The Effect of Missed Diagnoses and Underreporting on Concussion Injury Risk Functions

Gunter P. Siegmund, Naveen Jasty, Allen W. Yu, Stephanie J. Bonin, Benjamin S. Elkin

I. INTRODUCTION

Injury risk functions provide a link between a tissue's mechanical exposure (e.g. force, acceleration, strain, etc.) and its probability of injury. Injury risk functions are typically developed by relating a continuous exposure variable, measured either in the laboratory or in the field, to a binary outcome variable coded as either injured or not injured. For some injuries (e.g. fractures), the injury is relatively clear and misclassifying an injury is unlikely. For other injuries (e.g. concussions), the diagnosis can be less certain, and an injury can be misclassified as a non-injury (or vice versa). Player under-reporting can also lead to an injury being misclassified as a non-injury. Prior studies have shown that only 31–45% of concussions are accurately diagnosed [1-2] and 31–71% go unreported [3-5]. Both sources of injury misclassification are not typically considered in injury risk functions for concussion, and their exclusion potentially alters the resulting function. The goal of this study was to explore how misclassifying injured players as uninjured players affects injury risk functions for concussion.

II. METHODS

We used Monte Carlo methods to simulate a pool of American football players, and a predefined injury risk function (the "actual" risk function) to classify players as injured and uninjured (the "actual" injury data). We then applied different types and rates of missed diagnosis and underreporting (MD&UR) to the actual injury data to generate a representative real-world dataset (the "adjusted" data), which was then used to develop an "adjusted" risk function. We then compared the adjusted risk functions from multiple simulations to the actual injury risk function to determine how missed diagnoses (MD) and underreporting (UR) affected the adjusted risk functions.

We based our actual injury risk function on the Prevent Biometrics Impact Monitoring Mouthguard data [6-7] (Fig. 1a). This risk function used a logistic regression fit to peak linear accelerations (PLA) of the head acquired from football players (location parameter=59 g, scale parameter=6). We then simulated PLA values for pools of N=500 players and applied the injury risk function to generate a subset of actual injured players. We chose a normal exposure distribution (PLA=43±10 g, gray histogram in Fig. 1a) so that about 15% of players were injured (blue histogram in Fig. 1a) [8]. Each player was assigned only one PLA value to avoid oversampling bias [7]. Before considering MDs and UR, we iterated this simulation 500 times to show it yielded the actual injury risk function (blue risk function in Fig. 1a) and to define its confidence intervals (CIs).

For this study, we combined the players with a MD and the players who did not report their concussion into a single MD&UR rate. We considered a range of MD&UR rates from 0% to 97.5%. MD&UR rates above this level sometimes created adjusted datasets without any injured players. We also considered unbiased and biased MD&UR patterns. For the unbiased datasets, the MD&UR players were randomly distributed within the actual concussed players. For the biased datasets, the MD&UR players were biased toward lower PLA values on the assumption that lower PLAs would be associated with less severe concussions, which would be more likely to go unreported or have their diagnosis missed. For each type and rate of MD&UR, we extracted the PLA values associated with a 50th percentile and 2.5th percentile risk of injury and plotted these values as a function of MD&UR rate. We also calculated the 95th percentile CI for the PLA at these two levels of injury risk.

III. RESULTS

The simulations generated actual injury datasets with 67±8 concussions (95th percentile CI: 40–91), which represented an injury rate of 13.4±1.6% amongst a pool of 500 simulated players. For an MD&UR rate of 0% (no MDs and all players reporting), the simulated PLA associated with a 50% risk of concussion was 59 g (identical to the actual risk function) with a 95th percentile CI from 57 g to 62 g. For both the unbiased and the biased MD&UR

G. P. Siegmund (e-mail: gunter.siegmund@meaforensic.com; tel: +1 949 855 4632) is the Director of Research at MEA Forensic Engineers & Scientists in Laguna Hills, CA, USA and an Adjunct Professor in the School of Kinesiology at the University of British Columbia, Canada. N. Jasty and A. W. Yu are Engineering Associates and S. J. Bonin is a Senior Biomechanical Engineer at MEA Forensic Engineers & Scientists in Laguna Hills, CA, USA. B. S. Elkin is a Senior Biomechanical Engineer at MEA Forensic Engineers & Scientists in Toronto, ON, Canada.

datasets, an increasing rate of MD and UR increased the PLA values associated with the 50% and 2.5% risks of injury compared to the actual injury risk function (Fig. 1b and 1d). For the same MD&UR rate, the unbiased dataset generated larger PLA values at 50% risk and smaller PLA values at 2.5% risk than the biased data set (compare Fig. 1b to Fig. 1d). The 95th percentile CIs at 50% risk were also wider for the unbiased data than for the biased data (compare Fig. 1b to Fig. 1d). When plotted across all MD&UR rates considered here, the PLA values at 50% risk remained within the actual 57–62 g CI (horizontal gray band in Fig. 1c) for MD&UR rates below 23% in the unbiased datasets and below 56% in the biased datasets (Fig. 1c).

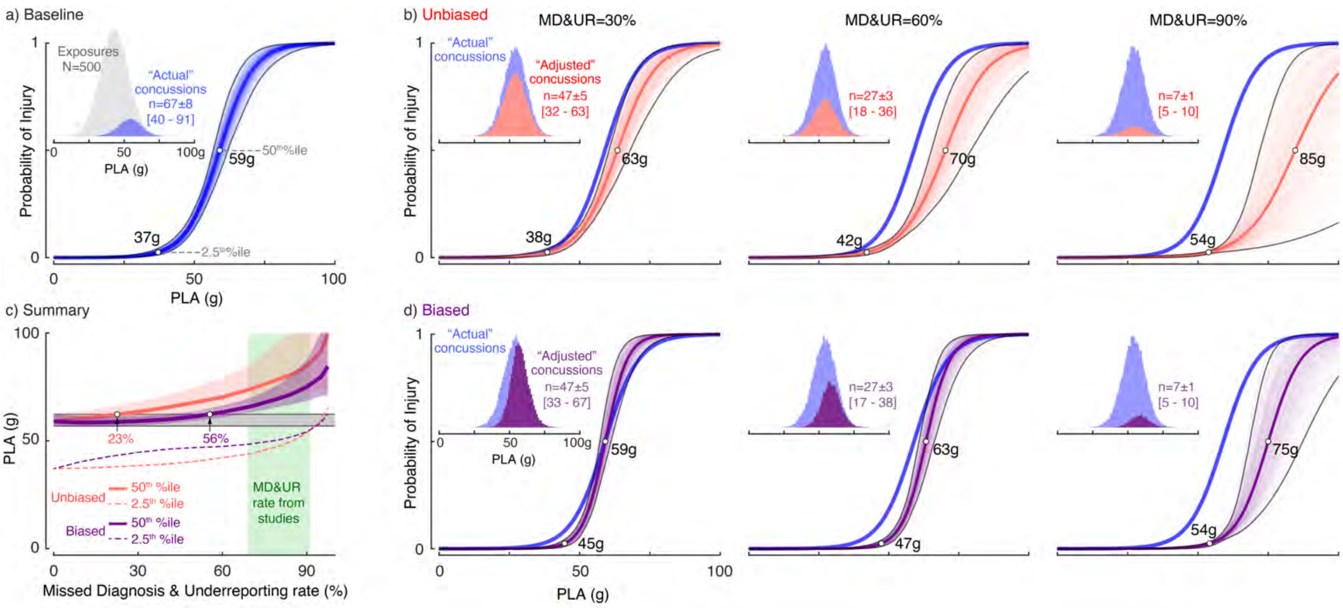

Fig. 1. a) Baseline condition showing the normal distribution (gray histogram) of maximum PLA exposures for N=500 players, the "actual" simulated concussions (blue histogram), the "actual" injury risk function (dark blue line), and the 95th percentile confidence bounds for the actual injury risk function (thin gray lines). b) Three injury risk functions calculated using unbiased MD&UR rates of 30%, 60% and 90%, with related histograms of the actual concussions (blue histograms) and adjusted concussions (orange histograms) after removing the MD&UR concussions. c) Summary of the peak linear acceleration (PLA) values associated with the 50% and 2.5% risks of concussion across a range of MD&UR rates. d) Three injury risk functions calculated using biased MD&UR rates of 30%, 60% and 90% with related histograms of the actual concussions (blue histograms) and adjusted concussions (purple histograms) after removing the MD&UR concussions. Blue = "actual" datasets, orange = unbiased "adjusted" datasets, purple = biased "adjusted" datasets, thin lines = individual simulations.

IV. DISCUSSION

Missed concussion diagnoses and player underreporting of injuries are relatively common [1-5] and, based on our analysis, can generate injury risk functions that predict a lower risk of concussion for a given exposure level. If only 31–45% of concussions are accurately diagnosed [1-2] and 31–71% go unreported in the first place [3-5], then only 9–31% of all actual concussions are identified and 69–91% of concussions are missed or unreported. These MD&UR rates lie at the right end of the summary graph (green area in Fig. 1c) and suggest the currently published concussion injury risk functions underestimate the actual risk of injury for a given impact exposure.

We analysed PLA in this study but expect similar results for other continuous variables (e.g. angular velocity change) related to concussive head injury. Although we accounted for oversampling, the effects of repetitive head impacts and data censoring were not considered. We also did not include players who were incorrectly diagnosed with concussion, but we believe this rate to be well below the MD&UR rates reported in the literature. Despite these limitations, our results suggest that concussion injury risk functions developed without considering diagnostic accuracy and underreporting may be biased.

V. REFERENCES

[1] Boutis, J., *Pediatrics*, 2015.
[2] DeMaio, *et al.*, *Br J Sports Med*, 2022.
[3] McCrea, *et al.*, *Clin J Sports Med*, 2004.
[4] Meehan, *et al.*, *Clin J Sports Med*, 2013.
[5] LaBotz, *et al.*, *Clin J Sports Med*, 2005.
[6] Bartsch, *et al.*, *Ann Biomed Eng*, 2020.
[7] Siegmund, *et al.*, IRCOBI, 2021.
[8] Rowson, et al., *Ann Biomed Eng*, 2012.