Failed	Damaged	Failed	Damaged	Failed	Damaged	Failed
Bauer N7 Nectech	0/4	0/4	0/4	0/4	0/4	0/4	0/4	0/4	0/4	0/4	2/4	2/4
Bauer BNP	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	1/1	0/1	1/1	0/1
Bauer Integrated Shirt	0/3	0/3	3/3	0/3	3/3	0/3	1/3	0/3	3/3	0/3	3/3	0/3
Nike Bauer NTP Sr.	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1
CCM R-471	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1
Easton NG	0/3	0/3	0/3	0/3	0/3	0/3	0/3	0/3	0/3	0/3	0/3	0/3
Itech Shirt	0/1	0/1	1/1	0/1	1/1	0/1	0/1	0/1	1/1	0/1	1/1	0/1
Itech NK20 Nectech Collar	1/1	0/1	1/1	0/1	1/1	0/1	1/1	0/1	1/1	0/1	1/1	0/1
Reebok 3K	0/3	0/3	0/3	0/3	0/3	0/3	0/3	0/3	0/3	0/3	0/3	0/3
Reebok 11K	0/3	0/3	1/3	0/3	1/3	0/3	2/4	0/4	2/3	0/3	3/3	0/3
Shock Doctor Core	0/3	0/3	0/3	0/3	1/3	0/3	0/3	0/3	0/3	0/3	2/3	0/3
Shock Doctor 569 Ultra Neck Guard	0/3	0/3	3/3	0/3	3/3	0/3	1/3	0/3	3/3	0/3	3/3	0/3
Skate Armor	2/3	0/3	3/3	0/3	3/3	0/3	3/3	0/3	1/3	0/3	3/3	0/3
Skate Armor-Short version	0/2	0/2	0/2	0/2	2/2	0/2	0/2	0/2	1/2	0/2	2/2	0/2
	3/32	0/32	12/32	0/32	15/32	0/32	8/32	0/32	13/32	0/32	21/32	2/32

Failed means that the neck protector did not prevent damage to the underlying foam. Damaged means that a laceration appeared in the outer fabric of the neck protector. In the failed column, the first number is the number of neck guards that failed to protect foam from laceration, and the second number is the number of neck guards tested. In the damaged column, the first number is the number of neck guards to sustain device injury, and the second number is the number of neck guards tested.

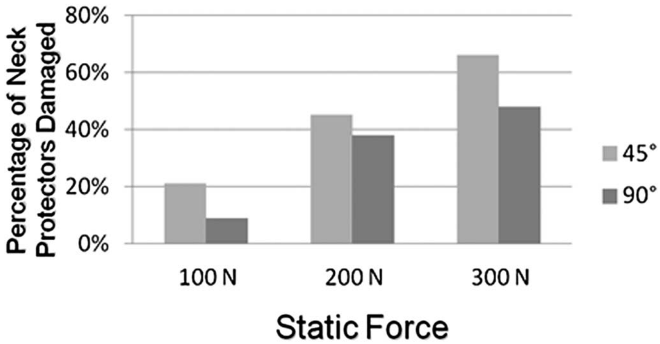

FIGURE 4. Percentage of neck guards damaged for each test condition neck guard, a risk that increased force and the 45-degree angle.

After each test, the neck guard and polyethylene foam were photographed and inspected for damage. Any damage to the foam underlying the skate constituted a failure. Lacerations to the neck guards were noted, photographed, and considered a device injury. The foam layer was replaced and the skate blade resharpened between evaluations of each protector. There was a 5-minute waiting period between tests. The position of the blade was adjusted, so tests were not run in the same location on the neck guard twice. The foam was replaced after each test battery was completed for each neck guard. The skate blade was sharpened before the testing of a new neck guard. For each brand of protector evaluated, up to 4 samples were tested.

A final test method was undertaken, increasing the preload to 600 N with a blade orientation of 45 degrees. As before, the skate was sharpened before each protector tested and the foam layer replaced, following the same steps in the low-force test. One high-force test was run on each neck guard; testing speed was 5 m/s.

Any foam laceration was noted as a failure to protect for the neck guard (Figure 3). Damage to the neck guard or device injury was defined as a laceration to the outer surface of the neck guard. Nominal logistic regression was used to analyze results of the low-force tests using the outcomes of damage to the foam or device injury to the protector. Independent variables for each nominal logistic regression were angle, force, neck guard type, and sample. The significant level was set at $P < 0.05$. For the high-force tests, the definitions for neck guard failures were the same as in the low-force tests. The number of failed neck guards was compared directly with the number of neck guards that did not fail.

Neck Guards

The neck guards were obtained through company donations. Fourteen different brands and types of neck guards were included and are listed in Table 1. Our research team has no significant relationship with any manufacturers. Neck guards were chosen based on commercial availability, as they were ones that hockey players would be able to purchase in a sporting goods store or online. The sample sizes for each neck guard brand or type tested reflect a limited number of certain brands that were available. For products in which the design was incorporated into a shirt, the relevant neck portion was isolated for laceration testing.

RESULTS

Overall, a total of 46 neck guards and 14 different brands and types of neck guards were examined. Thirty-two neck guards comprised the moderate set of tests, and 14 neck guards were subjected to the 600-N tests.

Low-Force Tests

No damage to the neck form was observed for any of the 100, 200, or 300 N tests with the blade angle at 90 degrees (Table 1). Only 2 instances of 32 tests for the conditions of 300 N and 45-degree blade angle group was damage to the foam noted, both of which being the Bauer N7 neck guard (Table 1). Nominal logistic regression showed that the type of neck guard and static force were significant predictors of neck guard failure (Table 1).

The potential of damage increased with increasing force and was higher for the 45-degree angle than the 90-degree angle (Figure 4). Additionally, risk of damage to the neck guard was dependent on the neck guard being tested (Table 1). For example, the Nike Bauer NTP Sr., CCM, and Easton NG had no damage to the neck guard for any tests, whereas the Bauer Integrated shirt was damaged 13 of 18 times tested.

High-Force Tests

Results of the high-force tests showed that the majority of neck guards failed at 600 N and 45-degree angle tests. Of 14 neck guards tested, 11 failed; of 3 neck guards that did not fail, 2 were of the Skate Armor brand (0/2), and 1 was a Reebok 11K (1/3) (Table 2). All neck guards sustained device injury for each of the high-force tests.

DISCUSSION

The purpose of this study was to investigate effectiveness of different neck guards at preventing lacerations to the neck. A secondary goal was to investigate how skate blade

TABLE 2. Results From 600-N Static Load and 45-Degree Angle Tests Show All Neck Guards Sustained Device Injury During Testing and Most Neck Guards Failed to Protect Foam

Name Brand and Type	600 N/45-Degree Tests Number Failed/Number Tested
Bauer N7 Nectech	2/2
Easton NG	2/2
Reebok 3K	2/2
Reebok 11K	2/3
Shock Doctor Core	2/2
Shock Doctor 569 Ultra Neck Guard	2/2
Skate Armor	0/2
Total	11/14

Regular-sized skate armor and the Reebok 11K neck guard did protect the foam. Both samples of regular size skate armor neck guard protected the foam. One of the 3 Reebok 11K neck guards protected the foam.

FIGURE 5. A skate armor neck guard with the spectra fibers showing. Spectra fibers have higher tensile strength and modulus of elasticity than Kevlar fibers.

angle and normal force influence the probability of a laceration. A total of 46 neck guards of 14 different types and brands were tested at 4 different force levels and 2 blade angles.

Standards described to characterize cut resistance of fabrics, including those used in hockey neck guards, are designed to quantitate effectiveness between products through application of controlled and repeatable test design and test parameters.[4,6–8] The methods vary in complexity, but generally use simple safety blades for cutting edges. When these materials are integrated into protective clothing, whether simple protective gloves or chaps to protect from chain saws, due diligence is warranted to evaluate their efficacy by simulating the intended use. Bench testing of neck guard using skate blades and the explosive impacts inherent in hockey is an attempt to elucidate their true value. This test focused on the ability of the currently used materials to prevent a skate from penetrating the protective boundary.

The majority of neck guards showed similar laceration resistance. Most neck guards withstood lacerations at loads of 300 N or less, but failed when initial loads of 600 N were applied. The Bauer N7 Nectech was the only neck guard that failed to protect at 300 N. This may be due to the material used for the protective outer layer, stated as "nylon" on the Bauer Web site with no other details provided.

The Reebok 11K and Skate Armor neck guard were the only 2 brands that did not consistently fail at 600 N. The Reebok 11K and Skate Armor prevented failure for 33% and 100% of times tested at the 600 N, respectively. Both neck guards had designs distinct from all other neck guards tested. The Reebok 11K had 2 layers of Kevlar, which decreased the probability of neck guard failure (damage to the foam). The Skate Armor neck guard was the only neck guard that incorporated Spectra Guard as its protective inner fabric (Figure 5). The Spectra fibers of the neck guard have a higher modulus of elasticity and tensile strength than Kevlar (Figure 6).[9,10] Added strength and stiffness from Spectra fibers contributed to the cut resistance throughout testing.

Analysis of the damaged neck guards demonstrated the expected outcome that likelihood of device damage increased with increasing force and increased stress for the blade at a 45-degree angle. Skate blades are unique due to hollowing out the midline of the blade at a specific radius, producing 2 sharp edges that are both in contact when the blade is oriented at 90 degrees from the contact surface. With the blade oriented at 45 degrees, 1 edge is dominant, and the contact area is reduced. At 45 degrees, the downward force is concentrated on 1 edge of the blade. This increases the stress felt by the neck because stress = force/(surface area). The 90-degree angle causes the 2 edges to contact, thus doubles the surface area and reducing the stress. In our study, this (1 edge) represents an increase in the likelihood of injury (Figure 4).

Neck guard types significantly predicted if the neck guard would sustain device injury. However, neck guards most vulnerable to sustain damage were not always those most likely to fail. For example, the Bauer N7 Nectech was damaged in 2 of 32 low-force tests. In the 2 tests where the neck guard was injured, the neck guard failed to protect the underlying foam. In contrast, 15 Skate Armor neck guards were damaged during testing, but none allowed a laceration to the foam layer. Perhaps some manufacturers designed the neck guard not to rip, so the consumer would not perceive the neck guard as weak. It is also possible that the damage to the neck guard dissipates energy, thus helping the Skate Armor neck guard avoid failure by dissipating energy from the system through the cutting of the outer layer.

Limitations

There are numerous limitations to this study. Three samples were not tested for each type of neck guard for the low-load tests. This prevented testing the repeatability of

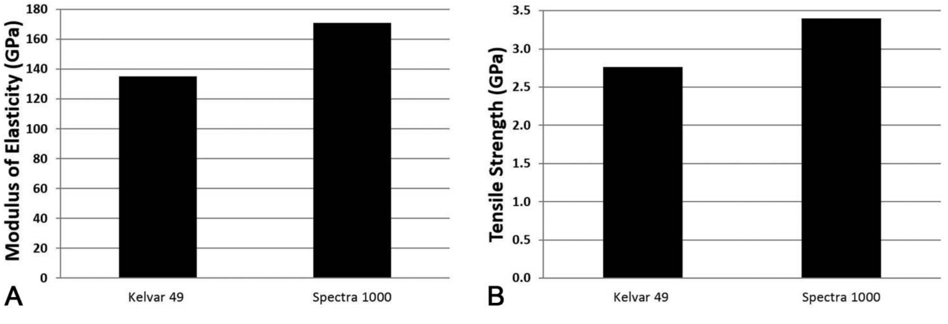

FIGURE 6. Mechanical properties of the Spectra fibers and Kevlar (A). Spectra fibers had a modulus of elasticity and tensile strength 27% and 23% higher than Kevlar (B).

each type of neck guard. Our supply of neck protectors was limited. As such, the main testing was at the low-level loads due to the assumption that these loads would produce failure. The remaining neck protectors were used to conduct the 600-N tests and is why not all of the neck guards were tested at 600 N. A 57.5-mm radius pipe was used to simulate the neck, which lacks both the curvature and the stiffness of the human neck. The range of test conditions did not have the sensitivity to properly stratify outcomes between all the products tested. This testing only differentiated the best and worst cut-resistant neck protectors. The cantilever load cells used impeded collection of dynamic force. The sharpness of the blades was not directly measured, but it was standardized by the technique used to sharpen them. Neck guards were tested on their effectiveness at preventing laceration to foam. It remains unclear how the force, speeds, and angles needed to lacerate foam relate to the parameters needed to lacerate a human neck. Last, the 2 sets of tests did not differentiate between the majorities of neck guards tested. This testing only differentiated the best and worst performing neck guards.

CONCLUSIONS

A custom-made laceration machine using a hockey skate blade and a neck surrogate was developed to evaluate the effectiveness of commercially available neck guards. Skate Armor neck guards had highest cut resistance, and the Bauer N7 Nectech had the lowest cut resistance. The neck guards that used Spectra Guard or 2 layers of Kevlar were found to be the most cut resistant. A skate blade angle of 45 degrees increased the likelihood of a neck laceration compared with a skate blade angle of 90 degrees due to decreased contact area. Damage to the neck guard is not an indicator of the cut resistance of a neck guard.

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