The Effect of Shoulder Pad Design on Head Impact Severity during Checking

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ABSTRACT

VIRANI, S., C. N. RUSSELL, M. L. BRUSCHETTA, K. N. HUA, B. M. POTVIN, D. N. COX, and S. N. ROBINOVITCH. The Effect of Shoulder Pad Design on Head Impact Severity during Checking. *Med. Sci. Sports Exerc.*, Vol. 49, No. 3, pp. 573–580, 2017. **Introduction**: Shoulder-to-head contact is the most common cause of concussions in ice hockey, accounting for 42% of cases in the National Hockey League. The goal of this project was to determine how shoulder pad stiffness, modified by adding foam padding over the shoulder cap of existing shoulder pads, affected head impact severity when participants delivered checks to an instrumented dummy. **Methods**: Fifteen participants administered "the hardest shoulder checks they were comfortable delivering" to the head of a dummy equipped with triaxial accelerometers and gyros mounted in its helmet. Trials were conducted with participants wearing two common types of shoulder pads, with and without a 2-cm-thick layer of polyurethane foam over the shoulder pad cap. **Results**: When participants delivered checks with foam-modified pads versus unmodified pads, there was a decrease of 25.0% in the average peak linear head acceleration (28.73*g* vs 38.31*g*, mean difference = 9.58*g*, 95% confidence interval = 6.35–12.81, $P < 0.0001$) and a decrease of 12.4% in the average value of peak rotational head velocity ($838.0°\cdot s^{-1}$ vs $956.7°\cdot s^{-1}$, mean difference = $118.65°\cdot s^{-1}$, 95% confidence interval = 55.37–181.94, $P = 0.001$). The protective benefit of the foam layer did not depend on the type of shoulder pad or the checking scenario. **Conclusion**: The integration of foam padding on top of the plastic caps of shoulder pads reduced impact severity to the head and warrants further examination as a method for contributing to the prevention of brain injuries in ice hockey. **Key Words:** CONCUSSION, TRAUMATIC BRAIN INJURY, BIOMECHANICS, SPORTS, PROTECTIVE EQUIPMENT, RISK COMPENSATION

Ice hockey is associated with the greatest number of team sports-related traumatic brain injuries among participating youth in Canada (1,6). Player-to-player contact (body checking) caused 67% of concussions among youth players between ages 5 and 19 yr (3,6) and 88% of concussions in the National Hockey League (NHL) (12). Furthermore, checks involving shoulder-to-head contact are ranked as the most common cause of concussions in hockey, accounting for 42% of cases in the NHL (12).

Several biomechanical factors influence the severity of shoulder-to-head collisions in hockey, in terms of peak linear and rotational accelerations of the head, and corresponding risk for concussion (11,15,16,19,22). The factors include the velocities, masses, and effective stiffness of the colliding players, the site of impact to the head, and the mechanical properties of the shoulder pad worn by the player who delivers the check. In support of the latter, a recent study (14) reported that the design features of shoulder padding had a significant effect on peak rotational accelerations of a Hybrid III head form when struck by a linear impactor at fixed contact velocities (6.5 and 7.5 $m\cdot s^{-1}$).

In general, a shoulder pad that has a lower effective stiffness throughout the impact will reduce the total impact force for a given set of initial conditions, including positions and velocities of the body segments at impact (4). However, several factors limit the minimal required stiffness of shoulder pads for a given pad thickness. The pad cannot be so soft that it "bottoms out" (stiffens rapidly after achieving near-maximum compression), and the minimum stiffness required to prevent this bottoming out will increase with increases in impact energy and with decreases in pad thickness (23). In addition, the protection a shoulder pad provides to the player who wears it depends on how the pad distributes force over the shoulder region (18). Accordingly, equipment manufacturers traditionally incorporate a plastic shell, or more recently, rigid foam, on the exterior of the shoulder cap (3), along with softer foam in the cap interior. The intent of the shell is to distribute the impact energy and force over a larger region of the pad and therefore protect the shoulder (14).

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It is unclear how the rigid shell in shoulder pads affects the magnitude of total force delivered to the checked player during a shoulder-to-head collision and subsequently the risk for concussion. One hypothesis that has been raised (9,24) but never tested is that the rigid cap protects the shoulder while allowing the player to deliver checks that are more likely to cause a concussion. This may be due to modifications in player behavior in response to the perceived level of risk for self-injury; that is, risk compensation (9,24), or perhaps due to the way the shell concentrates force to the head of the recipient while spreading it over the shoulder of the player delivering the check. In response to this concern, the NHL has considered rule changes concerning the stiffness of shoulder padding (21). At present, the NHL and Hockey Canada require that elbow pads must have "a soft protective covering of sponge, rubber or a similar material at least 1.27 cm (1/2 inches) thick." However, no equivalent rule currently exists for shoulder pads. To guide potential rule changes for shoulder pads, improved understanding is required on how pad characteristics affect the potential of shoulder checks to cause concussion in hockey.

In this study, we explored the potential of a low-cost solution for reducing head impact severity in shoulder-to-head impacts in hockey: the addition of a foam layer over the shoulder cap of existing shoulder pads. We considered that the foam layer should have minimal effect on the structural integrity and force distribution provided by the baseline pad, while causing a decrease in the total effective stiffness of the pad and thereby reducing peak head accelerations for a given set of initial conditions. We also considered, however, the possibility that the foam layer may cause players to feel more protected and increase their aggressiveness or impact velocity in delivering shoulder checks to the head.

We considered that a purely mechanical test system could not incorporate risk compensation and, therefore, may not provide an accurate and valid measure of the protective value of the foam layer—we needed to include the "human element" in our evaluation, with actual hockey players delivering checks. Accordingly, we conducted laboratory experiments in which hockey players delivered shoulder-to-head checks to an instrumented dummy. Checks were delivered with participants wearing commercially available pads in both a baseline condition (with no extra foam padding), and with a 2-cm-thick foam polyurethane layer adhered to the shoulder cap. Players delivered checks under two scenarios, approaching the dummy straight-on or from an angle. We hypothesized that the addition of the foam layer would (a) influence peak linear accelerations and peak rotational velocities of the instrumented dummy head during the collisions and (b) influence player impact velocity in delivering shoulder checks to the head.

MATERIALS AND METHODS

Participants. Fifteen males participated in this experiments, with mean age 21.8 yr (SD = 2.8, range = 16–25 yr), mean body mass 85.4 kg (SD = 10.2, range = 64–104 kg), and mean height 183 cm (SD = 5.3, range = 173–191 cm). All participants were currently playing hockey in a league that permitted body checking. Eight subjects were on the SFU Men's Hockey Team (collegiate level play), four were in juvenile level play, two were in junior level play, and one was in midget level play. None of the subjects had self-reported contraindications for participation in contact sports. All participants provided written informed consent, and the experimental protocol was approved by the Research Ethics Committee of Simon Fraser University.

Instrumented shoulder check dummy. During the experimental trials, participants delivered shoulder checks to a customized body-checking dummy (Fig. 1A). The torso, the neck, and the head of the dummy were molded from a single (continuous) block of urethane foam covered in plastisol and were taken from a commercially available kickboxing dummy, which is designed for multiple impacts (BOB XL; Century Martial Arts, Oklahoma City, OK). The torso/neck/head unit rested on a 20-cm diameter central aluminum tube, which replaced the plastic tube supplied with the dummy, and was mounted to the ground via a low-friction ball joint. The tube was filled with sand to provide the dummy with a total mass of 61 kg. When standing upright, the dummy had a height of 178 cm. An overhead spring of resting length 63 cm, diameter 3.75 cm, and stiffness 1157 N·m was connected to the dummy with a cable that provided the dummy with a uniform rotational stiffness during impact. The cable was wrapped around a one-way locking pulley, which prevented the dummy from rebounding after delivery of a check.

During the trials, we acquired the time-varying linear acceleration of the dummy head at 20 kHz from a triaxial accelerometer (Model 7624C; Endevco, Irvine, CA) and angular velocity of the head at 800 Hz from a 3-D gyro unit (G-Force Tracker, Artaflex Inc., Markham, ON, Canada). Both sensors were secured adjacently with double-sided tape (VHB; 3M, London, ON, Canada) to the inside of the crown of a CSA-certified caged helmet on the dummy's head. The G-Force Tracker has been used extensively in field and laboratory-based studies of head impact in sport (2,5). A Nikon S2 high-speed (1200 frames per second) camera mounted at head height, with its axis perpendicular to the plane of movement during the check, was used to record the time-varying position of the shoulder of the participant in delivering the check.

Shoulder pad selection and foam layer fabrication. Participants delivered checks to the dummy in separate trials wearing two different commercially available shoulder pads (Fig. 1B). Pad A (5030 Traditional; Sherwood, Sherbrooke, QC, Canada) features plastic shoulder caps, covered on top with a 1.5-mm-thick layer of low-density foam and a 2-mm-thick synthetic leather liner and on the bottom with a 3-mm-thick layer of higher density foam. The deltoid pads had similar construction to the shoulder caps. The arches were made entirely of foam and synthetic leather, with lacing at the sternum to adjust the fitting of the pad. Pad B (Supreme One.6; Bauer, Exeter, NH) also features plastic shoulder caps,

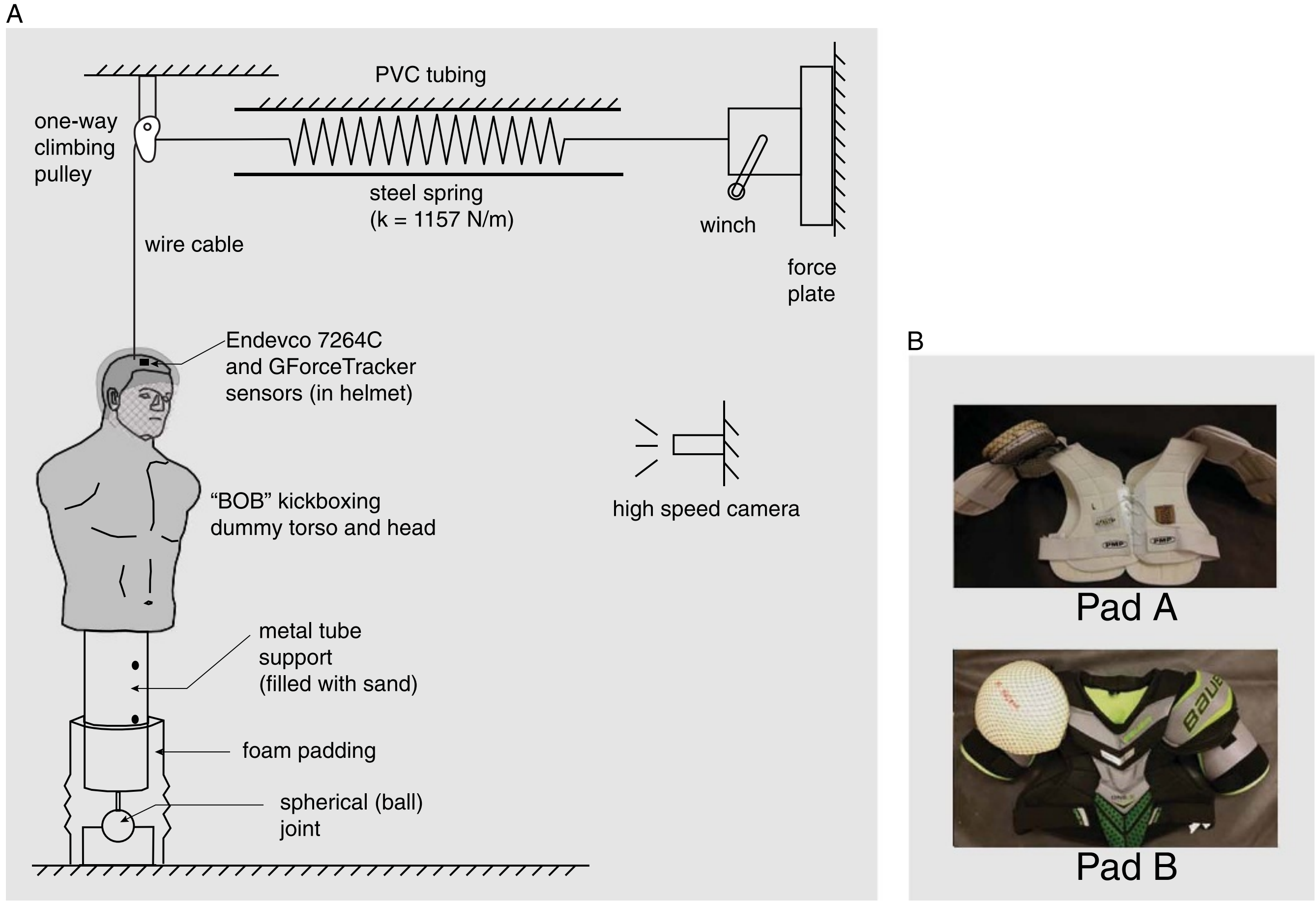

FIGURE 1—A, Schematic of the body-checking dummy. The foam head, neck, and torso of a commercial kickboxing dummy was mounted to a metal tube that was connected to a spherical joint on the ground. An overhead spring provided the dummy with a consistent rotational stiffness and a one-way locking pulley prevented the dummy from rebounding after the check. Sensors mounted in the helmet of the dummy measured linear acceleration and rotational velocity. B, Front views of pad A (top) and pad B (bottom). In each case, the right-side cap (reader's left) is shown with customized 2-cm-thick molded foam layer adhered over the shoulder cap.

covered on top with a 1.5-mm-thick layer of low-density foam and a 2-mm polymer mesh liner and on the bottom with a 5-mm-thick layer of higher density foam. Again, the deltoid pads had similar construction to the shoulder caps, whereas the arches were made entirely of foam, which is considerably thicker than that provided by pad A. The total mass was 886 g for pad B and 711 g for pad A.

We created customized 2-cm-thick foam layers, which matched the outer contour of the shoulder cap of both pad A and pad B. Each shoulder pad cap's surface profile was characterized using a 3-D digitizing stylus (MicroScribe G2X; Solution Technologies, Inc., Oella, MD). These data were then input to the Solidworks software package (version 2009; Dassault Systemes, Waltham, MA) to design molds that were then manufactured by a 3-D printer. The molds were filled with polyurethane expanding foam (FlexFoam-iT! 14; Smooth-On Inc., Macungie, PA), which was allowed to cure for 24 h before removal from the mold. The resulting foam density was 220 $\text{kg}\cdot\text{m}^{-3}$, which provides a hardness of approximately 50 durometer, which has been shown to provide optimal force reduction for impact to the human hip (7). The foam layers were secured over the shoulder caps using double-sided tape and a tightly fitting mesh net.

Experimental protocol. Our experiment, illustrated in Figure 2, was designed to examine how head impact severity was affected by the additional foam layer (foam vs no-foam) applied to two different types of shoulder pads (pad A vs pad B) and for checks delivered under two different checking scenarios (straight-on vs angled). In straight-on impacts, participants delivered checks to the front of the dummy (i.e., their approach was perpendicular to the frontal plane of the dummy). The dummy was inclined 20° from the vertical, and the vertical height of the head of the dummy was 167 cm from the ground. This scenario simulated shoulder checks to the front of the head while the receiving player is in a slightly crouched position. In angled impacts, participants delivered checks to the head of the dummy from an approach angle of 40° from the frontal plane. The dummy was inclined 0° from the vertical and, thus, had a vertical height of 178 cm. This scenario simulated shoulder checks to the right lateral aspect of the

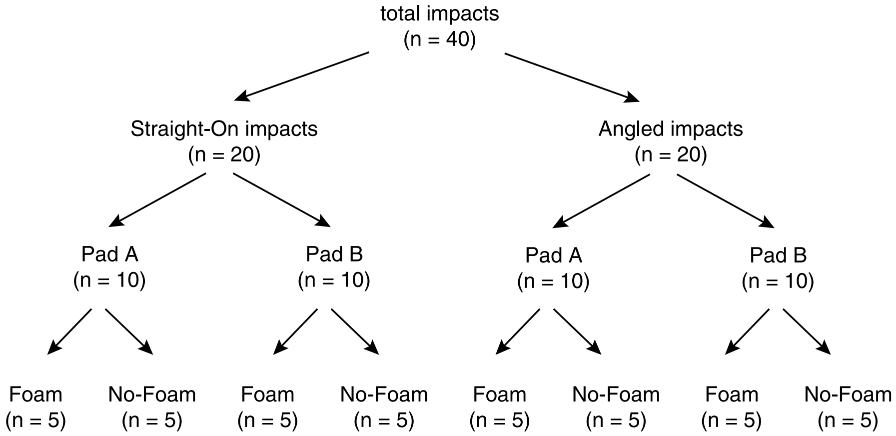

FIGURE 2—Experimental design. Each participant delivered a total of 40 shoulder checks to the head of the dummy. We randomized the order of presentation of checking scenario, shoulder padding type, and foam condition. See text for further explanation.

head where the checking player would deliver a blindside check to the receiving player. The two checking scenarios were presented in random order.

For each checking scenario, trials were conducted with participants wearing four different shoulder pad configurations, again presented in random order: pad A unmodified, pad A modified with a 2-cm foam cap, pad B unmodified, and pad B modified with a 2-cm foam cap. Participants delivered five repeated checks in each condition, for a total of 40 impacts.

Before each trial, the participants were instructed to "deliver the hardest shoulder check [they] were comfortable delivering" with their right shoulder to the head of the dummy, aiming for a target (a 4 × 4-cm neon green piece of tape) located on the side of the helmet for angled impacts or on the front of the cage for straight-on impacts. Participants were given a 3-m run-up to approach the dummy and were otherwise allowed to strike the dummy at the speed of their choosing. Each player took three practice trials before the start of data collection in the first condition to become familiar with the mass and stiffness of the checking dummy.

After completing all trials, participants completed a poststudy questionnaire, which asked about their comfort level (on a five-point Likert scale) in delivering checks to the dummy while wearing each of the four shoulder pads, from 1 (extreme discomfort in the shoulder) to 5 (extreme comfort in the shoulder). The questionnaire also probed the realism of the dummy in simulating the "feel" of an opposing player during a real-life shoulder check in hockey on a scale from 1 (extremely unrealistic) to 10 (extremely realistic).

Data analysis. Acceleration signals (Fig. 3) were filtered with a 300-Hz low-pass filter compatible with the SAE J211 protocol (13). Angular velocities were filtered with a low-pass filter of 100 Hz (GFT2; Artaflex Inc.). For each trial, we identified the peak magnitudes of the resultant linear acceleration at impact and the resultant angular velocity. High-speed videos were digitized using the common-source DLTdv5 toolbox (10) for MATLAB (Version 2015a; MathWorks, Natick, MA) to track the frame-by-frame vertical and horizontal position of a 1.3-cm diameter marker on the participant's right scapula. The displacement signals were then filtered with a fourth-order, 100-Hz Butterworth low-pass filter to remove digitization errors (17) and differentiated to estimate velocities. Shoulder impact velocity was taken as the horizontal velocity of the scapula at the instant of head impact detected to a resolution of 0.8 ms in the high-speed video by the onset of movement of the dummy head.

Statistical analysis. We used a full-factorial repeated-measures ANOVA to examine the effects of shoulder pad type, foam condition, and checking scenario on each outcome variable. All analyses were performed using JMP (Version 12.0.1; SAS Institute Inc., Cary, NC), with an assumed significance level of alpha = 0.05. We also summarize the results of the poststudy questionnaires completed by participants with descriptive statistics.

RESULTS

Results from repeated-measures ANOVA (Tables 1 and 2) indicated that foam condition, type of shoulder pad, and checking scenario had significant main effects on peak linear head acceleration and peak rotational head velocity. Checking scenario, but not foam condition or shoulder pad type, was associated with shoulder impact velocity. For all three outcomes, there were no significant interactions between independent variables, indicating that the effect of the foam layer on impact severity did not depend on the type of shoulder pad or the checking scenario.

When participants delivered checks with foam-modified pads versus unmodified pads, there was a decrease of 25.0% in the average value of peak linear head acceleration (28.73*g* vs 38.31*g*, mean difference = 9.58*g*, 95% confidence interval [CI] = 6.35–12.81, $P < 0.0001$) and a decrease of 12.4% in peak rotational head velocity (838.0°$\cdot$s^{-1} vs 956.7°$\cdot$s^{-1}, mean difference = 118.65°$\cdot$s^{-1}, 95% CI = 55.37–181.94, $P = 0.001$). In a given condition, at least 12 of the 15 participants delivered lower average values of peak linear head

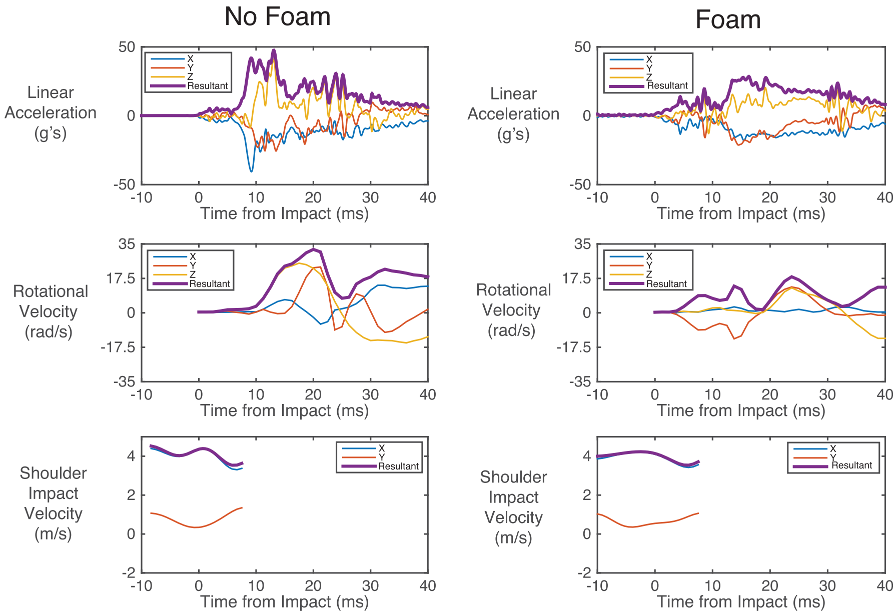

FIGURE 3—Typical raw traces and resultant values of linear acceleration (*top*), rotational velocity (*middle*), and shoulder velocity (*bottom*) for foam (*left*) versus no-foam (*right*) conditions. The onset of shoulder impact to the head of the dummy is indicated by time = 0 (dashed vertical line). For linear accelerations, the *x*, *y*, and *z* axes were perpendicular, respectively, to the coronal, sagittal, and transverse planes of the head. For rotational velocities, the *x*, *y*, and *z* axes were perpendicular to the sagittal, coronal plane, and transverse planes of the head. For shoulder velocity, the *x* and the *y* axes were perpendicular to the coronal and transverse planes of the head, respectively.

acceleration while wearing foam-modified pads versus unmodified pads (Fig. 4).

When participants delivered checks with pad B versus pad A, there was a decrease of 13.4% in the average value of peak linear head acceleration (31.12*g* vs 35.93*g*, mean difference = 4.81*g*, 95% CI = 1.90–7.73, $P = 0.003$) and a decrease of 8.3% in peak rotational head velocity (858.43°·s^{-1} vs 936.21°·s^{-1}, mean difference = 77.78°·s^{-1}, 95% CI = 11.31–144.25, $P = 0.002$).

When participants delivered straight-on versus angled impacts, there was an increase of 19.2% in the average value of peak linear head acceleration (37.09*g* vs 29.96*g*, mean difference = 7.12*g*, 95% CI = 3.16–11.08, $P = 0.002$) and an increase of 25.4% in peak rotational head velocity (1027.71°·s^{-1} vs 766.93°·s^{-1}, mean difference = 260.78°·s^{-1}, 95% CI = 44.97–476.58, $P = 0.02$), despite a decrease of 20.8% in shoulder impact velocity (3.31 vs 4.18 m·s^{-1}; mean difference = 0.87 m·s^{-1}, 95% CI = 0.60–1.14; $P < 0.0001$).

Participants generally reported feeling more comfortable delivering checks when wearing pad B as compared with pad A (median score 4.0 vs 3.0 on a five-point scale). The addition of the foam layer improved comfort levels when delivering checks with pad A (from 2.5 to 3.5) but had no effect on pad B. Players rated the realism of impacts to the dummy when compared with real-life shoulder checks in ice hockey, with a median score of 7.0 out of 10.

DISCUSSION

In support of our first hypothesis, we found that, during shoulder checks delivered by hockey players to the head of a body-checking dummy, the addition of a 2-cm-thick foam layer over the shoulder cap of the shoulder pad resulted in meaningful reductions in head impact severity. The foam layer caused a 25.0% reduction in the mean value of peak linear head acceleration and a 12.4% reduction in mean peak rotational head velocity.

Head impact severity was also affected by the type of baseline shoulder pad. When compared with pad B, checks

TABLE 1. Results from repeated-measures ANOVA on the association between independent variables (foam, type of shoulder pad, and checking scenario) and outcomes of impact severity (peak linear head acceleration, peak rotational head velocity, and shoulder impact velocity).

	F	*P*
Peak linear head acceleration (*g*)		
Foam	40.53	<0.001*
Type of shoulder pad	12.55	0.003*
Checking scenario	14.88	0.002*
Foam × type of shoulder pad	3.55	0.08
Foam × checking scenario	3.49	0.08
Type of shoulder pad × checking scenario	2.13	0.17
Foam × type of shoulder pad × checking scenario	3.00	0.11
Peak rotational head velocity (°·s^{-1})		
Foam	16.17	0.001*
Type of shoulder pad	6.30	0.03*
Checking scenario	6.72	0.02*
Foam × type of shoulder pad	0.02	0.90
Foam × checking scenario	1.63	0.22
Type of shoulder pad × checking scenario	3.24	0.09
Foam × type of shoulder pad × checking scenario	1.00	0.33
Shoulder impact velocity (m·s^{-1})		
Foam	0.42	0.53
Type of shoulder pad	3.02	0.10
Checking scenario	48.13	<0.001*
Foam × type of shoulder pad	0.17	0.68
Foam × checking scenario	0.89	0.36
Type of shoulder pad × checking scenario	0.00	0.98
Foam × type of shoulder pad × checking scenario	2.19	0.16

*Significant association ($P < 0.05$).

TABLE 2. Summary of mean (SE) values of peak linear head acceleration.

	Pad A				Pad B			
	Straight-on		Angled		Straight-on		Angled	
	No-foam	Foam	No-foam	Foam	No-foam	Foam	No-foam	Foam
Peak linear acceleration (*g*)	48.5 (2.1)*	32.3 (2.1)*	35.3 (1.5)*	27.7 (1.5)*	37.6 (2.1)*	30.0 (2.1)*	31.9 (1.5)*	25.0 (1.5)*
Peak rotational velocity (°·s^{-1})	1192.6 (65.6)*	1009.6 (65.6)*	792.3 (31.2)*	750.4 (31.2)*	1015.1 (65.6)*	893.5 (65.6)*	826.6 (31.2)*	698.5 (31.2)*
Shoulder impact velocity (m·s^{-1})	3.23 (0.06)	3.29 (0.06)	4.21 (0.08)	4.05 (0.08)	3.38 (0.06)	3.34 (0.06)	4.23 (0.08)	4.23 (0.08)

*Significant difference by paired *t*-test ($P < 0.05$) between foam and no-foam conditions for the given pad type and checking scenario.

delivered while wearing the lighter pad A had a 13.4% greater peak linear head acceleration and an 8.3% greater peak rotational head velocity. This result was independent of foam layer or checking scenario. This suggests that, although the shoulder cap of both pads contains a hard outer shell, pad B provides a greater reduction in the total effective stiffness of the body during impact. This may be due to the thicker, variable-density foam padding beneath the shell and in the deltoid pads and arches, and the more form-fitting coverage over the shoulder area.

Our results do not support our second hypothesis that the 2-cm-thick foam layer would affect player aggressiveness in delivering shoulder checks. Instead, we found that shoulder impact velocity was unaffected by the foam layer, or the type

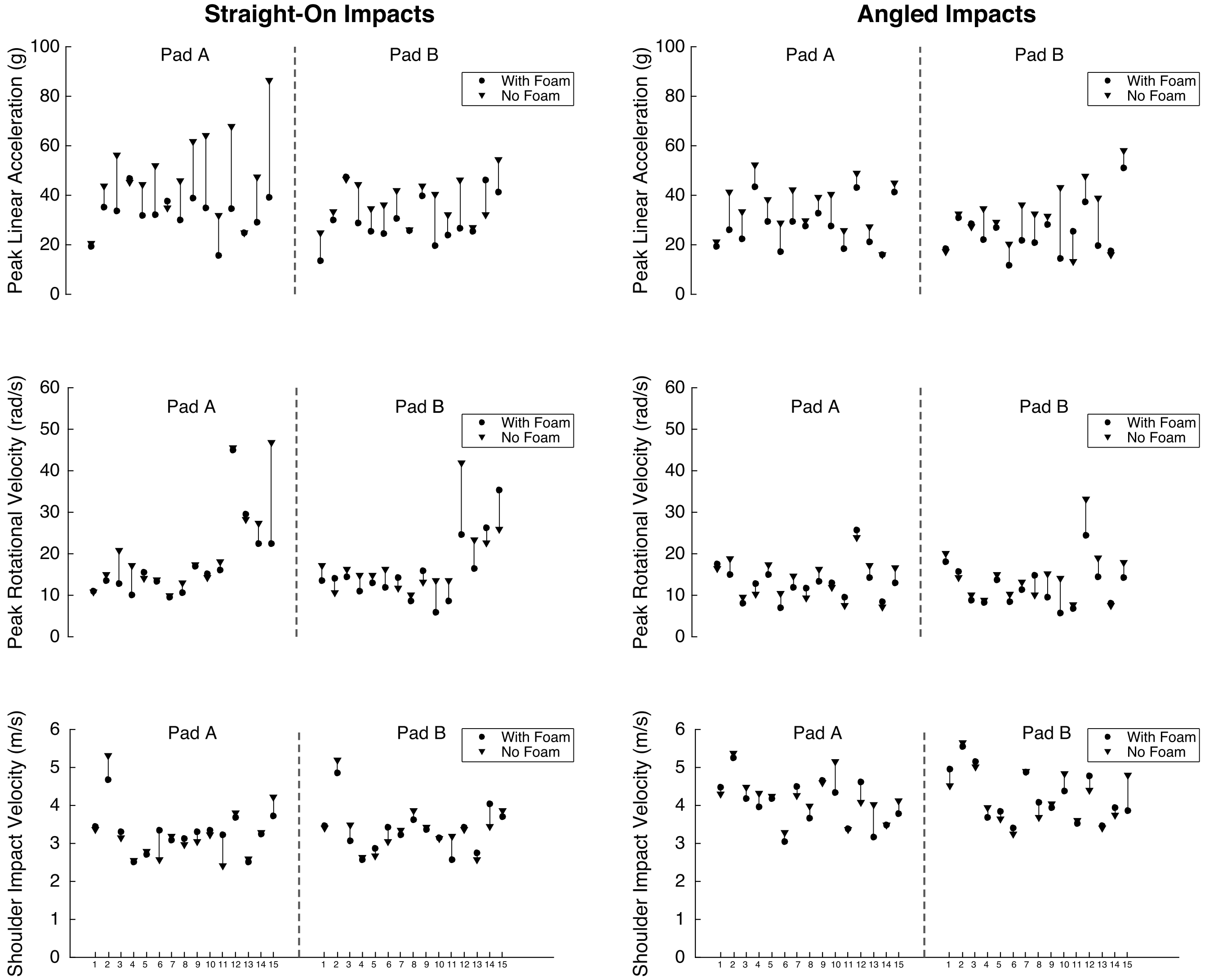

FIGURE 4—Changes in peak linear head acceleration, peak rotational head velocity, and shoulder impact velocity among individual participants ($n = 15$) between foam conditions (*filled circles*) and no-foam conditions (*filled triangles*). Data points show the average value from the five repeated trials in each participant. Data from straight-on impacts is shown in the left panel, and the right panel shows data for angled impacts. Within each graph, results are shown on the left for pad A and on the right for pad B.

of shoulder pad. This suggests that for the types of padding and range of impacts we examined, there was minimal risk compensation, in terms of an adjustment of impact velocity based on the perceived level of comfort or risk for shoulder injury. Instead, participants delivered checks with no detectable change in impact velocity for all shoulder padding conditions. Indeed, at least one participant commented that their desire was “to hit as hard as they could” regardless of the type of shoulder padding they were wearing.

Our study has several strengths. First, we demonstrate the value of a low-cost, simple modification to reduce the severity of shoulder-to-head impacts in ice hockey, which involves the addition of a 2-cm-thick foam layer over the shoulder cap. We found that the foam layer provided similar reductions in impact severity for both pad A and pad B, and for both straight-on and angled impacts. Furthermore, the observed reductions in impact severity should be meaningful in preventing concussions. Previous studies with helmet-mounted sensors during game play have found that concussion injuries can occur from head impacts producing peak linear head accelerations of 60*g* or greater (8). Four of our 15 participants delivered checks that produced mean values of peak head acceleration that exceeded 60*g* (for straight-on impacts with pad A). However, with the added 2-cm-thick foam layer, mean values of peak head acceleration were less than 60*g* for all participants, regardless of the baseline shoulder pad and checking style.

Second, we assessed the biomechanical effect of the foam padding through experiments with human participants, who applied “the hardest check they were comfortable delivering” to the head of an instrumented dummy. This allowed us to overcome the limitations of a purely mechanical system in accounting for the potential of participants to alter their checking behavior based on the nature of the shoulder pad, or the checking scenario. It also ensured the biofidelity (effective mass, stiffness, and contact velocity) of the “human” component of our experimental model.

Third, several lines of evidence support the validity of our modified “BOB” dummy in simulating the characteristics of players receiving checks and in providing reasonable measures of head impact severity. Participants on average rated the dummy as 7 out of 10 in providing a realistic simulation of an opposing player during a shoulder-to-head collision. The torso, the neck, and the head were made of a foam polymer that had sufficient compressive and bending stiffness to prevent excessive deformation under impact. The overall rotational stiffness of the dummy was controlled via an overhead spring. Furthermore, participants struck a metal cage and helmet secured over the head of the dummy, which is required in all minor hockey leagues as well as in the National Collegiate Athletic Association (3). The magnitudes of linear acceleration we observed, averaging 28.7*g* in the foam condition and 38.31*g* in the no-foam condition, are slightly higher (as would be expected given the mean age of our participants was 21.4 yr) but consistent with the range of values (mean = 18.4*g*, 95% CI = 18.3–18.6) reported by Mihalik et al. (16), based on helmet sensor recordings of 12,253 real-life head impacts in bantam (age = 13–14 yr) and midget (age = 15–16 yr) boys' ice hockey.

Our study also has limitations. First, because of safety precautions, participants delivered checks to the head of an instrumented dummy instead of a living human. Further research is required to determine the clinical effectiveness of shoulder pad modifications on concussions in game play. Furthermore, additional laboratory studies should examine how changes in the stiffness and effective mass of the player receiving the head impact influence the protective benefit of added foam over the shoulder pad. Of particular importance may be the rotational stiffness of the neck because neck stiffness will influence the effective mass of the head (by altering the contribution of the torso to the overall “moving mass”) and the corresponding peak acceleration and rotational velocity of the head for a given impact. Although we did not measure the rotational stiffness of the neck of our shoulder-checking dummy, it likely approximated a state of activation of the neck muscles, as opposed to relaxation. Although we see little reason for believing that changes in neck stiffness would eliminate the protective benefit of added padding over the shoulder, additional experiments are warranted to quantify the effect. Second, during our experiments, participants delivered checks while wearing shoes instead of skates, and the floor surface was rigid vinyl instead of ice. Third, we examined the effect of a single thickness and stiffness of foam padding on impact severity. Additional work is required to identify the optimal geometry and material properties of shoulder pads across different levels of play, including the ideal configuration of rigid (e.g., plastic) and soft (e.g., foam polymer) components. Finally, although we found no evidence of risk compensation or adjustments in shoulder impact velocity for the range of padding we examined, we did not include measures with participants wearing no shoulder padding (or very minimal padding), which might be examined in future studies. We also cannot rule out the possibility that with a longer period of accommodation, players might deliver more aggressive hits with the foam layer.

Our study was motivated by the observation that the greatest portion of concussions in ice hockey result from shoulder-to-head collisions and focused on determining how extra padding to shoulder pads affects head impact severity. However, our results have implications for alternative approaches, including the addition of extra padding in the helmet, which should provide added protection regardless of the object contacting the head (e.g., the boards or glass, as well as the hand, elbow, or shoulder). Support for this notion was provided by a recent biomechanical study, which found that, for the same head impact exposure, the risk for concussion was at least 80% lower with a football helmet, with its greater foam thickness, than for hockey helmets (20).

In summary, we found that foam padding over the shoulder cap reduces impact severity to the head, for a range of shoulder pads and checking scenarios. Although more research is required, our results lend concrete support for rule changes in ice hockey to require an exterior foam polymer layer on shoulder pads, as currently exists for elbow pads. The foam layer should have negligible effect on the structural integrity and force distribution provided by the baseline shoulder pad, and the same protection could theoretically be achieved by inserting the foam layer into the jersey, instead of adhering it to the shoulder pad. The foam covering may work in tandem with improvements in helmet design and rules of play as a strategy for protecting the brain health of players in hockey and other contact sports.

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