Ski Tip Display: Design and Implementation of an Unobtrusive Ski Mounted Visual Feedback System for Alpine Skiing

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Abstract: This paper presents the design, implementation, and field evaluation of *SkiTip Display*, a ski-mounted LED feedback system that provides terminal visual feedback on carving angle to support skill development in alpine skiing. Developed through a participatory design process with domain experts, the system was deployed in-the-wild and tested with nine recreational skiers. Results from sensor-based metrics and post-session interviews suggest that ski-mounted visual feedback is perceivable, motivating, and well-suited for post-run reflection, though not actionable during motion. We report key lessons on feedback timing, simplicity, and trust, and discuss implications for designing embedded performance feedback in high-speed outdoor sports. This work contributes to the field by expanding the design space for equipment-integrated feedback systems and by articulating challenges of in-the-wild deployment in dynamic environments.

1 INTRODUCTION

In alpine skiing, developing technique requires continuous feedback — often available only through in-person instruction or self-assessment based on delayed, indirect information. While commercial systems such as ski-tracking smartphone apps or wrist-worn devices offer post-run summaries, these technologies typically provide numerical feedback, rely on limited screen interfaces, and are hard to use in cold, fast-paced environments, especially when wearing gloves (Mencarini et al., 2019b; Colley et al., 2018). The need remains for a lightweight embedded device that can provide timely feedback and integrate directly into the flow of skiing without disrupting it.

We address this gap through the *SkiTip Display*, a ski-mounted LED feedback system designed to present *terminal feedback* (Walsh et al., 2009) — feedback provided immediately after performance - directly on the equipment. By leveraging the ski as a feedback surface, we explore the unique affordances of peripheral visibility and embodied integration in a context where traditional display surfaces are often inaccessible or unsafe to consult during motion. Prior work has investigated feedback displays on boards in other snow sports, such as snowboarding (Park and Lee, 2016b; Park and Lee, 2016a), and on shoes for running and cross-country skiing (Colley et al., 2018), but it remains unclear how such approaches translate to alpine skiing with its specific postures, edge control demands, and speed constraints.

We focus specifically on *carving angle*, the inclination of the ski relative to the snow surface during a turn, as a domain-relevant performance indicator. Carving angle is closely associated with advanced ski technique and is widely used in instruction and coaching to evaluate edge control, turn quality, and skier progression (Sigrist et al., 2013). It is also readily measurable via inertial sensing, and is intuitive enough to be communicated through simple visual abstractions on the ski itself.

This paper explores the feasibility and value of ski-mounted visual feedback systems through the design, implementation, and field deployment of SkiTip Display. The system was developed in collaboration with expert skiers via participatory design workshops and evaluated in-the-wild with nine recreational skiers.

We address the following research questions:

- **RQ1:** How can skis be used as a display medium for terminal feedback in alpine skiing?
- **RQ2:** What are skiers' perceptions of ski-mounted feedback after repeated use in realistic

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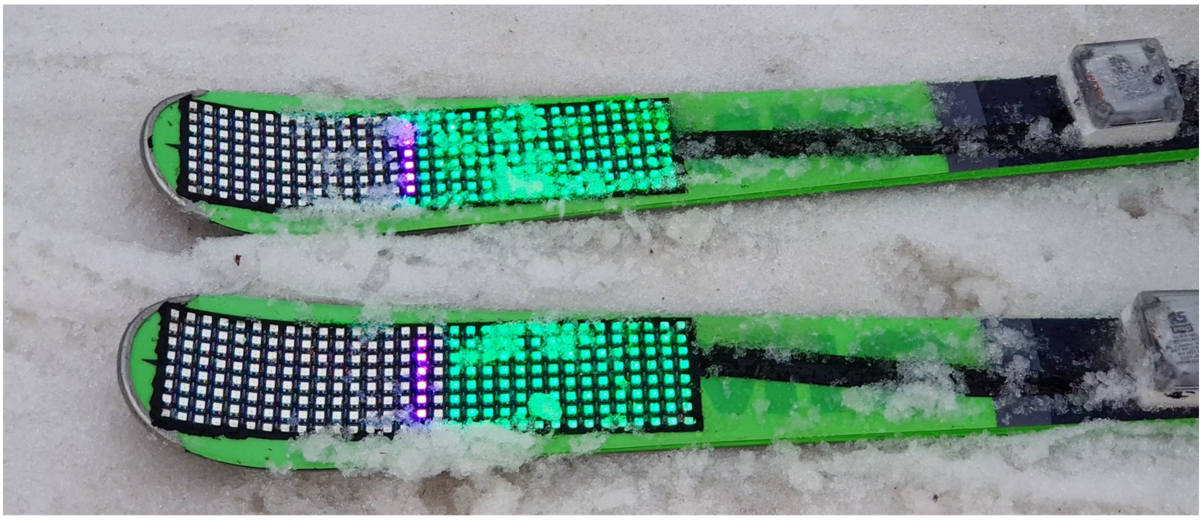

Figure 1: The SkiTip Display system on snow during the user study.

slope conditions?

- **RQ3:** How do carving angle metrics evolve with exposure to such feedback, and what contextual factors (e.g., fatigue, snow conditions) influence this?

Through this work, our objective is to contribute a situated understanding of equipment-integrated feedback in alpine sports and to reflect on the design challenges and opportunities of deploying such systems in real-world outdoor environments.

2 RELATED WORK

We situate our work within the domains of technology-enhanced alpine sports and the broader landscape of feedback systems in sports, particularly in relation to feedback modality, timing, and embodiment.

2.1 Feedback Systems in Alpine Snow Sports

Digital tools for skiing and snowboarding increasingly support skill acquisition through motion tracking, performance visualization, and gamified feedback. Prior systems have mounted feedback displays on snowboards (Park and Lee, 2016b) or integrated feedback into boot or helmet accessories. However, these systems typically offer coarse-grained information or use displays that are not in the skier's peripheral view. Our approach is most directly inspired by snowboard-mounted displays (Park and Lee, 2016b), but differs in several key respects: skiing posture limits opportunities for direct visual attention to the skis during movement, and carving technique places more emphasis on sustained edge angles and turn shape. Our system focuses on post-run feedback (terminal), allowing skiers to reflect on performance without compromising on-slope safety.

2.2 Wearable and Embedded Feedback Systems

More broadly, researchers have explored wearable and embedded systems that support bodily awareness and training. Colley et al. (Colley et al., 2018) proposed shoe-mounted displays for running, and different feedback modalities have been applied to a variety of sports (e.g., running (Jensen and Mueller, 2014; Mueller and Muirhead, 2015; Van Rheden et al., 2024), swimming (Wiesener et al., 2019; Bächlin et al., 2009), climbing (Mencarini et al., 2019a), and dancing (El Raheb et al., 2018; El Raheb et al., 2019)). Feedback modality has been a central concern, with comparative studies of visual, auditory, and haptic feedback showing trade-offs in terms of attention, bodily integration, and timing (Sigrist et al., 2013). Unlike wrist-worn or audio systems, our ski-mounted display aims to provide immediate, spatially grounded feedback using a surface already in the skier's visual field when stationary. This explores an under-addressed modality-location pairing: visual feedback on equipment rather than on-body or auditory overlays.

2.3 Timing and Modality of Feedback

The timing of feedback significantly shapes its effectiveness in motor learning. Sigrist et al. (Sigrist et al., 2013) distinguish between concurrent feedback (during action) and terminal feedback (after completion). While concurrent feedback may disrupt performance in dynamic, high-risk sports like skiing, terminal feedback offers a safer alternative, enabling reflection without cognitive overload or safety trade-offs. Our design prioritizes terminal feedback, communicated through a color-coded LED visualization immediately after a run. This allows skiers to connect the visualization to their just-completed performance while stationary, without interfering with run-time attention.

2.4 Summary

In contrast to prior work on wearable devices and snow sport augmentations, our system uniquely explores ski-mounted terminal feedback for carving angle awareness. We contribute an empirical evaluation of this design in field conditions, and reflect on the user experience of embedded feedback directly integrated into sports equipment.

3 APPROACH AND METHODOLOGY

3.1 Approach and Methodology

The development of the SkiTip Display followed a multi-stage process involving expert consultation, iterative prototyping, and in-situ evaluation. The overall objective was to design and assess a ski-mounted feedback system capable of supporting skill development through terminal visual feedback.

3.2 Expert Workshop

To inform the initial design, a structured participatory workshop was conducted with six domain experts, including two certified ski instructors, two competitive skiers, and two HCI researchers specializing in sports technology. The workshop, lasting approximately 2.5 hours, was organized into three phases. First, a contextual inquiry was carried out, during which participants were asked to reflect on common challenges encountered during technique development in alpine skiing, as well as their experiences with existing feedback systems such as smartphone applications and wearable devices. Second, an ideation session was facilitated. Participants, working in two groups, were prompted to generate concepts for embedded feedback systems. Each group was provided with worksheets and sketching materials and was asked to consider locations for feedback display, suitable information modalities, and preferred timing of feedback. Third, a consolidation and reflection phase was conducted. Each group presented its concepts, which were then evaluated through guided discussion based on visibility, intuitiveness, safety, and feasibility in outdoor skiing conditions. In total, 55 distinct design ideas were generated. These were subsequently analyzed using open coding and affinity mapping to identify cross-cutting themes. It was found that peripheral visual feedback was generally preferred, and that feedback was considered most useful when presented immediately after a skiing run. The ski itself—particularly the tip region—was identified as a promising location for integrating such feedback. These findings informed the subsequent design phase.

3.3 Design Rationale

The tip of the ski was selected as the display location based on its visibility while stationary, minimal interference with skiing movement, and potential for integration into existing equipment. This approach aligns with broader trends in embodied sports technologies that emphasize minimal intrusiveness and environmental robustness (Mencarini et al., 2019b). Carving angle was chosen as the primary performance metric. This parameter, defined as the inclination of the ski relative to the snow surface during turning, is frequently used by instructors as an indicator of edge control and technical proficiency. Furthermore, the carving angle can be reliably estimated using inertial measurement data, and its range can be intuitively encoded through color-based visualizations. It has been identified as a central quality metric for carved skiing turns by Müller and Schwameder (Müller and Schwameder, 2003).

3.4 Visual Design

The visual design was developed to represent the mean carving angles reached during one run in the most simplified way (See figure 2). The green bar (a) represents the mean carving angle of the last run. The purple line (b) indicates the respective previous run. Point (c) references the individual maximum carving angle, which was derived from the baseline runs maximum + 10° rotation angle.

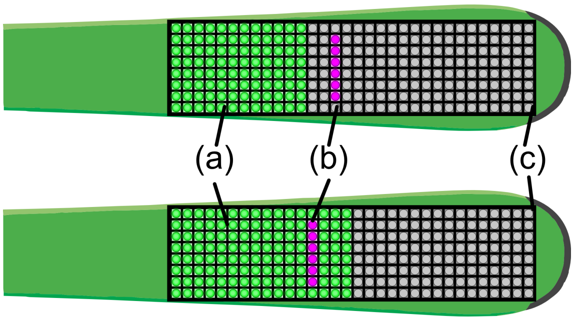

Figure 2: The visual design of the feedback on carving angles with ski-mounted displays in alpine skiing.

3.5 Prototype Implementation

The prototype system consisted of the following components (See figure 3):

a) A pair of Bluetooth-connected, six-axis Inertial Measurement Units (IMUs; Atomic Movesense) strapped to the shafts of standard ski boots.

b) An Android smartphone (Samsung Galaxy A52S 5G) running an application that collects and processes the IMU data, then triggers visualization.

c) An ESP-32 microcontroller (ESP32-Wroom) serving as a Wi-Fi access point for the smartphone and as the data hub for the ESP-NOW network.

d) A pair of skis equipped with the SkiTip Display ESP32 PICO-D4 microcontrollers on a custom light-emitting diode (LED) controller printed circuit board (PCB). These receive the processed data and handle the visualization. Each microcontroller is wired to an LED display and mounted on a ski in a waterproof housing with its own battery.

Upon completion of a skiing run and subsequent deceleration to a stationary state, the system computed the mean carving angle over the run and displayed the result via the ski-mounted LEDs. The feedback was presented for a brief interval before being reset. Multiple iterations were performed to improve system visibility under varying lighting conditions, robustness in snow environments, and synchronization between motion states and feedback presentation.

3.6 Smartphone-Based Skiing Quality Assessment

An Android smartphone (Samsung Galaxy A52S 5G) was used to a) connect to and receive data from two shaft-mounted IMUs, b) collect GPS data (location, speed, and elevation), and c) implement an activity recognition chain as presented by Jølstad et al. (Jølstad et al., 2021) using the methods described by Martinez et al. (Martínez et al., 2019) to calculate skiing turns in near real-time (with a maximum delay of about 10s). In the next step, c) classification features (based on speed, turn radius, edge angle, and g-force) are calculated that are finally used to d) classify those turns [Neuwirth, 2020] into carved and non-carved turns, assigning a quality score to carved turns (1-10, with scores greater than two indicating parallel turns, and scores seven to ten indicating carved turns). Carved turns are then further analyzed, each turn split into three phases ("initiation", "turning" and "completion" phase), with the edge angle calculated during the "turning" phase where the angle is largest. Edge angle for a run was calculated for each ski (left and right), using the mean value of the outer skis, since the greatest load during the turning phase is on this ski for classic parallel turns, and still high for carved turns (Müller and Schwameder, 2003). This information was e) then presented to the user after each run, once a stop was detected based on GPS data, on the app, and on the SkiTip Display.

3.6.1 Detection of Each Run

The boot-mounted IMUs' 3-axis rotation and 3-axis acceleration data is constantly recorded by the Android smartphone each participant carries. The start and end of the run are detected based on the algorithm presented by Jølstad et al. (Jølstad et al., 2021). To isolate active skiing runs from periods spent on the lift or waiting, an algorithm was applied that identifies the beginning of a run whenever the Android phone's GNSS-derived altitude was decreasing and the GNSS-derived speed from an Android smartphone exceeded 2 m/s. A run is considered finished once the speed dropped below 1 m/s.

3.6.2 Computation of the Edge Angle

Edge Angle calculation is a two-step process. First, the run is segmented into distinct turns based on the algorithm presented by Martínez et al. (Martínez et al., 2019). To derive the edge angle, the y-axis (roll angle) of the gyroscope signal for both skis is filtered and integrated over the time of a turn, representing the edge angle. To account for a possible drift of the gyroscope signal, the result is further normalized based on the assumption that each turn starts and ends at an edge angle of 0°. The maximum edge angle of each turn of the run is then extracted for the outer ski for right turns and left turns. Finally, the overall mean of all maximum edge angles is calculated. The first and the last turns are ignored because those are usually half-turns. The mean of the remaining outer ski

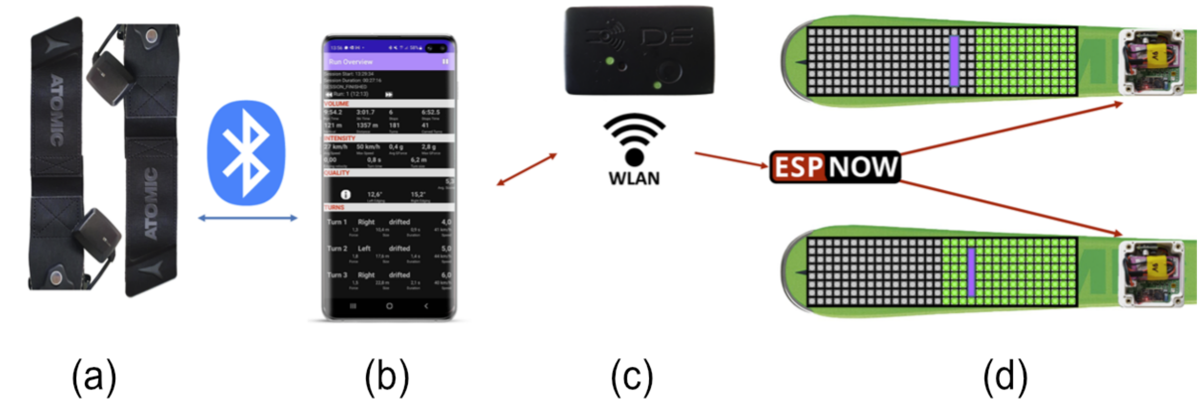

Figure 3: The components of the SkiTip Display prototypes, including the wireless connections: (a) pair of ski-boot mounted ATOMIC movesense IMUs; (b) Android smartphone with a custom app; (c) ESP-NOW to WiFi Hub; (d) pair of SkiTip Displays.

edge angles is finally presented on the respective ski (left ski: outer ski for right turns, right ski: outer ski for left turns).

3.7 Hardware

The SkiTip Display was designed as a standalone, waterproof system with an integrated battery. It contains an ESP32 PICO-D4 module (Unexpected Maker TinyPICO NANO) on a custom PCB, ensuring a lightweight, compact system that drives an 8×32 red-green-blue (RGB) LED matrix.

3.8 Custom LED Controller Board

The custom PCB (Figure 4) was designed to fit within a waterproof enclosure, leaving space for a LiPo battery. It integrates: (a) an Unexpected Maker TinyPico Nano ESP-32 PICO-D4 board, (e) three logic-level converters (3.3 V to 5 V) for segmented LED displays, (c) a connector for a 2S (7.4 V) LiPo battery with under-voltage protection, (b) a pin header for USB programming, (f) a backside connector for the LED matrix, a reset button and a RGB status LED, and an external for the voltage converter (d).

3.9 LED Matrix

Each ski-mounted display consists of 256 WS2182B RGB LEDs on a flexible PCB. To waterproof the matrix, both sides were sprayed with two layers of Plastik 70 and affixed to the ski using double-sided tape. The edges were reinforced with black liquid rubber paint to prevent water ingress, and five layers of transparent liquid rubber spray provided additional protection against moisture and mechanical stress (e.g., contact between skis).

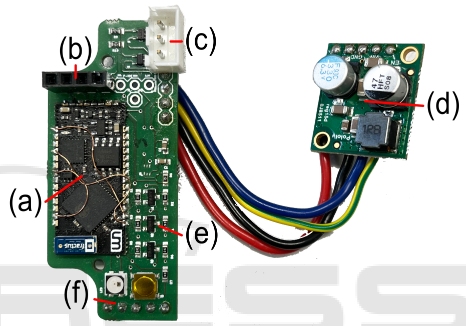

Figure 4: A photo of the custom LED controller PCB and the step-down-converter.

4 FIELD STUDY

To evaluate the feasibility and user perception of the SkiTip Display, a field study was conducted under real-world skiing conditions. The study aimed to explore skiers' experiences with ski-mounted terminal feedback and to gather preliminary data on changes in carving angle performance across repeated runs.

4.1 Participants and Setting

Nine recreational skiers (5 male, 4 female, aged 22–47) were recruited via convenience sampling. All participants self-reported intermediate to advanced skiing ability and were familiar with the use of wearable sports technology. Written informed consent was obtained from all participants prior to data collection. The study was conducted on a marked, easy (difficulty rating: blue), about 500m long slope with 120m difference in height (m= 24%/13.5° slope) at a European ski resort over five consecutive days. Weather conditions were generally stable, with occasional variation in visibility and snow quality. Participants were instructed to use a standardized set of skis onto which the SkiTip Display system had been mounted. Wearing a helmet was mandatory, and standard safety precautions were followed throughout.

4.2 Study Procedure

Each participant completed a total of 17 runs, divided into four sequential phases. Participants were instructed to ski safely within their personal limits.

1. **Warm-up (2 runs):** Participants skied without feedback to familiarize themselves with the equipment and environment.
2. **Baseline (5 runs):** Data were collected using the embedded sensors, but no feedback was shown.
3. **Intervention (M1, 5 runs):** The SkiTip Display system was activated, and color-coded feedback was presented after each run.
4. **Intervention (M2, 5 runs):** The SkiTip Display system was activated, and color-coded feedback was presented after each run.

The sequence was kept consistent across participants to minimize confusion and to ensure system stability in early use. To support within-subject comparison, each participant used the same ski set throughout. Environmental conditions were recorded per session (temperature, visibility, slope crowding) to contextualize potential performance variations.

4.3 Data Collection and Measures

Quantitative data were collected using the integrated IMU and GNSS units. For each run, average carving angles for left and right turns were computed post-run using a fixed segmentation threshold based on turn initiation. The resulting angles were used to derive a per-run mean angle metric. At the end of the session, a short semi-structured interview was conducted with each participant to gather qualitative feedback on the system's usability, understandability, and perceived value.

4.4 Data Analysis

Quantitative results were analyzed descriptively. Due to the small sample size, no inferential statistics were performed. Aggregated mean carving angles were plotted for each participant across the three phases (Baseline, M1, M2) to visualize trends. Qualitative responses were coded using thematic analysis with two rounds of open coding. Key themes related to visibility and timing, motivation and engagement, cognitive load, and perceived accuracy and trust were extracted and are reported in Section 6.

5 RESULTS

The results are reported in two parts: (1) quantitative performance data derived from sensor-based carving angle estimates, and (2) qualitative findings from post-study interviews.

5.1 Carving Angle Metrics

A total of 135 skiing runs were recorded (15 runs per participant across 9 participants). For each run, left and right carving angles were computed, and a mean value was derived. Figure 5 shows the mean carving angles across three phases: *Baseline* (no feedback), *M1* (after 5 feedback runs), and *M2* (after 10 feedback runs). While some participants exhibited gradual increases in average carving angle over the intervention period (e.g., P1, P2, P4), others showed inconsistent or plateaued performance. Minor decreases were observed between M1 and M2 in a subset of participants, potentially attributable to fatigue or environmental changes. No statistical significance was tested due to the small sample size and uncontrolled environmental conditions. However, individual trajectories suggest that some participants may have adapted their turning behavior in response to feedback.

5.2 Qualitative Findings

Thematic analysis of interview transcripts revealed four primary themes:

Visibility and Timing: Most participants reported that the display was clearly visible when stationary at the bottom of the run. Several noted that feedback was best interpreted immediately after stopping: "I liked that it lit up right away when I stopped; I didn't have to think back too far" (P4).

Motivation and Engagement: The visual feedback was seen as motivational by some participants. P2 stated, "It made me want to see more green — it gave me something to aim for."

Cognitive Load: No participants reported distraction during skiing. Several indicated that not having feedback mid-run was beneficial: "I could ski normally, and then reflect after. That's better than trying to think during turns" (P7).

Perceived Accuracy and Trust: Opinions varied on whether the display reflected true performance.

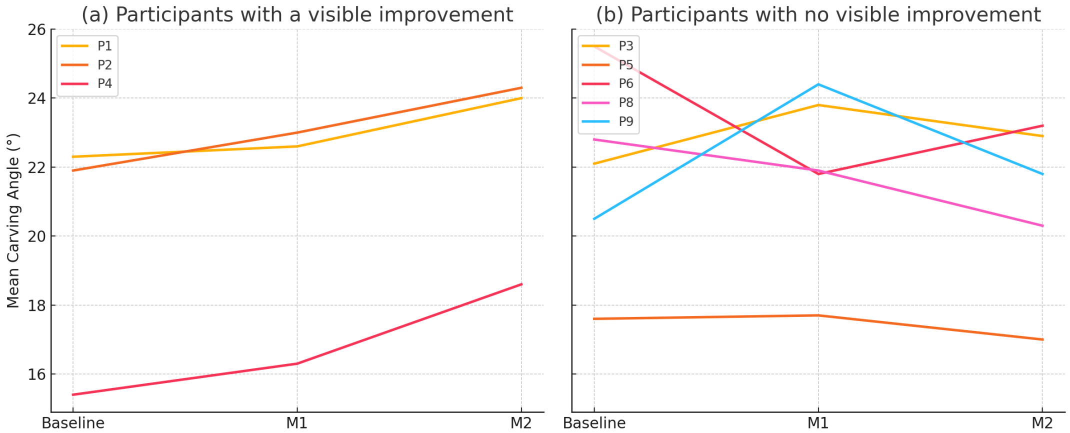

Figure 5: Mean carving angles per participant over three phases: Baseline (no feedback), M1 (after 5 feedback runs), and M2 (after 10 feedback runs).

While P5 remarked, "it matched how the run felt," others were less certain, noting lack of clarity on how the values were calculated.

6 DISCUSSION

This section reflects on key insights gained from evaluating ski-mounted visual feedback in realistic conditions. We summarize practical lessons learned, discuss methodological challenges in field deployments, acknowledge study limitations, and propose directions for future work.

6.1 Lessons from Embedded Visual Feedback in Skiing

L1: Equipment-mounted terminal visual feedback supports reflection but not real-time correction. Participants consistently reported that the visual feedback was helpful for post-run interpretation but not actionable mid-run, due to both motion dynamics and visibility constraints. This supports prior observations that in high-speed sports, embedded displays may serve better as *terminal feedback* channels rather than concurrent guides (Sigrist et al., 2013).

L2: Simplicity in feedback encoding fosters usability. Color-coded outputs were generally found intuitive, even without prior calibration or explanation. Participants valued the immediate interpretability ("More green light on the ski felt like a reward" – P4). This reinforces earlier findings from shoe-based systems (Colley et al., 2018) that low-complexity visual signals are sufficient for skill reflection in sports contexts.

L3: Motivation was enhanced by goal-oriented visual feedback. While not all participants improved their carving angle, several explicitly described the feedback as motivating. The act of comparing their own runs ("was that more green than last time?" – P2) appears to support self-regulated engagement. However, this effect may be sensitive to fatigue, novelty loss, or slope variability. All participants felt motivated by the immediate visual comparison of the current run (green area) and the previous run (purple bar).

L4: Trust and transparency must be supported through metric design. A number of participants questioned the source and meaning of the feedback. Without an explanation of how carving angles were derived, confidence in the system varied. Transparent feedback logic and optional metric breakdowns could enhance trust and user agency in future designs.

6.2 Methodological Considerations for In-the-Wild Ski Studies

MC1: Run segmentation accuracy was heavily dependent on reliable GNSS altitude data, as feedback was triggered post-run. Missing or erroneous height readings—particularly due to poor satellite reception or local atmospheric effects—led to false run detections. These issues were exacerbated when the study location was moved to a lower-elevation area with less consistent satellite coverage. Atmospheric anomalies (e.g., Sahara dust events) may have also interfered with signal integrity. For higher reliability, we recommend combining GNSS with barometric altimeters and validating run segmentation logic under varying conditions on a consistent slope.

MC2: Low-temperature effects on power systems also emerged as a critical constraint. Pre-tests at –10°C showed that battery life dropped drastically unless components were thermally insulated or actively warmed. In the final deployment, batteries enclosed in a compact housing and warmed by internal components (e.g., voltage regulators) maintained functionality. Power-critical components should be housed together and pre-warmed when operating in sub-zero environments.

MC3: Snow and weather variability significantly influenced both carving performance and display visibility. In warmer midday conditions, wet snow accumulated on skis and obscured the display. Softer snow also reduced carving force and potentially increased fatigue. Conversely, colder or icy conditions reduced grip and degraded ski edge performance over time. These environmental factors should be systematically recorded and, where possible, studies should be scheduled on groomed, low-traffic slopes early in the day to reduce variability. Smaller resorts may offer more stable testing conditions.

6.3 Limitations

Several limitations constrain the generalizability of our findings:

- **Sample size and control:** The field study involved nine participants without a control group. Although small-scale deployments are common in wearable systems research (e.g., (Van Rheden et al., 2024; Niforatos et al., 2018)), especially when working with custom hardware or in field environments, such designs typically constrain conclusions to preliminary or feasibility-level claims. The absence of counterbalancing may also have introduced learning effects.
- **Environmental variability:** External factors such as snow quality, lighting, and crowd density were not controlled. Performance changes may reflect these contextual variations rather than system effects.
- **Metric scope:** The system focused exclusively on average carving angle. While this is a relevant technique measure, it does not capture other performance aspects such as turn symmetry, speed control, or fatigue—factors which could influence user interpretation and feedback effectiveness.

6.4 Future Work: Designing for Embedded Feedback in Winter Sports

This study illustrates that embedding feedback into the sports equipment itself—rather than on-body devices—can support reflection while respecting the physical and attentional constraints of dynamic sports. The tip of the ski provided a compromise between peripheral visibility and unobtrusiveness, allowing feedback to remain in the skier's visual field post-run without interfering during motion. To address the limitations of this work, future studies should endeavor to recruit larger and more representative samples, implement randomized or counterbalanced designs, and test across varied, controlled conditions to substantiate the observed trends.

Future systems might explore:

- Multi-modal feedback to support more diverse learning strategies.
- Dynamic thresholds or personalized feedback ranges to increase relevance.
- Integration with instructor tools or comparative metrics across runs.

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