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ADAMS, Caroline, JAMES, David <http://orcid.org/0000-0002-1135-626X>, SENIOR, Terry <http://orcid.org/0000-0002-3049-5724>, ALLEN, Tom and HAMILTON, Nick <http://orcid.org/0000-0002-4807-3087>

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Development of a method for measuring quasi-static stiffness of snowboard wrist protectors

Caroline Adams[a*], David James[a], Terry Senior[a], Tom Allen [b], Nick Hamilton[a]

[a]*Centre for Sports Engineering Research (CSER), Sheffield Hallam University, Collegiate Campus, Sheffield, S10 2BP, UK*
[b]*School of Engineering, Manchester Metopolitan University, Manchester, M1 5GD, UK*

Abstract

In snowboarding, the wrist is the most common injury site, as snowboarders often put their arms out to cushion a fall. This can result in a compressive load through the carpals coupled with wrist hyperextension, leading to sprains or fractures. Wrist protectors are worn by snowboarders in an effort to reduce injury risk, by decreasing impact forces and limiting wrist hyperextension during falls. However, there is no international standard or universally-accepted performance specification that these products should conform to, resulting in an inability to judge which design elements offer the most protection. EN 14120:2003 prescribes requirements that roller sports wrist protectors should meet, and has been identified as a starting point for developing a snowboarding-specific standard. This paper critiques the EN 14120:2003 test protocol and goes on to present a mechanical test for assessing the ability of snowboard wrist protectors to resist extension of the hand under an applied load. A bespoke rig incorporating the hand/arm surrogate from EN 14120:2003 was mounted to a uniaxial test machine, and wrist protectors were strapped to the surrogate at a set tightness (tight, moderate, loose). Linear displacement of the uniaxial test machine was transferred to angular displacement of the hand via a galvanised steel cable passing through a low friction pulley. Linear displacement was set to 200 mm/min and force was measured at the load cell until 80 N was reached. The test, presented here, found that the ability of the protectors to limit hand extension was dependent on how tightly they were fitted to the surrogate; therefore, strap tightness must be accounted for during further wrist protector safety assessments. This test provides a repeatable way to characterise the ability of snowboarding wrist protectors to limit wrist extension.

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Keywords: injury prevention; mechanical testing; snowboarding; wrist

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1. Introduction

The upper extremity is the most common injury site in snowboarders, representing 35 to 45% of all snowboarding injuries [1]. Falls are the most common injury mechanism in snowboarding and account for 69 to 93% of all injuries [2]. In moments of instability, snowboarders attempt to cushion their fall by putting their arms out which can result in a load being applied to the outstretched hand. The load is transmitted along the upper extremity as an axial compression force and moment, often resulting in wrist hyperextension leading to wrist sprains or fractures [3,4]. Wrist protectors have been adopted as a preventative measure to reduce injury risk and different designs are available.

There is conflicting evidence regarding the effectiveness of snowboard wrist protectors, some studies show them to reduce risk of injury by attenuating impact forces in the wrist and limiting hyperextension during falls [1,5]. Whilst others argue that protectors transfer the load to another body region increasing the risk of injuries to the elbow or shoulder [6,7]. To date, there is no international standard that these products should conform to, or even a universally-accepted performance specification, making it hard to determine which designs offer the most protection. A repeatable method of characterizing snowboard wrist protectors is required to help identify products which reduce injury risks. The specific injury mechanisms of wrist fractures in

* Caroline Adams. Tel.: +44-114-225-2355
E-mail address: caroline.adams@shu.ac.uk

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snowboard fall scenarios is not well understood, however, mainly due to the complexity of the wrist joint and limited availability of cadavers for testing.

Some researchers state that snowboard wrist protectors should attenuate impact forces, absorb or shunt the impact energy away from the wrist and prevent hyperextension [8,9]. Whilst Maurel et al. [10] argue that there is no real literature basis for whether or not the prevention of hyperextension reduces the risk of fracture. A common approach to protector design is to include features intended to limit hyperextension, such as rigid splints on the palm and dorsal sides of the wrist. It is, therefore, deemed important to be able to assess the ability of protectors to resist wrist extension under an applied load. This paper presents a mechanical test for assessing the ability of snowboard wrist protectors to resist wrist extension.

1.1. EN 14120:2003 bending test

The international standard EN 14120:2003 [11], prescribes requirements that roller sports wrist protectors should meet. The standard includes a bending test to determine protector stiffness when fitted to a simplified hand and forearm surrogate. Schmitt et al. [12] deemed this test to be a suitable starting point for characterizing snowboard wrist protectors. It is unclear, however, how the size of the hand corresponds with published anthropometric data [e.g. 13] and three dimensions are missing from the drawing provided in the standard (a, b and c in Figure 1a). There are also a number of issues with the test protocol and setup as outlined below.

Protectors are deemed sufficiently stiff if the hand angle is between 35 to 55° when a 3 Nm torque is applied. Figure 1b illustrates the test setup, where angles greater than 45° cannot actually be reached as the load applicator would no longer be in contact with the hand. The suitability of transferring test parameters from a roller sports context to snowboarding is also questionable. For example, during an on-slope study measuring wrist moment and hyperextension, Greenwald et al. [14] observed extension angles 76.8 ± 15.8° (mean and standard deviation) at wrist moments of 15.9 ± 20.7 Nm in snowboard falls which didn't result in injury. These values are significantly higher than those currently used in the roller sports standard implying that higher thresholds might be more appropriate for snowboarders. The protocol also fails to state how tightly protectors should be strapped to the surrogate and the rate at which the load should be applied, which could lead to inconsistent results between operators.

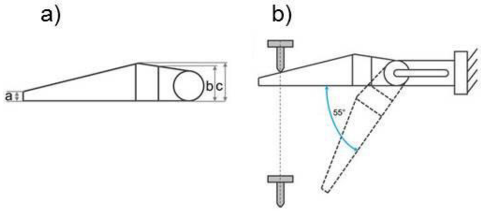

Fig. 1. a) Missing hand dimensions (a, b, c) and b) Schematic of EN 14120:2003 bending test (adapted from European Committee for Standardization, 2003)

This paper uses the surrogate from EN 14120:2003 and presents a method which is more appropriate for testing snowboard wrist protectors. A uniaxial testing machine (Instron 3367, fitted with a 5 kN load cell) and bespoke rig was used to apply an angular displacement to the hand while measuring load. The results for three protector designs are presented to demonstrate the method.

2. Methods

2.1. Test Setup

The experimental procedure is based on the approach described in EN 14120:2003, with modifications to the setup and testing protocol. The hand and forearm sections of the surrogate were made from plastic using additive manufacturing, based on the dimensions specified in EN 14120:2003 for range C users (>50kg). Assumptions were made for the three hand dimensions missing from the standard (a = 15 mm, b = 38 mm, c = 40 mm (Figure 1a)), based on approximations from the other dimensions. Figure 2a shows the test setup, which converted linear displacement of the uniaxial test machine to angular displacement of the hand. In contrast to Schmitt et al. [12] where angles were only obtained for torques of 3 and 16 Nm, the new setup enables load to be measured across a range of hand angles.

The rig consists of a low friction pulley and a mounting fixture to hold the forearm of the surrogate in a vertical position. The rig was mounted to the Instron machine via the flexure fixture and positioned with a galvanized steel cable (diameter 1.9mm) running vertically from the load cell through the pulley. The cable was connected to the load cell at one end via a cable lock (Rize Enterprises, USA) and the distal end of the hand via a karabiner at the other. Through vertical displacement of the load cell, a torque was applied around the wrist joint pulling the hand backwards. A tensile test of the cable resulted in a strain of <0.01 at 80 N (maximum load in the protector tests), confirming extension of the cable did not influence the results of the protector test.

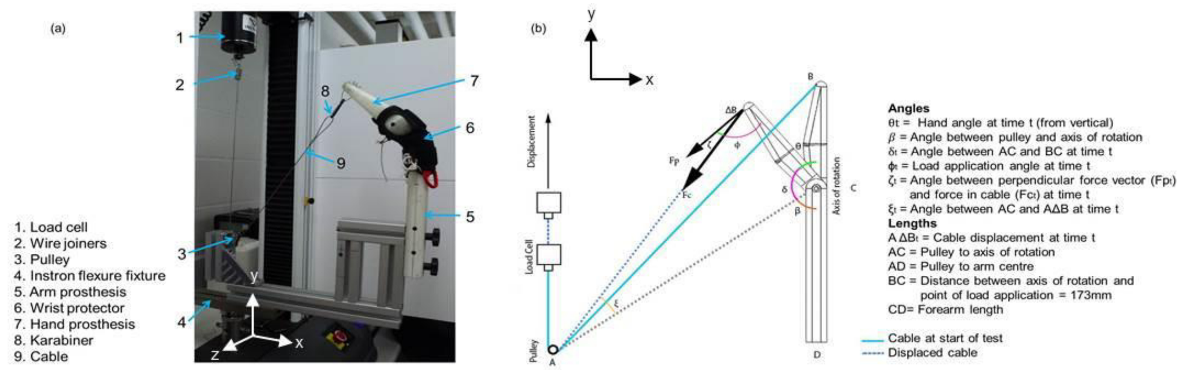

Fig. 2. a) Test rig mounted to Instron machine with short snowboard wrist protector experiencing a load b) Test analysis schematic

2.2. Test Protocol

To demonstrate the suitability of the method tests were performed on three adult size medium left hand wrist protectors. A short snowboarding wrist protector (Burton, Impact wrist guard); a long snowboarding wrist protector (Demon, Flexmeter double wrist guard); and an EN 14120:2003 certified skateboarding wrist protector (Oxelo, Black skateboard wrist guard). The two snowboarding protectors were chosen as they represent different design approaches, whilst the skateboarding protector acted as a comparison that was certified to EN 14120:2003. The long protector had a palmar splint three times longer than the short protector, and a dorsal splint that was 40% longer than the other two products.

Strapping tightness was investigated through tight, moderate and loose conditions. The protector was tightened by holding the surrogate arm horizontally and then attaching a weight of known mass (tight = 3kg, moderate = 2kg, loose = 1kg) to the Velcro strap before rotating the arm until the protector was securely fitted. The position of the strap and buckle at each strapping condition was then marked on the protector. It was not possible to test the skateboard protector at a moderate tightness due to the design of the straps, so eight different conditions were tested in total. Five repeated trials were performed on each protector for each strapping condition, resulting in 40 tests in total. If the protector slipped during testing and clear movement was observed, the trial was void and restarted until five complete trials were obtained for each condition.

For each trial the surrogate was mounted to the rig and the protector strapped to the desired tightness (loose, moderate or tight), using the marks defined previously as a reference. The protectors were found to hold the hand slightly backwards and the angle between vertical and the resting position of the hand was defined as the *neutral angle*. The neutral angle was measured using a digital inclinometer before connecting the cable to the hand. A manually applied preload of ~1 N removed any slack from the cable, although this caused the hand to rotate slightly further backwards. Therefore, the *start angle* ($\theta_{t=0}$) was also measured before initiating the trial, and if the difference between the neutral and start angle was $\geq 5°$ the trial was restarted. During the test, the load cell was displaced upwards at 200 mm/min until 80 N was recorded. The angle of the hand at the end of the test was then measured using the inclinometer, and defined as the *end angle* ($\theta_{t=\text{end}}$). A force of 80 N at the load cell was equivalent to a torque of 10 to 14 Nm, depending on the end angle (see equations 7-8 below). Load and displacement were recorded at 10 Hz and trials typically lasted between 60 to 80 seconds.

2.3. Data Analysis

The load cell data and start and end angle measurements were used to determine hand angle and torque throughout the trial. The *effective stiffness* of the protector was defined as the ratio of torque to hand angle. As the cable was pulled at a constant rate the angular displacement of the hand was also constant. Based on the known start and end angle, the hand angle and associated load was determined throughout the trial. The recorded load was in the vertical axis rather than perpendicular to the hand. Before the torque could be calculated it was necessary to determine the load application angle (ϕ_t) and hence load perpendicular to the hand (Fp_t). The load application angle (ϕ_t) was determined using trigonometry (Figure 2b). Before ϕ_t could be calculated it was necessary to determine a number of angles: β_t, δ_t and ξ_t.

Lengths AC, AD, BC and CD in figure 2 were constant throughout the entire test so were measured once using a tape measure, enabling β to be determined.

$$\beta = \sin^{-1}\left(\frac{\mathrm{AD}}{\mathrm{AC}}\right) \tag{1}$$

δ, the angle through which the hand moved relative to the vertical axis during the trial was then determined.

$$\delta_t = 180 - \beta_t - \theta_t \tag{2}$$

AΔB the displaced length of the cable was determined using the cosine rule, enabling ξ_t to be calculated using the sine rule. ϕ_t was then calculated as all other angles in the triangle are known.

$$A\Delta B_t = \sqrt{((BC^2 + AC^2) - 2(BC * AC * \cos\delta_t))} \tag{3}$$

$$\xi_t = \sin^{-1}\left(\frac{BC * \sin\delta_t}{A\Delta B}\right) \tag{4}$$

$$\phi_t = 180 - \xi_t - \delta_t \tag{5}$$

During the trial the angle between the cable and the hand changes from an acute angle to an obtuse angle so it was necessary to use Eq.6a or 6b to determine ζ_t the angle between the perpendicular force vector (Fp) and the measured force in the cable (Fc).

$$\zeta_t = \phi_t - 90 \ (\text{if}\ \phi_t > 90) \tag{6a}$$
$$\zeta_t = 90 - \phi_t (\text{if}\ \phi_t < 90) \tag{6b}$$

Fp_t was determined based on ζ_t and Fc_t using force vectors.

$$Fp_t = Fc_t * \cos\zeta_t \tag{7}$$

The torque was calculated by:

$$\text{Torque} = Fp_t * BC \tag{8}$$

Regression techniques were used to model the relationship between hand angle and torque. A line of best fit through the angle and torque data was used to determine a mathematical function for each condition. For each trial four different functions were considered: exponential, quadratic, linear and Weibull sigmoidal [15]. The function with the lowest sum of squared error (SSE) and highest R^2 adjusted was selected as the best representation of the data. A nonlinear regression analysis was performed using SPSS (SPSS Inc., Chicago, IL) to minimize the SSE term and determine the standard deviation. The hand angle at 1 Nm intervals was then determined based on the identified function for each condition.

3. Results

For all conditions the Weibull function provided the best fit to represent the data. Figure 3a shows the fit for the short snowboarding protector with loose strapping. The mean and standard deviation values for the start and end angles for all conditions are presented in Table 1. In general, the standard deviation for repeat trials of the same condition was smallest for the end angle (6 of 8 conditions). For all three protectors, the standard deviation of the end angle was smallest in the tightly strapped condition. The mean standard deviation for the end angle across all eight conditions was 1.2° (<1.8% of the mean measured end angle).

Figure 4a shows the relationship between hand angle and torque for the short snowboarding protector, for all three strapping conditions. The vertical black line represents the pass range for the EN 14120:2003 test and the short snowboard protector only met the requirements when tightly strapped. Figure 4b shows the relationship between hand angle and torque for all three protectors, when tightly strapped. The long snowboard protector exhibited the highest effective stiffness at torques above 1 Nm. The same models of snowboard protector were tested by Schmitt et al. [12] and their results are included in Figure 4b as a comparison.

Table 1: Mean ± standard deviation for start angle, end angle, torque at end angle and angle at 3 Nm from the function

Protector	**Strapping**	**Start angle** (°) (Mean ± SD)	**End angle** (°) (Mean ± SD)	**Torque at end angle** (Nm) (Mean ± SD)	**Angle at 3 Nm** (°) equivalent to EN 14120:2003
Short Snowboard	Loose	4.4 ± 2.8	91.1 ± 1.6	10.2 ± 0.4	61.1
	Moderate	3.5 ± 2.2	89.5 ± 1.6	10.5 ± 0.3	58.5
	Tight	3.9 ± 1.8	87.8 ± 0.8	10.9 ± 0.2	53.7
Long Snowboard	Loose	10.9 ± 1.0	70.1 ± 2.9	13.2 ± 0.3	32.2
	Moderate	11.5 ± 0.8	65.8 ± 0.8	10.6 ± 0.3	32.7
	Tight	12.3 ± 1.7	64.1 ± 0.5	13.6 ± 0.02	33.7
Skateboard	Loose	18.9 ± 1.3	77.7 ± 0.5	12.5 ± 0.1	54.7
	Tight	20.5 ± 1.4	78.5 ± 0.5	12.4 ± 0.1	53.9

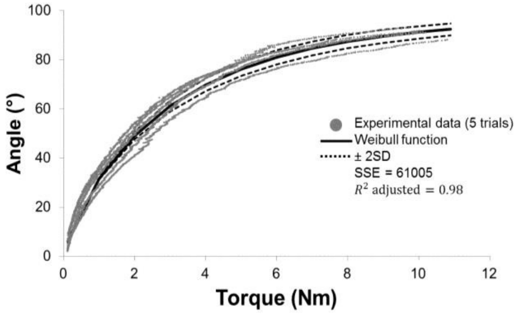

Fig. 3. Experimental data fitted with Weibull function for loosely strapped short snowboarding protector $y = a - b\exp^{(-cx^d)}$ (a=97.7, b = 97.5, c = 0.4, d = 0.8)

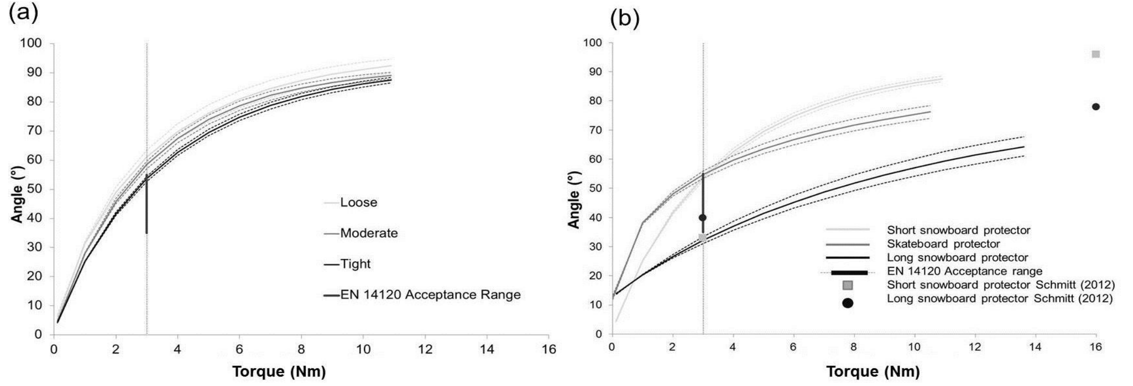

Fig. 4. a) Strapping comparison: three levels of strapping for short snowboarding protector b) Protector comparison: three products tightly strapped (dotted lines show ± 2SD)

4. Discussion

Three conclusions are drawn: (i) The proposed method enables the relationship between hand angle and torque to be obtained for a wrist protector, (ii) The proposed method is able to distinguish differences in effective stiffness between wrist protector designs and (iii) Strapping tightness influenced the effective stiffness of the protectors.

Three protectors based on different design principles were tested and different stiffness characteristics were observed using the proposed test. Smaller hand angles were observed for a given torque for the long snowboard protector, demonstrating it had a higher effective stiffness than the other two products. This is expected based on its long dual splint construction, compared to the other two products which had shorter and narrower splints. The short snowboard protector and the skateboard protector had similar hand angles, and hence effective stiffness, at 3 Nm. At higher torques the skateboard protector exhibited higher effective stiffness, and while both products have dorsal splints of the same length, they have different splint constructions indicating that a combination of design factors affect a protectors' ability to resist hand extension.

The proposed method also detected differences in end hand angle for different strapping conditions. At the tightest strapping condition the short snowboarding protector would meet the EN 14120:2003 requirements with a hand angle of 54° at 3 Nm, however at the moderate and loose strapping conditions it would have failed for being too flexible and not limiting the hand angle enough (Table 1). This highlights the importance of defining strapping tightness when testing wrist protectors. A product could be deemed suitable by one operator, but not another, simply due to strapping differences.

The same models of snowboard protector were tested by Schmitt et al. [12], yet their results were notably different (Figure 4b). At 3 Nm an angle of 33° was measured for the short snowboard protector in contrast to 61° (loose), 58° (moderate) and 54° (tight) measured in this study for the three strapping conditions. Schmitt et al. [12] measured a hand angle of 40° at 3 Nm for the long snowboard protector, yet this study found the protector to have a higher effective stiffness with lower hand angles; 34° (loose), 33° (moderate) and 32° (tight) for the three different strapping conditions. The maximum torque measured in this study was 13.6 Nm, so a direct comparison against the 16 Nm results measured by Schmitt et al. [12] was not possible. Discrepancies in protector performance between the two studies at 3 Nm could be due to a combination of factors, such as different hand dimensions for the three unspecified values, different loading rates and different strapping tightness. This disparity further emphasizes the need for a consistent and repeatable test protocol to measure wrist protector performance.

A number of tests had to be repeated as the protector slipped or the strapping came undone. Additional tests were required for 75% of the tested conditions. The poor fit between the surrogate and protector was likely to contribute to this unwanted movement during the test. Whilst the hand surrogate has a thumb representation it is only a small protrusion and in some instances the protector slipped off it during the test. The fit between the surrogate arm and protector was also quite poor due to the overly simplified cuboidal shape of the forearm. Payne et al, [16] argue that surrogates with biofidelic geometries should be used when testing protective equipment to maintain alignment and attachment during testing. The use of non-representative geometries in the surrogate is another weakness of EN 14120:2003. Modifying the surrogate to incorporate a thumb, more representative geometries, dimensions based on published anthropometric data and a higher friction surface should reduce variation in fitting protectors and improve consistency of the test.

The proposed setup is suitable for comparing and characterizing wrist protectors and implementation into existing test houses should be feasible following a few modifications. A limitation of this test method is the use of a relatively low magnitude load applied quasi-statically; whilst this facilitates an understanding of product stiffness, it doesn't take into account protectors that may incorporate rate dependent materials. A complementary approach employing a dynamic test in which a number of protective parameters can be measured including: stiffness; energy absorption; and load transfer will be developed. Another limitation of the setup is the shape of the hand. A number of snowboard wrist protectors are incorporated into gloves, so a hand surrogate with fingers is needed to test these products.

5. Conclusion

This paper presents a new test setup and method to determine the effective stiffness of snowboard wrist protectors fitted to a hand/arm surrogate across a range of loads. Unlike the work of Schmitt et al. [12] in which only two torques were studied, the proposed method enables a detailed understanding of the relationship between hand angle and torque. The results were shown to be dependent on how tightly the protectors were strapped to the surrogate, so strapping tightness should be accounted for in future work. Further efforts should focus on testing to a higher torque, modifying the design of the surrogate and attempting to create more realistic snowboard fall scenarios through a dynamic test. The proposed setup and protocol provides a method to evaluate the effective stiffness of wrist protectors. This approach can aid manufacturers in the design and development of future products, evaluating different splint element designs.

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