OPEN ACCESS

Crash-test dummy and pendulum impact tests of ice hockey boards: greater displacement does not reduce impact

Kai-Uwe Schmitt,[1] Markus H Muser,[1] Hansjuerg Thueler,[2] Othmar Bruegger[2]

[1]AGU Zurich, Zurich, Switzerland
[2]Bfu—Swiss Council for Accident Prevention, Berne, Switzerland

Correspondence to
PD Dr Kai-Uwe Schmitt, AGU Zurich (Working Group on Accident Mechanics), Winkelriedstrasse 27, 8006 Zurich, Switzerland; schmitt@agu.ch

Accepted 2 October 2017
Published Online First 30 October 2017

ABSTRACT

Background One injury mechanism in ice hockey is impact with the boards. We investigated whether more flexible hockey boards would provide less biomechanical loading on impact than did existing (reference) boards.

Methods We conducted impact tests with a dynamic pendulum (mass 60 kg) and with crash test dummies (ES-2 dummy, 4.76 m/s impact speed). Outcomes were biomechanical loading experienced by a player in terms of head acceleration, impact force to the shoulder, spine, abdomen and pelvis as well as compression of the thorax.

Results The more flexible board designs featured substantial displacement at impact. Some so-called flexible boards were displaced four times more than the reference board. The new boards possessed less stiffness and up to 90 kg less effective mass, reducing the portion of the board mass a player experienced on impact, compared with boards with a conventional design. Flexible boards resulted in a similar or reduced loading for all body regions, apart from the shoulder. The displacement of a board system did not correlate directly with the biomechanical loading.

Conclusions Flexible board systems can reduce the loading of a player on impact. However, we found no correlation between the displacement and the biomechanical loading; accordingly, displacement alone was insufficient to characterise the overall loading of a player and thus the risk of injury associated with board impact. Ideally, the performance of boards is assessed on the basis of parameters that show a good correlation to injury risk.

INTRODUCTION

Ice hockey is associated with a high risk of sustaining injuries such as lacerations, sprains, contusions, fractures and cerebral concussion.[1–10] The most common mechanisms for ice hockey injuries include collisions between two players, impacts with ice hockey boards and impacts with the ice.[2 4 11–14] Board contact was the relevant injury mechanism in approximately 20%–40% of all injuries.[3 5 11]

To investigate biomechanical loading during an ice hockey match, studies have been conducted with instrumented helmets to record head (helmet) impact.[13–16] Those findings led to the suggestion that new boards should be developed to reduce the biomechanical loading on a player at impact, and thus, reduce the injury risk due to impact.

Based on an evaluation of injuries sustained in World Championship ice hockey matches, Tuominen *et al*[1 6] estimated that a more flexible board design could reduce the injury risk by 29%. However, from these studies it remains unclear which injuries this estimate referred to and which features of the board design could effectively be modified to achieve that risk reduction. More recently, the authors reported that flexible boards significantly reduced concussion.[17]

Most current ice hockey board systems consist of a lower board element and an upper transparent shielding element. The conventional ice hockey board consists of framed board sections that are firmly attached to the floor and to each other through support posts; consequently, the board is not displaced or deformed significantly. The shielding is constructed of either glass or a synthetic material. Additionally, a kick plate can be installed to protect the board in the area just above the ice surface, and a handrail is placed in the transition area between board and shielding (figure 1).

These systems must comply with basic requirements, established in standards like the ASTM F1703-13 or DIN18306 as well as the rules defined by the International Ice Hockey Federation and National Ice Hockey associations. These standards define, for example, specific dimensions, and they require the system to withstand high-speed puck impacts. However, performance criteria related to player impacts are not defined.

Several manufacturers of ice hockey boards also offer modified designs, which they claim are more flexible. These so-called flexible boards are designed to be displaced on impact. The technologies implemented to achieve displacement vary; some systems claim that the complete system can deflect on impact and other systems use a mechanism to displace the shielding when hit by a player.

Generally, it is assumed that this displacement of the board (ie, the stopping distance during impact) would reduce the injury risk. Poutiainen *et al*[18] characterised the properties of three boards against a conventional board with an impact pendulum. The new design reduced the peak impact forces measured in the system by 16%–17%, provided greater stopping distance, and the board elements had less stiffness compared with the conventional design. However, they did not quantify the biomechanical loading experienced by an impacting player.

We aimed to assess the performance of six ice hockey boards to explore whether modified designs would reduce the loading experienced by a player on impact. We hypothesised that a board with high displacement would reduce the biomechanical loading on a player at impact.

To cite: Schmitt K-U, Muser MH, Thueler H, *et al*. *Br J Sports Med* 2018;**52**:1–7.

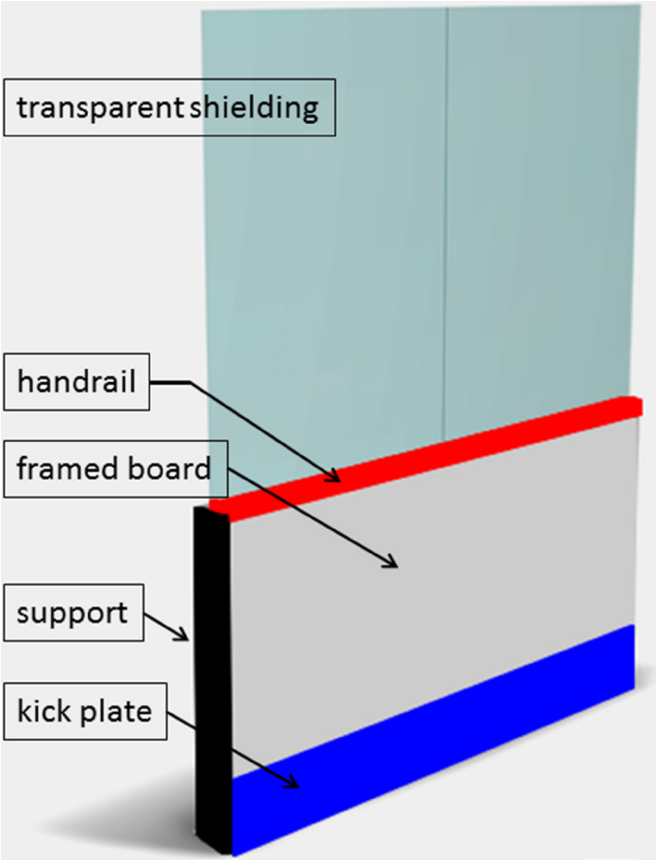

Figure 1 Components of an ice hockey board system. The support is part of the framed board and allows the system to be mounted to the floor (either directly or using an ice dam).

METHODS

We performed two types of impact tests: one with a pendulum to test board properties and one with a crash test dummy to determine the biomechanical loading on impact. Different dummy sizes were tested in different impact configurations. We compared six commercially available board designs.

Ice hockey boards

Our test series of six boards included the following board designs: Engo Olympic 2400, Engo Flexboard PPS, Raita Hornium, Icepro Steeline, AST Prototype and Vepe Beta (table 1). The Engo Olympic 2400 represented a conventional design and served as reference. The other five designs were so-called flexible boards.

For the impact tests, we mounted three sections of each board system in a straight-line configuration inside the test facility. The boards were mounted to the floor, according to the manufacturer's recommendations. The boards were screwed to the floor, whereas board B51 featured a rubber plate between bolt and nut. All impact tests were performed on the middle section.

The boards were instrumented identically for all tests. In the middle section, we mounted two potentiometers, one at 1 m (board area) and the other at 1.4 m above ground (shielding area) and one accelerometer at 1 m above ground. Additionally, various targets were tacked to the board and shielding for video analyses.

Table 1 Ice hockey boards included in the test series

Test number	Type of board	Width of one board section (m)	Height of one board section without shielding (m)	Shielding material
B02	Reference	2.4	1.25	Synthetics
B11	Flexible	3.0	1.10	Synthetics
B22	Flexible	2.4	1.10	Synthetics
B31	Flexible	2.4	1.10	Synthetics
B41	Flexible	2.4	1.10	Synthetics
B51	Flexible	3.0	1.10	Synthetics

Test procedures and data analysis

All tests were conducted at room temperature (approximately 22°C) in the Dynamic Test Center, Vauffelin, Switzerland.

Pendulum tests

The pendulum tests were conducted in a standard manner.[18] The pendulum was a sand-filled punching bag (mass 60 kg), which impacted the board system at 1 m (board area) and at 1.4 m (shielding area) above ground. We selected two impact velocities of 3.37 m/s (V1[18]) and 4.76 m/s (V2); thus, V2 possessed twice the kinetic energy of V1. To check for repeatability, all impacts were recorded in duplicate. An accelerometer was placed inside the bag to measure the acceleration of the pendulum. Furthermore, the displacement (sensor type 161-1283H, SpaceAge Control, Palmdale, California, USA) and the acceleration (sensor type XJ50-500, Messring, Krailling, Germany) of the boards were recorded. All measurements were made at 20 kHz sampling rate. All tests were captured with three high-speed video cameras (types AOS S-Motion and X-Pri, AOS Technologies, Baden, Switzerland, 500 frames/s, resolution of 1280×1024 pixels). The videos enabled determination of the pendulum rebound velocity after impact. Based on these measurements, the stiffness of the boards and the effective mass were calculated, as described in Poutiainen *et al*.[18] The overall energy absorption was the difference between the kinetic energies of the pendulum at the initial contact (initial velocity) and at the end of the contact phase (rebound velocity).

Impact tests with a crash test dummy

In a second test series, the boards were impacted with a crash test dummy to measure the biomechanical loading experienced by a player at impact. An ES-2 dummy (Humanetics, Plymouth, Michigan, USA) was used. This dummy is a standard test device in automotive crash testing and was designed to measure loads during side impacts.

The dummy represents a 50th percentile male (mass 78 kg, height 1.75 m) and was instrumented to measure head acceleration, neck forces and moments, shoulder force, rib deformation, thoracic and lower spine acceleration, pelvis acceleration, abdomen force and pubic symphysis force. These parameters are typically used to assess injury risk in automotive safety testing.

All sensors used in the experiments were specified and calibrated according to the relevant standards in the automotive industry (eg, SAE J211). Data acquisition and postprocessing (including filtering) were performed according to those standards as well. For our purposes, the dummy was placed on a sled in an upright position (figure 2). The sled was accelerated and then stopped shortly before contact with the board (figure 3). The dummy slid off the sled and impacted the board at a velocity of 4.76 m/s. The upright dummy position represented a player that remained upright or standing, respectively, at board impact (eg, due to a body check). In the test series presented here, the dummy did not wear any

Figure 2 Dummy positioned on the sled in the upright position. The different targets and markers on the dummy were used to verify that the same position was used in every test.

personal protective equipment such as a helmet or shoulder/hip pads. The head, shoulder and hip of the dummy were marked with paint that resulted in a corresponding imprint on the board. Thus, the impact position on the board could be analysed and compared with to assess the repeatability of the impact configuration. Again, all tests were performed in duplicate.

Evaluating the biomechanical loading

The biomechanical loading experienced by the dummy was recorded and compared with threshold values. In addition to the values directly recorded at the dummy, we determined the head injury criterion (HIC), to characterise the severity of a head impact, and the viscous criterion, to account for the compression and deformation velocity of the thorax.[19] Given that an average is not meaningful when calculated from only two data points, we used the highest loading values recorded in each body region for further evaluations; that is, we addressed a worst-case scenario with respect to the risk of injury.

Data analyses

All data were processed with MS Excel software (V.2013). To analyse board performance, the biomechanical measurements were normalised with corresponding threshold values derived from automotive testing or other experimental data. The sum of all normalised points was the overall assessment score, which was used to rate performance. Low scores indicated low biomechanical loading on the dummy, that is, high board performance. The highest values out of two measurements recorded were analysed.

RESULTS

Table 2 summarises the board performance as characterised by the pendulum tests. The displacement, the energy absorption, the stiffness and the effective mass were determined. To allow comparison with other work,[18] the displacement determined at the lower velocity (V1) was also included. Some so-called flexible boards were displaced four times more than the reference board and the effective mass was reduced significantly by some of the new designs.

Furthermore, player loading was evaluated with the dummy experiments. The results of the biomechanical measures for different body regions are listed in table 3.

To simplify comparisons of the different board designs, the biomechanical measurements were normalised to the reference values (assessment scores). The overall performance score was the sum of the individual scores (table 3) with equal weighting. Figure 4 shows the relationship between performance ranking and board displacement (determined with the potentiometer at 1 m above ground).

DISCUSSION

The flexible boards in this test series did not feature any specific devices or mechanisms to obviously increase flexibility (eg, spring/damper elements). The design changes were too subtle to be detected by eye. Thus, board performance could not be assessed simply by reviewing the design or with a

Figure 3 Example of impact tests with the ES-2 crash test dummy. (Left) Sled motion was stopped abruptly; (middle) dummy slides off the sled towards the board in an upright position and (right) dummy position on impact.

Table 2 Results from the pendulum tests, all recorded at a height of 1 m

Parameter	Test condition	Results for all boards (max values)					
		B02	B11	B22	B31	B41	B51
Displacement (mm)	V1	10.7	20.8	45.5	27.2	41.8	39.3
	V2	18.4	30.5	65.3	39.2	59.6	56.2
Energy absorption (Δ% to B02)	V2	–	5.8	1.6	5.6	−2.3	3.4
Stiffness (Δ% to B02)	V2	–	25.5	55.9	61.5	40.7	50.8
Effective mass (kg)	V2	151.0	111.0	60.5	60.4	60.6	71.4

Tests at V1=3.37 m/s allow comparison with similar pendulum experiments performed previously.[18] Tests at V2=4.76 m/s allow comparison with tests performed with the crash test dummy. Energy absorption and stiffness are reported relative to the reference board (B02).

static analysis; dynamic tests were required to elucidate board behaviour under impact conditions.

Generally, we found that all new board designs underwent larger displacements than the reference board, but performance varied greatly among flexible boards (figure 4). Tests showed that energy absorption was equivalent between flexible boards and the reference board; that is, the new designs allowed greater displacement, but did not absorb shock better. Note that energy absorption as determined here is influenced by various components of the system including the board and shielding (and its oscillation due to impact, respectively) as well as the sand-filled pendulum. Nevertheless, due to the increased displacement, the stiffness and the effective mass in the flexible systems were generally lower than in the reference board. The effective mass is relevant as it represents the portion of the board mass that the player is experiencing on impact. All flexible boards had lower effective masses than the approximately 150 kg of the reference board. While system B11 had the highest effective mass (over 100 kg), the other designs had masses of around 60 kg, which represented a significant design improvement resulting in a lower impact load.

Assessment of the biomechanical loading

The dummy tests were derived from procedures commonly used in automotive testing and represented a novel approach to assess ice hockey boards. These tests required a test facility, because they could not readily be conducted in an actual ice rink, unlike pendulum tests. However, the dummy tests allowed analyses of the loading on different body regions during impact. These data were not previously available. The results showed that the pendulum and the dummy produced very similar board displacement; that is, both methodologies resulted in similar impacts. Therefore, the outcomes could be compared.

Our study raises the question of whether biomechanical reference values used in automotive testing are reasonable for a sports application. Automotive testing focuses on life-threatening injuries. Our test result values were well below the threshold values used in automotive testing (eg, all HIC values were less than 15% of the 1000 threshold). This difference could be explained by

Table 3 Results from the dummy experiments

Parameter	Test condition	Results for all boards (max values)						Reference for assessment
		B02	B11	B22	B31	B41	B51	
Displacement (mm)	V2, h=1 m	16.5	35.6	70.6	39.8	61.1	56.0	–
Head injury criterion (–)	V2	131	28	143	90	35	59	1000*
Assessment score		0.131	0.028	0.143	0.090	0.035	0.059	
Shoulder force (lateral, y-axis) (N)	V2	146	1585	1273	1155	1339	1541	3000†
Assessment score		0.049	0.528	0.424	0.385	0.446	0.514	
Lower spine force (lateral, y-axis) (N)	V2	2492	1443	1324	1115	648	885	1500*
Assessment score		1.661	0.962	0.883	0.743	0.432	0.590	
Moment of lower spine (around x-axis) (Nm)	V2	69	56	45	47	45	36	120‡
Assessment score		0.575	0.467	0.375	0.392	0.375	0.300	
Compression of lower rib (mm)	V2	18	7	11	5	7	8	42*
Assessment score		0.429	0.167	0.262	0.119	0.167	0.190	
Viscous criterion (–)	V2	0.1	0	0	0	0	0.0	1*
Assessment score		0.100	0.000	0.000	0.000	0.000	0.000	
Abdominal force (N)	V2	818	407	287	96	106	117	2500*
Assessment score		0.327	0.163	0.115	0.038	0.042	0.047	
Pubic symphysis force (N)	V2	1456	2610	1589	2032	1502	1551	6000*
Assessment score		0.243	0.435	0.265	0.339	0.250	0.259	
Overall assessment score (sum)		3.515	2.750	2.467	2.106	1.747	1.959	

Assessment scores were calculated as the measured value divided by the reference value.
*Reference values used in automotive testing.[19]
†Reference values based on previous studies.[20 21]
‡Current standards do not include a threshold value for the lower spine moment; therefore, we chose 120 Nm, because it represented the highest spine moment recorded in this test series (recorded in a dummy configuration which is not part of this publication).

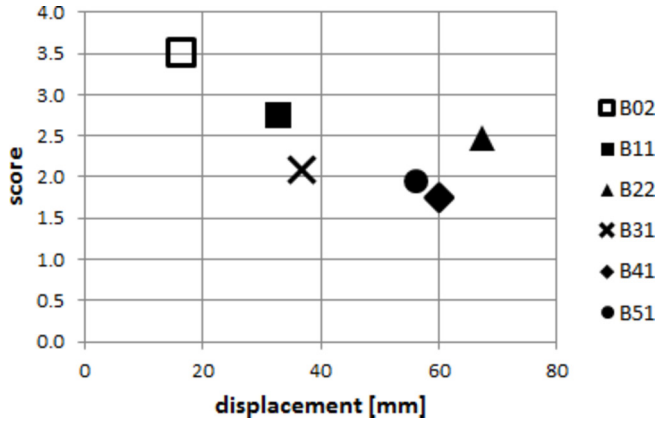

Figure 4 Poor relationship between the biomechanical assessment score and board displacement (measured at 1 m).

the kinematics of the impact. The dummy's shoulder contacted the system first; thus, the head contacted the displaced shielding.

More sports-specific reference values should be established for this method to enhance assessments of sports injury risks with a board system. Previous studies[13–16] have determined that ice hockey impacts cause head accelerations in the 25–35 g range, but 80 g is a common threshold in the automotive field (the so-called 3 ms criterion[19]). For our study, reference values commonly used in automotive dummy tests were helpful in comparing biomechanical loading between different boards.

The overall biomechanical assessment included several body regions: the head, neck, shoulders, thorax, abdomen and pelvis. All of these regions might be injured in board impacts. However, in the assessment, all body regions were regarded equally important; thus, they contributed equally to the final scoring of board performance. This procedure could be refined in future by weighting the body regions differently, for example, depending on the injury risk as determined in ice hockey games. To some extent, applying different threshold values would also approximate weighting for the overall assessment; for example, a lower threshold could be used for the HIC. It is common to use maximum values in an assessment procedure, but analysing the loading over time might additionally reveal relevant insights for improving board design.

Due to its design, the reference board produced kinematics different from the kinematics of flexible boards. Given that the dummy orientation was repeatable, the design caused the lower thorax and abdomen to make initial contact with the board, while the shoulder made first contact in flexible board designs. Consequently, the reference board design resulted in higher loadings of the thorax and abdomen and the maximum shoulder force was low.

A more elaborate evaluation procedure could consider these types of phenomena, which can only be detected with a dummy. Biomechanical analyses could be included in future standardised test procedures. In the overall assessments, flexible boards displayed lower scores than the reference board; thus, the new board designs could potentially reduce the risk of injury. Given that the board systems tested here had incorporated relatively small design changes compared with the reference board, it seems possible that even better performance might be achieved in future. However, it is worth mentioning that the overall score as implemented here could be improved to show a closer link to actual injury risk of different body parts.

This study also showed that board displacement was not well correlated to biomechanical loading. Explanations for this finding include dynamic effects of the different mechanical structures of a board system as well as different ways how to mount the boards to the floor. However, this finding also illustrates that measuring the displacement only is insufficient. Some flexible boards (eg, B31 and B51 in figure 4) resulted in similar biomechanical loading, despite very different stopping distances. Thus, other design properties are likely to play relevant roles in the loading of a player on impact.

Strengths and limitations

To our knowledge, the present study was the first to assess the biomechanical loading of an ice hockey player by employing a crash test dummy. The dummy in this test series did not wear any protective equipment. This eliminates any influence of different personal protective equipment product designs on the measurements, but should be considered when interpreting the results.

We selected the position of the dummy to ensure that it impacted both the board and the protective shielding. A lateral impact was simulated to mimic observed body checks against the board. The use of a sled to accelerate the dummy is a common procedure that is well repeatable, because the position of the dummy is well defined. Checking the impact orientation of the dummy which was marked with paint that resulted in an imprint on the board confirmed this. Overall, the repeatability of our dummy experiments was similar to that achieved in automotive testing, but inferior to that achieved with pendulum tests.[19]

The pendulum test is a straightforward way to characterise the dynamic behaviour of these boards. This test is easy to control, repeatable and the results can be readily compared with previous studies. Here, we selected pendulum mass and impact velocities that would represent the conditions observed in ice hockey matches and that were also used in previous studies.[18] The use of a sand-filled punching bag works in principle, but we recommend a more standardised pendulum design to also account for effects such as the pendulum deformation and sand compression. Furthermore, the pendulum test allows limited interpretation of the risk of injury.

Performing the tests to the middle of three connected board sections seems appropriate to account for any potential effects of attaching the sections to each other. However, the use of straight sections might have limited the interpretation of the results to areas behind the goal and, to some extent, the sides of an ice rink. Another potential limitation was that we tested the boards in a laboratory at room temperature. The lower temperature of the rink might influence the dynamic behaviour of the board materials. However, in principle, this parameter should not have substantially influenced our findings, because we used the same boundary conditions to compare different designs. Furthermore, we used only one dummy size (the only one available); thus, we could not capture the variable anthropometry of ice hockey players. In addition, all dummies have some limitations in biofidelity inherent in their design.

All the so-called flexible board designs were compared with a conventional reference design. All new designs were lower in board height than the reference design. The handrail was 1.1 m above ground, compared with 1.25 m in the reference design. Consequently, the ratio of the board-to-shielding areas differed between the conventional and new designs. However, we did not change the points of impact in either the pendulum or the dummy tests; that is, both areas were impacted in all tests of this series to ensure comparability among the results.

Practical implications

Currently, (1) no standard defines minimum performance requirements for ice hockey boards and (2) there is no consensus on test procedures for assessing the performance of ice hockey boards. Our test series indicates that pendulum tests alone are insufficient to assess board performance. Also, standards that define minimum displacement requirements in board design will not accurately capture the loading of a player. Importantly, design should not focus on a single parameter such as displacement only. A more holistic approach is needed also taking into account other relevant aspects of the board design (eg, the material of the board and the shielding).

A board performance standard should focus on player loading; more advanced assessment procedures using instrumented test impactors with a sufficient degree of biofidelity to mimic a player on impact should be considered.

As a result of our study, the Swiss Ice Hockey Federation has specified requirements for board performance of products accepted in the national league. We note the principle of epidemiology that influencing a surrogate measure (eg, impact load) does not guarantee that the outcome of interest (player injury) is similarly affected. At the same time, we believe that initiatives promoting improved board designs have the potential to reduce injury due to board impact.

CONCLUSION

Flexible design of ice hockey boards could reduce the biomechanical loading on a player at impact. Thus, compared with the conventional design, the so-called flexible boards seem to have the potential to lower the risk of injury. Although flexible boards exhibited larger displacement than the conventional board, we found no correlation between the stopping distance and biomechanical loading. Consequently, displacement alone is not sufficient for characterising the overall biomechanical loading of a player associated with board impact.

This study also highlighted design features that should be addressed in future design assessments, such as the effective mass and the energy absorption properties. From a methodological perspective, we showed that the application of dynamic testing with crash test dummies provided additional relevant information on biomechanical loading that could not be acquired with pendulum tests.

What are the findings?

- Flexible ice hockey boards can reduce the biomechanical loading experienced by a player on impact.
- The board displacement alone is insufficient for characterising the dynamic impact behaviour of a board. Hence, to assess the injury risk associated with an impact, more complex test procedures, for example, utilising crash test dummies are needed.
- Compared with pendulum tests, dynamic impact testing with crash test dummies provides more specific insight into the biomechanical loading experienced by a player on impact.

How might it impact on clinical practice in the future?

- Standardised test procedures with defined minimum performance requirements of ice hockey boards would push the development of board designs that would reduce the loading of a player on impact.
- Introducing improved board designs would be expected to prevent injuries.

Acknowledgements We would like to thank the staff at the Dynamic Test Center (DTC) for their support in this study. The following manufacturers supported the project by providing ice hockey boards for testing: AST, Engo, Icepro, Rai-ta and Vepe.

Contributors K-US and MHM planned, conducted and evaluated the test series in this study. K-US took the lead in writing the manuscript. HT and OB initiated and planned the project and reviewed the manuscript.

Funding This study was funded by the Swiss Council for Accident Prevention (bfu) and the Swiss Ice Hockey Federation.

Competing interests None declared.

Provenance and peer review Not commissioned; externally peer reviewed.

REFERENCES

1 Tuominen M, Stuart MJ, Aubry M, *et al*. Injuries in men's international ice hockey: a 7-year study of the International ice hockey federation adult world championship tournaments and olympic winter games. *Br J Sports Med* 2015;49:30–6.
2 MacCormick L, Best TM, Flanigan DC. Are there differences in ice hockey Iinjuries between sexes? A systematic review. *Orthop J Sports Med* 2014;2:2325967113518181.
3 Agel J, Dompier TP, Dick R, *et al*. Descriptive epidemiology of collegiate men's ice hockey injuries: National collegiate athletic association injury surveillance system, 1988–1989 through 2003–2004. *J Athl Train* 2007;42:241–8.
4 Agel J, Harvey EJ. A 7-year review of men's and women's ice hockey injuries in the NCAA. *Can J Surg* 2010;53:319–23.
5 Flik K, Lyman S, Marx RG. American collegiate men's ice hockey: an analysis of injuries. *Am J Sports Med* 2005;33:183–7.
6 Tuominen M, Stuart MJ, Aubry M, *et al*. Injuries in world junior ice hockey championships between 2006 and 2015. *Br J Sports Med* 2017;51:36–43.
7 Tuominen M, Stuart MJ, Aubry M, *et al*. Injuries in women's international ice hockey: an 8-year study of the world championship tournaments and olympic winter games. *Br J Sports Med* 2016;50:1406–12.
8 Darling SR, Schaubel DE, Baker JG, *et al*. Intentional versus unintentional contact as a mechanism of injury in youth ice hockey. *Br J Sports Med* 2011;45:492–7.
9 Emery CA, Meeuwisse WH. Injury rates, risk factors, and mechanisms of injury in minor hockey. *Am J Sports Med* 2006;34:1960–9.
10 Benson BW, Meeuwisse WH. Ice hockey injuries. *Med Sport Sci* 2005;49:86–119.
11 Agel J, Dick R, Nelson B, *et al*. Descriptive epidemiology of collegiate women's ice hockey injuries: National collegiate athletic association injury surveillance system, 2000–2001 through 2003–2004. *J Athl Train* 2007;42:249–54.
12 Wennberg R. Collision frequency in elite hockey on North American versus international size rinks. *Can J Neurol Sci* 2004;31:373–7.
13 Wilcox BJ, Beckwith JG, Greenwald RM, *et al*. Head impact exposure in male and female collegiate ice hockey players. *J Biomech* 2014;47:109–14.
14 Wilcox BJ, Machan JT, Beckwith JG, *et al*. Head-impact mechanisms in men's and women's collegiate ice hockey. *J Athl Train* 2014;49:514–20.
15 Mihalik JP, Guskiewicz KM, Marshall SW, *et al*. Head impact biomechanics in youth hockey: comparisons across playing position, event types, and impact locations. *Ann Biomed Eng* 2012;40:141–9.
16 Wilcox BJ, Beckwith JG, Greenwald RM, *et al*. Biomechanics of head impacts associated with diagnosed concussion in female collegiate ice hockey players. *J Biomech* 2015;48:2201–4.
17 Tuominen M, Hänninen T, Parkkari J, *et al*. Concussion in the international ice hockey world championships and olympic winter games between 2006 and 2015. *Br J Sports Med* 2017;51:244–52.
18 Poutiainen P, Peltonen J, Isolehto J, *et al*. Comparison of impact characteristics of four different ice hockey arena dasher boards. *Eur J Sport Sci* 2014;14:11–18.
19 Schmitt KU, Niederer P, Cronin D, *et al*. Trauma biomechanics: an introduction to injury biomechanics. *Heidelberg, Springer* 2014.
20 Duprey S, Bruyere K, Verriest JP. Human shoulder response to side impacts: a finite element study. *Comput Methods Biomech Biomed Engin* 2007;10:361–70.

21 Usman J, McIntosh AS, Fréchède B. An investigation of shoulder forces in active shoulder tackles in rugby union football. *J Sci Med Sport* 2011;14:547–52.