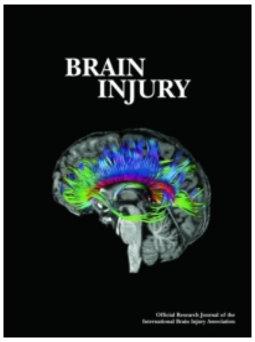

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ORIGINAL ARTICLE

Development of the Sports Organization Concussion Risk Assessment Tool (SOCRAT)

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ABSTRACT

Objective: In this paper, we describe the development of a novel tool—the Sports Organization Concussion Risk Assessment Tool (SOCRAT)—to assist sport organizations in assessing the overall risk of concussion at a team level by identifying key risk factors.

Methods: We first conducted a literature review to identify risk factors of concussion using ice hockey as a model. We then developed an algorithm by combining the severity and the probability of occurrence of concussions of the identified risk factors by adapting a risk assessment tool commonly used in engineering applications.

Results: The following risk factors for ice hockey were identified: age, history of previous concussions, previous body checking experience, allowance of body checking, type of helmet worn and the game or practice environment. These risk factors were incorporated into the algorithm, resulting in an individual risk priority number (RPN) for each risk factor and an overall RPN that provides an estimate of the risk in the given circumstances.

Conclusion: The SOCRAT can be used to analyse how different risk factors contribute to the overall risk of concussion. The tool may be tailored to organizations to provide: (1) an RPN for each risk factor and (2) an overall RPN that takes into account all the risk factors. Further work is needed to validate the tool based on real data.

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Concussion; sports; risk assessment; risk factors; ice hockey; FMEA

Introduction

Concussion is a major public health concern. It is estimated that over 3.8 million concussions occur annually [1], with many occurring in sport contexts. By high school, half of all student athletes will have sustained a concussion, and by college, a third will have had multiple concussions [2]. More importantly, there is an increased risk of repeat concussion after an initial concussion [3]. Over a lifetime, repeated brain trauma is associated with increased incidence of depression [4] and an increased risk of cognitive decline in later life [5]. Consequently, there is a critical need for tools to help sports organizations evaluate the risk of concussion within their sport and to use this information to effectively minimize this risk.

Currently, concussion prevention focuses on the implementation of proper protective equipment, amendments to rules and regulations, encouragement of fair play and information about how to recognize concussions [6]. However, there are no available tools that can be used to assess the risk of concussion in sports organizations. Numerous factors contribute to increased risk of concussion at both the individual and organizational levels [7,8]. In this paper, we propose a novel assessment tool for the associated risk of concussion of independent risk factors: the Sports Organization Concussion Risk Assessment Tool (SOCRAT). The SOCRAT can ultimately be used to identify risk factors and to assess the overall risk of concussion within a given sport organization. By applying this tool iteratively as amendments are made to risk factors, the level of concussion risk may be monitored and used as a measure of overall team safety. Here, we describe the components of the risk assessment tool using the sport of ice hockey as an example model.

Risk factors in ice hockey

Risk factors in ice hockey can be classified into the following categories: Player Characteristics, Sport and Regulations, Equipment, and Environment (Figure 1). Below, we review the evidence for the risk factors in each category.

Player characteristics

History of previous concussions

Athletes with a history of previous concussions are more likely to sustain another concussion than athletes with no previous history of concussion [3,9,10]. Specifically, ice hockey players who have had previous concussions are 1.87 times more likely to receive another concussion and are 2.4 times more likely to receive a severe concussion that results in 10 or more days lost from play [9]. Additionally, time lost from competition is 2.25 times higher with every subsequent concussion [11], which may be due to the longer symptom resolution time and length of recovery in players with recurrent concussions [12,13].

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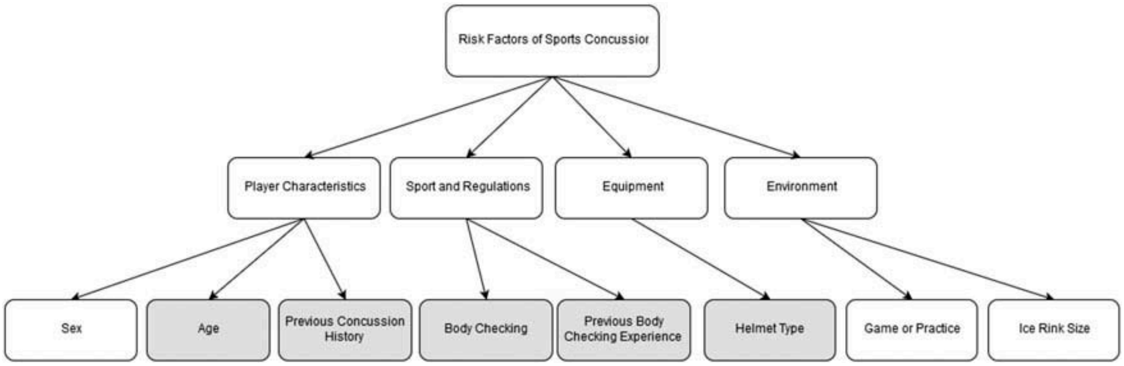

Figure 1. Risk factor categories of sports concussion. This figure 1 shows the four categories of risk factors that are included in the Sports Organization Concussion Assessment Tool (SOCRAT). Risk factors that are greyed out are included in our model for ice hockey.

Sex

In many gender-comparable sports such as soccer, basketball and baseball/softball, females have a higher overall concussion rate [12]. Although male and female ice hockey players show one of the highest rates of concussion compared to other sports, ice hockey is one of the few sports that do not show sex-related differences in concussion rates [14]. Therefore, the sex of the ice hockey player was excluded as a risk factor for ice hockey in our model.

Age

Age is a risk factor in ice hockey; however, there is contradictory information in the literature about this factor. Schneider et al. [15] report similar injury rates per 1000 player hours for both the Pee Wee (0.55) and Bantam (0.53) age groups. However, others report that the risk of concussion and other ice hockey injuries may either decrease [16] or increase with age [17–20]. Since body contact with another player is the most likely mechanism of hockey-related injury [14,19,21], statistical data from divisions where body checking is banned were used to accurately assess the risk of concussion in all age groups. Agel et al. [22] studied injuries in collegiate women's ice hockey, while Black et al. [10] compared injury and concussion risk between a sample of 11- to 12-year old males where body checking was allowed with a sample where body checking was banned. The comparison between collegiate women and boys aged 11–12 years was made with the assumption that sex does not significantly impact the risk of concussion. Only data from the samples where body checking was banned were used for the ice hockey model of the SOCRAT. Overall, the literature suggests that the risk of concussions increases with increasing age. This may be due to the higher level of competition and increased athletic skill [20].

Sport and regulations

Body checking

Body checking is associated with an increased risk of game-related injuries [9,10,19–21]. This risk is modulated by the competitive level of the specific league [20]. The risk of injury is lower in House leagues, which do not permit body checking in comparison with Representative teams, which do permit body checking in certain age groups [20]. At the collegiate level and in minor hockey, player-to-player contact while body checking is the most common mechanism of concussion [14,19,23]. In our model, we used the data from Emery et al. [21] who report 3 times higher rates of concussion, severe concussion, injury and severe injury in leagues where body checking is permitted.

Previous body checking experience

There is an immediate increase in injury rates in leagues where players are first introduced to body checking [9,20,21]. Therefore, a decline in injury rates is expected in players who have had previous body checking experience [20]. In our model, we used the data from Emery et al. [9], who compared players entering the Bantam league who had 2 years of previous body checking experience with those being newly introduced to body checking. They report that a player is 1.19 times more likely to receive a concussion and 1.67 times more likely to receive a severe concussion (resulting in a loss of 10 or more days of play) if the player has had no previous body checking experience.

Equipment

Helmet type

Ice hockey players that do not use facial protection are 2 times more likely to be injured compared to players that wear half-face shields, and approximately 7 times more likely to be injured compared to players who wear full-face shields [24]. However, there is no statistically significant correlation between the type of facial protection worn and the occurrence of concussion [24–26]. However, Benson et al. [25] have shown that facial protection does affect the severity of concussion. They report that players who wore half-face shields at the time of concussion lost 2.4 times more games and practices than those that wore full-face shields. players that wore full-face shields sustained concussions from body checking that resulted in contact with the boards, Plexiglas or net, whereas players that wore half-face shields sustained concussions largely from player-to-player contact [25]. We used these data to calculate the severity of a resulting concussion as a function of facial protection in the ice hockey model.

Environment

Game vs. practice

The risk of injury is approximately 6–8 times higher in games than in practice [23,27], where concussions account for a majority of all game-related injuries [14,20,23,27]. There is no significant difference in practice-related injuries in leagues where body checking is allowed when compared to leagues where body checking is banned [21]. Furthermore, all concussions that occurred in a group of players that wore full-face shields occurred during games [25]. This suggests that even with the highest level of facial protection, there is an increased risk of concussion depending on the setting of play. Zuckerman et al. [14] report data for men and women during both competitions and practice. These data are used to calculate the associated concussion risk of this risk factor.

Ice rink size

Reducing the number of collisions that occur in hockey games may lead to a reduction in the risk of concussions [28]. One way to reduce the number of collisions is to increase the ice rink size. The International ice hockey surface (approximately 200ft x 100ft), which is 15 ft wider than the standard North American ice hockey surface, is associated with a reduced number of collisions [28,29]. As ice rink size increases, the rate of hockey-related injuries decreases significantly. However, Watson et al. [30] report that there is no significant difference in the occurrence of neurotrauma in different sized rinks. Due to the conflicting reports regarding the impact of concussion risk associated with rink size, we did not include this risk factor in our model.

Risk factor inclusion criteria

Risk factors were included in the ice hockey SOCRAT model if they meet one of the following criteria:

(1) The risk factor is modifiable by the organization and will result in a decrease in occurrence and/or severity of concussion
(2) The risk factor is non-modifiable and is identified by literature as having a significant contribution to the occurrence and/or severity of concussion. (These risk factors are included so that coaches and athletes may become aware of the inherent risk of the sport through the use of the assessment tool.)
(3) The risk factor falls into one of the criteria of prevention outlined by policies on concussion awareness and safety [6,8,31,32].

Development of the assessment tool

The Failure Mode and Effect Analysis (FMEA)

The Failure Mode and Effects Analysis (FMEA) is a risk assessment tool commonly used in engineering applications [33–35]. Within an engineering context, possible failure modes in product designs and manufacturing processes are first evaluated. The associated risks of failure are then predicted based on outputted risk priority numbers (RPNs), which indicate the level of risk associated with each failure mode. The RPN allows the user to compare the risk of each possible failure mode associated with the engineering application and to make the appropriate changes to minimize these risks.

Risk management and risk reduction within health care are of high priority, and various interpretations of FMEA have been used as a method of reducing procedural errors [36–40]. Due to differences in applications and limitations of the FMEA, modified versions of the FMEA have been proposed to provide a mathematically more accurate method of assessing risk.

The FMEA relies on three variables to determine the RPN: O, a measure of the probability of the failure occurring; S, a measure of the severity of the effects of a failure; and D, a measure of the difficulty of detecting a failure having occurred. Although various equations have been used to define the relationship between the RPN and the three variables [36,39,41,42], the typical equation used is

$$RPN = S \times O \times D$$

Generally, the variables S, O and D are assigned numerical values ranging from 1 to 10, with 10 reflecting the maximum possible consequence relating to the variable. Thus, a higher RPN represents a higher risk of failure and a more prioritized need for reduction.

When the RPNs for multiple failure modes are calculated, failure modes may be prioritized based on their associated risk. When corrections to reduce the RPNs are made in respect of specific failure modes, the RPNs for those failure modes must be recalculated to reflect the corrections made.

The Sports Organization Concussion Assessment Tool (SOCRAT)

Limitations of the FMEA prevent its use in assessing the risk of sports injury at an organizational level. Such limitations include the RPN's vague definition and lack of mathematical basis [40,42,43], the inability to account for the probability of different mutually exclusive effects of the same failure mode, and the assumption that the occurrence of a failure mode always results in an effect.

The proposed algorithm attempts to address the above limitations by modifying the definition of the RPN based on Bayesian probability and allowing multiple mutually exclusive effects to occur from the same failure mode. The RPN is defined as a numerical value reflecting the multiplication of the severity of a concussion and the probability of a concussion occurring. This is mathematically expressed as

$$RPN_j = \sum_{i=1}^{N} S_i \times E_{ij} \times F_j$$

The variables of the RPN for risk factor j are functions of the parameter O_j, a measure of the presence of risk factor j. S_i is a measure of the severity of effect i, E_{ij} is the probability of the occurrence of effect i given the occurrence of the failure mode, and F_j is the probability of the occurrence of the failure mode. (Please see Supplementary Material for a detailed explanation of these variables).

The proposed algorithm has been modified specifically for concussion risk reduction. Each risk factor of sports concussion results in an RPN based on the presence of the risk factor in the organizational setting. The RPNs produced may then be used to assess the need to reduce certain risk factors and be summed to provide an overall measure of the risk of concussion. This algorithm may be used in similar applications such as in other injuries.

Application of the assessment tool

The use of the assessment tool is similar to that of the FMEA. The process of conducting an assessment occurs in four stages.

Pre-assessment

Before conducting an assessment of the risk present in any organizational setting, the risk factors and the numerical parameters of their associated functions must first be determined. For each risk factor j, the functions of S_i, E_{ij} and F_j must first be determined. Although the level of rigour required to accurately determine these functions differs based on the user's preference and the application of the assessment tool, it is suggested that epidemiology data obtained through scientific literature be used first, followed by the expert opinions from personnel familiar in the area of interest when the former is unavailable. An example of derived functions of the listed concussion risk factors is shown in Table 1.

When epidemiology data for certain risk factors vary between studies, the use of a weighted average between these studies is suggested in order to determine the most representative functions. Weightings of the confidence of different studies may be determined based on criteria such as the Levels of Evidence of the studies [44].

Assessment

During the assessment, the organizational setting is evaluated based on the risk factors present. This step involves determining a value for the parameter O_j for each risk factor. A numerical value ranging from 0 to 1 is assigned to the parameter O_j for each risk factor in the organizational setting, where 0 indicates that the risk factor is not present and 1 indicates that the risk factor is fully present. To remain consistent between all organizational settings, criteria for each risk factor should be determined so that all assigned scores are consistent.

Post-assessment

The parameters O_j for all risk factors are assigned numerical scores, and the variables S_i, E_{ij} and F_j are calculated correspondingly based on their derived functions. The RPN for each risk factor may then be calculated. Risk factors with relatively higher RPNs are critical risk factors, which may result in higher risk of concussion, whereas risk factors with relatively lower RPNs are considered less significant.

To provide an overview of the total risk of concussion, an overall RPN may be calculated by summing the RPNs of all risk factors. Similar to the FMEA, thresholds for individual RPNs and the overall RPN, representing the maximum allowable risk, may also be set objectively to evaluate whether action must be taken. RPNs above the threshold may indicate a critical need for reduction, whereas RPNs below the threshold require no action to be taken.

Reassessment

Once critical risk factors are identified, action may be taken to reduce the associated risk of concussion. Such actions may include the removal or reduction of the presence of the risk factor, which would lower the score of parameter O_j accordingly and thus, the overall RPN. Note that any change in the score of parameter O_j may result in changes to the scores of variables F_j and E_{ij}, as they are functions of O_j.

When these actions have been taken and the associated parameter scores have been changed, the RPNs for the individual risk factors and the overall RPN should be recalculated. The risk of concussion should then be re-evaluated to determine whether any additional actions should be taken to further lower the RPN. This is an iterative process that should be completed repetitively until the user is satisfied with the current risk.

Discussion

We conducted a literature review of the risk of concussion in ice hockey and identified the following risk factors: age, history of

Table 1. Example of proposed algorithm for sports concussion risk reduction.

Risk factor	Severity (*S*)	Effect (*E*)	Failure probability (*F*)	Occurrence (*O*)	RPN	Source
Age (11.5 to 20 years old)	All (2)	1	1.57× o − 0.57			[19, 20]
Previous concussion history	Severe (3)	0.07× o + 0.24	0.87×o + 1			[21]
	Non-severe (1)	−0.07×o + 0.76				
Body-checking allowance	Severe (3)	−0.01×o + 0.39	2.88×o + 1			[18]
	Non-severe (1)	0.01×o + 0.61				
Previous body- checking experience	Severe (3)	0.11×o + 0.28	0.19×o + 1			[21]
	Non-severe (1)	−0.11×o + 0.72				
Use of helmet face shields	Severe (3)	−0.29×+0.32	1			[24]
	Non-severe (1)	0.29×o + 0.68				
Game v. practice (male)	All (2)	1	8.92×o + 1			[10]
Game v. practice (female)	All (2)	1	5.70×o + 1			[10]

This table outlines the variables of the different concussion risk factors in ice hockey that were accumulated from literature. The equations used to calculate Severity (S), Effect (E), Failure Probability (F) are included in their respective column. The articles used to derive the equations are cited in the last column, labelled 'Source'.

previous concussions, body checking, previous body checking experience, helmet type and game vs practice play. Based on recent evidence, we calculated the numerical parameters of the functions for the necessary variables for the model. In implementing and applying SOCRAT to individual sport associations, we suggest that users should first review current literature to determine the types of risk factors for concussion that predominate in their respective sport. In the Assessment stage, the user can then determine if the risk factors identified in the literature are present in their respective setting. The SOCRAT variables, S_i, E_{ij} and F_j, can then be calculated by first determining the value for the parameter O_j for each risk factor j. The specific risk factor RPNs and the overall RPN can then be calculated in the Post-Assessment stage using the identified SOCRAT variables. By analysing the specific risk factor RPNs, users can focus on critical risk factors to modify the play setting in order to mitigate the risk of concussion in the organization.

One of the limitations of our approach is that identification of risk factors is based on published reports. Users will need to evaluate the evidence, which can often be conflicting, in order to determine how best to incorporate the specific factors into the model. A lack of published studies regarding a specific risk factor may not necessarily represent the actual presence or absence of concussion risk. Published studies must be carefully considered to ensure that the methodology used is valid and the results are reliable and do not overestimate or underestimate the associated risk of concussion. Furthermore, conclusions interpreted from conflicting studies may result in a poor representation of the concussion risk of the associated risk factor, thus making the RPN of the particular risk factor inaccurate. Methods of weighing the reliability of studies, such as the Level of Evidence [44], should be used when there are multiple studies related to one risk factor. In addition, many studies may not necessarily include the data needed for the calculation of SOCRAT variables.

The proposed algorithm may also produce inaccurate RPNs due to limitations in the calculation process. There are currently no standardized objective and quantitative measures of assessing the severity of a concussion. Thus, the values of the severity variable S_i may have to be determined subjectively. Depending on the available statistical data, certain risk factors, such as history of previous concussions, are characterized into two different subcategories: overall concussions and severe concussions. The time lost from play is typically used as a measure of severity of a concussion in many studies. For example, some studies use 7 days of play lost [25], while others use 10 days of play lost [9,10,23] to characterize severe concussions. For our current model, a score of 1 was assigned for non-severe concussions, 2 for concussions in general and 3 for severe concussions, based on the associated study's definition. We suggest that each organization develop a standardized method of determining severity until such time that objective measures are identified.

One advantage of the SOCRAT is that it provides the flexibility of including additional risk factors as new evidence emerges. The successful inclusion of such risk factors must include specific data such as the incidence rate ratio or the incident rate, sample population sizes and characteristics, and a measure of the severity of occurred concussions. An objective measure of concussion severity would significantly reduce subjectivity and improve the algorithm.

Conclusion

Concussions are highly prevalent in sport environments, and a consistent and repeatable method of assessing its associated risk is necessary to reduce the risk to athletes. The SOCRAT provides a feasible method of assessing the risk of concussion within a sports organization. By assessing the probability of occurrence and identifying individual risk factors, an estimate of the associated risk for each risk factor may be determined. In addition, the summation of RPNs of all risk factors provides an overview of the total risk associated with specific sports. Consistency of listed risk factors and variable score criteria upon assessments allows comparison of concussion risk of different sports organizations and of different time points within one sports organization. Adjustments made to risk factors in the sports organizations will be reflected in changes to the variable score of these risk factors, thus providing a new assessment of the associated concussion risk. By completing this process iteratively, concussion risks associated with individual risk factors, as well as the overall concussion risk, may be reduced.

Improvements to the algorithm will be possible as new research on risk factors is incorporated into the model. In addition, this theoretical tool needs to be validated with real data. To evaluate the effectiveness of the SOCRAT in reducing the risk of concussion in sports organizations, a comparison of the before-and-after data of the actual number of concussions needs to be conducted in different sports.

Supplementary material: Derivation of the proposed algorithm

For our application, the risk is defined as a function of the severity of the effects and the probability of the effects occurring. That is,

$$Risk = Severity \times Probability$$

For each independent risk factor, the risk priority number (RPN) can thus be defined as the probability-weighted average of the severities of the corresponding effects. That is,

$$RPN_j = \sum_{i=1}^{N} Severity_i \times Pr\left(Effect_i \cap Failure\ Mode_j \cap Risk\ Factor_j\right)$$

where j is the risk factor of consideration and $i = 1, 2, \ldots N$ is the number of effects corresponding to the failure mode (i.e. a concussion occurring).

Using the Law of Total Probability, we can derive the probability to be

$$\begin{aligned}\Pr\left(Eff_i \cap FM_j \cap RF_j\right) &= \Pr\left(Eff_i \cap \left(FM_j \cap RF_j\right)\right) \\ &= \Pr\left(Eff_i \middle| \left(FM_j \cap RF_j\right)\right) \\ &\quad \times \Pr\left(FM_j \cap RF_j\right)\end{aligned}$$

where Eff_i is effect i, FM_j is the failure mode and RF_j is the risk factor j. From the above derivation, we can represent the probability of an effect as a multiplication of two terms. The two terms, as listed above from left to right, may be defined as such:

- Probability of the occurrence of effect i given the occurrence of risk factor j and the occurrence of the failure mode
- Probability of the occurrence of the failure mode and the occurrence of risk factor j

For simplicity, these two terms can be represented with two variables E_{ij} and F_j, respectively. We can thus define the modified RPN for risk factor j as

$$RPN_j = \sum_{i=1}^{N} S_i \times E_{ij} \times F_j$$

where parameters E_{ij} and F_j are functions of the parameter O_j.

The construction of this equation and its variables is explained in the following sections.

Occurrence of risk factor, O

The parameter O_j can be described as a measure of the occurrence of risk factor j. For our application, a higher score for O_j indicates a higher occurrence of the risk factor. The possible values of O_j range from 0 to 1.

The presence of risk factors may either produce binary or continuous scores. For example, the allowance of body checking only allows two possibilities: allowed and disallowed. Thus, when body checking is allowed, the maximum score of 1 is given. Otherwise, when body checking is disallowed, the minimum score of 0 is given. For risk factors that produce continuous scores, such as age, the possible range of the risk factor is scaled to a range from 0 to 1, and the proper value of O_j is assigned accordingly.

Severity of effect, S_i

The variable S_i is a measure of the severity of effect i that may result from the failure mode. For our application, the different possible effects are distinct based on the return-to-play time and the physical symptoms. The scores of this parameter have a limited range, with 1 as minimal severity and the maximum score, as decided by the user, as maximum severity.

To our knowledge, no studies have successfully quantified the severities of these different effects relative to each other for the risk of concussion. Thus, the scores of the parameter S would be determined based on the opinions of experts in the effects of concussion.

Effect probability, E_i

The variable E_{ij} is a measure of the probability of effect i given the occurrence of the failure mode due to risk factor j. For our proposed modifications, the scores of the parameter E_{ij} range between 0 and 1. Because we define individual effects as non-overlapping levels of severity due to the failure mode, we assume that only one effect may occur for every instance of the failure mode. Thus, when all possible effects are accounted for,

$$\sum_{i=1}^{N} E_{ij} = 1$$

Changes in the occurrence of the risk factor O_j may result in changes in the probability of each effect occurring. Thus, we can define E_{ij} as a function of O_j. The function may vary based on the application of the proposed algorithm and the user's preference. Common functions may include linear and exponential functions in the forms of

$$E_{ij} = a \times O_j + b$$
$$E_{ij} = c \times d^{e \times O_j}$$

where a, b, c, d and e are constants to be determined through test cases.

To determine these constants, a minimum of two cases of E_{ij} and O_j must first be known. This is most easily achieved using cases provided by studies in which the risk factor is applied and not applied. When the constants are solved for, the variable E_{ij} may be solved for any parameter O_j. Therefore, any change in parameter O_j must be reflected with a corresponding recalculation of parameter E_{ij}.

The availability of variable E_{ij} for each effect is dependent on the studies conducted in regards to the associated risk factor. If distinct scores are unavailable or cannot be determined from raw data provided from epidemiology studies, the scores should be estimated based on expert opinions or similar risk factors.

Failure probability, F

The variable F_j is a measure of the probability of the failure mode occurring (i.e., a concussion occurring) given the occurrence of a risk factor. To determine a score for the variable F_j, epidemiology results from scientific literature or other reliable sources should be used.

The increase in the occurrence of a concussion due to the occurrence of a risk factor may be represented as the incidence rate ratio (IRR) and can be calculated directly from data provided from reviewed studies, as shown below:

$$IRR = \frac{\#\ of\ concussions\ with\ risk\ factor\ j}{\#\ of\ concussion\ without\ risk\ factor\ j}$$

The probability of a failure occurring given no existing risk factor is denoted as x. Therefore, the probability of a failure occurring given that risk factor j exists is

$$IRRx$$

Because the RPN is a relative measure between cases where a risk factor exists and where no risk factor exists, the actual value of a failure occurring given no existing risk factor, x, is of no significance. Therefore, we can define the variable F_j as a relative variable where x is removed. Thus, the relative probability of a failure occurring given no occurrence of risk factors is

$$F_j = 1$$

and the relative probability of a failure occurring given the occurrence risk factor j is

$$F_j = IRR$$

where IRR is a numerical score greater than 0.

The occurrence of risk factor j is represented as parameter O_j. Therefore, the variable F_j is a function of the parameter O_j. This relationship can be represented with a variety of functions, such as linear or exponential functions, as shown below:

$$F_j = (IRR - 1) \times O_j + 1$$
$$F_j = IRR^{O_j}$$

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Declaration of interest

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