SHORT COMMUNICATION: STAPP CAR CRASH CONFERENCE

Exploring Heart Strain from Blunt Trauma through a Parametric Investigation of Real-World *Commotio cordis* Cases

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ABSTRACT – *Commotio cordis* (CC) is a fatal condition seen mostly in sports when a projectile strikes an individual over the heart, resulting in pump failure. A multisport analysis of reconstructed CC real-world cases was conducted to understand the biomechanical response of the heart across 4 different sports projectiles in adults. Left ventricular strain of the heart was analyzed and used as a surrogate for determining CC. The results showed that impact speeds of 90-mph from both baseball and hockey pucks induced strain values upwards of 30% across the left ventricle of the heart. A cricket ball of 60-mph induced similar peak strains to the left ventricle as seen in the 90-mph baseball impacts. This study highlights the complex interplay between impact velocity, projectile type, and resultant cardiac strain, leading to the refinement of safety standards for CC in adults and children.

INTRODUCTION

Commotio cordis (CC) is a fatal phenomenon that occurs primarily to individuals playing sports, and takes the lives of 20 to 30 Americans every year (Maron et al., 2013). While more than 70% of CC cases occur in children, a significant number of cases also manifest in teenagers and adults (Maron et al., 2011). During CC, the heart experiences blunt trauma that stretches the cardiac tissue to a critical point. This tissue strain triggers a reentrant arrhythmia resulting in pump failure, which is fatal unless immediate defibrillation is administered (Maron et al., 2002). Previous studies in the literature have investigated pathophysiological processes for CC, while others have used computational modelling to determine the mechanical forces and responses from the human body, and in particular, the heart, during CC inducing impacts (Dickey et al., 2023).

CC occurs over a diverse range of sports and projectile types, including lacrosse balls, hockey pucks, and cricket balls. Despite differing in mass, size, and shape, these projectiles share a common theme of having heart-threatening kinetic energy. The current state of the research reveals a notable gap, where existing studies have concentrated solely on baseball and lacrosse in both computational and animal studies (Dickey et al., 2023; Link et al., 2003). However, a comprehensive multisport analysis does not exist regarding the reconstruction of CC cases. While CC incidents occur across all these sports, only baseball and lacrosse have safety standards in place set by NOCSAE (National Operating Committee on Standards for Athletic Equipment).

A multisport reconstruction study is essential to understand how variations in projectile speed, angles, mass, and shape can influence the biomechanical response of the heart from chest impacts. Analyzing real-world CC cases in adults will bridge a significant gap about the role of sports-related impacts in CC induction. Additionally, the need for accurate and updated impact speed thresholds is evident due to their applicability across age groups, as previous animal studies (Link et al., 2003) suggested a 30 to 50-mph range for CC induction, which may not uniformly apply to both children and adults.

METHODS

This study used the Total Human Model for Safety (THUMS Toyota) finite element models of a 50th percentile adult male. Four cases consisting of news media and published literature (Montgomery & Roden, 2015) of CC using various projectiles were reconstructed accounting for recall error in both location of impact (radius of projectile in all directions) and speed of impact (±5 mph) (Figure 1). This resulted in 15 unique impacts per projectile, totaling 60 simulations. The projectiles were a hockey puck, lacrosse ball, baseball, and cricket ball. Impact locations were determined through bruising analysis of photos or videos, while speeds were approximated based on recall. Sport projectiles were created using Ls-PrePost V4.7, with material properties and sizing

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conforming to adult sport standards. Projectile material properties were collected from literature and are listed in Table 1 (Kays & Smith, 2015; Sridharan et al., 2015; Vedula, 2004).

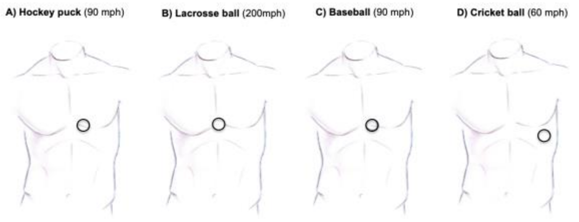

Figure 1. Impact locations on adults (black circles) based on bruising, recall, and video analysis. A) hockey puck, 90 mph, B) lacrosse ball, 200 mph, C) baseball 90 mph, and D) cricket ball 60 mph.

Table 1. Material properties and sizes of the sporting projectiles used in each unique reconstruction case.

Projectile	Bulk modulus (MPa)	G_o (MPa)	G_i (MPa)	Decay constant (ms)
Hockey puck	41260.00	414.00	26.90	78500.00
Lacrosse ball	41260.00	414.00	26.90	78500.00
Baseball	93.00	31.00	10.30	5.025
Cricket ball	134.00	43.40	11.50	10.50

	Volume (cm^3)	Diameter (mm)	Mass (g)
Hockey Puck	229.84	76.00	159
Lacrosse ball	141.68	64.68	143
Baseball	191.38	72.00	142
Cricket ball	195.43	71.49	166

Simulation Data Collection and Analysis

Simulations were computationally solved using LS-DYNA R901. A 20 ms simulation time matched the timing of potential CC cardiac cycle events, and left ventricular strain was used to assess the heart's mechanical response during impact. Maximum principal strain data was collected for peak values and thresholds. The metrics calculated include average peak strain, elements above and below the mean strain, and those beyond 0.1, 0.2, and 0.3 strain thresholds.

RESULTS

Hockey puck impact

Average peak left ventricular strain in the hockey puck impacts was higher than the baseball impacts at the same speed. Moreover, when considering the elements experiencing strain thresholds greater than 0.30, the minimum was 3.03% in the 85-mph radius right impact, while the maximum seen was 9.02% in the 95-mph frontal impact (Table 2).

Table 2. Minimum and maximum ranges for average peak strain, and the percentage of elements above and below the mean values.

Projectile	Average peak strain	Elements above mean	Elements below mean
Hockey puck	0.170 - 0.229	20.81 - 28.50%	71.50 - 79.19%
Lacrosse ball	0.175 – 0.294	25.80 - 34.02%	65.98 - 74.20%
Baseball	0.152 – 0.207	19.76 - 27.83%	72.17 - 80.24%
Cricket ball	0.141 – 0.202	19.16 - 24.20%	75.80 - 80.84%

Lacrosse ball impact

The lacrosse ball impact strain accumulation and distribution were much higher when compared to the other sporting projectiles, as the speed was over double the baseball and hockey puck, and over triple the speed of the cricket ball. Compression of the left ventricle was severe, and the elements experienced upwards of 29.40% average peak strain (Figure 2).

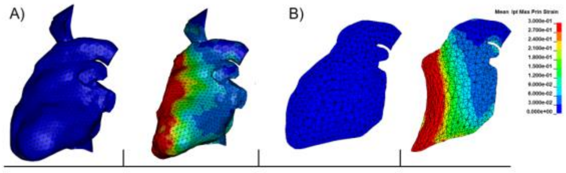

Figure 2. Lacrosse ball 200 mph sternum impact, A) Lateral view pre-impact (blue) and peak-impact showing strain distribution across the left ventricle, B) Sliced lateral view of the heart pre-impact (blue), and peak-impact, illustrating major compression of the tissue resulting in high strain in the left ventricle.

Baseball impact

The baseball impact generated lower strain values than the hockey puck at the same speed, while narrowly inducing higher strain values than the cricket ball which was travelling 30-mph slower. However, the baseball did have upwards of 6.52% of left ventricular elements over the 0.30 strain threshold, and up to 25.47% over the 0.20 threshold (Table 3).

Cricket ball impact

The cricket ball impacts, while having the lowest speed, induced very high peak left ventricular strain (0.142 to 0.202) relative to the other projectiles which had much higher speeds. Additionally, the cricket ball almost matched the percentage of elements below and above average peak strain in both the baseball and lacrosse ball (Table 2).

Table 3. Percentages above strain thresholds showing the minimum to maximum ranges seen among all impact locations and speeds per projectile.

Projectile	Elements above 0.10	Elements above 0.20	Elements above 0.30
Hockey puck	63.69 - 80.78%	14.41 - 32.39%	3.03 - 9.02%
Lacrosse ball	75.36 - 91.14%	18.21 - 65.37%	1.05 - 25.46%
Baseball	52.17 - 74.82%	8.89 - 25.47%	1.60 - 6.52%
Cricket ball	44.35 - 65.51%	7.69 - 20.84%	1.01 - 5.00%

DISCUSSION

The multisport analysis conducted in this study has provided the foundation for further reconstruction studies across sport and non-sporting events. Most notably, the cricket ball, while travelling 30-mph slower than the baseball, was able to induce similar peak left ventricular strain values (Table 2). This could be partially explained by the specific impact location and cricket ball mass. Similarly, the hockey puck exhibited greater strain accumulation throughout the left ventricle compared to a baseball of the same impact speed, evident in average peak strain and elements surpassing 10%, 20%, and 30% thresholds (Table 3). The 17g higher mass of the hockey puck compared to the baseball likely explains this increased strain under identical impact conditions.

Considering higher velocity impacts, the lacrosse ball results were revealing. CC is typically induced by impacts over the cardiac silhouette or slightly offset. Despite being positioned over the sternum and usually distant enough from the heart to cause CC, the lacrosse ball's extreme velocity of 200-mph led to significant left ventricular strain values ranging from 0.175 to 0.294. Elements exceeding the 30% strain threshold reached 25.46% (Table 3), further illustrating the danger this impact speed can cause even away from the heart.

Previous animal studies established the CC induction speed range at 30 to 50-mph (Link et al., 2003). These speeds may be accurate for children, but based on four reconstructed CC cases, they do not match the response observed in adult thoraxes. During our reconstruction of real-world CC cases, we discovered a broader spectrum of heart impact speeds: 60 to 90-mph, and even more substantial forces during sternum impacts, reaching 200-mph. Our results suggest that NOCSAE safety standards for CC could include higher speed requirements than the current 30 to 50-mph range. These findings offer initial heart strain measurements regarding CC incidents during high-speed impacts, serving as a suggestion towards designing chest protectors that can effectively limit heart strain below the range of 15 to 30%.

Recall from personal statements, eyewitnesses and video analysis informed this study, but accuracy regarding impact speed and location in each retrospective case may be limited. We have addressed this by providing a range for both. Additionally, CC has been shown to occur during the T-wave of the cardiac cycle and the models used in this study were based on general clinical imaging without controlling the stage of the heartbeat. To better mimic the T-wave, we applied internal pressures of 120 mmHg to the heart of the THUMS model to replicate internal pressure found during the T-wave. Clinical images of the T-wave stage of the cardiac cycle are being collected as a reference to refine the heart model. Future research will continue to reconstruct real-world cases, gathering data on speed, location, and the type of object that causes CC in both sporting and non-sporting events to further improve safety standards and equipment.

CONCLUSION

Through reconstructing real-world *Commotio cordis cases*, this multisport analysis and the establishment of new impact speed requirements together contribute to a more comprehensive understanding of CC incidents. The multidimensional nature of this study enhances the relevance and potential impact on athlete safety across various sports and age groups.

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