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OptiPath: A Multidimensional Educational Platform for Enhancing Technical Skills in Alpine Skiing

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Abstract: *OptiPath is a multidimensional desktop application designed to enhance alpine skiing technique by integrating video analysis, artificial intelligence, and machine learning. The platform enables users to upload skiing footage, from which it performs frame-by-frame detection of gates and skier trajectory, allowing for a comparative analysis between the actual and optimal skiing paths. This feedback mechanism supports athletes and coaches in identifying technical execution errors and improving performance outcomes. Developed in Python, the system utilizes object detection and image processing algorithms to deliver accurate visualizations, all without requiring an internet connection—making it particularly suited for training in remote environments. Tested under real-world giant slalom conditions, OptiPath demonstrated both reliability and ease of use, offering a lightweight, data-private solution that does not rely on user accounts or cloud storage. Its minimalist design and efficient processing capabilities make it accessible across a range of hardware configurations. By bridging traditional coaching methods with modern technological tools, OptiPath provides a precise, adaptable, and user-friendly means of technical evaluation, ultimately contributing to more effective skill development and injury prevention in alpine skiing.*

Keywords: *alpine skiing, artificial intelligence, image processing, ideal path, algorithm, mathematical model, performance analysis.*

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Introduction

The objective of this work is to present OptiPath as a technological solution for enhancing performance in alpine skiing, specifically designed to support coaches and athletes in improving technique and optimizing training strategies. The primary goal is to provide a comprehensive analysis of the skier's route, comparing the actual path taken with the ideal route, in order to identify technical flaws and suggest improvements. Another aim is to integrate advanced technologies, such as image processing, machine learning, and artificial intelligence, to offer a personalized and real-time feedback system. This feedback helps athletes and coaches monitor progress and refine techniques that will ultimately improve performance.

In alpine skiing, small differences in time—measured in hundredths of a second—can determine the success or failure of an athlete. As time measurement methods have advanced, new approaches and strategies for training have become necessary. OptiPath addresses this need by providing a solution that is both accessible and effective, enabling detailed analysis and optimization of ski path. Through precise monitoring and statistical processing of movement data, OptiPath facilitates the identification of key performance indicators, helping to improve the skier's technique and, in turn, reduce the overall race time. The technology's user-friendly interface ensures that both coaches and athletes can easily interpret the results and make data-driven adjustments to their training.

Theoretical considerations

Image processing technologies are essential in alpine skiing, as they enable precise monitoring of a skier's movements and their interaction with the terrain (Supej & Holmberg, 2011). By utilizing video cameras and advanced algorithms, the application can quickly and efficiently analyze each sequence during training sessions or competitions, providing real-time feedback. This allows coaches to detect deviations from the ideal path and suggest adjustments that can enhance performance. Additionally, video processing technology helps minimize human errors, ensuring an objective evaluation of each skier's technique (Franks & Hughes, 2004).

In alpine skiing, every detail plays a pivotal role in determining success, where even the smallest variation in technique, speed, or route can result in significant differences in performance. Factors such as body posture, edge control, carving precision, and the ability to navigate the course with optimal efficiency all contribute to the final time recorded (Federolf et al., 2014). With

competition times often separated by mere hundredths of a second, there is little room for error, and the difference between winning and losing can come down to fractions of a second (Supej & Holmberg, 2011).

In recent years, artificial intelligence (AI) and machine learning (ML) have gained substantial traction in the field of sports performance analysis. These technologies enable not only accurate movement tracking but also the ability to learn from historical performance data to provide tailored insights. In alpine skiing—where optimizing body posture, trajectory, and speed is essential—such advancements can significantly enhance training efficiency. The integration of AI and ML allows for the development of intelligent systems capable of delivering specific, data-driven recommendations, moving beyond generic assessments. This personalized approach empowers athletes and coaches to target individual weaknesses with precision. Moreover, recent progress in deep learning, particularly in motion tracking and activity recognition, has demonstrated promising applications across various sports, from beach volleyball to soccer, underscoring the growing potential of AI-powered tools in elevating both strategy and individual performance (Kautz et al., 2017).

In this highly competitive environment, technology plays a crucial role in pushing the boundaries of performance. Advanced tools, such as motion sensors, video analysis, and real-time data processing, allow athletes and coaches to break down each aspect of a skier's run (Kirby, 2009). From analyzing the precise angles of turns to evaluating the athlete's reaction times, technology enables a deeper understanding of how small adjustments can lead to improved results. Furthermore, the application of artificial intelligence and machine learning allows for the creation of personalized feedback systems, where data from past performances can be analyzed to provide specific recommendations for improvement (Claudino et al., 2019). The evolving role of AI, specifically, has also initiated an era of hyper-personalized training where all the strengths and weaknesses of each athlete are thoroughly charted in order to achieve maximum efficiency of movement (Rai, 2020)

As part of this research, various sources and platforms were explored to identify existing applications capable of performing advanced analysis of skiing trajectories, comparing actual paths with optimal ones and providing detailed, personalized feedback. To date, no application has been identified that integrates image processing, machine learning, and artificial intelligence in an accessible format tailored specifically for alpine skiing. While there are applications that provide performance analysis for other sports, they do not focus specifically on alpine skiing and do not integrate the advanced

technologies needed for detailed route evaluation and technique improvement.

OptiPath is an innovative desktop application designed to meet the increasingly complex demands of skiers and coaches in the field of alpine skiing. In a sport where every detail matters and performance is influenced by factors such as technique, speed, and the chosen route, technology plays a crucial role (Supej & Holmberg, 2019). The OptiPath application employs advanced image processing algorithms, machine learning, and artificial intelligence to provide precise and personalized analyses of ski path. Its primary goal is to compare the actual route with the ideal route, identify differences, and offer recommendations for improving technique and performance. Since ski athletes are usually presented with the problem of having to adjust their movements in real time, being able to depend on technology to provide instant feedback enables quicker adaptation and improved performance both in training and competition (Baca & Kornfeind, 2006).

Training in alpine skiing requires precision and attention to detail, as competition times can differ by mere hundredths of a second. OptiPath offers a technological solution that enables a detailed analysis of skiers' movements by comparing the actual route with the ideal one. This way, the application helps identify and correct technical deficiencies, allowing athletes to enhance their performance.

To strengthen the technical claims of the study, it is essential to position OptiPath within the broader evolution of artificial intelligence applications in sports science. In recent years, AI—particularly deep learning—has been increasingly utilized to enhance performance analysis through video-based motion tracking. Markerless systems such as OpenPose (Cao et al., 2021) and DeepLabCut (Nath et al., 2019) have demonstrated high accuracy in extracting biomechanical data in real-time, without the need for wearable sensors. Beyond pose estimation, AI has also proven effective in interpreting complex movement patterns and optimizing technical performance in high-intensity sports such as football (Liu et al., 2020). These methodologies highlight the growing role of AI in performance analytics, especially in environments where precision and adaptability are critical. OptiPath aligns with these developments by integrating video-based object tracking and AI-driven trajectory modeling into a user-friendly application specifically designed for alpine skiing. Its ability to compare actual versus ideal skier paths in real conditions underscores the relevance of AI tools in individual sports, reinforcing both the scientific value and international applicability of the proposed solution.

In this context, OptiPath represents a significant leap in integrating cutting-edge technology into alpine skiing, providing athletes and coaches with a powerful tool for analyzing and improving technique in a way that would not have been possible with traditional training methods.

The main objectives of the OptiPath application are to provide a fast and precise method for analyzing skiers' path, thus enabling the identification and correction of technical errors. Additionally, the application allows coaches and athletes to collaborate more effectively in the performance improvement process, benefiting from detailed and personalized feedback. Another key objective of OptiPath is the integration of modern technologies, which are essential for maximizing athletic performance and optimizing training, thus contributing to achieving higher standards in alpine skiing.

Mathematical model

For this application to be developed, a mathematical model was needed to calculate the ideal path, enabling the comparison between the skier's actual path and the ideal one. Alpine skiing can be defined as a continuous movement composed of alternating phases of "loading" (the turning phase) and "unloading" (the edge change phase) (Müller & Schwameder, 2003) and this characteristic is symmetric for both the right and left legs. In order to determine the mathematical model to be used in the application, it is necessary to understand how the perfect turn works and what are the steps required to perform it:

1. **beginning of the turn** – this is the first phase of the turn, where the inner ski begins to take on the skier's force.
2. **apex of the curve** – the hips are slightly rotated and tilted towards the snow until a slight counter-rotation occurs, depending on the skier's flexibility for building centrifugal force. In this phase, the ski is fully unloaded, and the outer ski bears 90% of the skier's weight. In an ideal turn, the snow left behind is minimal.
3. **end of the turn** – in the final part of the turn, the energy reaches its peak, being released and directed towards the next turn (Müller et al., 1997).

The equation of the ideal turn has already been studied and analyzed by other researchers, which has made the implementation of the ideal path much easier, thanks to the availability of this equation.

The following equations determine the curve of a turn and the skier's motion along the curve. The main aspect that was improved with the work of Jentschura and Fahrbach, "Physics of Skiing: The Ideal-CARVing Equation and Its Applications," was the fact that there was no differentiation between

the end of one turn and the beginning of another. Additionally, in slalom and giant slalom races, the turn radius is smaller than the ski's edge radius (Jentschura & Fahrbach, 2004). The aforementioned work is not the only one presenting an ideal path equation, but the equation from this paper is the best and easiest to implement in an application.

In calculating the ideal equation, the following must be taken into account:

- parameters
  - the slope inclination;
  - gravitational acceleration;
  - sidecut radius;
- variables
  - the skier's speed
  - the angle between the skier's trajectory and the horizontal;
  - the instantaneous curvature of the skier's trajectory (Jentschura & Fahrbach, 2004).

It is assumed that the skier's trajectory is horizontal, and for a direct trajectory along the slope line, the following values are distinguished:

$\beta = 90^{\circ}$

$F_{lat} = 0$

$F_S = F_P$

where:

F_{lat} – lateral force

F_S – force

F_P –parallel force (Jentschura & Fahrbach, 2004)

For balance, we have the following equation:

$F_{load} = W - F_P = F_N - F_{lat}$

Executing a turn requires that the effective weight of the force F_{LOAD} acts along the straight line connecting the ski boots with the skier's center of mass. The equation for the ideal turn results from the combination of the two equations below:

$$tan\phi = \frac{v^2}{gRcos\alpha} - \frac{tan\alpha\ cos\beta}{\sqrt{\frac{R_{SC}^2 - 1}{R^2}}}$$

where:

v – skier's speed;

β - the angle between the skier's trajectory and the horizontal, and the radius R of the skier's trajectory

R – ski radius;

α - slope inclination;

R_{SC} -sidecut radius of the ski;

g – gravitational acceleration.

The equation of the optimal path is:

$$\sqrt{\frac{R_{SC}^2}{R^2} - 1} = \frac{v^2}{gRcos\alpha} - tan\alpha\ cos\beta$$

Given the equation of the optimal path, the variables of this equation are the skier's speed v, the angle β between the skier's trajectory and the horizontal, and the radius R of the skier's trajectory. The parameters of the equation for the optimal path are the slope inclination α, gravitational acceleration g, and the sidecut radius of the ski R_{SC}. Furthermore, the equation of the optimal path also defines a function for the optimal path, which is (Jentschura & Fahrbach, 2004)

$$(v, R, \beta) = \frac{v^2}{gRcos\alpha} - tan\alpha\ cos\beta - \sqrt{\frac{R_{SC}^2}{R^2} - 1}$$

System requirements, compatibility, and user interface design

The educational value of OptiPath is closely tied to its technical design, particularly its user-friendly interface, accessibility across various environments, and minimal system requirements. These features are essential in a sports training context, where the primary focus must remain on the learning process, not on overcoming technological barriers. The application's simple and intuitive interface allows both athletes and coaches to use it effectively without requiring advanced technical knowledge, thereby supporting self-guided learning and instructional flexibility. Whether analyzing a routine training session or preparing for a major competition, the platform facilitates precise monitoring of skier performance, making it a valuable tool for both skill acquisition and coaching strategies.

OptiPath is compatible only with computers running Windows 10 or later, as certain libraries used in development are not supported by Linux or

macOS. The application requires an Intel Core i5 processor (or equivalent) and at least 4 GB of RAM, ensuring smooth operation even on mid-range systems. With no need for user accounts or cloud storage, the application consumes minimal local resources—approximately 150MB for installation—while also allowing the uploading of videos and coordinate files directly from the cloud if needed. This ensures the application remains functional even in remote mountain locations with limited or no Internet connectivity.

Designed for portability and low-friction deployment, OptiPath requires only a basic folder structure (as shown in Figure 1) and the presence of a few essential software components:

- Python version 3.8;
- JRE (Java Runtime Environment) version 1.4.2 or later;
- JAVA;
- Excel

These dependencies are common in most institutional or personal computing setups, ensuring the software can be installed and used without extensive configuration.

The user interface is deliberately minimalistic, using a single-window layout with standard window control symbols and an English-only menu system. Although the language cannot be changed, the menu design is intuitive and straightforward, eliminating the need for localization. Additionally, the platform restricts simultaneous video processing due to resource demands, which simplifies the focus of each training session and minimizes distractions.

The workspace of the application has been designed to support intuitive and efficient interaction, particularly in educational and training contexts (see Fig. 1). The main interface includes standard window controls in the top-right corner, with a simplified layout that avoids unnecessary complexity. All key functions—such as video upload, trajectory comparison, and visual feedback interpretation—are grouped in a logically structured menu system. This allows users to access essential tools quickly, with minimal cognitive load, which is especially important during real-time analysis or when working with athletes in training sessions. The default language of the application is English, and although it cannot be changed, the simplicity of the interface design ensures usability for a wide range of users. Figure 1 illustrates the main interface of OptiPath, highlighting its focus on clarity, accessibility, and functional relevance in the context of alpine skiing technique development.

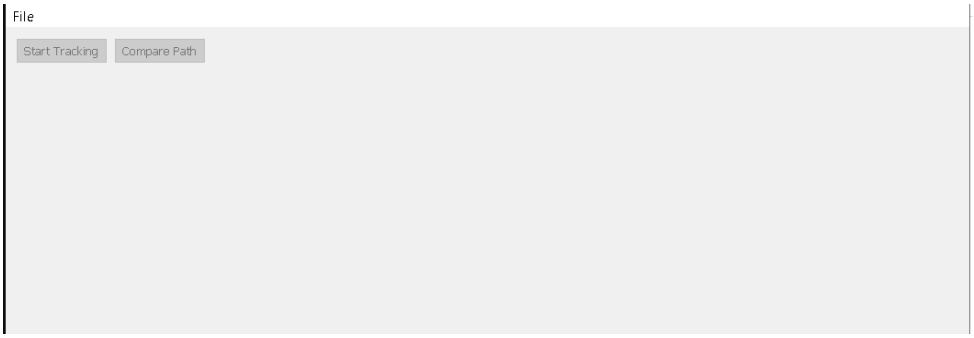


Fig. 1. The Main Interface of the OptiPath Application

Most importantly, OptiPath was developed with key pedagogical principles in mind, aiming to support both independent learning and coach-assisted instruction in alpine skiing. These principles include:

- ease of use by individuals involved in ski training, regardless of their level of digital literacy;
- minimal setup time, reducing the number of steps required before initiating a training session;
- adaptability to various environments, allowing use on any slope or training location, including remote areas;
- compatibility with commonly available devices, ensuring the application is accessible to coaches and athletes without specialized hardware;
- accuracy and reliability of data analysis, ensuring that processing errors do not distort real-world skier performance;
- support for focused, distraction-free sessions, by intentionally limiting simultaneous video processing and interface complexity.

These design choices ensure that the platform not only meets technical expectations, but also enhances the instructional process, making alpine skiing training more accessible, precise, and effective.

The algorithm behind the application

In the application, a video of an athlete in motion, skiing between gates, is uploaded. When the video starts, the application detects the gates and analyzes frame by frame the path followed by the skier. Based on the positions and coordinates of the gates, the application calculates the optimal path. The application performs the analysis based on the skier's movement, capturing not only the position of the gates but also the skier's motion to evaluate the trajectory.

Once the video starts playing, the algorithm behind the application will begin to track the skier's movement. Upon completion of the video, the application will detect the gates and then the path the skier followed. Subsequently, the application will mark the path the skier took with a line. However, to display the comparison between the two paths—the ideal path and the skier's path—the coordinates of the gates must be uploaded. Only after the coordinates are loaded will the application be able to display the comparison between the two paths.

OptiPath was developed using the Python programming language. With the help of the libraries provided by this programming language, gates can be detected, with the model identifying the gate using Python's built-in algorithms. Moreover, the gate detection structure is based on object detection models, and through image processing, the application detects the gate. Once the gate is detected, the information is sent to the backend, where the detected gate is saved. Next, OptiPath begins processing to detect the skier's movement, using image processing algorithms and machine learning. These algorithms detect the movement, and based on this detection, the skier's path is calculated and traced from the video. Additionally, the application uses artificial intelligence models, which, along with the gate coordinates and the skier's path, draw both paths. When the skier moves, AI-based models come into play, which, together with machine learning models and image processing, detect the movement in the video and capture it. It is important to note that the AI model stores the skier's path information, and then a mathematical model is used to compare the two paths. The AI model in use refers to the personalization server that runs AI and the backend.

In order for the application to find both the optimal path and the skier's path, it is necessary to have the coordinates of the gates, as the application relies on these coordinates to calculate the paths. The coordinates are uploaded by the user into the application, and based on this data, OptiPath draws the optimal path, which is then compared with the skier's actual path.

Results and discussions

This study introduces OptiPath, a novel desktop application developed to enhance performance analysis in alpine skiing by combining video-based trajectory detection with artificial intelligence. The tool was tested during giant slalom trials and proved effective in identifying deviations between the skier’s actual path and an ideal trajectory. While OptiPath demonstrates strong potential for training optimization, certain limitations should be acknowledged to contextualize its use, particularly in international or high-performance environments.

The primary data collected for analysis included: GPS coordinates of race gates, skier trajectories extracted from video recordings, and deviation metrics computed between the actual and ideal skiing paths. These data sets were visualized and analyzed to evaluate skier movement accuracy, identify execution errors, and assess performance consistency. The deviation data allowed for detailed technical feedback based on distance offsets at each gate and across the full race trajectory.

One of the main contributions observed throughout the implementation of the OptiPath platform is its role in enhancing technical skills in alpine skiing. The system integrates a series of interactive modules that combine video analysis, simulated practice environments, and personalized feedback mechanisms. These features allow athletes to engage in targeted training sessions adapted to their individual skill levels, focusing on key technical components such as carving, body posture adjustment during turns, and optimal weight distribution. The inclusion of real-time feedback facilitates immediate error correction, promoting more efficient motor learning. Moreover, the performance tracking functionality enables longitudinal monitoring of progress, providing valuable insights into the athlete's technical development over time. These elements collectively support a structured and adaptive training experience, emphasizing the practical relevance of OptiPath in optimizing alpine skiing technique.

This data-driven feedback not only provides quantitative insights into skiing performance but also supports a reflective learning process. By visually comparing their actual and ideal trajectories, athletes are empowered to recognize specific errors, understand their causes in context, and apply corrective actions in future sessions. Such an approach is consistent with experiential learning theory and formative assessment principles widely adopted in sports education. The visual clarity of OptiPath's trajectory comparisons makes it an intuitive and pedagogically valuable tool for both self-guided improvement and coach-led instruction.

From an international perspective, OptiPath contributes meaningfully to innovation in training methodologies. It provides a scalable and reproducible solution that requires only standard video footage and smartphone-based GPS input, enabling broader adoption in both resource-rich and resource-limited settings. Furthermore, the integration of AI-powered visual tracking into a user-friendly application bridges the gap between theoretical models and practical deployment in alpine skiing-opening opportunities for adaptation to other technical sports, both in winter and summer disciplines.

In Figure 2, the final result is presented, showing the purpose for which the application was created. The skier's path is represented in green, while the ideal path is shown in red. "S" represents the start, and "E" represents the finish, with the numbers indicating the gates. Based on this image, athletes and their coaches can analyze the differences between the two paths, identifying where mistakes occurred and what technical adjustments are needed. This comparison directly supports skill refinement and performance enhancement.

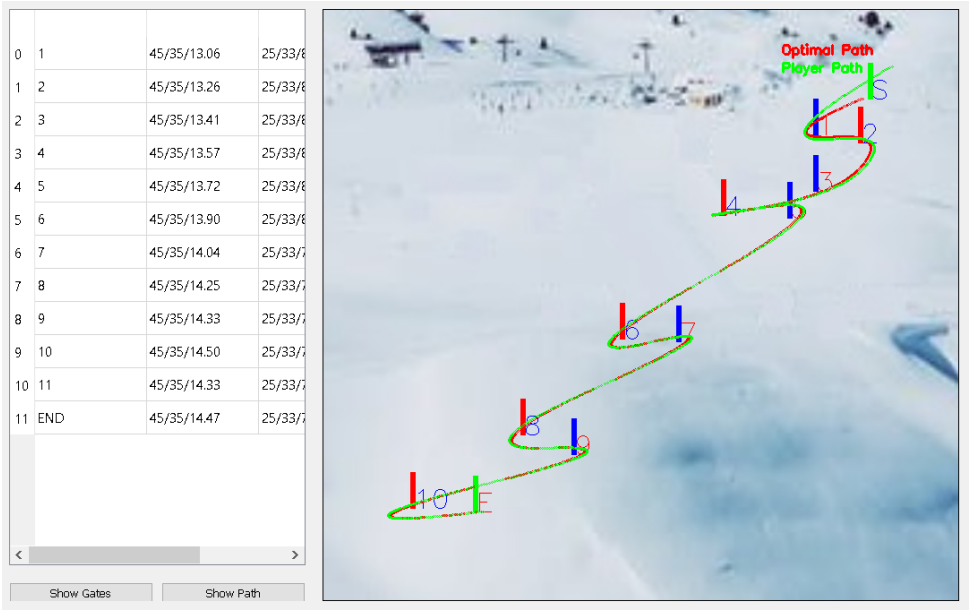


Fig. 2. Comparing the two paths (ideal and real)

The testing of the OptiPath application was conducted directly by the authors during a controlled giant slalom training session, organized specifically for this study. The course was set up over a 100-meter slope with 10 gates (flags) placed at an average distance of 10 meters. The starting point was located at an altitude of 1,546 meters, and the finish line at 1,517 meters, resulting in a 29-meter vertical drop. Each athlete participating in the trial was filmed using a mobile phone operated by the research team, and the resulting videos were uploaded into the OptiPath application for analysis. The goal of the trial was for each athlete to complete the course in the shortest time possible, while maintaining technical precision. The authors designed and supervised the data collection process, configured the experimental parameters, and performed the comparative analysis of actual versus ideal

trajectories using the OptiPath platform. Deviations were identified, execution errors were highlighted, and corrective strategies were proposed based on trajectory data. This procedure allowed the authors to evaluate the educational relevance of the tool by observing its capacity to support performance feedback, visual learning, and targeted skill improvement under realistic alpine skiing conditions.

Considering that in alpine skiing, technical events require a number of 40-50 gates (flags) depending on the type of event (giant slalom or slalom), determining the GPS coordinates of each flag using topographic stations would require a very lengthy process, which is not available before the event. Additionally, the slopes on which competitions take place are not mapped, which is why interested parties, or the general public do not have access to certain technical data regarding the surface on which the competition takes place. The GPS coordinates provided by a mobile phone are not as precise as those provided by a topographic station.

While GPS accuracy from smartphone apps such as "Ski Track Lite" introduces a positional error margin of approximately ±4 meters, this solution was intentionally chosen due to its accessibility and ease of use in training contexts. The application "Ski Track Lite" was identified as the most accurate among those tested, as it provides coordinates with a third decimal value, crucial for ensuring the correct placement of gates and generation of ideal routes. Although this may impact precision on steep or technically complex slopes, the trade-off allows teams without access to professional topographic equipment to still benefit from trajectory analysis. The application must be started in advance to allow for data calibration, and while some map discrepancies remain, this method remains practical and effective for visual and technical evaluation in alpine skiing training

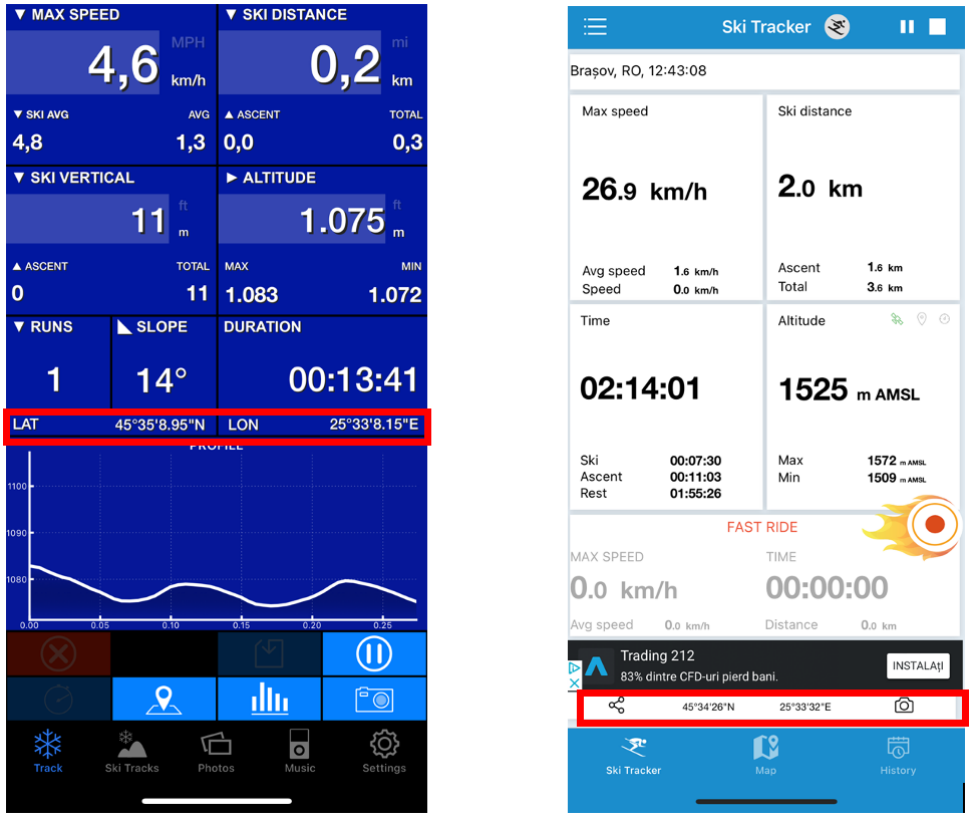


Fig. 3. Coordinate display in the "Ski Track Lite" application (left) vs. a low-precision application (right)

To further validate the application's analysis capabilities, additional tests were performed using controlled skier distances from the gates: 0.5 m, 1 m, 1.5 m, and 2 m. These tests revealed visible differences in trajectory comparisons depending on gate proximity, confirming that OptiPath can capture and reflect fine deviations. The visual comparisons (see Fig. 4) clearly demonstrate how the real path diverges from the ideal, especially at larger distances. This allows coaches and athletes to identify specific points of deviation, understand the cause (e.g., turn execution or posture), and plan targeted corrections. Although OptiPath operates in post-session mode, this functionality aligns with experiential learning principles, enabling reflection, self-assessment, and technical refinement. Thus, the tool supports both immediate feedback after practice and long-term tracking of individual progress in technical skill development.

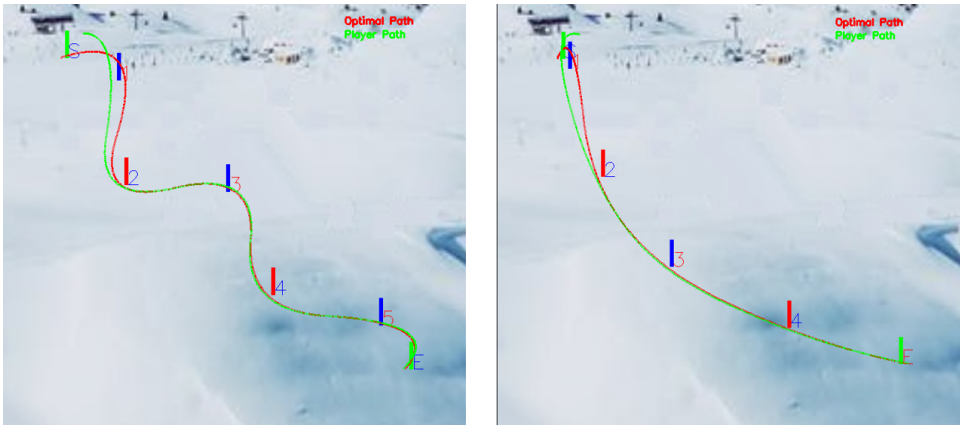


Fig. 4. The ideal and real route of the skier for 2 m (left) and 0.5 m (right)

Comparing the two paths (ideal and real) is a crucial step in evaluating the skier's performance and identifying areas for improvement. By visually examining the differences between the ideal path (represented in red) and the skier's actual path (shown in green), coaches and athletes can pinpoint specific sections where the skier deviated from the optimal route. These deviations may occur due to incorrect turns, poor edge control, or improper posture.

Through this comparison, the application provides a detailed analysis of the skier's performance, helping to assess factors such as speed, carving precision, and course navigation efficiency. It also allows for the identification of mistakes in specific gates or turns, enabling targeted corrective actions to enhance technique. Over time, consistent feedback and adjustments based on these comparisons can lead to significant improvements in the skier's ability to follow the ideal path, ultimately enhancing performance and reducing race times.

Another current limitation is that OptiPath is designed for post-session analysis rather than real-time feedback, which may reduce its immediate applicability in elite coaching scenarios. Nevertheless, the software offers a valuable contribution by facilitating visual comparisons between actual and ideal skiing trajectories. This supports reflective learning, allowing athletes to identify and correct errors based on targeted, visual feedback—an approach consistent with experiential learning theories and formative assessment in sports education.

Conclusions

OptiPath represents a significant leap in integrating advanced technology into alpine skiing, providing athletes and coaches with a high-performance tool for analyzing and improving technique in a way that would not have been possible with traditional training methods. The application uses advanced video processing algorithms, artificial intelligence, and machine learning to offer a detailed and objective assessment of the paths taken by skiers, allowing for the comparison of the real route with the ideal route. This comparison is essential in performance analysis, helping to correct mistakes and refine movements.

The original contribution of the authors lies in the integration of AI-based object detection and path modeling into an accessible and easy-to-use application, which visualizes both the real and ideal trajectories, facilitating the correction of skiing technique. The system was tested under real giant slalom conditions, and the results suggest strong potential for practical use in performance optimization. Unlike previous studies that use wearable sensors or complex calibration setups (such as high-precision GPS or motion capture labs), OptiPath offers a more accessible solution, requiring only a standard video input and a minimal set of gate coordinates. This simplified solution allows for flexible use in real-world training environments, even on uncatalogued slopes.

The international significance of the article lies in the innovative approach to analyzing skiing technique through the integration of emerging technologies, which are increasingly being used in elite sports but have not been applied in an accessible manner for most coaches and athletes. The application contributes to the development of winter sports by applying cutting-edge technologies at an accessible level, which directly impacts training processes and the optimization of athletes' techniques globally. The study emphasizes the importance of making performance technology accessible in winter sports, enabling coaches to improve training processes and optimize athletes' techniques in a fast and effective manner.

However, there are some significant limitations that need to be discussed. One of these limitations is the ±4-meter error margin resulting from the use of the "Ski Track Lite" mobile app for GPS coordinate collection. This margin of error can affect the precision of the route comparison, especially in high-performance training conditions. While this choice was made to ensure the app's accessibility, the authors recommend that future developments consider integrating more accurate data acquisition methods to improve reliability and precision. Despite this limitation, OptiPath remains an innovative and effective tool for enhancing alpine skiing

performance, making a significant impact in both the sports field and international sports education.

Moreover, regarding platform compatibility, the current version of OptiPath is designed as a desktop-based application for controlled testing environments. However, future development will aim to extend its usability through cross-platform implementations, including mobile and web-based versions, ensuring greater accessibility and flexibility for both athletes and coaches in field conditions.

In conclusion, OptiPath is not just a simple analysis tool but a genuine platform for continuous performance improvement, offering athletes and coaches a significant advantage on their path to excellence. As technology advances, applications like OptiPath will become increasingly essential, radically transforming the way winter sports are prepared and performed at the highest level. Therefore, OptiPath opens new horizons in athlete training and winter sports research, with the potential to evolve into a robust platform supporting high-performance sports at the international level.

References

Baca, A., & Kornfeind, P. (2006). Rapid feedback systems for elite sports training. *IEEE Pervasive Computing*, *5*(4), 70-76. https://doi.org/10.1109/MPRV.2006.82

Cao, Z., Hidalgo, G., Simon, T., Wei, S. E., & Sheikh, Y. (2021). Openpose: Realtime multi-person 2d pose estimation using part affinity fields. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *43*(1), 172-186. https://doi.org/10.1109/TPAMI.2019.2929257

Claudino, J. G., Capanema, D. O., de Souza, T. V., Serrão, J. C., Pereira, A. C., & Mujika, I. (2019). Current approaches to the use of artificial intelligence for injury risk assessment and performance prediction in team sports: A systematic review. *Sports Medicine Open,* *5*(1). https://doi.org/10.1186/s40798-019-0202-3

Federolf, P., Reid, R., Gilgien, M., Haugen, P., & Smith, G. (2014). The application of principal component analysis to quantify technique in sports. *Scandinavian Journal of Medicine & Science in Sports*, *24*(3), 491–499. https://doi.org/10.1111/j.1600-0838.2012.01455.x

Franks, I., & Hughes, M. (Eds.). (2004). *Notational analysis of sport: Systems for better coaching and performance in sport* (2nd ed.). Routledge. https://doi.org/10.4324/9780203641958

Jentschura, U. D., & Fahrbach, F. (2004). Physics of skiing: The ideal carving equation and its applications. *Canadian Journal of Physics*, *82*(4), 249-261. https://doi.org/10.48550/arXiv.physics/0310086

Kautz, T., Groh, B., Hannink, J., Jensen, U., Strubberg, H., & Eskofier, B. (2017). Activity recognition in beach volleyball using a deep convolutional neural network. *Data Mining and Knowledge Discovery, 31*, 1678–1705. https://doi.org/10.1007/s10618-017-0495-0

Kirby, R. (2009). Development of a real-time performance measurement and feedback system for alpine skiers. *Sports Technology*, *2*(1-2), 43-52. https://doi.org/10.1080/19346182.2009.9648498

Liu, H., Gómez, M. A., Gonçalves, B., & Sampaio, J. (2015). Technical performance and match-to-match variation in elite football teams. *Journal of Sports Sciences*, *34*(6), 509–518. https://doi.org/10.1080/02640414.2015.1117121

Müller, E., & Schwameder, H. (2003). Biomechanical aspects of new techniques in alpine skiing and ski-jumping. *Journal of Sports Sciences*, *21*(9), 679–692. https://doi.org/10.1080/0264041031000140284

Müller, E., Schwameder, H., Kornexl, E., & Raschner, C. (Eds.). (1997). Science and Skiing (1st ed.). Taylor & Francis. https://doi.org/10.4324/9780203476178

Nath, T., Mathis, A., Chen, A., Patel, A., Bethge, M., & Mathis, M. (2019). Using DeepLabCut for 3D markerless pose estimation across species and behaviors. *Nature Protocols, 14*, 2152–2176. https://doi.org/10.1038/s41596-019-0176-0

Rai, A. (2020). Explainable AI: From black box to glass box. *Journal of the Academy of Marketing Science*, *48*, 137-141. https://doi.org/10.1007/s11747-019-00710-5

Supej, M., & Holmberg, H. C. (2011). A new time measurement method using a high-end global navigation satellite system to analyze alpine skiing. *Research Quarterly for Exercise and Sport*, *82*(3), 400–411. https://doi.org/10.1080/02701367.2011.10599772

Supej, M., & Holmberg, H. C. (2019). Recent Kinematic and Kinetic Advances in Olympic Alpine Skiing: Pyeongchang and Beyond. *Frontiers in physiology*, *10*, 111. https://doi.org/10.3389/fphys.2019.00111