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 Bruegger2

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.11–16 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 al16 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 al18 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.
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.

**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. 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) 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. 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

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**Table 1** Ice hockey boards included in the test series

<table>
<thead>
<tr>
<th>Test number</th>
<th>Type of board</th>
<th>Width of one board section (m)</th>
<th>Height of one board section without shielding (m)</th>
<th>Shielding material</th>
</tr>
</thead>
<tbody>
<tr>
<td>B02</td>
<td>Reference</td>
<td>2.4</td>
<td>1.25</td>
<td>Synthetics</td>
</tr>
<tr>
<td>B11</td>
<td>Flexible</td>
<td>3.0</td>
<td>1.10</td>
<td>Synthetics</td>
</tr>
<tr>
<td>B22</td>
<td>Flexible</td>
<td>2.4</td>
<td>1.10</td>
<td>Synthetics</td>
</tr>
<tr>
<td>B31</td>
<td>Flexible</td>
<td>2.4</td>
<td>1.10</td>
<td>Synthetics</td>
</tr>
<tr>
<td>B41</td>
<td>Flexible</td>
<td>2.4</td>
<td>1.10</td>
<td>Synthetics</td>
</tr>
<tr>
<td>B51</td>
<td>Flexible</td>
<td>3.0</td>
<td>1.10</td>
<td>Synthetics</td>
</tr>
</tbody>
</table>
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 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.

Figure 3  Example of impact tests with the ES-Z 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.
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 2 Results from the pendulum tests, all recorded at a height of 1 m

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Test condition</th>
<th>B02</th>
<th>B11</th>
<th>B22</th>
<th>B31</th>
<th>B41</th>
<th>B51</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (mm)</td>
<td>V1</td>
<td>10.7</td>
<td>20.8</td>
<td>45.5</td>
<td>27.2</td>
<td>41.8</td>
<td>39.3</td>
</tr>
<tr>
<td></td>
<td>V2</td>
<td>18.4</td>
<td>30.5</td>
<td>65.3</td>
<td>39.2</td>
<td>59.6</td>
<td>56.2</td>
</tr>
<tr>
<td>Energy absorption (% to B02)</td>
<td>V2</td>
<td>–</td>
<td>5.8</td>
<td>1.6</td>
<td>5.6</td>
<td>–2.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Stiffness (% to B02)</td>
<td>V2</td>
<td>–</td>
<td>25.5</td>
<td>55.9</td>
<td>61.5</td>
<td>40.7</td>
<td>50.8</td>
</tr>
<tr>
<td>Effective mass (kg)</td>
<td>V2</td>
<td>151.0</td>
<td>111.0</td>
<td>60.5</td>
<td>60.4</td>
<td>60.6</td>
<td>71.4</td>
</tr>
</tbody>
</table>

Tests at V1=3.37 m/s allow comparison with similar pendulum experiments performed previously. 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).

### Table 3 Results from the dummy experiments

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

Assessment scores were calculated as the measured value divided by the reference value.

* Reference values used in automotive testing.

† Reference values based on previous studies.

‡ 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).
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.

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. 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.

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

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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.

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Kai-Uwe Schmitt, Markus H Muser, Hansjuerg Thueler and Othmar Bruegger

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