JOURNAL OF
EMERGING INVESTIGATORS

Article

A systematic study of cut-resistant socks for hockey players

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SUMMARY

Hockey skate-blades can cause serious injuries, so players typically wear padding to lower the risk of possible catastrophic wounds. However, the padding is unable to provide complete protection, and serious injuries still occur. Cut-resistant socks have emerged as a helpful addition to aid in preventing laceration injuries from skate blades during play. There are two main materials that are often used in cut-resistant hockey socks – Kevlar and Dyneema. These materials are the most common due to their high tensile strength and flexibility. Our goal was compare the two materials' cut-resistive properties to determine which is a more effective material for injury prevention for hockey players. We hypothesized that Kevlar would have a higher cut resistance than Dyneema because of its long molecular chains linked by hydrogen bonds. Six samples of varying cut-resistant material percentages, three Dyneema and three Kevlar, were tested to identify which material was more cut-resistant. A total cut resistance parameter was needed to provide a fair comparison between each sample due to varying amounts of cut-resistant material in the reinforced area. After testing with varying degrees of cut force, we discovered that Dyneema has a higher cut resistance per unit of high-performance fiber strength and is therefore better suited for the application of cut-resistant socks.

INTRODUCTION

Ice hockey is a popular sport, most notable for its fast pace of play (1). It is particularly well-liked in North America as well as in multiple European countries due to their cold-weather climates and the availability of natural ice rinks to play on. However, it is also a relatively dangerous sport due to its physical nature and the use of skate blades during play. Players can hit other players who are in possession of the hockey puck. This leads to over 25% of players suffering from at least one concussion in a single season, which is approximately eight months long (2). To protect against injuries resulting from these collisions, players wear padding covering large portions of their bodies. Although current protective equipment aids in reducing injury from the physicality of the sport, the skate blade still poses a serious danger. As a result, protective equipment for skate lacerations must be approached differently due to the higher severity level. In recent years, the USA Hockey organization has taken several steps to prevent skate-related injuries. For example, as of August 1, 2024, neck laceration protectors are now mandatory for all players (3). However, laceration injuries to the leg and ankle area can prove to be life-changing or fatal (4). For instance, severing the posterior or anterior tibial artery could lead to potential limb amputation or fatal amounts of blood loss (5). Therefore, despite the USA Hockey organization not requiring lower-body protection, players are recommended to wear cut-resistant socks, which has inspired greater research and development on methods of preventing calf and ankle-related skate injuries.

Cut-resistant materials have been implemented into hockey protective equipment in an attempt to limit the damage caused by skate-related incidents. Because the material must be both flexible and protective against lacerations, two materials have become the most popular for hockey: DuPont Kevlar and Dyneema. Since both materials are lightweight and moisture resistant, they do not slow or restrict the movement of the players and allow them to stay dry and comfortable (6). Kevlar (poly-para-phenylene terephthalamide; PPTA), which is classified as an Aramid polymer, has been most popularly used in bulletproof vests due to its high tensile strength of 3.6 GPa (7,8). This high tensile strength stems from the hydrogen bonds that link the long molecular chains within Kevlar's molecular structure and contribute to its uniquely high cut-resistance (9). Dyneema (ultra-high-molecular-weight-polyethylene; UHMWPE) is also known for its high tensile strength (6). Despite Dyneema and polyethylene having the same repeating unit (C_2H_4), the difference is that Dyneema's molecular weight is 10 to 100 times higher than regular polyethylene (6). Dyneema has a tensile strength of 2.2–3.9 GPa, varying with fiber type, while low-density polyethylene, often used in plastic bags, has a tensile strength of 0.01 GPa (10,11). Materials with high tensile strengths are more resistant to deformation and breaking, thus requiring a higher force to be cut. A previous study tested the cut resistance of Kevlar, Spectra (high-performance polyethylene, similar to Dyneema), and Zylon (polybenzobisoxazole) (12). Zylon was the most cut-resistant of the three materials (12). However, Zylon is often not used in wearable protective equipment, such as socks, because it degrades over time when exposed to moisture (13).

Although there are numerous types of cut-resistant socks, with varying compositions and materials, Kevlar and Dyneema are the primary types of cut-resistant clothing. To help discern which fiber is more effective for hockey players, we performed a series of experiments on multiple samples of Dyneema or Kevlar-dominant socks. We hypothesized that Kevlar would be more cut-resistant than Dyneema, adjusting for percent composition, due to the densely packed hydrogen bonds linking the molecular chains. Kevlar has a density of 1.43 g/cm^2, while Dyneema has a density of only 0.97 g/cm^2

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EMERGING INVESTIGATORS

https://doi.org/10.59720/24-357

(a) (b)

Figure 1: Experimental setup for fabric holder and magnetic weight attachment. a) The fabric holder (ii) was secured to the cutting board (iii) and scale (iv). A strip of double-sided tape was placed on the fabric holder to hold the sample in place. The sample (i) was then stretched and placed on the double-sided piece of tape on the fabric holder. b) The blade was used to apply the force onto the sample. Magnetic 500 g weights were attached to the two magnets (indicated with asteriks*) on the blade. The knife, with the attached weights, would slide across the sample, applying a constant force. If there were not any signs of lacerations on the sample, the sample would be recentered, the knife would be resharpened, and an additional 500 g weight would be added to the blade. This is repeated until the sample is lacerated. The steps are repeated for a new sample for the next trial.

(6). Therefore, we predicted that the higher density would better disperse the force, thereby improving the material's cut-resistance. From these experiments, we found that Dyneema had a higher cut-resistance per unit of high-performance fiber strength. This suggests that socks made of Dyneema fibers are generally more effective at preventing skate lacerations. Therefore, hockey leagues of all levels should encourage players to wear Dyneema-woven hockey socks to decrease the risk of skate-blade injuries to the leg and ankle.

RESULTS

The general setup for the cut resistance measurements consisted of magnetic weights that were attached to a straight edge knife to apply a uniform force onto the sample, which was measured by a scale (**Figure 1a-b**). The knife was used to replicate the edge of a skate blade since they are both straight edges. The magnetic weights were added to the knife incrementally until a force was reached that penetrated the sock. Over three trials, we tested three Dyneema-based socks—Fastbon Cut-Resistant Hockey Socks Moisture Wicking, Bataidis Cut-Resistant Hockey, and Elite Hockey Pro-Cut Protection—and three Kevlar-based socks—Swiftwick Hockey Knee High 360° Cut-Resistant, Bauer Pro 360 Cut-Resistant Tall Sock, and Dickies KEVLAR® Crew Socks (**Figure 2**). The maximum force that must be applied to cut each sample was recorded (**Table 1**). Each of the six socks was tested over three trials, with a baseline sock without cut-resistant material tested for comparison. The percentage of cut-resistant material averaged throughout the entire sock, "% Cut-Resistant Material," and the American National Standards Institute, "ANSI Level," were given by the manufacturer (14). All Kevlar socks consistently had the same ANSI Level of 4, while the Dyneema ANSI Level varied from 3 to 6 (**Table 1**). As a result, the Kevlar socks tended towards approximately the same average force applied to cut the sock, while the force needed to cut the Dyneema socks varied depending on each sample (**Table 1**).

The relationship between the cut force and total cut resistance parameter was used to compare the cut resistance of the two materials. The total cut resistance parameter was used because it represents the amount of cut-resistant material adjusted for percent cut-resistant material by mass, areal density, and the material-specific tensile strength. This metric eliminates possible external factors that could contribute to the cut force of the material, ensuring a more direct comparison of the cut-resistant materials. A significant positive relationship (t=27.12, p<0.05) between the cut force and the total cut resistance parameter for Dyneema was observed (**Figure 3**). There was also a positive relationship between the cut force and the total cut resistance parameter observed for the Kevlar socks, but it was not significant (t=9.56, p=0.0664). Each of the three Dyneema samples required different average cut forces: Fastbon recorded 19.62 N, Bataidis recorded 21.255 N, and Elite Hockey recorded 14.715 N. The three Kevlar samples had relatively similar average cut forces: Swiftwick recorded 16.35 N, Bauer recorded 13.08 N, and Dickies recorded 16.35 N. The force required to cut through a Dyneema or Kevlar sock increases as the amount of cut-resistant material in the sock increases, thus creating a positive sloping trend line (**Figure 2**). Also, the R^2 values were 0.9986 for Dyneema and 0.99892 for Kevlar (**Figure 2**). The closeness of these values to 1 showed that

https://doi.org/10.59720/24-357

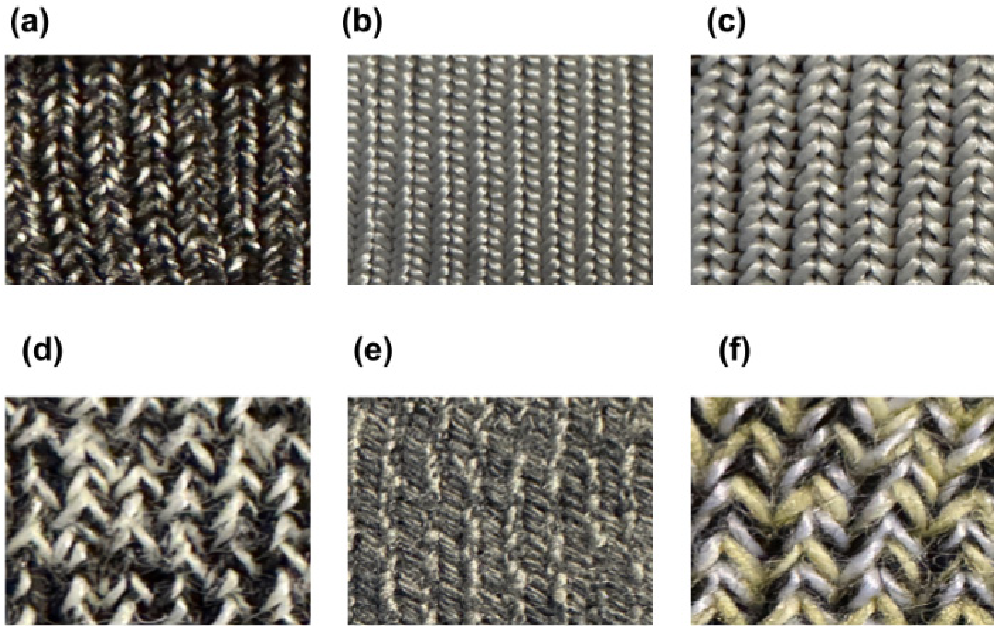

Figure 2: Magnified knit patterns for all Kevlar and Dyneema Samples. a) Fastbon 10x magnification, b) Bataidis 10x magnification, c) Elite Hockey 11x magnification, d) Swiftwick 15x, e) Bauer 11x magnification, and f) Dickies 10x magnification. Optical photographs of each sample were obtained with an ultra-wide camera with a 13 mm lens.

there was a strong correlation between the force required to cut the socks and the total cut resistance parameter of the socks for both Dyneema and Kevlar. The slope of the trendline for Dyneema is approximately 0.00007 N/(GPa·g/m²), while Kevlar's is 0.00005 N/(GPa·g/m²). Because Dyneema has a greater trendline slope, this means that it has a higher cut force per unit of cut resistive material. A relationship between the ANSI level and the required cut force for the Dyneema samples was not observed. Furthermore, ANSI/ISEA 105-2016 standard suggests that a higher level indicates a higher cut force. However, Bataidis Cut-Resistant Hockey has an ANSI level of 3, yet it performed better than Elite Hockey Pro-Cut Protection which had an ANSI level of 5. There was a relationship between the ANSI and the cut force required for the Kevlar samples. Each of the samples had an ANSI level of 4, meaning they were within the 1,500-2,199 g range.

DISCUSSION

The goal of our study was to compare the cut-resistive properties of Kevlar and Dyneema hockey sock samples to determine which is more suitable for hockey players. We hypothesized that Kevlar would require a higher force to cut than Dyneema. Multiple trials of experiments were performed to accurately compare the materials. The force required to cut three Dyneema and three Kevlar samples over multiple trials was recorded. A positive relationship between the cut force and the adjusted amount of cut-resistant material, the total cut resistance parameter, was observed for both Kevlar and Dyneema. However, the slope of the trendline for the Dyneema samples was observed to be larger than Kevlar's trendline, thus indicating a higher force to cut Dyneema samples than Kevlar per unit of adjusted cut-resistant material.

The relationship between cut force and the total-cut resistance parameter was used to compare the ratio of force required to cut the material per unit of the adjusted amount of cut-resistant material, accounting for percent cut-resistant material by mass, areal density, and the material-specific tensile strength. Since Dyneema had a higher slope, this means it required a higher force to cut per unit of cut-resistant material. Thus, Dyneema is more cut-resistant. This finding is supported by the fact that Dyneema exhibits a higher Young's modulus and surface hardness than Kevlar fibers (8,10). Dyneema SK75, the variant often used in cut-resistant socks, has a tensile modulus of 109–132 GPa, while Kevlar has a tensile strength of 83 GPa (8,10). Furthermore, Young's modulus is the ratio of tensile stress to tensile strain of a material (15). This means that Dyneema fibers will deform less, or exhibit less tensile strain, than Kevlar under the same force, or tensile stress, thus offering greater cut resistance.

Additionally, our results align with existing literature comparing the strength of Kevlar and Dyneema. One study compared the cut resistance of Zylon, Kevlar, and Spectra (12). Spectra is nearly identical to Dyneema, with both materials being an ultra-high molecular weight polyethylene (UHMWPE). The main difference is that they come from different manufacturers. In the study, Spectra was consistently more cut-resistant than Kevlar (12). Therefore, due to Spectra's similarities along with the data observed in this work, Dyneema is suggested to be a more cut-resistant material than Kevlar.

Dyneema's higher cut force per unit of material strength is most likely due to its molecular structure. Dyneema consists of highly crystalline polyethylene chains (16). This high degree of crystallinity, approximately 85%, and nearperfect chain alignment provide the fibers with very high tensile strength and excellent energyabsorption capacity (16). Kevlar, however, is made up of a more amorphous structure, consisting of only 50% crystalline (17). The low crystallinity means that less force is required to break the linking hydrogen bonds and fracture Kevlar's molecular chains than Dyneema's. Dyneema-reinforced socks would therefore better protect hockey players of all levels from skate blade lacerations than

https://doi.org/10.59720/24-357

Sock type	% Cut Resistant material	ANSI Level	Trial 1		Trial 2		Trial 3		Avg. Force (N)
			Tear (Y/P)	Force (N)	Tear (Y/P)	Force (N)	Tear (Y/P)	Force (N)	
Baseline	0	1	Y	4.905	Y	4.905	Y	4.905	4.905
Fastbon (**Dyneema**)	43	Not Listed	Y	19.62	Y	19.62	Y	19.62	19.62
Bataidis (**Dyneema**)	50	3	Y	24.5	Y	19.62	Y	19.62	21.255
Elite Hockey (**Dyneema**)	40	5	Y	14.715	Y	14.715	Y	14.715	14.715
Swiftwick (**Kevlar**)	28	4	Y	19.62	Y	14.715	Y	14.715	16.35
Bauer (**Kevlar**)	15	4	Y	14.715	Y	14.715	Y	9.81	13.08
Dickies (**Kevlar**)	6	4	Y	19.62	Y	14.715	Y	14.715	16.35

Table 1: Results of three trials of cut force experiments for all samples. Baseline sock type is a cotton sock without any cut-resistant material. The "% Cut Resistant Material" is the percentage of cut-resistant material in the entire sock. The American National Standard Institute Level (ANSI) is a metric used with the ANSI/ISEA 105 test to determine force required to cut a sample. Trial tears were determined to be torn (Y) or partially torn (P).

Kevlar-reinforced socks.

One limitation of our study was the varying knit patterns. Because the socks used are from different manufacturers, the knit structure is different for each sample. Typically, knit patterns can vary by stitch density, loop size, and other factors (18). Therefore, the structure of a knit can significantly impact the effectiveness of a material's cut resistance (18). Although the knit patterns varied across the samples used, the grams per square meter (GSM) calculation is responsible for a large part of the variations in knit strength. Typically, a tighter knit weighs more, thus having a higher weight per m^2. This is directly accounted for by the GSM value because it measures the grams per square meter of each sock swatch tested. In real-world scenarios, the knit can be optimized to increase cut resistance. However, due to the limited market for cut-resistant hockey socks, a consistent knit pattern was not possible for the experimental procedure.

Additionally, throughout the trials, some samples showed more force required to cut the sample on the first trial than on ensuing trials. This phenomenon is most likely due to the procedural sharpening of the knife after each trial, causing the knife to become sharper over time as testing was performed. Due to the limitation of using the same blade across multiple trials, this is most likely why the force to cut decreased as the trials progressed for the samples.

Another limitation is that the static force testing used did not fully replicate the dynamic and variable conditions of a hockey game. In real-world scenarios, factors such as blade angle, impact speed, and movement can influence the effectiveness of cut-resistant materials. While this study provides insights into material performance under controlled conditions, additional research regarding dynamic testing would be necessary to more accurately assess on-ice situations. Furthermore, the speed and angle of the cuts for skate-related injuries for goalies may differ from the speed and blade angle for players. This is important because the static tests performed do not replicate the kinetic energy or shear stresses created during game-like scenarios. As a result, skaters will experience higher forces on average. Additionally, since goalies and players wear different protective material, exposed areas will vary with position.

Through the relationship determined between cut force and the total cut resistance parameter and the works of other studies, Dyneema is more cut-resistant than Kevlar per unit of adjusted amount of material (13). This data suggests that Dyneema is a more effective material in hockey-sock applications. Because the sample's cut-resistant strength can depend on knit patterns, this offers the possibility of optimizing cut resistance and flexibility throughout the reinforced areas for maximum performance. Although Dyneema has higher cut resistance, its low coefficient of friction, 0.05–0.07, makes it a relatively slick material, thus possibly compromising tear resistance or grip (10). Manufacturers must develop composite designs that blend Dyneema with ductile or high-friction fibers, such as nylon or spandex, to improve the flexibility without sacrificing protection. These design parameters, informed by the outcomes of our study, show areas where hockey equipment manufacturers can take a holistic approach to manipulate the knit pattern and material composition to improve the standards of protective hockey socks.

MATERIALS AND METHODS

Experimental Socks

Cut force experiments were performed to determine the maximum force that can be applied before cutting sample socks of each material with varying percentages of Kevlar or Dyneema. Dyneema socks with 40 wt% (Elite Hockey Pro-Cut Protection), 43 wt% (Fastbon Moisture Wicking Socks), and 50 wt% (Bataidis Cut Resistant Hockey Socks), and

https://doi.org/10.59720/24-357

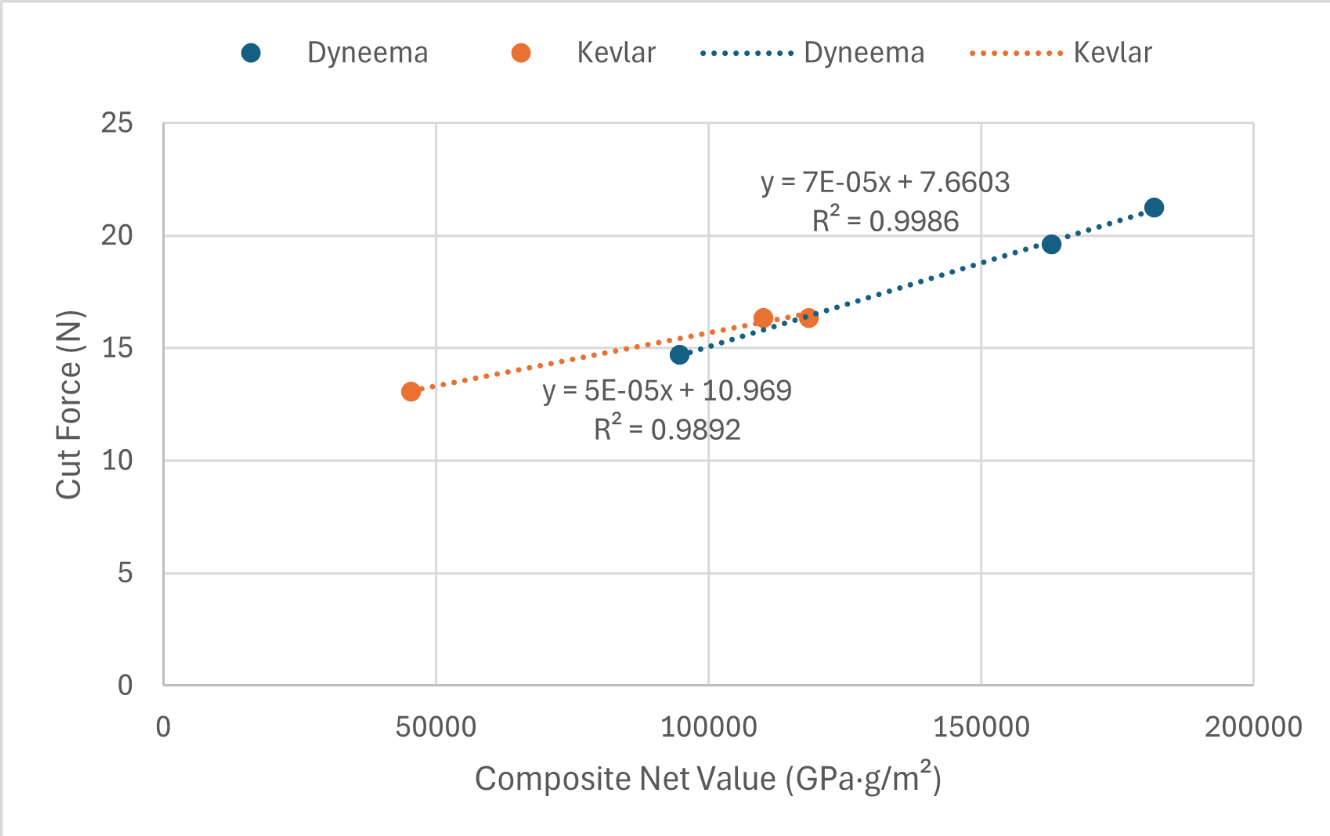

Figure 3: Cut force vs total cut resistance parameter for Kevlar and Dyneema samples. . The Dyneema samples (blue: Elite Hockey, Fastbon, and Bataidis) and the Kevlar samples (orange: Bauer, Swiftwick, and Dickies) were tested for cut resistance in 500 g increments until the weighted knife penetrated the sample. The total cut resistance parameter represents the amount of cut-resistant material adjusted for percent cut-resistant material by mass, areal density, and the material-specific tensile strength. The average force required to cut each Dyneema sample was 14.715 N for Elite Hockey, 19.62 N for Fastbon, and 21.255 N for Bataidis (p=0.0235, t-statistic=27.12, 95% Confidence Interval=[2.4039,12.9167]). The average force required to cut each Kevlar sample was 13.08 N for Bauer, 16.35 N for Swiftwick, and 16.35 N for Dickies (p=0.0664, t-statistic=9.56, 95% Confidence Interval=[4.9108,17.0274]). A linear regression trendline is observed for the Dyneema (blue dotted line) and Kevlar (orange dotted line) samples.

Kevlar socks with 6 wt% (Dickies KEVLAR® Crew Socks), 15 wt% (Bauer Pro 360 Cut Resistant Tall Sock), and 28 wt% (Swiftwick Hockey Knee High 360° Cut-Resistant) were used for this study (**Table 1**).

Setup

Prior to testing, the unstretched length of the cut-resistant area for each sock was measured. Then, the sock was put on, and the stretched length of the cut-resistant area was measured. The percent stretch for each sock was calculated and ultimately averaged to be 118%. 3-inch by 1-inch samples were cut from the cut-resistant area and stretched to 118%, or 3.55 inches, to ensure consistent tension throughout the sample. Because the sample was only being cut in the lengthwise direction, the sample was stretched in the lengthwise direction, thus remaining 1 inch in width. The force applied to the samples was measured in Newtons through the Taylor Pro Digital high precision scale. Once the scale was reading grams, a cutting board was placed on top of the scale (**Figure 1a**). After the cutting board was secured to the scale, the fabric holder was placed in the center to ensure accurate readings. The fabric holder was rounded to create a more stable and consistent cut (19). A 3.55-inch double-sided piece of tape was placed onto the holder (**Figure 1a**). Then, the sample was positioned in the center to ensure accurate readings. Once the sock had been secured, the scale was zeroed to precisely measure the force applied. Neodymium magnets were placed on the flat side of the knife (**Figure 1b**). 500 g weights were added to the magnets. The knife was pulled backward along the sample, applying 4.90 N of force onto the sample. After, the knife was set aside to examine any signs of lacerations on the sample. If there were no cuts or tears, the sample would be recentered. The knife was then resharpened before the next trial. The force applied was increased in 4.90 N, 500 g weight, increments. Once the sample was cut, the force required to cut the sock was noted, as was whether the sock had been fully or only partially cut. A new 3-inch by 1-inch sample of the same sock was then prepared for the second trial. This process was repeated for each sample for three trials.

Calculations

Following the cut force trials, a total cut resistance parameter was created for each sample. First, the percentage by mass of the cut-resistant material (either Kevlar or Dyneema) in the reinforced area, p_{cut}, was calculated from the overall percentage of cut-resistant material using **Equation 1:**

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https://doi.org/10.59720/24-357

Sock type	p_{cut}	m_{swatch} (g)	Area (m^2)	Grams per square meter (g/m^2)	Cut-resistant-grams per square meter (g/m^2)	Total cut resistance parameter ($GPa{\cdot}g/m^2$)
Fastbon (Dyneema)	95.05	1.229	0.0025806	476.24	45,266.46	162,959.27
Bataidis (Dyneema)	97.92	1.33	0.0025806	515.28	50,465.62	181,676.24
Elite Hockey (Dyneema)	69.57	0.9751	0.0025806	377.85	26,287.16	94,633.79
Swiftwick (Kevlar)	74.67	1.057	0.0025806	409.59	30,583.96	110,102.26
Bauer (Kevlar)	25.65	1.2695	0.0025806	491.93	12,618.06	45,425.02
Dickies (Kevlar)	38.67	0.5488	0.0006452	850.64	32,894.31	118,419.53

Table 2: Summary of cut-zone swatch measurements and derived material metrics for each sock sample. . For each sock type, p_{cut} is the local cut-fiber mass fraction, m_{swatch} is the mass of the panel sample, Area is its area in m², and Grams per square meter (GSM) is the panel's total areal density. Cut-resistant-grams per square meter (CR-GSM) is the areal density of cut-resistant fiber alone (GSM × p_{cut}), and total cut resistance parameter (T) is the strength-weighted areal density (CR-GSM × fiber tensile strength).

$$p_{overall} = (m_{cut}\, p_{cut} + m_{non\text{-}cut}\, p_{non\text{-}cut}) / (m_{cut} + m_{non\text{-}cut}) \quad (1)$$

where poverall is the overall percentage of cut-resistant material, $p_{non\text{-}cut}$ is the percentage of cut-resistant material in the non-reinforced area, m_{cut} is the mass of the reinforced area, and $m_{non\text{-}cut}$ is the mass of the non-reinforced area.

The GSM was found for the cut-resistant area. A swatch the size of 1 inch by 1 inch or 2 inch by 2 inch, depending on the available area, was cut from the same area the cut force experiments were performed on. The GSM was calculated to find the areal density of all the fibers in the sample using **Equation 2:**

$$GSM = m_{swatch} / area \quad (2)$$

where m_{swatch} was the mass of the swatch, and area was the area of the swatch.

The cut-resistant-grams per square meter (CR-GSM) value was calculated to find the areal density of the cut-resistant material in the sample,

$$i \in \{d, k\}\ CR\text{-}GSM_i = p_i \times GSM_i \quad (3)$$

where pi is the percent by mass of the cut-resistant material in the reinforced area, i=d represents the CR-GSM for Dyneema, and i=k represents the CR-GSM for Kevlar.

The total cut resistance parameter, T, was calculated for each material by weighing the CR-GSM by its respective material's approximate tensile strength to account for tensile variability in **Equation 4:**

$$i \in \{d, k\}\ T_i = CR\text{-}GSM_i \times \sigma_i \quad (4)$$

where σ_i is the approximate tensile strength for the cut-resistant material, i=d represents the total cut resistance parameter for Dyneema, and i=k represents the total cut resistance parameter for Kevlar.

The tensile strength of Kevlar was 3.6 GPa (8). Since there are multiple fiber types for Dyneema, the most appropriate fiber to use was SK75 because it is meant for knitting and weaving. Dyneema SK75 had an average tensile strength of 3.6 GPa (10).

Data and Statistical Analysis

A direct comparison between the listed percentage of cut-resistant material and cut force is not an effective way to compare the cut-resistive properties of the two materials. A direct comparison does not consider the fact that the listed percentage of cut-resistant material is calculated based on the entire sock, even though the cut-resistant material is only applied to high-risk areas that have the greatest likelihood of being exposed to a skate blade while playing hockey, such as the ankle and calf. Therefore, the listed percentage is generally much lower than the actual percentage of cut-resistant material in the areas where skate blade lacerations are likely to occur. For the purposes of evaluating the usefulness of these samples in real hockey game situations, only the areas that included the Kevlar or Dyneema were tested. This means that there is a higher percentage of Kevlar or Dyneema in targeted high-risk areas than in the sock as a whole. As a result, a "total cut resistance parameter" of the relevant cut-resistant materials was created to determine the percentage of Kevlar or Dyneema knitted into the cut-resistant regions of the socks, adjusting for varying areal densities and tensile strengths.

The total cut resistance parameter involved a series of calculations. The calculation used the percentage of cut-resistant material in the cut-resistant area by mass, the

https://doi.org/10.59720/24-357

areal density of the cut-resistant material, and the tensile strength (**Table 2**). This allows the index to adjust for the local concentration of the cut-resistant material, varying areal densities of the samples, and the theoretical strength capacity.

After collecting the cut force data for each sock, the average cut force across the three trials for each of the six socks was calculated. Two simple linear regression models, one for Kevlar socks and one for Dyneema socks, were performed between the total cut resistance parameter (GPa·g/m²) and the average sample cut force (N). The *p*-values, *t*-statistics, and 95% confidence intervals were calculated for each linear regression model. All calculations were performed using GraphPad's linear regression analysis tool, which automatically computes slope statistics, confidence intervals, and *p*-values. The *t*-statistic was found using the provided slope and standard error.

Received: October 31, 2024
Accepted: June 7, 2025
Published: December 3, 2025

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