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TOPICAL REVIEW

IMU-Based Systems For Skiing Sports: A Scoping Review

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ABSTRACT Inertial sensor (IMU)-based wearable systems are the most employed technology to acquire in-field information about athletic gesture in skiing sports since they are portable, easy to setup, not bulky and they are compliant with this sport's extreme conditions, i.e. on-snow measurements, borderless working area. This scoping review wants to map the current scientific works on IMU-based wearable systems in the skiing contexts with the peculiarity of being used in the field: what type of information can be obtained, taking into account number and body position of the inertial sensors, whether other kind of sensors are involved and which type of data analyses techniques applied. A search on various databases identified 134 publications from 2013 to 2025, of which 39 met the inclusion criteria. Three main application areas emerged: 1) skier kinematics characterization, particularly the reconstruction of center of mass and joint trajectories; 2) classification tasks, such as automatic detection of skiing techniques, movement phases, and skier performance levels; and 3) injury prevention and rehabilitation monitoring, including applications in Paralympic skiing. While the reported findings are promising, research in this domain would benefit from deeper investigations, larger participant samples, and standardized protocols, to allow generalization and support the development of robust, field-deployable systems.

INDEX TERMS Injuries prevention, inertial sensors, kinematics, performance evaluation, skiing, sports, wearable sensors.

I. INTRODUCTION

Winter sports, and specifically skiing, are increasing in popularity all over the world. The 2021/22 winter season recorded over 370 million skier visits globally [1]. Skiing is also a key discipline in the Winter Olympics, involving different events such as alpine skiing, cross-country skiing, ski jumping, Nordic combined, freestyle skiing and snowboarding. Among these, alpine skiing is one of the oldest forms, being part of the Winter Olympics since 1924.

In alpine skiing competitions, participants ski downhill on a course approved by the International Skiing Federation (FIS, Fédération Internationale de Ski [2]), and they aim to complete the course in the shortest possible time. The course consists of various turns between poles or gates set at certain distances depending on the type of ski race (Figure 1):

- slalom (SL) is the alpine event with the shortest course and the most turns;
- giant slalom (GS) has fewer and smoother turns compared to the slalom;
- downhill (DH) is the longest event with the greatest vertical drops and highest speed;
- super giant slalom combines the speed of downhill with the more precise turns of GS.

The more frequent turning sub-techniques are: (i) snowplow, mainly used by beginners to control speed by keeping ski tips together and tails apart; (ii) parallel, where skiers roll

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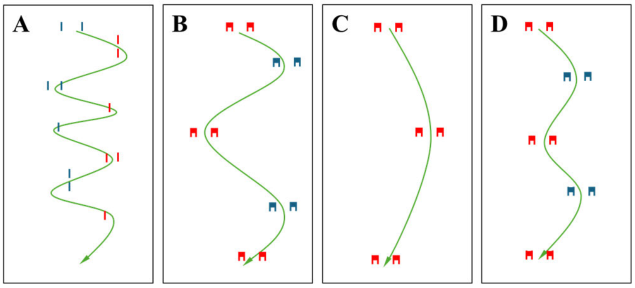

FIGURE 1. **Schematic examples of alpine discipline course: slalom (A), giant slalom (B), downhill (C) and super giant slalom (D).**

the skis onto their edges to carve arcs without sliding; (iii) drifting, where the skiers actively steers the skis by adjusting both the angle between the ski and snow (roll or edge-angle) and the angle between the ski and ski trajectory (yaw or steering angle); (iv) carving, which involves edging the skis to engage their sidecut, resulting in a self-steering effect.

In cross-country (XC) skiing, athletes compete within the classical and skating styles in race courses consisting of different uphill, flat and downhill sections. The varying terrain requires an appropriate selection of pacing strategies, sub-techniques, and related kinematic patterns [3]. In the classical style, XC skiers alternate (i) double poling (DP), in which the athlete's feet remain parallel and they pole with both poles at once; (ii) kick double poling (DK), which is mostly employed in the transition between different terrains and that combines DP with a leg kick; (iii) diagonal stride (DIA), in which skiers move body weight from a balanced position on a ski to another balanced position over the other ski and it is primarily used at low speeds in moderate to steep uphill terrain; (iv) the herringbone technique (HRB), which is typical at low speeds in very steep uphill terrain, involving alternate arm and leg movements having the skis in a V-shape. In the skating style, skiers mainly use four different sub-techniques, called gears (G2–5): G2 (V1 skate) is an uphill technique with an asymmetrical poling action on every second leg stroke; G3 ("double dance" or V2) is used in level terrain up to moderate uphill inclines and it is performed with one poling action for every leg stroke; G4 (V2 alternate skate) is used in level terrain with a symmetrical poling action on every second leg stroke; G5 (skating without poles) is mainly used in downhill slopes, where skating strokes are performed without poling. During descents, athletes adopt a tuck position without pole and leg actions, and alpine turns to manage curves.

Ski jumping is a winter sport in which competitors aim to achieve the farthest jump after sliding down on their skis from a specially designed curved ramp. Along with jump length, the competitor's aerial style and other factors affect the final score assigned by the judges. Each jump can be divided into four parts: in-run, take-off (jump), flight, and landing. Ski jumping can be performed using different techniques depending on the skis and the athletes' pose during the different jump phases. The most common techniques are the parallel or classic style having the skis parallel to each other, and the V-style having the ski tips spread outwards in a highly aerodynamic "V" shape. Skiers are required to land in the Telemark style, with one foot in front of the other. Alternatively, athletes may use a parallel leg landing, with both feet at the same height in a squat position. Differently from the telemark landing, the parallel leg landing negatively influences the technical score.

It is evident that these disciplines can be quite different from each other in terms of physical and technical demands. Professional and recreational skiers can improve their performance and prevent injuries by practicing alone or in dedicated groups, with or without the support of an experienced coach. Successful training can be obtained if useful feedback is provided to the athlete. Qualitative analyses based on one's own experience and external evaluations from a coach or a ski instructor can provide important feedback, but objective and quantitative analyses of the athletic gesture can offer a wide variety of information not always inferable without sensor measurements. These quantitative analyses can also be a useful resource for coaching, especially in elite sports. A wide variety of sensors are available to monitor and evaluate human movement [4], [5], [6], [7]. However, the primary feature required in the skiing context is wearability, as the setup of a recreational or racing track can limit the usage of the system itself and the study outcomes, which depends on the chosen course. Therefore, electromagnetic tracking devices and video-based optoelectronic systems can be affected by environment-dependent limitations [8]. Commonly employed technology is the Global Navigation Satellite System (GNSS), but its accuracy is not sufficient for detecting displacements of a few centimeters or less of any human body segment during skiing activities [9], [10]. On the other hand, there are currently no strain sensors compatible with large human motions on the market, especially for sports [11], [12], [13].

One of the most employed devices is the inertial measurement unit (IMU): it can monitor human movement without hindering it and with no workspace limitation or cumbersome setup procedure [14], [15], [16]. An IMU typically consists of a triaxial gyroscope, which provides estimations of angular velocities, and a triaxial accelerometer to measure linear accelerations. Depending on the type, it can also integrate other sensors (e.g. magnetometers) to extend the range of obtainable information describing object orientation in space. The same estimations could also be provided through video-based systems that, in the skiing context, are generally used as reference systems in comparative studies for testing new measurement sensors [17], [18], [19], [20], [21], since they are not convenient for in-field measurements. On the other hand, IMUs are wireless, portable, wearable and do not require environmental setup. Furthermore, although MEMS-based IMU sensors are subject to various limitations such as noise and drift, their accuracy and precision can be significantly enhanced through the application of advanced sensor fusion algorithms, enabling their use in demanding applications [22], [23], [24]. Magnetometer measurements suffer from Earth's magnetic field perturbations, but this is a manageable aspect for in-field skiing activities [25], [26], [27], [28]. IMUs have proven highly applicable in the context of human motion analysis for rehabilitative, work-related, and sporting purposes [29].

In elite sports, IMUs can serve as a means for obtaining objective performance monitoring during the execution of dynamic sporting gestures in ecological environments [30].

There are systematic reviews that provide a general overview of these systems across different sports disciplines [14], [31]. However, most of these works either focus on human movement detection in controlled settings, or do not specifically target skiing sports. Other studies have reviewed selected skiing-related applications, such as ski jumping injury prevention [32] or alpine skiing technique analysis [33], but these are discipline-specific and limited in scope. To the best of our knowledge, no previous review has systematically mapped the in-field usage of IMU-based wearable systems across all skiing disciplines—including alpine skiing, cross-country skiing and ski jumping—regardless of the research purpose, presence of additional sensors, or the target population. The novelty of this review lies in its focus on the real-world applicability of IMUs in on-snow conditions, synthesizing findings across multiple disciplines to assess how IMU data can support kinematic analysis, technique classification, performance evaluation, injury prevention, and adaptive coaching strategies. This broader perspective fills a gap in the literature by offering a unified view of how IMUs contribute to both scientific understanding and practical implementation in skiing sports. Therefore, this scoping review aims to report IMU-based studies with a focus on the skiing context – specifically, on the in-field capabilities of these systems in alpine, cross-country and ski jumping – and to analyze the type and amount of information they can provide to athletes and coaches.

Importantly, this review does not aim to suggest that only IMUs are relevant in the skiing context. Indeed, many of the included studies employed multi-sensor wearable systems, and this aspect was carefully considered during the current analyses, distinguishing between estimations obtained merely through IMUs and information resulting from different sensors. Kinetic sensors are also needed for a comprehensive biomechanical assessment. However, our intent was not to provide an exhaustive account of all instrumentation used in ski performance research, but rather to map and synthesize how IMUs have been applied across different studies, both independently and in combination with other systems.

Section II reports the research and selection methods followed to conduct the review, including a clear definition of the search criteria. Section III describes the key points of the found studies. Section IV includes a discussion about the scoping review findings. Finally, conclusions are outlined in Section V.

II. MATERIALS AND METHODS

For the searching stage, three databases - Scopus [34], IEEE Xplore [35] and PubMed [36] - were explored between February and May 2023 with the search string ((winter AND sports) OR ((downhill OR cross-country OR alpine) AND (skiing OR ski-jumping))) AND (imu OR inertial). The literature search was last updated in June 2025 to include the most recent publications available at the time of submission. The search string was intentionally designed to be broad and inclusive, to identify all studies involving IMU-based wearable systems applied in skiing sports, regardless of the research objective, sub-discipline, or the presence of additional sensors. Given the interdisciplinary nature of this field, including studies from engineering, biomechanics, rehabilitation, and sport science, a highly specific search strategy using narrow or domain-specific keywords was avoided. This approach ensured that the review captured the full landscape of relevant applications without excluding studies due to differences in terminology.

The first step of the screening stage consisted of reviewing papers' titles and abstracts. Some search results were excluded in advance: off-topic studies, book chapters and reviews that were previously conducted. The remaining articles were read and filtered by means of these eligibility criteria:

- Publication year equal to or greater than 2013;
- Publication language should be English;
- Studies concerning in-field activities, excluding laboratory and treadmill-based experiments;
- Studies on on-snow skiing disciplines, or comparative studies which performed on-snow skiing experiments;
- Studies with at least a dedicated IMU (tri-axial gyroscope and/or accelerometer) employed, whether as stand-alone or as component of a multi-sensors dedicated system. Studies regarding sensors embedded in smartphones and smartwatches were not considered in the current review;
- Studies in which IMU estimations are collected, analyzed and processed in a reproducible manner. IMU's data elaboration should play a key role in the assessment, system or algorithm proposed and must be described in detail.

III. RESULTS

The search stage identified a total of 134 papers. These documents were filtered through a multi-step screening process (summarized in the PRISMA [37] diagram in Figure 2). The first, title-based screening step excluded 40 papers. The second, abstract-based filtering rejected additional 22 papers. In the third and final stage, each of the 72 remaining documents was examined and ultimately 39 papers fulfilled the requirements. Despite the broad scope of the research, which did not target specific topics but was limited to the skiing context and the use of IMUs, it was notable that the papers converged on common themes. This allowed us to categorize

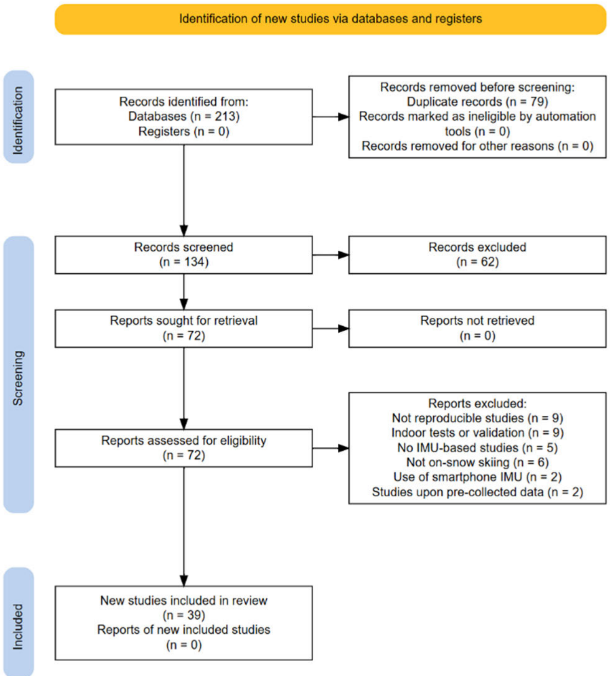

FIGURE 2. **PRISMA diagram of included studies.**

the papers according to their primary objectives and evaluate the contribution of IMUs to these central themes, as outlined in the following subsections:

- Skier kinematics characterization (Subsection A);
- Methods for automatic sub-techniques classification or turns detection algorithm (Subsection B);
- Skier performance evaluation (Subsection C);
- Injury prevention (Subsection D);
- Paralympic sports (Subsection E).

A schematic representation of paper distribution is shown in Figure 3 and for each main topic, the IMU data processing results and related studies are reported.

Across the 39 included studies, the average number of IMUs used per study was 5.74 ± 5.62 (std), and a median of 3 IMUs. The average number of participants per study was 11.74 ± 11.05, highlighting the generally small and highly variable sample sizes. Only 8 out of 39 studies (20.5%) relied exclusively on IMU data, while others integrated additional sensors: GNSS (48.7%), video cameras (20.5%), pressure insoles (20.5%), heart rate monitors (12.8%), barometers (12.8%), electromyography (EMG, 5.1%), blood lactate sensors (5.1%), external magnetometers (5.1%), and strain sensors (2.6%).

A. SKIER KINEMATICS CHARACTERIZATION

The approach of these twelve papers is to reconstruct skier movement to infer information about the athlete's Center of Mass (COM) or other body segment trajectories and pose tracking. The movement reconstruction can provide hints also on the turn structure and on the quality of technique execution. These papers are briefly summarized in this section, but more technical information can be found in Table 1. Figure 4 illustrates the placement of IMUs on the skier's body segments and highlights the primary kinematic features analyzed in the reviewed studies.

Nine studies focused on the alpine skiing context, and the most wanted parameter, as highlighted by Fasel et al. [38], is the trajectory of an alpine skier's CoM. The authors combined differential Global Navigation Satellite System (dGNSS) technology and inertial sensors by adapting the forward kinematic model proposed by Gilgien et al. [39]. They examined two different models depending on IMU numbers and locations: (i) full 3D model with seven IMUs on skier's chest, helmet, shanks, thighs and pelvis; (ii) a simplified model having two IMUs on skier's chest and helmet. The usage of IMUs improved the accuracy and precision of CoM position and speed estimation with respect to the reference dGNSS-based system [39]. Despite that, no differences between models were observed, probably because lower limbs have similar speed to head and trunk segments, thus having a low impact on overall CoM speed. Two years later, the same research group tried to compute 3D CoM kinematics by placing magnets at each gate of a giant slalom track to correct both velocity and position drifts for IMU-based measurements [40]. However, when removing the anchor points to simulate a DH race, position accuracy and precision of the CoM decreased. In the same year, Fasel et al. [41] expanded the capabilities of their approach, proposing a second wearable system which provided a drift-reduced estimation of 3D segment orientations. Their algorithm takes advantage of the highly dynamic movement patterns and turns centripetal acceleration by estimating stationary and non-stationary gyroscope biases. Yoshioka et al. [26] proposed a different approach to reduce the skier pose tracking error using only 3D gyroscopes. After a preliminary assessment of the position of the center of the joint by means of an optical motion capture system, the proposed algorithm was able to track the IMUs orientations for 300s with a root mean square error less than 2°. Once the gyroscope biases were estimated, the IMUs orientation could be tracked by gyro signal integration. The statistical analysis performed by Zorko et al. [42] highlighted that the kinematics of the knee joint depends on the ski width: a decreased mean abduction and increased knee external rotation were observed with the medium and wide skis in comparison with the narrow ski in steering phases, due to the changed point of application of the Ground Reaction Force (GRF). Three papers focused on turn structure and execution technique. Buxadé et al. [43] investigated the influence of turn cycle structure on the time elapsed between the first and the last gates of four different slalom courses. By merging accelerometer information and a Magnet-Based Timing System (M-BTS) for gate positions [44], it was possible to identify each turn phase. The authors noticed that lengthening the turn initiation time and shortening the steering phase time could improve the descent time. The pilot study of Russo et al. [45] introduced a motion

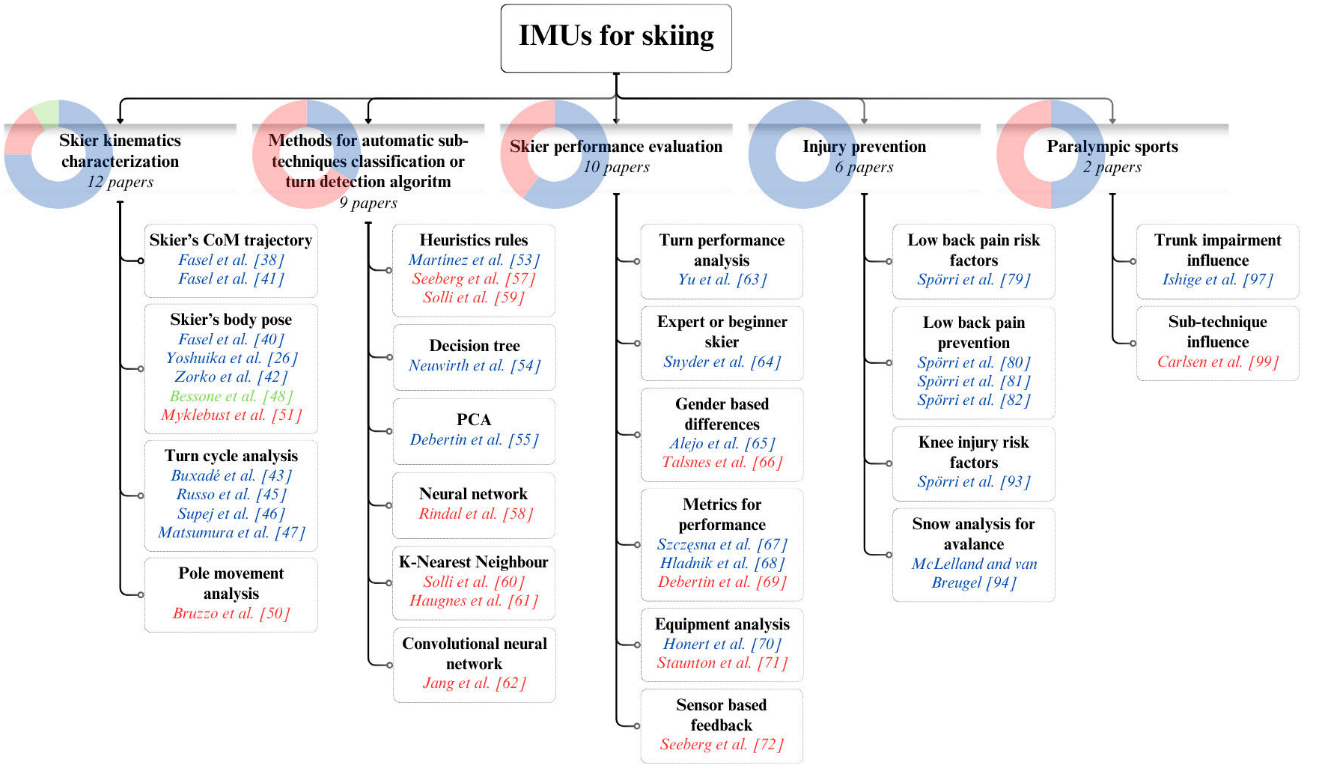

FIGURE 3. Papers distribution according to their main topics. The colors are related to examined disciplines: blue for alpine skiing, red for cross country and green for ski jumping.

analysis system to monitor alpine ski activities during training sessions. From IMUs data it was possible to obtain the number of turns, the average time of each turn, and the average roll and yaw angles of each monitored joint. A different approach was proposed by Supej et al. [46]. Their aim was to examine whether dissipation of mechanical energy can be influenced by asymmetries in technique and by the GRF associated with left and right turns. The involved elite alpine skiers performed left and right turns quite symmetrically. While this investigation was extensive, the full-body 3D kinematics assessment lacked information about ankle joints. Another method for the alpine ski-turn skills assessment through IMU and plantar pressure sensors is proposed by Matsumura et al. [47]. They targeted their system for recreational skiers. IMUs data were analyzed to estimate ski and waist motion and these data were combined with insoles data to assess the left-right symmetry of the turns. The proposed system was able to differentiate between expert skiers and beginner skiers.

A similar wearable IMU- and insole-based system was proposed also in the ski jumping environment: Bessone et al. [48] quantified the kinetic magnitude during telemark and parallel leg landing by using loadsol systems and 11 IMUs. A longer duration of the flight phase corresponded to a higher GRF during the landing. The athlete can increase the duration of the landing phase by acting on the hip, knee and ankle. The proposed system can be effective in giving suggestions to athletes about how to reduce impact kinetics. A larger number of subjects should be investigated to better describe the landing biomechanics [49]. Finally, Bruzzo et al. [50] and Myklebust et al. [51] proposed two different wearable IMU-based systems for cross-country skiing. Bruzzo et al. [50] system aimed to resolve the dynamic lean angle of the right pole during the DP technique. They successfully provided a potential non-invasive solution for measuring and evaluating poling performance during free skiing on outdoor courses, even though it was tested with only the DP technique and a single skier. Myklebust et al. [51] investigated kinematics differences between treadmill, uphill roller and on-snow skiing during the V2 sub-technique. Temporal patterns of the pole and ski ground contact were derived from pole and boot accelerometers [52]. Their system was able to highlight the differences between roller and on-snow XC skiing, although the single 3D gyroscope on the sacrum did not reflect the effects of arms and upper body movements.

1) IMU PLACEMENT AND PROCESSING APPROACHES

The reviewed studies employed different IMU configurations and processing pipelines depending on the application:

- CoM estimation: Fasel et al. [38] used up to 7 IMUs (helmet, chest, pelvis, thighs, shanks) or a simplified 2-IMU setup (helmet, chest). CoM trajectory was

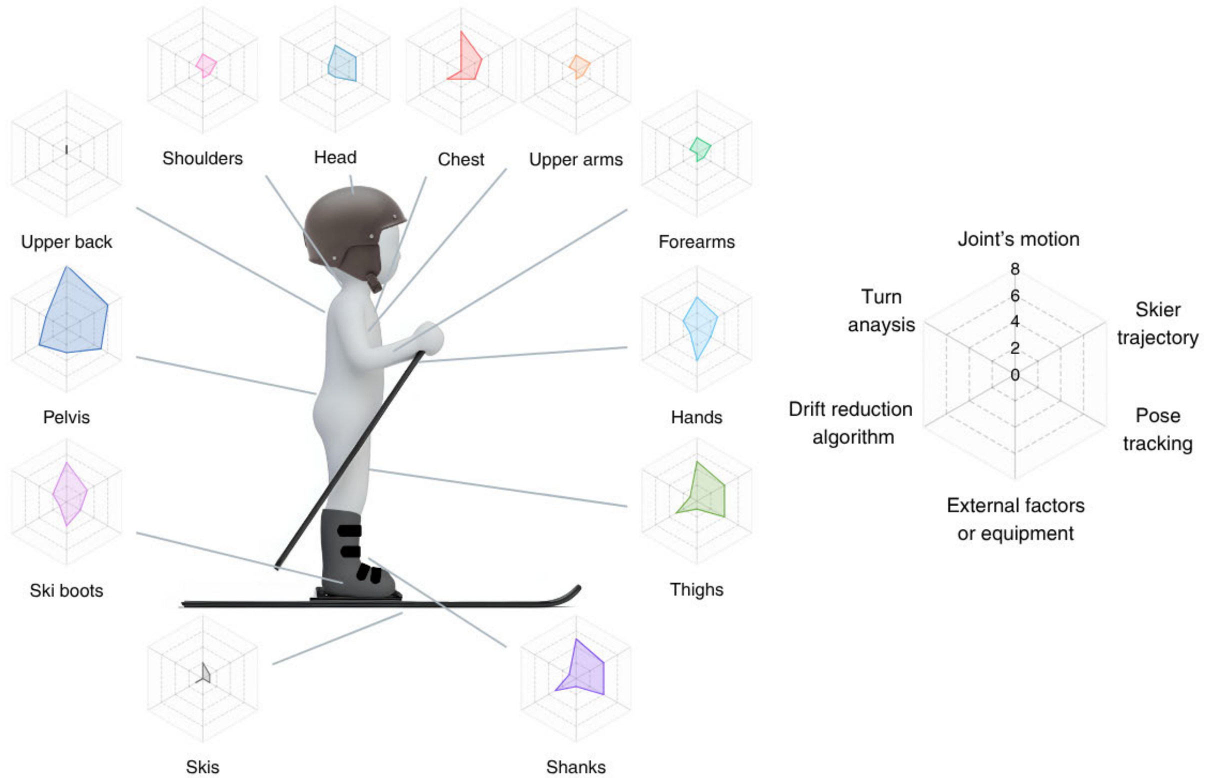

FIGURE 4. Left: schematic representation of IMU placements on the skier's segment, with radar charts at indicating the relative contributions reported in the studies. Right: legend of the radar chart axes, illustrating the main topics investigated in these studies.

derived via forward kinematics adapted from Gilgien et al. [39]. Subsequent work [40] added gate-embedded magnets for drift correction. Later, Fasel et al. [41] estimated gyroscope biases exploiting turn dynamics and centripetal acceleration to obtain drift-reduced 3D segment orientations.

- Orientation tracking with minimal sensors: Yoshioka et al. [26] employed 3D gyroscopes only. Joint centers were calibrated via optical motion capture; IMU orientations were tracked for 300 s using integrated gyroscope signals after bias estimation.
- Technique monitoring: Russo et al. [45] extracted joint roll/yaw angles, turn count, and duration from IMUs during training. Matsumura et al. [47] combined IMUs (waist, skis) with plantar pressure insoles to assess turn symmetry and classify skill levels via fused motion and force features. Bruzzo et al. [50] placed IMUs on ski poles to compute dynamic lean angles in the DP technique. Myklebust et al. [51] used sacrum, pole, and boot sensors to extract pole/ski contact timings across treadmill, roller, and on-snow conditions.
- Landing kinetics (ski jumping): Bessone et al. [48] used 11 IMUs and pressure insoles to estimate GRF during landing. Kinetic patterns were related to flight time and joint contributions (hip, knee, ankle).

In all studies, raw IMU signals were processed via sensor fusion, bias estimation, or kinematic modeling to estimate body segment orientations, CoM trajectory, or performance-related metrics

B. METHODS FOR AUTOMATIC CLASSIFICATION OR TURNS DETECTION ALGORITHM

In this section, nine papers focusing on automatic algorithms for turn detection and skiing techniques or sub-techniques classification are described. Besides basic pattern recognition, these studies investigate possible correlations between skier's strategic choices and competition results or gender differences. A brief description of each paper is provided here and further information can be read in Table 2, and an overview of the skiing techniques and corresponding classification methods adopted in the reviewed studies is illustrated in Figure 5.

In alpine skiing, Martínez et al. [53] developed and validated a methodology to determine turn switches and sequences of parallel skiing turns based on a set of heuristic rules. They assumed that a turn switch is a single point in time when the roll component signals of both skis angular velocities have local extrema, and the algorithm correctly identified parallel and carved style techniques. Subsequently, the same research group [54] aimed to classify four different

TABLE 1. **3D Kinematics of the skiers.**

Study	Discipline	Results	Details of the in-field test	Num. of IMUs	Body locations	Other sensors
[38]	Alpine skiing	Accurate CoM position and speed estimation	Participant: 6 European Cup Level (n/a) Tracks; GS (slope: 26°; 11 gates: 27 m distance; 8 m offset) Total runs: 12	7	Chest Head R, L shanks R, L thighs Sacrum	GNSS
[40]	Alpine skiing	Accurate CoM position and speed estimation	Participants: 11 European Cup level (n/a) Tracks: 4 GS (slope: n/a; 30 gates: 21-28 m distance, n/a offset); DH (n/a) Total runs: 17	7	Chest Head R, L shanks R, L thighs Sacrum	External magnetometers
[41]	Alpine skiing	Drift reduction method for body segments orientations and joint angles	Participants: 6 European Cup Level (n/a) Tracks; GS (slope: 26°; 11 gates: 27 m distance; 8 m offset) Total runs: 12	6	Chest R, L shanks R, L thighs Sacrum	None
[26]	Alpine skiing	Pose tracking for 3 min with a tracking error of 2° (RMSE)	Participant: 1 ski instructor (M) Tracks: DH (slope: 15°) Total runs: n/a	7	R, L shanks R, Li skis R, L thighs Sacrum	Camera External magnetometers
[42]	Alpine skiing	Relationship between knee kinematics and ski width	Participants: 6 expert skiers (n/a) Tracks: GS (slope: 14.5°, 11 gates: 30 m distance, 11 m offset) Total runs: 15	16	Head R, L boots R, L forearms R, L hands R, L scapula R, L upper arms R, L shanks R, L thighs Sacrum	GNSS
[43]	Alpine skiing	The influence of the turn cycle structure on the total descent time	Participants: 5 elite skiers (n/a) Tracks: 4 SL having different slope and gate settings (slope: n/a, 10 gates: n/a) Total runs: n/a	1	Sacrum	None
[45]	Alpine skiing	Turn definition, roll and pitch angles for skis and the back, angles for the poles	Participants: 6 agonist skier (M: 5; F: 1); 1 World Cup skier (n/a) Tracks: 10 GS (n/a gates: 18-20 m distance; 6-8 m offset); SL (n/a gates: 8-12 m distance; 2-3 m offset) Total runs: n/a	5	R, L poles R, L boots Sacrum	Barometer
[46]	Alpine skiing	Influence of asymmetries in the left and right turns on the slalom performance	Participants: 9 Swedish National skiers (M) Tracks: SL (slope: 16°; 20 gates: 12 m distance, 4 m offset) Total runs: 36	16	Head R, L boots R, L forearms R, L hands R, L scapula R, L upper arms R, L shanks R, L thighs Sacrum	GNSS Insoles
[47]	Alpine skiing	Method to assess ski-turn skills based on angular velocity time series	Participants: 1 expert (M); 4 intermediate (M: 3; F: 1) Tracks: DH (slope: 25°) Total runs: 10	3	R, L skis Sacrum	Insoles

TABLE 1. *(Continued.)* 3D Kinematics of the skiers.

[48]	Ski jumping	Correlation between kinetics and kinematics during landing	Participants: 1 professional skier (n/a) Hills: HS100 in Oberhof (Germany); HS106 in Oberstdof (Germany); HS98 in Ramsau-am-Dachstein (Austria); Total runs: n/a	11	Chest Upper back R, L shanks R, L skis R, L boots R, L thighs Sacrum	Camera Insoles
[50]	XC skiing	Ski pole orientation and contact detection	Participants: 1 experienced skier (n/a) Tracks: flat Total runs: 20	1	R pole	Camera
[51]	XC skiing	Kinematic differences between roller skiing and on-snow skiing	Participants: 9 experienced skiers (M) Tracks: n/a (slope: 8°) Total runs: n/a	6	Chest R, L poles R, L boots Sacrum	Camera

GS = giant slalom, R = right, L = left, GNSS = Global Navigation Satellite System, DH = downhill, M = males, F = females, SL = slalom, XC = cross-country.

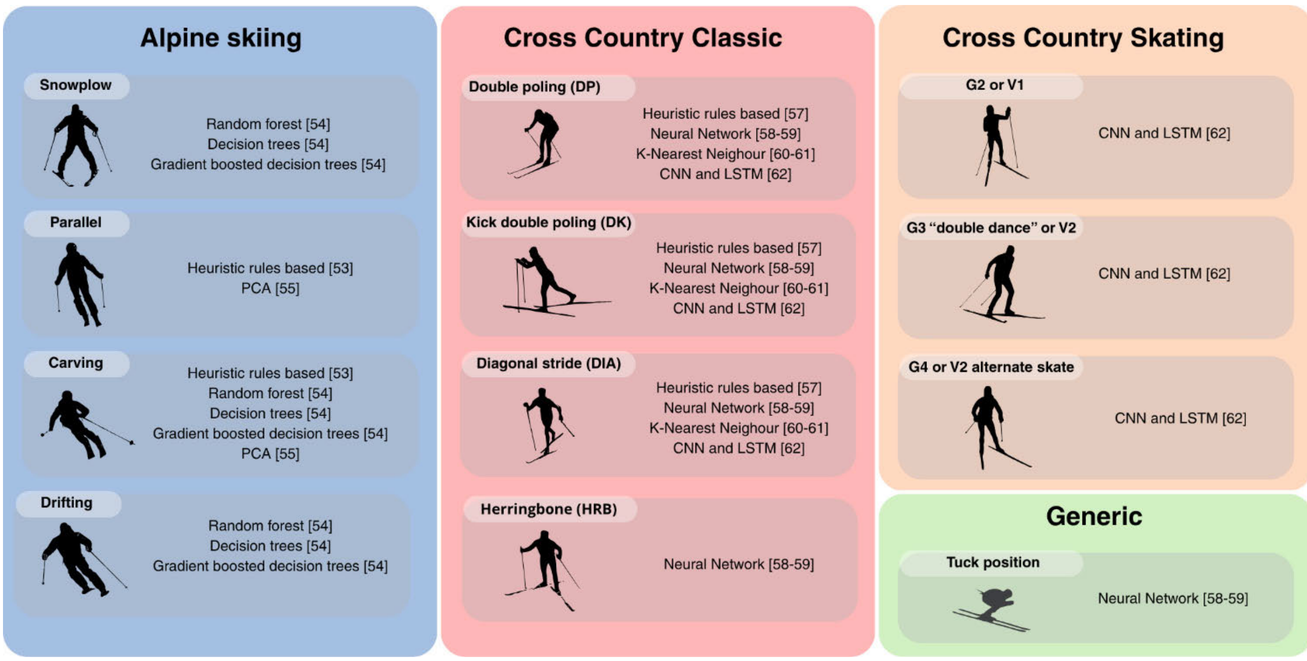

FIGURE 5. Summary of skiing technique classification approaches across different skiing disciplines. Each box presents the main movement patterns analyzed in alpine skiing, cross-country classic, cross-country skating, and generic skiing techniques, along with the corresponding classification methods adopted in the reviewed studies. References indicate the source for each method.

techniques: snowplow, snowplow-steering, drifting and carving. Three different classifiers were developed and compared: decision trees, random forest and gradient boosted decision trees. The decision tree method was easily interpretable but performed worse than the others. Both random forest and gradient boosted classification trees achieved high accuracy in the parallel classification task and moderate accuracy in the non-parallel case. A possible reason for the lower accuracy could be the smaller size of the non-parallel turn training datasets [54].

Unlike previous approaches, Debertin et al. [55] described a 3-step proof-of-concept study focused on principal component analysis (PCA) to evaluate technique performance. Their system was able to detect differences between parallel and carving turns based on the curricular descriptions provided in instructional material [56] and to compare skier abilities to those of reference ski instructors.

An important research branch in the field of automatic XC skiing sub-technique classification algorithms started with the work of Seeberg et al. [57]. They investigated: (i) the usability of a multisensory system and (ii) the validity of classical XC skiing sub-techniques identification from IMUs on arms and legs based on correlation heuristics. The algorithm classifies XC skier movements as DIA, DK, DP or miscellaneous (MISC). To evaluate the classifier performance, data samples were manually combined and synchronized with

TABLE 2. Automatic classification or turn detection algorithms.

Study	Discipline	Results	Details of the in-field test	Num. of IMUs	Body locations	Other sensors
[53]	Alpine skiing	Turn detection algorithm based on a set of heuristics rules	Participants: 11 expert skiers (M) Tracks: 8 m corridor; 4 m corridor (n/a) Total turns: 220	2	R, L boots	None
[54]	Alpine skiing	Comparisons between decision trees, random forest and gradient boosted decision trees for techniques classification	Participants: 20 advanced skiers (n/a) Tracks: blue and red Austrian slopes (n/a) Total turns: 180	2	R, L boots	GNSS
[55]	Alpine skiing	Principal component analysis (PCA) to evaluate technique performance according to the instruction curricula description	Participants: 8 ski instructors (M: 5; F: 3) Tracks: moderately steep slopes at Austrian ski resorts Total turns: 280	17	Chest R, L forearms R, L hands Head R, L scapula R, L upper arms Sacrum R, L shanks R, L boots R, L thighs	None
[57]	XC skiing	Classical XC skiing sub-techniques identification based on correlation heuristics	Participants: 11 (M: 10; F: 1) Tracks: several types Total runs: n/a	7	Chest R, L forearms Upper back R, L boots Sacrum	GNSS HR Barometer
[58]	XC skiing	Neural network to classify classical XC sub-techniques	Participants: 10 (M: 9; F: 1) Tracks: n/a Total runs: n/a	2	Chest L forearm	GNSS HR Barometer
[59]	XC skiing	Principal component analysis (PCA) to evaluate technique performance according to the instruction curricula description	Participants: 12 competitive skiers (M: 6; F: 6) Tracks: 4 20 m maximal speed test on flat and uphill terrain; 5 km LIT; 5 km HIT Total runs: 72	4	R, L forearms R, L skis	GNSS Barometer HR BLA
[60]	XC skiing	K-Nearest Neighbor algorithm for sub-technique classification	Participants: 33 world-class skiers (M: 25; F: 8) Tracks: 15 km time-trial (M); 10 km time-trial (F) Total runs: n/a	1	Upper back	GNSS Camera
[61]	XC skiing	K-Nearest Neighbor algorithm for sub-technique classification	Participants: 30 National and World-Class skiers (M) Tracks: 1.7 km sprint time-trial Total runs: 30	1	Upper back	GNSS Camera
[62]	XC skiing	Convolutional neural network (CNN) and long-short term memory (LSTM) based deep learning model for classifying both classical and skating techniques	Participants: 4 professional skiers (M: 1; F: 3) Tracks: 500 m long Total runs: 40	17	Chest R, L forearms R, L hands Head R, L scapula R, L upper arms R, L shanks R, L boots R, L thighs Sacrum	None

CoM = center of mass, M = males, R = right, L = left, GNSS = Global Navigation Satellite System, F = females, XC = cross-country, HR = heart rate, LIT = low intensity training, HIT = high intensity training, BLA = blood lactate concentration.

the video of the session. In a follow-up study [58], they improved the system [57] reducing the number of IMUs and developing a neural network for the classification. They were able to distinguish additional classes such as the tuck position (TCK), HRB, turns (TRN) and transitions to DIA from DP or DK (tDIA) and reverse (fDIA). However, the new classes had lower sensitivity and precision compared to the main ones. As a further development, Solli et al. [59] investigated sex-based differences in speed, sub-technique selection and kinematic patterns during XC training through a refined version of the algorithm [57]. They correlated for the first time gender characteristics and skiing performance. It emerged that women used more DIA and less MISC than men, while men used more DP during uphill sections. They additionally employed a Global Positioning System (GPS) wristwatch, but it was not accurate enough to detect the instantaneous speed variations typical of XC ski racing [59]. The same research group [60] proposed a system to compare speed, sub-technique selection and temporal patterns among world-class male and female XC skiers during an international time-trial competition in classical style. The sub-technique classification was undertaken using a K-Nearest Neighbor algorithm, which revealed that: (i) men spent less time using DIA and more using DP and other techniques than women, and (ii) men and women used similar temporal patterns in the various sub-techniques when compared within the same speed intervals. Haugnes et al. [61] published further results on the same system [60], investigating how race tactics influence skiers' performance in the heat of an international XC sprint in classical style. All skiers selected similar sub-techniques during the race, but better-performing skiers produced longer cycle length and higher cycle rate in DIA in the last uphill segment. In a separate contribution, Jang et al. [62] proposed a unified convolutional neural network (CNN) and long-short term memory (LSTM) based deep learning model for classifying eight techniques of both classical and skating styles. Five different sensor configurations were used to train the model: whole-body, upper body, lower body, "sports biomechanics configuration" (5 sensors on pelvis, hands, feet) and pelvis only. Even though the model was trained on outdoor flat course data, it achieved very high accuracy on irregular course tracks. Most misclassifications occurred for upper body and pelvis movements and transitions between similar techniques.

1) IMU PLACEMENT AND PROCESSING APPROACHES

The reviewed studies employed various sensor setups and classification strategies to detect turns or identify skiing techniques and sub-techniques:

- Alpine skiing: Martínez et al. [53], [54] used IMUs on both skis to extract roll angular velocity and detect turn switches via heuristic rules. In [54], the same signals were used to classify skiing techniques (snowplow, drifting, carving) with decision tree-based models, highlighting trade-offs between interpretability and accuracy.
- Feature extraction and dimensionality reduction: Debertin et al. [55] applied PCA to full-body IMU data to evaluate technique consistency and compare skier performance with reference profiles from instructional material.
- Cross-country skiing (XC): Seeberg et al. [57] used IMUs on arms and legs to classify classical techniques (DIA, DK, DP) using correlation-based rules. Later, in [58], they reduced the number of IMUs and introduced a neural network classifier, expanding the classification to transitions and additional postures (e.g., TCK, HRB, TRN), though with reduced sensitivity for minor classes.
- Sex-based and elite performance analysis: Studies [59], [60], [61] adopted refined versions of Seeberg's algorithm to assess sub-technique selection and kinematic patterns in male/female elite skiers. IMUs were combined with GPS watches to contextualize technique selection across course segments, although GPS lacked sufficient temporal resolution.
- Deep learning classification: Jang et al. [62] developed a CNN-LSTM model trained on five sensor configurations (from full-body to single-pelvis). Despite training on flat terrain, the model generalized well to irregular courses, with misclassifications mainly occurring in transitional phases and with reduced sensor sets.

Across studies, raw IMU signals were processed using handcrafted features, rule-based logic, or machine learning techniques (RF, GBDT, KNN, neural networks), depending on the classification complexity and available sensor data.

C. SKIER PERFORMANCE EVALUATION

Alpine skiing and XC skiing consist of various events and have different demands. A thorough understanding of these demands can enhance athletic performance by tailoring training to the specific discipline. The papers in this section demonstrate that IMU-based systems can provide a wide range of information related to skier performance evaluation: the effectiveness of athlete's training [63], quantified differences between professionals and amateurs [64] or males and females [65], [66], methods for athletic gesture evaluation [67], [68], [69] equipment analysis [70], [71] and advantages of sensor-based feedback [72] (Figure 6). These studies are summarized below, and additional details are reported in Table 3.

As in the previous section, alpine skiing is the most extensively explored discipline. Yu et al. [63] aimed to identify the best IMU location for turn performance analysis. They selected the pelvis, based on discrepancies in turn duration between left and right turns. They also evaluated whether the IMU can capture training adaptation effects: the skier adapted to the test environment and his turn performance improved as the experiment proceeded. Two papers investigated the differences between skiers: Snyder et al. [64], who developed a system which quantifies motion quality to differentiate between an expert and a beginner skier, and Alejo et al. [65], who described the kinematic pattern and impacts (G-forces movements that exceeded 5g [73]) in male and female skiers during the course of an alpine skiing competition. Snyder et al.'s system [64] successfully distinguished between skill levels, but only when skiing styles differed (e.g., carving vs. drifting). Although the algorithm was suitable for comparing skiers, it did not provide guidance for performance improvement. The accuracy of sub-technique classification depended on the quality of feature extraction, which in turn relied on the segmentation step. Alejo et al. [65] found sex-related differences in technical disciplines, such as SL, by comparing the number of impacts, but no differences emerged in the GS.

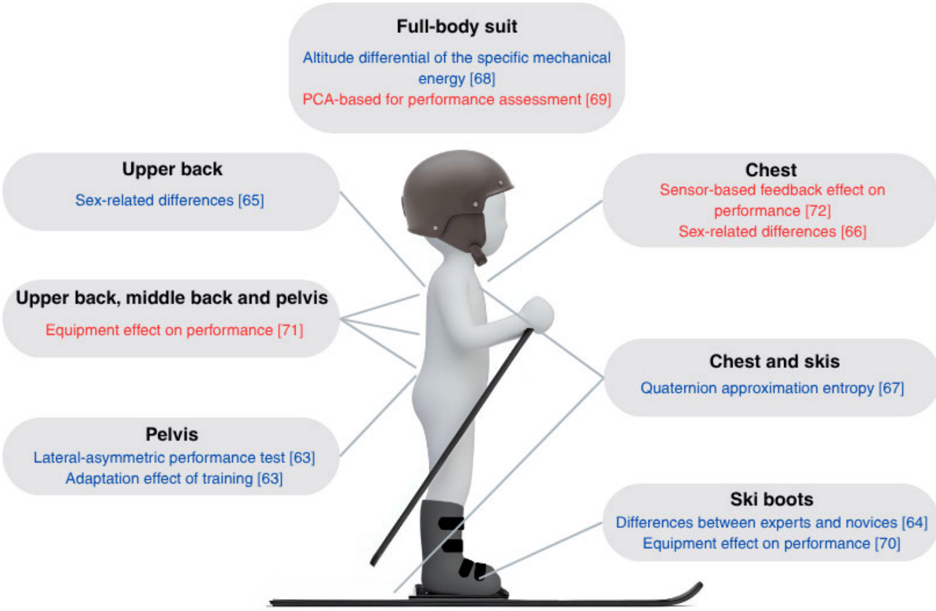

FIGURE 6. Overview of sensor placements and corresponding performance-related studies in skiing. Studies focused on alpine skiing are shown in blue, while studies in cross-country skiing are shown in red. Performance metrics investigated include sex-related differences, training adaptation, equipment effects, biomechanical asymmetries, and sensor-based feedback, with sensors positioned on different body segments such as the upper back, chest, pelvis, ski boots, and full-body suits.

Impacts were measured as G-forces (>5g) along the vertical, anteroposterior and mediolateral axes experienced during competition. Among male slalom skiers, covering longer distances at higher speeds was associated with shorter course completion time. Female skiers, by contrast, accelerated and braked more frequently, struggling to maintain high peak speeds. This speed discrepancy resulted in different impact patterns between sexes. A nonlinear method to analyze skier movements was proposed by Szczęsna and Janiak [67], who applied quaternion approximation entropy for human motion analysis during DH skiing. Skier motion is represented as time series of orientations (quaternions) of the skis and chest. They found that more advanced skiers exhibited lower entropy values with narrower ranges, indicating greater repeatability of orientation patterns. In other words, skilled skiers maintained better control and were less affected by local perturbations, such as bumps or icy patches. Conversely, Hladnik et al. [68] focused on the altitude differential of specific mechanical energy, $diff(e_{mech})$, a metric correlated to skiing performance [74], [75], [76]. In a simplified mass point (MP) model, the skier's total specific mechanical energy (e_{mech}) is the sum of specific translational kinetic energy (e_{KE}) and specific gravitational potential energy (e_{GPE}). If e_{mech} remains constant during descent, a reduction in e_{GPE} translates entirely into an increase in e_{KE}, meaning the skier accelerates. If the skier moves at a constant speed, the entire decrease in e_{GPE} would dissipate in the environment and in the skier's body, which was approximated as a MP. Hladnik et al. [68] developed a more complex linked segment (LS) model, which accounted for limb movements and rotational kinetic energy. The authors found no significant differences in $diff(e_{mech})$ between the MP and LS models for performance evaluation, suggesting that limbs movements contribute negligible energies compared to the skier's CoM. However, under specific conditions, such as high-frequency turns on steep slalom terrain, differences might emerge. Model accuracy may have been affected by equipment mass distribution and the precision of anthropometric tables used for estimating segment masses and moments of inertia. Honert et al. [70] proposed a different usage of an IMU-based system: they systematically evaluated the performance and fit of two different ski boot shell enclosure mechanisms, the BOA closure [77] and a traditional buckle closure. Using one IMU per boot to compute peak edge angles, plantar pressure insoles to measure the normal force, and a GPS watch to assess speed, they found that the BOA system improved carving performance and reduced rearfoot plantar pressures, offering a better overall fit. Four studies addressed the cross-country skiing. Seeberg et al. [72] investigated the effectiveness of video- and sensor-based feedback for implementing terrain-specific micropacing strategies. Skiers were randomly assigned to an intervention (INT) or control (CON) group. Between races, the INT group received both video- and sensor- based feedback, while the CON group only received race results. After the intervention, the INT group significantly reduced their time on downhill and flat sections compared to the CON group. However, no improvements were observed in uphill segments or overall race time. Staunton et al. [71] explored

TABLE 3. Skier performance quantification and analysis.

Study	Discipline	Results	Details of the in-field test	Num. of IMUs	Body locations	Other sensors
[63]	Alpine skiing	Best sensor location for performance analysis	Participants: 1 professional skier (M) Tracks: GS (slope: 41°; 6 gates: 25-30 m distance, offset n/a) Total runs: 8	16	Head R, L forearms R, L hands R, L upper arms Middle back Upper back R, L shanks R, L boots R, L thighs Sacrum	None
[64]	Alpine skiing	Algorithm to quantify motion and differentiate between expert and beginner skiers	Participants: 20 expert skiers (M: 8; F: 11); 1 ski instructor (n/a); 1 beginner (n/a) Tracks: blue or red slopes Total runs: 154	2	R, L boots	GNSS
[65]	Alpine skiing	Method to quantify the competitive race parameters in alpine skiing competition	Participants: 15 experienced skiers (M: 9; F: 6) Tracks: super GS (n/a), GS (n/a), SL (n/a) Total runs: 61	1	Upper back	GNSS
[67]	Alpine skiing	Correlation between entropy values and skiing skills	Participants: 6 differently skilled skiers (M: 3; F: 3); Track: DH (slope: n/a) Total runs: 184	2	Chest R, L skis	GNSS Barometer
[68]	Alpine skiing	Differences between mass point and whole-body modeling of skier for performance evaluation	Participants: 9 expert skiers (n/a) Tracks: GS-alike (6 gates: 30 m distance, 11 m offset; 6 gates: 27 m distance, 8 m offset) Total runs: 18	17	Chest Head R, L forearms R, L hands R, L scapula R, L upper arms R, L shanks R, L boots R, L thighs Sacrum	GNSS
[70]	Alpine skiing	Performance evaluation of BOA closure [73] and Buckle closure	Participants: 21 expert skiers (M) Tracks: DH (n/a) Total runs: 63	2	R, L boots	Insoles GNSS
[72]	XC skiing	Video- and sensor-based feedback for the implementation of an terrain-specific micropacing strategy	Participants: 26 expert skiers (M) Tracks: 10 km time-trial (uphill: 38%; flat: 17%; downhill: 45%) Total runs: 52	1	Chest	GNSS Camera HR Barometer
[71]	XC skiing	The effect of rifle carriage during biathlon skiing	Participants: 28 professional biathletes (M: 17; F: 11) Tracks: 2.3 km time-trial (n/a) Total runs: 56	3	Middle back Upper back Sacrum	GNSS HR BLA
[66]	XC skiing	Sex differences in classical and skating cross-country skiing	Participants: 55 elite- to world-class skiers (M: 35; F: 20) Tracks: 3.3 km time-trial Total runs: 243	1	Chest	GNSS
[69]	XC skiing	PCA-based approach to quantitatively assess V2 ski-skating technique	Participants: 10 experienced skiers (M: 5; F: 5) Tracks: 100 m of flat and straight track Total runs: 320	17	Chest Head R, L forearms R, L hands R, L scapula R, L upper arms R, L shanks R, L boots R, L thighs Sacrum	None

M = males, GS = giant slalom, R = right, L = left, F = females, GNSS = Global Navigation Satellite System, SL = slalom, DH = downhill, XC = cross-country, HR = heart rate, BLA = blood lactate concentration.

the impact of the biathlon rifle carriage during the XC skiing component of biathlon. They found that (i) the rifle had minimal effect on physiological responses, as neither heart rate (HR) nor blood lactate concentration (BLA) changed; (ii) it impacted time-trial skiing performance, increasing physiological intensity; and skiing speed showed a strong positive linear relationship with accelerometer-derived metrics across uphill, flat, and downhill terrains.

A recent time-trial study by Talsnes et al. [66] compared elite male and female skiers during 10 km classical and skating competitions using combined GNSS–IMU units. They reported that men were approximately 12 % faster overall, with terrain-dependent differences—18 % faster uphill, 10 % on flat, and 5 % downhill in classical skiing (similarly 17/6/5 % in skating). Sex-specific technique usage also emerged: men spent ∼10 % more time double poling in classical style and ∼9 % more time in Gear-3 skating, compared to women. Furthermore, men exhibited 7–19 % longer cycle lengths in both disciplines. These findings highlight notable sex differences in performance, sub-technique selection, and kinematic patterns, providing valuable insights for developing tailored training strategies. A recent study by Debertin et al. [69] proposed a data-driven framework to quantify relevant technique elements of the V2 skating sub-technique using a full-body IMU-based system. The authors extracted specific time series features—including joint angles, angular velocities, and poling movements—and applied principal component analysis (PCA) to reduce dimensionality and identify interpretable technique descriptors. The PCA analysis allowed for the extraction of "principal movements" (PMs), which are the main components representing the most variable and distinctive movements associated with each technical element. These PMs effectively differentiated extreme variations in technique, enabling quantitative comparisons between different executions and among athletes. The PCA-derived measures were particularly sensitive to large-amplitude movements and those occurring farther from the athlete's center of mass, making them valuable for both individual analysis and group comparisons. Overall, this approach provides enhanced support for coaching and technical feedback compared to previous methods relying on discrete metrics.

1) IMU PLACEMENT AND PROCESSING APPROACHES

This group of studies explored multiple performance-related aspects in alpine and cross-country skiing using diverse sensor configurations and processing pipelines:

- Sensor location optimization: Yu et al. [63] tested several placements and identified the pelvis as optimal for detecting turn asymmetries and training adaptations. IMU signals revealed improvement in turn consistency over time.
- Skill level and sex-related analysis: Snyder et al. [64] used multi-IMU setups to distinguish beginner vs. expert motion patterns, relying on feature quality from well-segmented phases. Alejo et al. [65] analyzed G-forces (>5g) in three axes using limb-mounted IMUs during races, revealing different impact patterns and kinematics in male and female skiers. Talsnes et al. [66] employed combined GNSS–IMU systems to analyze speed, technique usage, and cycle length in elite male vs. female skiers, showing terrain- and technique-specific differences. Debertin et al. [69] extracted joint angle and angular velocity features from full-body IMUs, applied PCA to derive principal movements (PMs), and identified technique-relevant motion patterns for feedback and comparison.
- Kinematic entropy and energy modeling: Szczęsna and Janiak [67] computed quaternion approximation entropy from ski and chest IMUs to evaluate motion repeatability; lower entropy correlated with expertise. Hladnik et al. [68] combined IMUs and anthropometric models to compute specific mechanical energy changes, comparing simplified (MP) and articulated (LS) biomechanical models.
- Equipment analysis: Honert et al. [70] used boot-mounted IMUs, plantar pressure insoles, and GPS to evaluate performance differences between BOA and buckle closures. Peak edge angle and rearfoot load were key outcome measures.
- Feedback and external load: Seeberg et al. [72] used sensor-based terrain pacing feedback (via IMUs and GPS) to improve downhill/flat pacing in XC skiing. Staunton et al. [71] monitored accelerometer-derived metrics and physiological data to assess the effect of biathlon rifle carriage on XC performance.

Overall, these studies combined body-mounted IMUs, GPS, plantar sensors, and external measurements with advanced processing techniques (entropy, PCA, biomechanical modeling) to quantify performance, assess equipment, and deliver actionable feedback across skiing disciplines.

D. INJURY PREVENTION

Papers reported in this section have in common the usage of IMU-based data for injury prevention purposes. The skier's back and knees are the most frequently injured body parts. In particular, the back is prone to overuse injuries [78]; therefore, studies have investigated the leading potential mechanisms [79]: the correlation between gate distances in slalom courses and spinal disc loading [80], the vibrations transmitted to the spine during alpine ski racing [81], and the shape of the boots [82] (Figure 7). These papers are reported in Table 4. Spörri et al. [79] first observed that frontal bending, lateral bending, and torsion signals of the skier's trunk had higher average values during the turn phase, in which the total GRF is greatest. These specific loading patterns are known to increase disc loading [83], [84] and spine deterioration [85], [86] which raises the risk of developing low back pain [87], [88]. As a potential prevention strategy, the same research group studied the effects of increased gate offsets on biomechanical variables related to spinal disc loading in GS and SL [80]. However, variations in GS course setting showed no remarkable effects. This might be explained by the "quasi-static loads" concept [89]: even extreme alterations in course setting do not force athletes to ski in a more dynamic mode. In SL, the total GRF during turns was found to be significantly lower when increasing the gate offset. They then further investigated the topic of back overuse injury prevention [81]. Excessive exposure to whole-body vibrations, particularly at components close to the resonant frequency of the spine (∼ 4 – 10 Hz [90]), increases the risk of spinal structural deterioration and the development of low back pain [91]. The aims of this study were (i) to describe the power spectral density (PSD) of the vibrations acting on the different body segments, and (ii) to quantify and compare the root-mean-square (RMS) accelerations acting on the lower back. PSD was estimated using the single-sided amplitude spectrum of the inertial acceleration, and RMS was determined based on inertial acceleration data along the sacrum's longitudinal axis. While being transmitted through the body, a distinctive attenuation of ski racing-specific vibrations, at frequencies between 4 to 10 Hz, was observed, performed by the spinal structures. These vibrations could be considered potential contributors to mechanisms leading to overuse injuries of the back in alpine ski racing. A potential limitation is that, since IMU sensors were fixed on the skin rather than directly on the bones, small relative movements might have been recorded. In 2018, the same group assessed the effect of reduced standing height (the distance between the bottom of the running surface of the ski and the ski boot sole) on overall trunk kinematics and the acting GRF in GS, from an overuse injury prevention perspective [82]. As previously stated [80], during the turn phase in which the acting GRF is greatest, a combined occurrence of frontal bending, lateral bending, and torsion in the trunk was observed. This combination is crucial in the development of overuse injuries of the back. The authors' findings indicated that skis with decreased standing height might help reduce overall back loading: mean total GRF values were found to be 2.5% lower than with standard skis.

As well as lower back injuries, traumatic knee joint injuries are frequent too in the sport of competitive alpine skiing [92], and the same research group published a paper in which they describe an anterior cruciate ligament (ACL) rupture mechanism [93]. During the skier attempt to get up after a fall, electromyography (EMG) sensors recorded sudden activation of the vastus medialis, while all other knee stabilizing muscles remained deactivated. Such rapid and imbalanced muscle activation patterns likely resulted in excessive anterior translation of the tibia relative to the femur. This ACL injury trigger is hardly avoidable once the skier has decided to stand up during the lateral slide. It seemed that when gravity is used to passively drop the outer leg, the knee-stabilizing muscles functionally deactivate themselves. Another potential ACL injury trigger could be a boot-induced anterior drawer of the tibia relative to the femur. While the skier was falling backward, the mechanical constraint of the ski tail acting as a lever and the rigid connection of the ski with the rear part of the ski boot may have exerted an anteriorly directed force on the tibia. Based on these data, ski racers should be taught not to get back up after a side slip until they have come to a stop, even though this contradicts the coaches' doctrine of "always fighting your way back on course".

Understanding the structure, quantity, and type of snow is crucial for avalanche safety, interpreting satellite imagery, and choosing appropriate skiing equipment. For these reasons, McLelland and van Breugel [94] proposed a system for recreational skiers to assess the characteristics of the top layer of snowpack. The IMU mounted to the ski below the ski boot provided a proxy for the forces and torques applied to the ski (by modelling the ski and boot as a rigid body) while six strain gauges configured in a quarter Wheatstone bridge circuit, placed on the top of the ski, measured the bending and vibrations of the ski. They analyzed the Discrete Fourier Transform (DFT) ratio of angular velocity and the strain gauge data in 10-second segments, and it emerged that the data self-organized well according to snow type in the reduced-order Singular Value Decomposition (SVD) space. Finally, a trained Naïve Bayes classifier assigned a qualitative snow-type label to each 10 second segment of the trial: powder snow, slushy snow, groomer snow, and icy snow.

1) IMU PLACEMENT AND PROCESSING APPROACHES

This group of studies utilized IMU data primarily to investigate injury mechanisms and develop prevention strategies in alpine skiing, with a focus on the skier's back and knees:

- Spinal loading and trunk kinematics: Spörri et al. [79] analyzed trunk motion signals (frontal bending, lateral bending, torsion) during turns, correlating increased values with spinal disc loading and low back pain risk. They further explored the effect of gate offsets on spinal loading in GS and SL [80], finding reduced GRF with increased gate offsets in SL but no significant changes in GS. Another study [81] characterized whole-body vibrations transmitted to the lower back using IMU accelerations on the sacrum, revealing spinal attenuation of harmful vibrations near the spine's resonant frequencies (4–10 Hz), which could contribute to overuse injuries. The authors noted potential measurement limitations due to sensor placement on skin rather than bone. In addition, the effect of ski boot sole height on trunk loading and GRF was investigated [82], showing a 2.5% reduction in mean GRF with decreased standing height, potentially lowering back injury risk.
- Knee injury mechanisms: Investigating ACL rupture risk, EMG and biomechanical data indicated sudden vastus medialis activation and muscle deactivation patterns during a lateral slide recovery attempt, coupled with mechanical forces from ski boot and tail interaction, suggesting important triggers for ACL injuries [93]. These

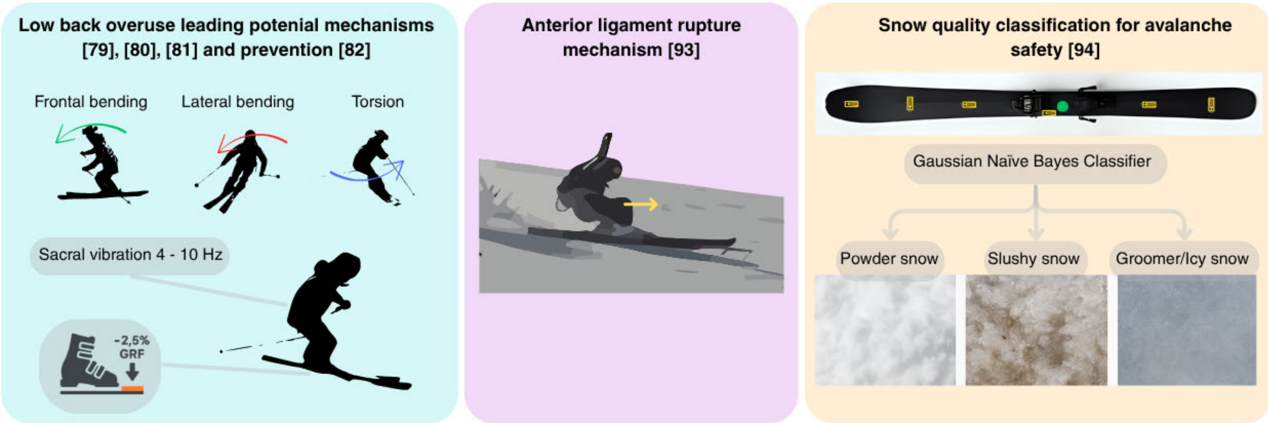

FIGURE 7. Left: Investigations into low back overuse identify frontal/lateral bending and torsion as key loading mechanisms, with sacral vibration (4–10 Hz) linked to spinal overload and equipment-based mitigation strategies such as reducing ski standing height [79], [80], [81], [82]. Center: Description of the anterior cruciate ligament (ACL) rupture mechanism, involving excessive anterior tibial translation due to rapid, unbalanced muscle activation and ski tail leverage [93]. Right: Snow quality classification using IMU (green dot on the ski) and strain gauges (yellow sensors) to support avalanche safety decisions. The approach combines Discrete Fourier Transform and Singular Value Decomposition, followed by Gaussian Naïve Bayes classification to distinguish powder, slushy, and groomer/icy snow types [94].

TABLE 4. Injury prevention.

Study	Discipline	Results	Details of the in-field test	Num. of IMUs	Body locations	Other sensors
[79]	Alpine skiing	Assessment of the movements that might be a potential mechanism leading to overuse injuries of the back	Participants: 8 European Cup-level skier (n/a) Tracks: GS (slope: 21°; 10 gates: 27 m distance, 6 m offset) Total runs: 32	2	Chest Sacrum	Insoles
[80]	Alpine skiing	Assessment of the effects of increased gate offset on the skiers' overall trunk kinematics	Participants: 10 World Cup and European Cup skier (n/a) Tracks: GS (slope: 26°; 8 gates: 25 m distance, 6 m or 10 m offset); SL (slope: 26°; 8 gates: 10 m distance, 3 m or 4.5 m offset) Total runs: 30	2	Chest Sacrum	Insoles
[81]	Alpine skiing	Evaluation of the vibrations that act on the human body	Participants: 6 European Cup skier (M) Tracks: GS (slope: 19°; 8 gates: 25 m distance, 6.5 m offset); SL (slope: 19°; 8 gates: 10 m distance, 3 m offset) Total runs: 24	6	Chest R, L shanks R, L thighs Sacrum	None
[82]	Alpine skiing	Assessment of the effects of reduced standing height on the skier's trunk kinematics	Participants: 7 European Cup skiers Tracks: GS (slope: 19°; 8 gates: 25 m distance, 6.5 m offset) Total runs: 14	2	Chest Sacrum	Insoles
[93]	Alpine skiing	Description of the anterior cruciate ligament rupture mechanism from a functional perspective	Participants: 1 European Cup skier (M) Tracks: GS (slope: 21°; 8 gates: 27 m distance, 6 m offset) Total runs: 1	3	R, L shanks R, L thighs Sacrum	Insoles Camera EMG
[94]	Alpine skiing	Classification of snow quantity and type for avalanche safety	Participant: 1 (n/a) Tracks: DH-alike tracks at the Mount Ros Ski Resort near Reno (NV) Total runs: 14	1	R ski	GNSS Strain sensors

GS = giant slalom, SL = slalom, M = males, R = right, L = left, EMG = electromyography, DH = downhill, GNSS = Global Navigation Satellite System.

findings inform coaching advice to avoid premature attempts to stand after a fall.

- Snow type assessment: McLelland and van Breugel [94] combined IMU data mounted on skis with strain gauge measurements to classify snow types via angular velocity and vibration analysis, enabling improved skier safety through informed equipment and technique choices.

Together, these studies demonstrate the critical role of IMUs in quantifying biomechanical loads, characterizing injury mechanisms, and enabling actionable interventions for injury prevention in competitive alpine skiing.

E. PARALYMPIC SKIING SPORTS

In recent years, the number of studies on Paralympic sports has increased. However, the research progress in skiing is

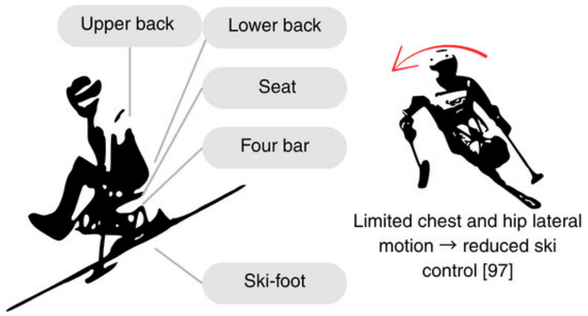

FIGURE 8. Illustration of sensor placement and biomechanical limitations in sit-skiing. IMUs were positioned on the upper back, lower back, seat, four-bar linkage, and ski-foot to assess trunk motion. Limited lateral chest and hip mobility were associated with reduced ski control during turns [97].

limited compared to other sports, such as athletics [95] and swimming [96]. In this scoping review, two papers fulfilled the inclusion criteria. They are briefly described in this section, and further details are provided in Table 5.

Ishige et al. [97] focused on alpine sit-skiing. Since sit-skiers control their skis by trunk motion and balance, trunk impairment is believed to lead to activity limitations during skiing. This work aimed to examine the relationship between trunk range of motion and sit-skiing performance through five IMUs placed on the upper trunk, lower trunk, seat, four-bar linkage, and ski-foot (Figure 8). The experimental results revealed that chest and hip motion decrease depending on the impairment. The authors noticed that insufficient lateral chest flexion probably caused a decrease in the edging angle, and insufficient chest and hip flexion/extension caused lower loading in the latter half of the turn. Since edging angle and loading are key factors in ski control [98], the joint motions could be considered measures of sport-specific activity limitation in sit-skiing classification.

Carlsen et al. [99] proposed a system, based on the same single device as [60], for in-field analysis of performance and sub-technique selection in Para XC and able-bodied (AB) XC skiing. The sub-techniques were classified as DP, DK, DIA (including both DIA and HRB) and Other. The proposed framework can provide information on where and why Para XC skiers lose or gain time compared to their competitors in a race. This could help Para XC skiers to individually define targeted training and competition strategies.

1) IMU PLACEMENT AND PROCESSING APPROACHES

These studies employed IMU data to assess functional limitations and performance in Paralympic skiing:

- Trunk mobility in sit-skiing: Ishige et al. [97] used five IMUs placed on the upper and lower trunk, seat, linkage mechanism, and ski-foot to quantify trunk range of motion and its relation to sit-skiing performance. Reduced lateral chest flexion and hip motion were linked to impaired edging and turn loading, key factors in ski control.
- Sub-technique classification in Para cross-country skiing: Carlsen et al. [99] utilized a single IMU device combined with pattern recognition algorithms to classify sub-techniques (DP, DK, DIA/HRB, Other) and compare performance between Para and able-bodied skiers.

Together, these works highlight the use of IMUs to capture sport-specific biomechanical variables relevant to activity limitation assessment, performance analysis, and classification in Paralympic skiing.

IV. DISCUSSION

To the best of our knowledge, this is the first scoping review that collects IMU-based wearable system studies in the context of skiing, regardless of the discipline and research objective, over the last ten years. It is worth noting that most of the studies focused on the alpine skiing discipline (62%). One-third of the papers concerned cross-country skiing, and only one paper was about ski jumping. Skier motion characterization, performance analysis, and injury prevention are the most commonly investigated topics in the alpine skiing context, while the development of technique detection and classification algorithms predominantly concerns cross-country skiing.

A. SKIER KINEMATICS CHARACTERIZATION

Across all twelve studies, the average number of IMUs used was 7.17 $\pm$ 4.97, with a median of 6.5.

Nine papers out of twelve focused on alpine skiing. These systems had an IMU positioned over the sacrum, and they all integrated sensor data to obtain joint positions and orientations of the lower part of the body (specifically the waist), with the exception of Buxadé et al. [43]. The seven-IMU systems mostly covered the lower body (thighs and shanks). Two of them also employed external magnetometers [26], [40](both alpine skiing), to infer the absolute CoM trajectory, and one additionally used a marker-based optical motion capture system to register the skier's stationary posture before the measurements on the ski slope [26]. Three studies further integrated a GNSS system [38], [42], [46] (all alpine skiing) to obtain skier speed, total distance covered, CoM kinematics measurements, global position, and altitude. Finally, two studies [46], [47] added pressure insole data to investigate asymmetries between the left and right sides, as well as the turn radius, and the device used by Russo et al. [45] included an integrated barometer. Only two studies relied solely on IMUs without any complementary sensors [41], [43] (all in alpine skiing). The two papers that focused on cross-country skiing [50], [51] used an IMU on the right pole grip and integrated accelerometer and gyroscope data with video analysis to evaluate the pole motion, although Myklebust et al. [51] employed five additional IMUs to also evaluate leg and arm movements and CoM kinematics. The only included paper on ski jumping [48] fused data from eleven IMUs with camera

TABLE 5. Paralympic skiers.

Study	Discipline	Results	Details of the in-field test	Num. of IMUs	Body locations	Other sensors
[97]	Alpine sit-skiing	Assessment of the relationship between the trunk impairment level and the trunk kinematic characteristics	Participants: 3 National Para sit-skiers (M: 2; F: 1) Tracks: 2 ski areas in Japan at different slope and gates settings Total runs: 5	5	Four-bar Seat Ski foot Lower back Upper back	EMG
[99]	XC skiing	Performance analysis in Para XC skiing	Participants: 3 elite standing Para skiers (M: 2; F: 1); 7 elite AB skiers (M: 3; F: 4) Tracks: 15 km time-trial (M); 10 km time-trial (F) Total runs: 10	1	Upper back	GNSS

GS = giant slalom, SL = slalom, M = males, R = right, L = left, EMG = electromyography, DH = downhill, GNSS = Global Navigation Satellite System.

and pressure insole signals, investigating the correlations between these sensor data.

Only two papers out of twelve that concerned skier kinematics characterization employed a full-body motion suit [42], [48], the remaining ones placed IMUs mostly on the trunk and lower limbs, and extracted a wide variety of information from the orientation, angular velocity, and linear accelerations of these body segments: ski trajectories [45], [46], [47], CoM trajectories [38], [40], [46], [47], relative body segment orientations [26], [41], [42], [45], [47], [48], [51], and skier body models [38], [40], [46]. Exceptions were the cross-country studies, which placed at least one IMU on the ski pole grip, suggesting that, at first glance, upper-limb motion is more informative in this discipline than in the others, even though Fasel et al. [38] noted that their results might have differed if they had considered the movements of non-monitored limbs.

The average number of participants across the twelve studies was 7.5 ± 5.5. Six papers reported the small number of participants as a limitation for the generalizability of their findings [26], [43], [45], [46], [48], [50]. Further factors that may have influenced the final results include experimental constraints on athletes' trajectories [40], considering more than one sub-technique [50] and environmental conditions [46]. Some of the proposed systems required external components like dGNSS reference stations equipped with antennas and receivers mounted near the start of the race track [38], an optical motion capture system to acquire skier's stationary posture before the collection of skiing data [26], and magnets positioned at each gate of the GS course [40].

Despite a diversity of approaches, most studies on skier kinematics using IMU-based systems converge on the ability to accurately reconstruct skier motion and key biomechanical parameters (e.g., [36], [38], [39], [40], [41], [43]), though their findings are often limited by small sample sizes and the need for complex setups [26], [41], [43], [46], [48]. Overall, the literature demonstrates that IMUs can provide detailed insights into skier movement [36], [39], [45], but generalizability and ecological validity remain common challenges [38], [44], [46].

B. METHODS FOR AUTOMATIC CLASSIFICATION OR TURNS DETECTION ALGORITHM

Across all studies in this section the average number of IMUs was 5.89 ± 6.57, with a median of 2.

Most systems (6/9) integrated GNSS technology: one in alpine skiing [54] and five in cross-country [57], [58], [59], [60], [61]. Additionally, barometers and heart rate sensors were used in three XC studies [57], [58], [59], BLA sensors in one [59], and video cameras in one [61]. Only three studies out of nine adopted an IMU-only system [53], [55], [62].

Three papers focused on turn detection and classification algorithms in the context of alpine skiing. Debertin et al. [55] employed the same seventeen-IMU-based system as [62], while Martínez et al [53] and Neuwirth et al. [54] worked with a two-IMU-based system, both placed on ski boots. Only one system [54] integrated IMU data with another type of sensor, the GNSS, to register skier global position. All systems were able to detect and classify carving turns. Martínez et al.'s [53] system could distinguish between long and short turns and, like Neuwirth et al. [54], identified drifting turns and snowplow steering, but only Neuwirth et al. [54] could recognize a simple snowplow run. Parallel turns were considered only by one algorithm [55].

Six papers out of nine focused on cross-country skiing. Three of them employed a single IMU-based system on the skier's upper back [60], [61]. The other systems employed several IMUs. In those studies, forearms and chest were the most frequent locations. It is worth noting that all except one system [62] integrated GNSS data to obtain altitude [57], [58], [59], [60], [61], global position [57], [59], [60], [61], skier speed [58], [59], [60], [61], and run time [59] for the analysis. Indeed, three systems [57], [58], [59] employed a smartwatch to measure barometric altitude and heart rate (as a run effort parameter), in addition to GNSS. Solli et al. [59] measured skier blood lactate accumulation (BLA) for their studies.

As for the classification algorithm, it emerged that all systems could identify diagonal strides (DIA), double poling (DP) and kick double poling (KDP) classical techniques. Rindal et al. [58] included also the herringbone (HRB) technique, by using only one IMU (upper back). Jang et al. [62]

even detected skating techniques. It emerges that alpine turning styles classification and XC sub-techniques classification can be performed by monitoring different body segments. For alpine analysis, Martínez et al. [53] and Neuwirth et al. [54] acquired IMU data from the ski boots, while for XC analysis, data from upper limbs [57], [59] and trunk [59], [60], [61] were recorded. Only the full-body system developed by Jang et al. [62] and Debertin et al. [55], having seventeen IMUs, could be employed for both disciplines. However, future research in this field could challenge this observation, as it is based on only a few studies. Indeed, the generalization of findings was limited by the low number of involved participants (15 ± 10.40) [53], [54], [59], [60], [61], and by additional factors that could have influenced their results but that were not considered, such as male-only participants [59], environmental conditions [59], [60], racing styles [59]. Debertin et al. [55] reported that the performance of their PCA-based algorithm depended on the skills of the involved expert skiers.

Research on automatic classification and turn detection algorithms using IMUs has yielded robust methods for distinguishing skiing techniques and identifying event-specific movement patterns [51], [52], [55], [56], [60]. These advancements underline the potential of wearable sensors for real-time performance feedback, yet most studies are constrained by limited participant numbers and controlled experimental conditions [51], [52], [57], [58], [59], which may affect broader applicability.

C. SKIER PERFORMANCE EVALUATION

Across all studies in this group, the average number of IMUs used was 6.3 ± 7.20, with a median of 2.5, reflecting high variability in system complexity.

The average number of participants was 19.3 ± 15.38, higher than in other sections of the review. All systems except two [63], [69] integrated GNSS sensors to record skier speed [64], [70], and global position [64], [67], [68]. Pressure insoles were used in two alpine skiing studies [63], [70], while a barometer was employed in one alpine [67] and one XC study [72]. Only one paper used solely IMUs, and it was in the cross-country domain [69]. Additional sensors included heart rate monitors (in two XC studies [71], [72]) and BLA sensors (in one XC study [71]), while video footage was used in one XC study [72].

Most of the papers, whose aim was the analysis of skier performance and skills, focused on alpine skiing (six out of ten). Yu et al. [63] and Hladnik et al. [68] employed similar motion capture suits (sixteen and seventeen IMUs, respectively), while the other systems employed three or fewer sensors, placed on the skis and chest [67], ski boots [64], [70], and upper back [65]. Yu et al. [63] and Honert et al. [70] integrated ground reaction force (GRF) data from pressure insoles, while Szczęsna and Janiak [67] also employed a barometer. The remaining four papers that investigated performance analysis in cross-country skiing proposed wearable systems with one sensor (upper back [66], [72]), three sensors (upper back, middle back and sacrum [71]), and a full-body motion suit [69]. Seeberg et al. [72] integrated a camera and a smartwatch equipped with GNSS, a barometer and a heart rate sensor, to reconstruct the distribution of sub-techniques by percentage of time and distance. Staunton et al. [71] acquired BLA measurements and heart rate signals and finally integrated IMU data with GNSS, such as Talsnes et al. [66]. The types of information derived from IMUs placed in different locations varied significantly: the differential mechanical energy $diff(e_{mech})$ [68], [72], exercise intensity from acceleration measurements [71], quaternion approximation entropy [67], G-forces impacts [65], differences between novice and expert skiers [64], correlations between the technique adopted and final ranking [69], [72], besides relative position of body segments [63], [66], [67], [69]. Apart from Hladnik et al. [68], who developed a full-body motion suit, this information was obtained from sensors positioned on the skis (or ski boots) and the trunk.

The studies on IMU-based performance evaluation highlight the ability of these systems to differentiate skill levels, assess training adaptations, and analyze equipment, contributing valuable quantitative metrics for athletes and coaches [61], [62], [63], [66], [67]. Nonetheless, the scope of findings is often limited by the homogeneity of study populations [61], [64] and the specificity of the tested settings [65], [67], [68].

D. INJURY PREVENTION AND PARALYMPIC SPORTS

In the context of injury prevention, six studies were identified and included in this scoping review, focusing on the alpine skiing environment. Across these studies, the average number of IMUs used was 3 ± 2, with a median of 2 units per system. The average number of participants was 5.5 ± 3.73, indicating that most investigations were conducted with small cohorts, a limitation commonly acknowledged by the authors.

Four systems employed pressure insoles to estimate GRF and turn events [79], [80], [82], [93], while other sensor types were rarely used: one study employed electromyography and video [93], and one used GNSS [80]. Only one study [81] relied exclusively on IMU data.

As for motion characterization in alpine skiing, the sacrum is the most frequent location [79]. Spörri et al. in [80] and [82] employed two IMUs (chest and sacrum), while in [93] they developed a wearable system with five IMUs (sacrum, shanks and thighs) and in [81] they worked with six IMUs (chest, sacrum, shanks and thighs). On the other hand, McLelland and van Breugel's [94] system consisted of a single IMU sensor placed on the right ski. Ski position can provide valuable information about the skier and the snowpack conditions. Four out of six studies merged inertial information with pressure insole data [79], [80], [82], [83] to estimate normal GRF and turn switches [80], [93]. The case study proposed in [93] also recorded electromyographic activity of some muscle groups and video footage for the biomechanical description of an ACL injury. Spörri et al. in [81] did not use additional sensors. Throughout these studies, the authors focused on different IMU data processing methods and, consequently, obtained different information: in [80], they searched for biomechanical parameters related to spinal disc loading and turn identification; then in [81], they focused on power spectral density of vibrations acting on body segments and root mean square accelerations acting on the lower back; in [82], they estimated CoM trajectory, frontal and lateral bending, torsion angles and they finally assessed possible correlations between standing height measures and spinal disc loading; in the case study [93] IMUs data provided information about flexion/extension joint angles. In the 2017 study, Spörri et al. [81] did not consider the small relative movements between IMU sensors fixed on the skin and the underlying bones, which can be regarded as a limitation. Studies leveraging IMU data for injury prevention—particularly regarding the back and knees—demonstrate the technology's utility in identifying harmful movement patterns and overuse mechanisms [75], [76], [77], [78], [89], [90]. However, the translation of these insights into generalized preventive strategies is limited by small cohorts and the technical complexity of some monitoring setups [75], [77], [78], [90]. Two papers focusing on Paralympic athletes were included in this scoping review. Ishige et al. [97] used IMUs to provide orientations and movement of the trunk relative to the ski, but the system did not consist only of IMUs; it also included EMG signals that were recorded to establish possible correlations between impairment level and trunk kinematics data derived from inertial measurements. Carlsen et al. [99] system, for XC performance analysis, correlated skiing technique selection, based on the single IMU located on the skier's upper back, with final rank, race time, and skier speed measured via GNSS.

Although research in Paralympic skiing is still emerging, IMU-based analyses have begun to shed light on the relationship between impairment level and performance, offering promising directions for future work [97], [99]. The main limitation remains the very limited number of studies and participants (seven [99] and three [97]), which restricts the strength of current conclusions.

V. CONCLUSION

This scoping review examined the state of the art of IMU-based wearable systems in the context of skiing sports, with a specific focus on in-field applications. The analysis revealed that these systems are increasingly employed for diverse objectives, often introducing novel approaches in data processing, biomechanical modeling, and physiological monitoring. Three main application areas clearly emerged: (i) skier kinematics characterization, including center of mass and joint motion estimation; (ii) classification tasks such as movement phase detection and skill-level differentiation; and (iii) injury prevention and return-to-sport support through load analysis and symmetry assessment. The findings confirm that IMU-based wearable systems can provide valuable information across multiple domains, and that many analysis methods, algorithms or principles are transferable between applications. At the same time, common limitations persist across studies: small sample sizes, insufficient attention to environmental factors, and a strong dependency on additional sensing systems reduce the generalizability of results and hinder real-world implementation. This highlights a clear gap between methodological innovation and experimental validation, which future studies should aim to bridge.

To our knowledge, this is the first scoping review specifically addressing IMU-based systems in skiing, and was intentionally conceived as a pilot effort to provide a structured overview of this growing research area. Future studies should aim to validate existing approaches under more ecologically valid conditions and with larger, more diverse populations. Such approach would help consolidate current knowledge and may eventually support the development of common frameworks or standards for IMU use in alpine skiing, cross-country skiing, and ski jumping. In line with this perspective, future progress will also depend on the availability of dedicated, standardized measuring systems and on the establishment of interdisciplinary collaborations that integrate expertise from engineering, biomechanics, sports science, and data analysis. These elements will be essential to translate current prototypical solutions into robust tools for both scientific research and professional training.

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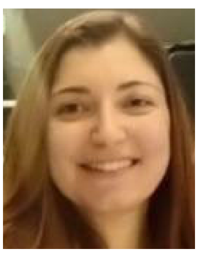

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