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Published in:
Journal of Men's Health

DOI:
10.31083/j.jomh1809193

Published: 01/09/2022

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Evans, S. A. (2022). The Biomechanics of Ice Hockey: Health and Performance Using Wearable Technology. *Journal of Men's Health*, *18*(9), 1-12. [jomh1809193]. https://doi.org/10.31083/j.jomh1809193

JOMH
Journal of Men's Health

J. Mens. Health **2022**; 18(9): 193
https://doi.org/10.31083/j.jomh1809193

Review

The Biomechanics of Ice Hockey: Health and Performance Using Wearable Technology

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Submitted: 2 March 2022 Revised: 22 May 2022 Accepted: 25 May 2022 Published: 19 September 2022

Abstract

Background: Ice hockey is a dynamic and challenging sport that encompasses forward and backward skating, speed, agility, mobility and coordination. The physical and biomechanical demands on players mean that injuries occur due to collusions and impacts. Whilst player performance remains important for success, the likelihood of game-related injuries is vast. Contemporary wearable technology allows precise measurements of kinematic and kinetic characteristics that can help performance and mitigate injury. Therefore, there has been increasing interest amongst players, coaches, sports scientists, health officials and the sports engineering community to enhance understanding. **Methods**: This scoping review searched three electronic bibliographic databases (Pubmed, GoogleScholar and Scopus) using a structured search strategy to identify articles published between 2000 and 2022. The reference lists of selected papers (not found in the original search) were also examined for relevance. Thus, a review of epidemiological, biomechanical and technological studies are presented. **Results**: An ability to link performance with athlete health and wellbeing using wearable technology is not clear. It is apparent that for the majority of data metrics, legitimacy, usage and dependability are multifactorial, in that it is reliant upon a variety of factors including wearable technology brand and model. Reasons exist to support the usage of wearables to track performance and manage athlete health and wellbeing, although the benefit accrued from devising a consistent approach depends on the nature of the how the technology is applied. **Conclusions**: Specific biomechanical assessments should be created using wearable technology given that player position and role requirements may have different injury considerations.

Keywords: ice hockey; biomechanics; sensors; wearables; injury

1. Introduction

Ice hockey is demanding and fast-paced, requiring exceptional physical conditioning and refinement of technical skills such as passing, skating and shooting. In 2020, over 1.6 million players took to the ice in more than 70 countries [1]. Thanks to this worldwide interest, national hockey federations look for ways to optimize player development, increase athlete health and wellbeing whilst monitoring player safety in order to meet the highest possible standards.

Ice hockey comprises three periods of 20 minutes with 15 minutes allocated after the conclusion of each period. A team can have a maximum of 20 players, however, only six players are on the ice at any one time. The six players include a goal tender and five outfield players. The remaining players are substitutes but are permitted to enter the rink as required by the coach. Regarding the rink, the dimensions are approximately 26 m by 61 m (85 ft by 200 ft) [1]. This includes a middle section which is known as the neutral zone. At either side of the neutral zone are attacking and defending zones that contain two faceoff circles.

Information pertaining to the biomechanics of the skating characteristics of ice hockey players is important due to the implications for performance and athlete health, wellbeing and injury mitigation. In this regard, performance and athlete welfare is contingent on the optimization of physiological, psychological and biomechanical parameters. Despite reviews concerning physiologic or psychological performance parameters [2–4] there is a need to better understand the biomechanical parameters associated with on-ice movement. This applies to performance, health and injury prevention. Yet, the dynamic aspect of ice hockey combined with its unique on-ice conditions can make data collection challenging [5].

Sports biomechanics includes kinetics and kinematics with electromyographic (EMG) a common metric for performance evaluation. Kinetic variables that can partly explain modifications in skating performance include changes in reaction forces and joint torques. In contrast, spatial-temporal variables are subject to player movement variability when players are on the ice.

Data that compares player performance is commonly obtained using invasive and non-invasive techniques. It remains clear, however, that because ice hockey is played under specialized conditions, that is, on a surface of low friction, players encompass a unique set of skills that are distinctive from other sports. It is therefore necessary to consider both player skill and movement given the importance of performance and the increased risk of injury.

Hawkins and Metheny [6] states that the application of clinical biomechanical information is developed around the technique of movement, equipment and materials. This can be extended to the health and wellbeing and the prevention/attenuation of injuries. It has therefore been the subject of much research [3]. Notwithstanding this, previous studies have examined ice hockey biomechanics on smaller scales [7] using skating treadmills [5] or on synthetic ice [8]. Although research outcomes have provided valuable insights, laboratory settings do not necessarily replicate the demands of the sport. In this sense, limitations on player actions and activities due to the artificial setting of skating treadmills or synthetic ice surfaces can question the validity of the data.

A laboratory provides an environment whereby conditions can be controlled. Yet, ice hockey skills are not continually performed in a predictable way. In this instance, ice hockey is unique and presents some considerations in terms of mobility (i.e., side-to-side leaning) and biomechanical properties (e.g., a low coefficient of friction which affects movement). Unobtrusive wearable sensors can be integrated into player clothing and equipment that allows for the real-time monitoring of the athlete's progress [9]. Using sensor data, it is possible to analyse movements relative to both local and global reference frames.

Understanding the biomechanics and athlete wellbeing in ice hockey necessitates various technological approaches. A popular and cost-effective technological option previously used is Kinovea. This open-source software allows for 2D motion analysis. Whilst Kinovea is a valid, precise and reliable program that allows for the capture of absolute and relative angles and data from local and global coordinates, its role in injury prevention and athlete health remains unclear.

Wearables such as mobile/cellular phones, smart watches and wearable bracelets (e.g., Fitbit) are increasingly prevalent for detecting location, position, physical activity, exertion and athlete collisions. Its usage is largely based on justification to quantify the acceleration of body segments induced by postural response. Lee *et al.* [10] proposed that wearable technology (e.g., pedometers and inertial measurement units (IMU)/micro-electromechanical systems (MEMS) and global positioning systems (GPS) allows for the unobtrusive assessment of human movement [10]. This permits for the real-time tracking of velocity, oscillation, acceleration/deceleration and angular acceleration.

Relative to ice hockey, wearable technology allows for unobtrusive data capture including hits, goals and body checks whilst the player is on the ice. Therefore, this allows for an objective way to evaluate performance. However, this is arguably only affordable for elite teams in the North American, Canadian, Russian and Scandinavian leagues [9,11,12]. At the recreational level, the evaluation of movement often occurs according to subjective observations by the coaches. This raises questions: while neurophysiology and biomechanics need to be understood and measured to determine adequate performance levels whilst minimizing injury, what is the role of wearable technology relative to athlete health and wellbeing?

Despite the global popularity of ice hockey, the incorporation of evidence-based approaches to on-ice biomechanical analysis and athlete wellbeing remains a neglected area of applied sports science and men's health research. Thus, the main objective of this study is to conduct a review and analysis of the literature examining the biomechanics and health and wellbeing of ice hockey players when wearable technology is considered. This allows for a contemporary biomechanical and health profile in male ice-hockey players taken from trends in wearable technology. Current injury management recommendations and the role of wearable technology and its possible transfer to player health and wellbeing are evaluated with gaps in the literature identified. Furthermore, this review will (1) highlight biomechanical differences between players and positions, (2) determine strengths and weaknesses of wearable technology used for biomechanical analysis, and (3) outline the resultant injury and health associations.

2. Methods

A scoping review was conducted between December 2021 January 2022 using three electronic bibliographic databases (Pubmed, GoogleScholar and Scopus) using a structured manual search strategy to identify articles published 2000 and 2022. The search strategy was directed towards articles published from 2000 and 2022 due to the rapid changes in microtechnology advancements. Earlier articles would have been misleading because of the changes to data capture, sample rates, portability, validity and reliability of wearable technology. Studies included must have been (1) original research investigations; (2) full-text articles written in English; (3) published in a peer-reviewed academic journal; and (4) evaluated the usage, prevalence or reliability of wearable technology to quantify on-ice movements or specific actions common to recreational and/or professional (elite) male ice hockey performance and athlete health and wellbeing inclusive of injury prevention. The search strategy relative to each database used a set of core key words: ice hockey biomechanics AND* wellbeing OR* health *OR injury AND* wearable technology *OR sensors with the word male ice hockey players added. Of the returned titles, database-specific filters were then applied to narrow the search. Limitations applied to the use of academic and scholarly journals, conference proceedings and literature reviews with subjects limited to >18 years of age male players. Articles were discarded if they were not written in English, and if the text did not present data on ice hockey biomechanics, wearable technology, health and wellbeing and/or injury prevention. Unpublished dissertations were excluded from the search strategy. Reference lists of selected papers (not found in the original search) were examined for relevance to the topic. This study followed the participants, interventions, com-

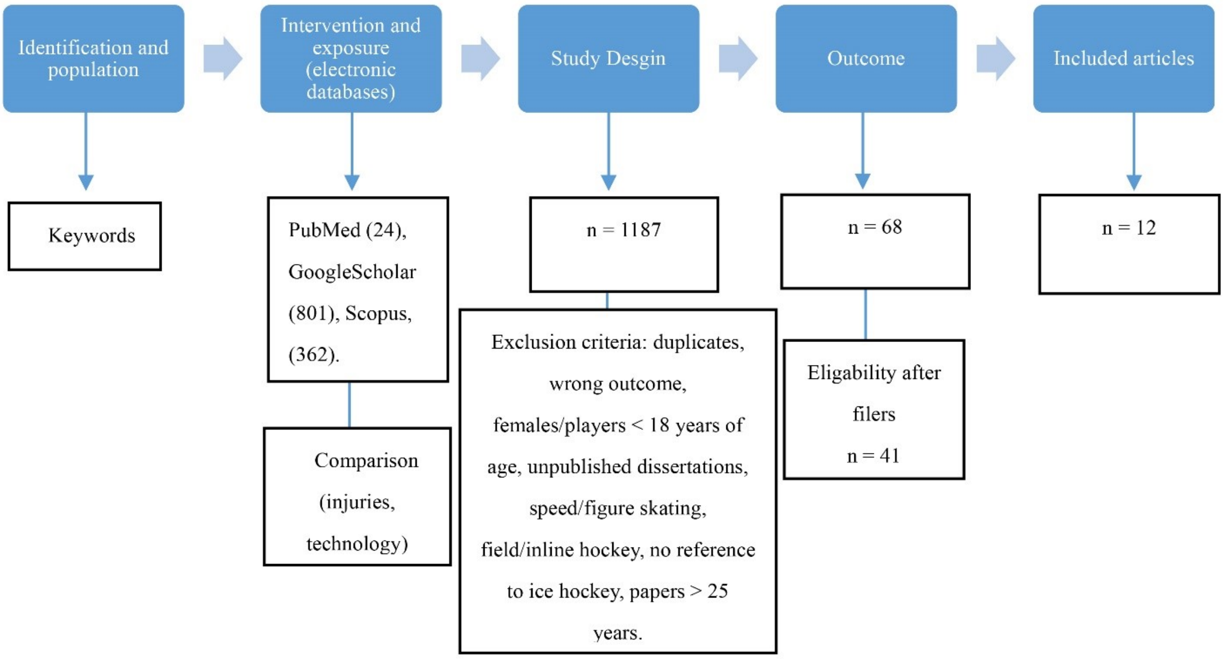

Fig. 1. Flow diagram of the search strategy and article selection process.

parisons, outcomes and study design (PICOS) framework. Thus, a review of past biomechanical, epidemiological and technological studies is presented.

3. Results

A total of 1187 studies were retrieved from this review. The titles and abstracts of 98 studies were screened and the full texts of 68 manuscripts were assessed. Additional studies, identified via reference list assessment, were included. After applying relevant filters, 68 studies were reviewed for eligibility. Duplicates were manually removed to obtain 41 titles ready for screening (Fig. 1). The literature was then collated and sorted according.

4. The Biomechanics of Ice Hockey

The biomechanics of ice hockey includes the widespread movement patterns of forward and background skating, stick handling, and body checking. These movement patterns are exemplified by a succession of voluntary spatial actions while on an ice-rink. Depending on the influence of various factors, skills may be executed individually, in combination or sequentially with other skills (Table 1) [13].

The array of techniques, tactics and combinations of skills that are utilized by ice hockey players within an ever-changing and dynamic environment can lead to unpredictable outcomes. This may help to explain why ice hockey is complex to analyse within a laboratory environment. In this regard, to understand and appreciate the biomechanics of ice hockey, the numerous tasks required of the player should be categorized. Some skills of ice hockey may be considered “closed”, meaning that certain features of the environment are constant: for example, ice rink dimensions, player equipment and established drill activities set by the coach [13]. In contrast, other skills are considered “open” with the performance of a skill varying according to the changing surroundings in space and time: for example, the position of opponents and team members, whether a player is static or moving, and the level of competition. In this review, the term technique refers an ice hockey player’s on-ice coordination, agility and movement and how the kinetics and kinematics are applied relative to injury and health. Performance denotes force, velocity and acceleration magnitude, or the time spent to travel a certain distance on the ice. The player’s performance depends on individual capability (e.g., training age, anthropometrics), equipment (stick length, skates), and environment (ice surface, synthetic ice). Additionally, the resultant motor commands directly or indirectly manipulate the degrees of freedom. These can be broadly defined as the variables that influence motor output, such as the inference of muscular forces and activations and joint angles. Collectively, these performance variables may also impact the prospect of injury. Thus, to understand the biomechanics of hockey skills relative to performance, injury and athlete wellbeing, one needs to consider each of the aforementioned factors (Table 2, Ref. [2,5,7,8,14–20]).

Table 1. Ice hockey skill inventory and identification of categories. From Pearsall *et al*. [13].

Definition	Kinematics	Factors	Environments	Equipment
Skating	**Linear: Forward and backward** Maximization of centre of mass (transverse impulse applied to the ice to increase the kinetic energy of the center of mass **Angular: External center of rotation (changes of direction and changes to movement)** Large radius of turns and skating crossovers and pivots (forward and backward) Small radius of turns (parallel blade pivot) **Internal center of rotation (change of body position)** About longitudinal axis front to back, back to front External center of rotation Changes of direction and changes to movement Stride frequency and stride length Support and swing time, push off and gliding distance	**Participants** Participant age, level of experience and training age, gender, level of fitness, psycho-social, anthropometrics	**Ice surface (indoor or outdoor)** Low coefficient of friction closely tied to temperature, surface texture, ice and air resistance **Rink** Dimensions, lines and boards **Context** Practice or game (recreational, competitive) Game rules Playing positions	**Skates** Skate design, blade thickness and edges **Puck** Puck weight **Stick** Composite material, stiffness and length **Clothing** Protective attire, helmets, guards, pads, shock-absorption qualities of materials
Stopping	**Forward** One foot (front or rear 'T' strategy) or two foot **Backward** One foot (rear) Two foot **Sideways** Two foot One foot (front)	**Participants** Level of experience and training age, gender, level of fitness	**Ice surface (indoor or outdoor)** Low coefficient of friction closely tied to temperature, surface texture, ice and air resistance **Rink** Dimensions, lines and boards **Context** Practice or game (recreational, competitive) Game rules Playing positions	**Skates** Skate design, blade thickness, blade edges
Stick and puck handling	**Passing (player static / moving)** Forward and backward **Receiving** Forward and backward **Faceoff** Blocking, backhand and forehand draw Moving forward, backward, fainting (dummy play)	**Participants** Level of experience and training age, gender, level of fitness	**Ice surface (indoor or outdoor)** Low coefficient of friction closely tied to temperature, surface texture, ice and air resistance **Rink** Dimensions, lines and boards **Context** Practice or game (recreational, competitive) Game rules Playing positions	**Puck** Puck weight **Stick** Composite material, stiffness and length
Shooting	**Player static/moving and towards goal/clearing goal** Slap, wrist, snap, sweep, backhand, flick, lob shots	**Participants** Level of experience and training age, gender, level of fitness	**Ice surface (indoor or outdoor)** Low coefficient of friction closely tied to temperature, surface texture, ice resistance and air resistance **Rink** Dimensions, lines and boards **Context** Practice or game (recreational, competitive) Game rules Playing positions	**Puck** Puck weight **Stick** Composite material, stiffness and length
Checking	**Non-contact (stick) and contact (body)** For puck and/or for position. In open play and/or into boards	**Participants** Level of experience and training age, gender, level of fitness		**Clothing** Protective attire, helmets, guards, pads, shock-absorption qualities of materials

Table 2. Summary of studies investigating ice hockey biomechanics, technology and injury.

Author (by year)	Year	Health, wellbeing relevance	Player status	Technology used	Comment
Moghaddam and Kwok [14]	2019	Head impact and associated acceleration magnitudes.	Not applicable	Role and fitting of helmet on angular and linear accelerations of head.	Not conducted on players but on an outfitted headform with a commercial helmet. Suggests that frontal impacts while introducing a gap reduced the risk of focal injuries. The loose fit helmet model suggested lower risks of concussive injuries. However, regular and loose fit helmets showed better protection against focal and concussive injuries.
Popkin *et al*. [15]	2017	Evaluation and treatment of injuries, return to play and prevention strategies.	Variable	Not provided	Shoulder dominance, which determines stick grip, is an important con-sideration in the treatment of shoulder instability in an ice hockey player.
O'Connor *et al*. [16]	2017	Head impact and associated acceleration magnitudes.	Variable	Head-impact sensors.	Head impact sensor may provide sideline staff with estimates of athlete exposure and real-time data to monitor players.
Buckeridge *et al*. [2]	2015	Not applicable	Nine high caliber and nine low caliber hockey players.	Two 3D accelerometers, located on the skate and the waist. Biaxial electro-goniometers used to quantify hip and knee angles, and in-skate plantar force was measured using instrumented insoles.	High caliber exhibited greater hip range of motion and forefoot force application.
Tuominen *et al*. [17]	2015	Injuries in men's International Ice Hockey Federation World Championship tourna ments over a 7-year period.	International players	Not provided	528 injuries were recorded resulting in an injury rate of 14.2 per 1000 player-games (52.1/1000 player-game hours). The most common types of injuries were lacerations, sprains, contusions and fractures.
Post *et al*. [18]	2013	Responses were examined through the use of a brain model.	Not applicable	Helmeted hybrid headform to elicit linear and angular acceleration responses.	Differences between when helmet is examined using peak resultant linear acceleration a 3D brain deformation response.
Stidwill *et al*. [8]	2010	Not provided	11 male hockey players	Comparison of skating biomechanics on ice and on a synthetic ice using a portable strain gauge system adhered to the outside of the skate blade holder. This was synchronized with electrogoniometers for tracking dynamic knee and ankle movements during forward skating.	Forward skating technique and technique differences across skill levels.
Upjohn *et al*. [5]	2008	Not provided	Ten hockey players from the general public and the University men's varsity ice hockey team.	Synchronized digital video cameras while players wore wearing reflective marker triads. Participants skated on a specialized treadmill with a polyethylene slat bed.	Three-dimensional kinematics of the lower limbs during forward skating to contrast skating techniques between low- and high-calibre skaters. Specific kinematic differences in both joint and limb segment angle movement patterns were observed between low- and high-calibre skaters.
Lafontaine [7]	2007	Not applicable	Not applicable	Relative motions at the knee and ankle joints were computed using a joint coordinate system approach. High-speed video cameras and video cassette recorders with movement analysis system.	Differences at the knee joints in push-offs indicated that skating skill gradually changed with each push-off. Ankle stability and angles attributed to the skate boot design.
Nobes *et al*. [15]	2003	Not applicable	15 male varsity hockey players.	Motorised skating treadmill.	Stride rate and stride length significantly different on-ice compared to treadmill.
Lafontaine and Lamontagne [19]	2003	Not applicable	Not applicable	Design and validation of a mobile data collection system composed of a camera cart that allows the tracking.	Data was valid for recording and analyzing ice hockey skating.
Turcotte *et al*. [20]	2001	Not applicable	Not applicable	Instron™ material testing apparatus used to obtain the force/displacement data and stiffness from hockey boots.	Distinguished stiffness characteristics for different types of skates whilst quantitative measures of stiffness were possible for all six ranges of motion.

Bracko *et al.* [21] noted that forwards apply the highest percentage of ice time, 39%, gliding on two feet, suggesting that this is an important characteristic. Consequently, skill requirements extend to the maintenance of balance, demonstration of agility when turning, and power when engaging in contact or body checking. Hence, additional skating features, including body contact and checking, originate from a two-foot balance position.

When a player glides on the ice, that is in a typical skating yet balanced position, the skates are positioned slightly wider than shoulder width apart. The ankles are dorsiflexed, knees flexed, trunk flexed, and the hockey stick is located close to, but not always on, the ice [21]. This positions the player's centre of mass (COM) outside of the base of support. The COM is an important yet often overlooked kinematical consideration. Consequently, the ability to maintain balance relative to COM acceleration or displacement has received minimal attention. This is surprising as the COM might influence player technique and limit the effectiveness of the external forces applied to the ice. The purpose of the above-mentioned classifications is to gain a better understanding of a player's strengths and susceptibilities on the ice. The data attained from such variables could be better used to support both the training process and overall athlete wellbeing.

4.1 Skating

Unsurprisingly, on-ice kinematics relies on a player having a foundation of skating ability upon which additional skills such as acceleration, stick handling, shooting and agility are constructed. The unique combination of an ice surface and skates allows a player to move with agility and speed. Hence, skating is the single most important skill [22] and is considered one of the main characteristics of a highly accomplished ice hockey player [23].

Ice surfaces possess mechanical properties that permit skating motion. For example, ice surfaces provide a sufficiently low coefficient of friction in order to allow a player to glide. However, the surface must deliver sufficiently high friction for players to push off during starts and strides [24]. In this regard, the skates provide the tools by which the diverse frictional properties of the ice surface are elicited and controlled by the player. Moreover, various biomechanical constraints can make the relationship between technique and performance complex. Therefore, skating performance is determined by mechanical factors inclusive of distance, average speed, summation of joint moments, muscular forces, ice reaction time and the coefficient of friction [25]. Montgomery *et al.* [26] noted that 40% of ice hockey play is spent by players in a two-foot gliding position with frequent changes in direction and short bursts of speed. Indeed, in a National Hockey League (NHL) game less than 5% of on-ice time was spent in possession of the puck with an average of 301 skating movements performed by the players [26].

Similar gross motor patterns are exhibited in speed and figure skating. However, the context of ice hockey is fundamentally different from both speed and figure skating. Thus, caution is needed when interpreting movements from speed and figure skating given the alterations in skating settings and blade design. Despite this, skating remains a novel form of locomotion in that the reactive push-off force cannot be elicited in the backward direction. Due to the relatively low coefficient of friction between the skate blade runner and the ice, little force can be elicited by pushing off parallel to the long axis of the skate blade [27]. Therefore, players rely on the reactive force that is elicited perpendicular to the skate blade. Hence, to generate forward motion, players rotate the blade out of direction of forward progression. As shown in Fig. 2 (Ref. [28]), during the rear leg push off phase a perpendicular force is exerted on the skate. The force component that points forward (in the direction of motion) is what pushes the player forward. In contrast, the contralateral skate is either raised or is gliding on the ice. As the player pushes forward, he quickly shifts to the other leg and pushes off the ice. This process is then repeated. The restrictive force of fiction acts to oppose linear motion. Notably, this force increases and is variable relative to individual technique [27].

When skating at different velocities, a player's stride rate can increase with velocity without a subsequent change in stride length [29]. This suggests that velocity is reliant upon the number of strides rather than the actual length of the stride. According to Page [30], knee flexion is greater in faster skaters prior to propulsion compared to slower skaters. The faster skaters were observed to have flexed their trunks (greater forward lean) while slower skaters remained more vertical (reduced forward lean) during fast skating. Therefore, the relative or absolute degree of joint flexibility or configuration constrains the amount of trunk flexion. The inference is that trunk flexion and changes to the player's COM could be a trainable parameter.

Upjohn *et al.* [5] obtained 3D kinematics of an ice hockey player's lower limbs during forward skating. Their data illustrated those kinematic differences in the weight acceptance and the propulsive stride phase existed between low and high calibre hockey players as they skated on a specialized treadmill. McCaw and Hoshizaki [31] observed a wide variation in range of motion with high-calibre skaters having a greater range for most body segments and joint angles throughout the stance phase. Therefore, a longer stride length was seen in high-calibre players compared to lesser calibre hockey skaters. Although frontal plane variances in joint movement patterns were limited, high-calibre athletes demonstrated further tilting of the lower limb. In this instance, greater COM displacement would ensue given the larger stride width when pushing off the ice. Pearsall *et al.* [13] reported similar kinematic patterns, although their findings indicated that ankle inversion appeared beyond 60% of the stride (3.58 inversion).

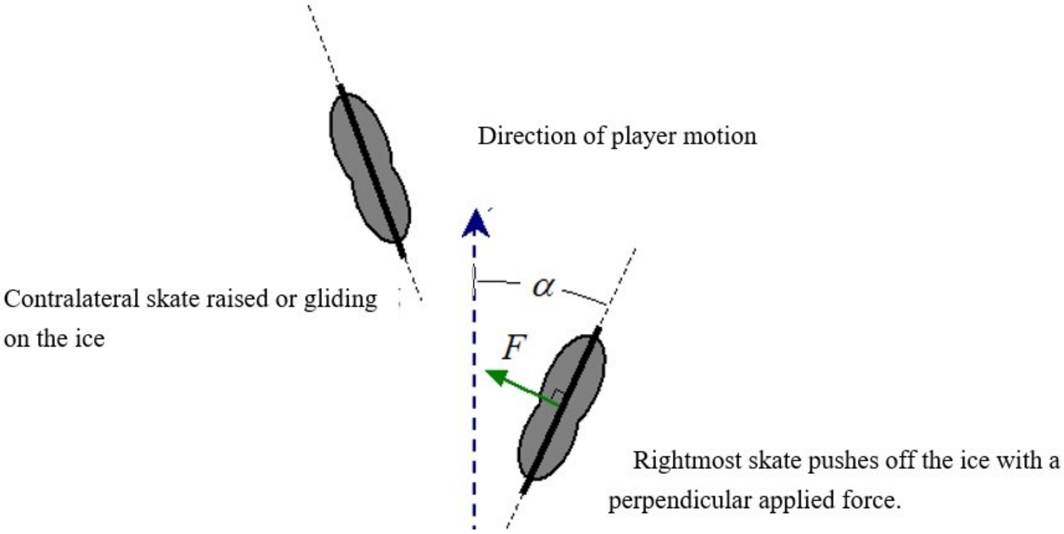

Fig. 2. The push off in ice skating. To push off the ice with greater forward force, an ice hockey player must increase the angle α that increases the component of force in the direction of motion. Where F is applied force. Image used courtesy of Alain Haché (Professor adjoint, Universite de Moncton) [28].

Whilst differences exist between the studies [5,29,30], variations could be due to methodological factors. For example, whereas Pearsall *et al.* [13] used twin axis electrogoniometers placed on a player's rear foot and along the longitudinal axis to measure ankle kinematics, Upjohn *et al.* [5] used reflective triads placed on the exterior of the skate boot. In this instance, Upjohn *et al.* [5] estimated where the medial and lateral malleoli lie in order to describe lower limb kinematics within a global reference frame. Notwithstanding these methodological differences, player performance depends on the interaction of factors related to the individual, the environment, and the equipment. These factors are mutually interdependent.

The electromyography (EMG), as well as force, torque and angular acceleration measurements, provides indirect measurements of muscular forces. This allows for a good indication of player intensity by way of muscular contractions. Nevertheless, EMG is not a practicable device to use outside of the laboratory given the restrictive nature of the equipment. It is therefore suggested that some of the biomechanical changes observed with ice hockey players—that is, force, torque or asymmetry—may be attained by wearable technology.

The technology required for a comprehensive biomechanical analysis is probably specific to the individual player and position. Hardegger *et al.* [9] used a portable system known as SkateTracker to monitor player movement on the ice. This system allowed for the unobtrusive data of player-based acceleration and deceleration as well as skate turns and jumping. The authors [9] noted that SkateTracker provides time and intensity information with optimized on-ice step counts. Their results suggested that the players exhibited different skills depending on their position. Whether the data obtained by Hardegger *et al.* [9] has any practical consequences for injury mitigation is not clear. In summary, quantifiable biomechanical data on skating characteristics is significant given that there are implications for fitness training, injury prevention and ongoing athlete wellbeing. For the player, without the above considerations performance is likely to stagnant whilst the risk to injury will likely increase.

4.2 Shooting

Along with skating and body-checking, shooting is a fundamental skill that is associated with match results [13]. Players must maximize shooting speed combined with accuracy in order to be an effective [32]. This is achieved whilst skating to a high velocity in what is a variable, fluid and dynamic playing environment. In ice hockey, the ability to shoot a puck at speed encompasses complex biomechanical considerations. Firstly, shooting is not a fundamental motor skill [33] as it necessitates long term learning and systematic practice [34]. One commonly used method to increase shooting skills is to vary the weight of the puck. It has been shown that puck weight may also be related to grip strength given the connection to the wrist shot [35]. On the other hand, the stiffness of the hockey stick could influence shooting ability [36,37].

Pearsall *et al.* [13] distinguish shots into categories, namely: slap, wrist, sweep flick, backhand, and lobs, with the common shots being wrist and slapshots [32]. The goal of each shot is to perform them as rapidly and efficiently as possible. Other authors have demonstrated that the wrist and slapshots are the most common shots taken [37,38]. During the slapshot, the player must strike the ice with the stick before striking the puck. The slapshot is questionably the most challenging to perform. Wu *et al*. [35] recounted that at the outset of the shot, the stick is lifted and reeled forward with maximum force in order for the payer to strike the puck at speeds up to 100 km/h. In spite of this, the accuracy of the shot is not as high when compared to the wrist shot. Likewise, the composition and construction of the hockey stick combined with player anthropometrics and skill level, and differing ice surface conditions, can influence shoulder angular acceleration relative to the blade-puck contact time [38,39]. Evaluating both the kinetics and the kinematics involved in the wrist and slapshots is required. This is due to individual player characteristics and technique that can influence the torque, muscular force and/or intensities imparted to both the ice and to the puck. Therefore, obtaining or defining an optimal level of shooting is not straightforward. This is possibly because of the multifaceted characteristics of player skill, biomechanics and anthropometrics. In theory, the ideal solution to this situation would be to increase the usage of practical sensor technology to obtain biomechanical movement patterns.

4.3 Ice Hockey Skates

The ability to minimize the interaction between hockey skate and the ice can be crucial to performance. This is particularly relevant when the skate boot design and construction are considered. The contemporary ice hockey skate boot consists of an outer covering of leather or composite material, ankle support, toe box, heel counter, rigid sole, skate blade casing, and skate blade. While the design of skate blades has evolved, the specific biomechanical effects of skating continue to be actively researched.

Additional skate design features are known to influence skating performance. For example, Broadbent [40] suggests that blade edge sharpness, blade thickness, blade taper, radius of curvature and the boot-to-blade angle impact skating performance in figure skaters. This designates a change in skate design or skate boot features may affect a skater's ability to perform linear skating, cross-overs, turns, stops, passes, and/or shooting. The runner of the blades (the portion of blade in contact with the ice) has inside and outside edges with an intermediate shallow channel to accentuate the sharpness of the blade edges [14]. During the gliding phase, either one or both of the edges interact with the ice. Through the push-off phase, the blade is angled acutely to the ice surface, therefore permitting the inside edge of the blade to cut into the ice. During turns such as pivots, crossovers and stops, the outer edge of the skate blade is important in applying force to the ice surface [14,41]. Less trained players have less developed technical skills specific gliding and pivots. Players may experience a greater decrement in performance as well as prove to be at a higher risk of injury.

4.4 Injury and Health

Some of the greatest and most exhilarating characteristics of ice hockey, including the speed and aggression of players, can create potential for injury. Injuries sustained by ice hockey players can be multifaceted due to the high-intensity and dynamic nature of the game. Despite this, injuries due to impact and collisions can be lessened with protective clothing such as helmets and shoulder padding. Likewise, fatigue related injuries can be reduced with appropriate physical training (e.g., strength and conditioning, appropriate loadings), adequate recovery, well-managed pre and post-game nutrition and player hydration strategies.

Fatigue is defined as a decrease in muscle force or power that ensues with exercise [42]. In general, fatigue is a reduced ability to maximally activate the muscles (e.g., due to tiredness and possible exhaustion) alongside a weakening function of the muscles. Researchers have sought to classify fatigue as either above the neuromuscular junction or as a peripheral aspect and beneath the neuromuscular junction [43]. However, with minimal data available from wearable technology, attempting to diagnose or monitor fatigue remains an area for exploration. Despite this, numerous interventions designed at making ice hockey a safer sport have been implemented with varying success. Arguably the most important intervention is the introduction of full facial shields that are fitted to player's helmets. This has reduced the frequency of injuries to the facial areas inclusive of both dental and visual areas [44].

The NHL authorized the use helmets for on-ice performance in 1978 [45]. This is relevant as since the introduction of helmets the occurrence of catastrophic head injuries has decreased. However, the extent to which players feel protected appears to be affected by the presence of protective headwear. According to one study [46], a paradoxical increase in the rate of concussion could be due to players feeling more invincible. Notwithstanding this, increased concussions have also coincided with improved awareness, scrutiny and the uptake of reporting concussions. Collectively, these differences suggest more research is desirable.

Analogous to other sporting codes, the advancement of unobtrusive wearable technology can provide coaches, medics and sports scientists with data to assist with athlete health and wellbeing. For instance, wearables can yield data to assist researchers to develop improved on-ice attire (e.g., shock-absorbing garments) along with enhancements in helmet design. At a basic level, on-ice and in-game impacts can be quantified to help coaching and medical staff to make better-informed decisions. Yet, this is not straightforward in that it is not necessarily feasible to solely rely on impact sensor systems alone for real-time concussion screening. Therefore, technology alone should not substitute the need for clinical judgement. Additionally, whilst impact-based sensors can support staff with valuable data in the course of a game situation, not all sensors and related systems work or function similarly. This is due to the type of sensor and the relative settings of the sensor. Furthermore, depending on the sensor configuration considerations such as drift are needed.

The evolution of ice hockey helmets is just one part of the increased awareness of athlete wellbeing. Yet, preventing and managing head injuries remains an area of focus [47]. Still, ice hockey players require additional attention. For instance, further injuries might be a consequence from whole body impacts that result from unintentional contact. In this regard, a player may become injured due to deliberate body checking or non-checking related impacts. A non-checking related impact is credited to a player contacting or colliding with the exterior boards and/or hoardings, or falling whilst skating at a high speed.

The literature implies that concussions are the most common injury suffered by ice hockey players. Kontos *et al*. [48] estimated that concussions occur in 13% of all sporting activities. Concussion can arise when a player strikes the hoardings, another player, or hits the ice with their head. Management of concussion remains a serious issue, particularly with the growing knowledge and dangers associated of repetitive concussion. Preventative measures include well-fitting helmets and spatial awareness-based training to help players become more aware of their own and their opponents' position. Nevertheless, Pfister *et al*. [49] states that ice hockey records approximately 1.2 athlete exposures per 1000. In contrast, American football has 0.53 per 1000 athlete exposures according to a meta-analysis published in the British Journal of Sports Medicine [49]. As a result, the NHL regular reviews concussion protocols and athlete exposures in order to better prevent, recognize and manage concussions. While concussion is one of the most common injuries sustained by players, other body-related impacts also result in player injuries unrelated to concussion. Consequently, defining quantitative and reliable data relative to on-ice impacts is an area of vigorous research.

Considering the challenges associated with on-ice movement and data collection, data analysis is challenging [2]. For example, unlike dry land walking or running, skating involves substantial movements in both the sagittal and frontal planes on a surface with a low coefficient of friction. In this instance making direction comparisons is problematic. However, analysing the capability of wearables to accurately identify both the impact and the duration of on-ice collisions have occurred [50]. Even so, challenges persist in that some wearable systems remain relatively expensive and thus difficult to implement for players from a recreational or semi-professional standing.

4.5 Cervical Spine Injuries

Various authors have suggested that the extent to which cervical spine injuries occur in ice hockey remain a significant concern [51,52]. Notwithstanding the numerous safety interventions and the array of existing safety protocols in place, ice hockey has the highest incidence of cervical spine injuries of any sport [51]. Injury to the cervical spine can occur when a player receives a forcible strike by an opponent to behind the head. The ramifications being that a player who has been hit will contact the exterior boards/hoardings with a slightly flexed neck [52]. This is largely due to the high-speed nature of the game given the requirement for sudden bursts of acceleration and changes of direction. Further concern relates to players colliding with the moderately rigid boards that border the on-ice playing surface.

Field evidence suggests that the injury sustained to the cervical spine will depend on the magnitude of axial load. Thus, the larger the force the greater the injury sustained. Safety checks and adjustments to the rules and game-play such as banning checking from behind, stricter administration of the rules of play, and increased spine injury prevention have considerably reduced the incidence of cervical spine injuries. However, a combination of impact sensors (accelerometers, gyroscopes) and video analysis (game video) are now commonly used to verify the accuracy of impacts recorded (e.g., magnitude and duration). Thus, clinical diagnosis is increasingly common when technology is used to assist in identifying player impacts. Nevertheless, a more complete assessment of the validity of all existing sensors relative to the impacts sustained by players is required to optimize protocols for injury mitigation and management.

4.6 Upper Extremity

Ice hockey-related injuries to the upper-extremity are common. Notably, the injury rate for males aged 12 to 17 is almost double compared to those aged 6 to 11 years (27%), 18 to 24 years (26%), 25 to 30 years (30%), and 35 to 44 years of age (28%) [53]. Common sites for injury include the acromioclavicular joint [47], although clavicle fractures remain prevalent with players that present with pain, and in some situations, deformity. Because of the continued expansion of innovative materials that have high shock-absorbing properties, the ability to lessen upper extremity injury continues to show promise. Yet there is a general paucity of data in the literature concerning wearable sensors in ice-hockey. In practical terms, the first step in quantifying shock absorption and associated impacts is validating the information provided by wearable sensors. Further research is therefore warranted in order to better understand how quantitative sensor data may help classify key movement patterns to help limit or avoid upper extremity injuries.

4.7 Lower Body Injuries

The fact that a similarly high proportion of lower body injuries occur is not unexpected given the side-to-side and vertical changes seen during skating. Injuries to the lower-body of ice hockey players account for 30%–45% of all ice-hockey player-related injuries with knee injuries being the most common [54]. In NHL players, thigh and knee injuries account for the second and third most frequent injuries, resulting in the greatest tally of games lost respectively [55]. Although the exact figure of lower body injuries in recreational ice hockey is unknown, it is likely to be more compared to the NHL given the lack of medical personnel available compared to the professional leagues.

Medial collateral ligament (MCL) injuries are one of the most frequently reported knee injuries in hockey players [56]. Other injuries are commonly instigated by player-to-player interaction that can result in a valgus stress on the knee [57]. Skate bite (a.k.a., lace bite) is another common injury experienced by a player. Skate bite can cause anterior ankle discomfort due to stiff, infrequent use of new skates or the overuse of older skates whereby the skate tongue has become inflexible [57]. This can result in continued pressure on the ankle due to the contact with the skate boot tongue. The ability to dorsiflex the ankle is therefore compromised due to tendon inflammation [51]. It is noteworthy that the rigid nature of hockey skates helps to prevent lateral ankle sprains, but then again offers little protection to the ankle syndesmosis.

A biomechanical understanding of the mechanical, muscular and movement properties is essential of any motor performance task that is performed on the ice. *In vivo* muscle mechanics is possible using laboratory apparatus (e.g., isokinetic devices) or EMG measures, yet logistical difficulties make such measurements challenging to undertake on the ice. The interpretation is that while game-performance movement patterns are well established, coaches and skating instructors have infrequently used this information [21]. This is extended when wearable technology is considered given the relative absence of research and applied application to biomechanical analysis and athlete wellbeing.

5. Practical Applications

By understanding the relationship between the variables examined in this review, it may be possible to establish a range of health and wellbeing responses that are desirable to determine the risk posed to players or to reduce the risk of injury. The current review shows that further investigation is required: (a) to determine to what extent the conditions in which a player is exposed during on-ice activity influences biomechanical changes that could enhance injury risk (linear and angular kinematics, internal centre of rotation, centre of mass, environment); (b) to investigate the reliability and validity of wearable performance for injury and health; and (c) to investigate the effect of varying biomechanical parameters—for example, volume, intensity, frequency, recovery type, and duration—during on-ice activity has on subsequent health and wellbeing measures via wearable technology. Therefore, coaches and sports scientists should focus on tracking longitudinal athlete biomechanics and health and wellbeing data in players of different ages and positions. This could offer instructive data and conceivable correlations to injury prevention and mitigation strategies.

6. Limitations

In general, this review had limitations. Firstly, some studies had a small number of participants which possibly impacted the validity of their results. Second, some studies differed in the homogeneity of their participants (i.e., age, training age, position, playing status), and in the implementation of the technological device used. Third, the wearables, equipment and tests used to assess specific components of athlete wellbeing and injury differed in the studies. Thus, based on these factors, it is assumed that the effect of the biomechanical analysis or focus of injury in the different studies also contrasted.

7. Conclusions

The goal of this review is to present contemporary scientific investigations published about the biomechanics of ice hockey combined with performance and athlete health and wellbeing when wearable technology is used. The literature appears to show that a greater number of whole-body biomechanical studies are necessary to strengthen the understanding of ice hockey performance, athlete wellbeing and the ongoing risks of injury. Specific yet novel biomechanical and sensorial adaptations are required for enhanced performance and injury reduction. Thus, deficiencies in the current literature were found. A low number of studies on amateur and recreational players, a lack of distinction between player position in the results section of studies, and a lack of precision in the methods and protocols used were also observed.

The link between the practical use of wearable technology, biomechanical considerations relative to performance and player health and wellbeing remains inconclusive. This finding is important because it can uncover strengths and weaknesses of the differences between players and their respective positions. Nevertheless, these results should be interpreted carefully. The benefit that is accrued from devising a consistent approach to using wearable devices depends on the nature of the how the technology is applied. Reasons exist to support the premise of using wearables to track performance and manage athlete health and wellbeing. It is apparent that for the majority of data metrics, legitimacy, usage and dependability are multifactorial, in that it is reliant upon a variety of factors including wearable technology brand and model, sampling rate, type and direction of movement performed and intensity of movement. Thus, based on the results presented, specific biomechanical assessments should be created using wearable technology given that player position and role requirements may have different injury considerations.

Abbreviations

AE, athlete exposures; COM, centre of mass; EMG, electromyography; NHL, National Hockey League.

Author Contributions

SE performed the research. SE designed, wrote, revised and approved the manuscript.

Ethics Approval and Consent to Participate

Not applicable.

Acknowledgment

Not applicable.

Funding

This research received no external funding.

Conflict of Interest

The author declares no conflict of interest.

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