The kinematic changes following a training intervention on pumping in slalom

Christian Magelssen[1,2*], Robert Reid[2], Live Steinnes Luteberget[1], Matthias Gilgien[1], Petter Andre Husevåg Jølstad[1], Per Haugen[1]

[1]Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway
[2]Norwegian ski federation, Oslo, Norway

*Correspondence: cmagelssen@gmail.com

Cite as: Christian Magelssen et al. (2024). The kinematic changes following a training intervention on pumping in slalom. *SportRxiv.*
Supplementary Materials: https://osf.io/6s4g8/

Abstract

Slalom racers rely on effective strategies to bring them down the course in the shortest amount of time possible. One proposed strategy that skiers can use to achieve this goal is to pump themselves to higher velocities by extending their center of mass closer to the turn's axis of rotation from a laterally tilted position during the turn. However, the effectiveness of this proposed strategy and its potential magnitude are much debated. In a previous study, we found that skilled skiers (n=66) greatly improved their race times after training to pump on flats in slalom. Here, we ran a follow-up study and explored the kinematic changes that may explain this improvement in a smaller sample (n=18) of this larger pool of skiers, where we recorded the positions of the skiers using a local positioning system in the upper section of the course. Using a Bayesian estimation approach, we found that the speed profile of the skiers changed greatly, with a change pattern consistent with what we would expect from pumping. We also found a general trend that the skiers had a longer path length at retention, though the change was less consistent from gate to gate. Pumping to increase speed on flats thus appears to be an important strategy for increasing speed on flats.

Keywords: *pumping to increase velocity; alpine skiing; elite skiing; biomechanics of alpine skiing*

Introduction

Slalom racers rely on effective strategies to bring them down the course in the shortest amount of time possible (Lešnik & Žvan, 2007; Spörri, Kröll, Schwameder, & Müller, 2012; Spörri, Kröll, Schwameder, Schiefermüller, et al., 2012; Supej et al., 2015; Supej & Cernigoj, 2006). Since situations in alpine skiing vary widely, skiers need different strategies for different scenarios. Therefore, skiers must acquire an extensive repertoire of strategies and learn to select the best strategies for each situation (Supej et al., 2015). Consequently, both coaches and skiers have long strived to identify the most effective strategies for each scenario (Hébert-Losier et al., 2014; Howe, 2001; Joubert, 1978; Joubert & Vuarnet, 1967; LeMaster, 1999, 2010; Lind & Sanders, 2004; Müller, 1994; Spörri, Kröll, Schwameder, Schiefermüller, et al., 2012; Spörri et al., 2018; Supej et al., 2011; Supej et al., 2015), which is crucial for ski instruction and skill development.

One course section that stands out as pivotal for performance is the flat section, where notable time differentials often emerge among skiers (Supej & Cernigoj, 2006; Supej & Holmberg, 2011). A defining characteristic of flat sections is that the amount of potential energy available for skiers to accelerate is lower than that available in steeper sections with steeper elevation profiles (Supej, 2008). Therefore, it is important for skiers to minimize energy dissipation to maintain the highest possible velocity. Conventional strategies that the skier can employ to achieve this goal include carving instead of skidding and regulating the weight distribution along the length of the skis (fore/aft balance) during a turn (Reid et al., 2009; Reid, 2010; Supej, 2008; Supej et al., 2015).

Another, yet more debated, strategy is whether skiers can pump themselves to higher velocities in slalom (Lind & Sanders, 2004; Luginbühl et al., 2023; Mote & Louie, 1983). According to Lind and Sanders' model (Lind & Sanders, 2004), skiers can increase their kinetic rotational energy during a turn by shortening the radius of the axis around which they rotate. This can be achieved by skiers extending their legs to move their center of mass closer to the rotational axis from a laterally inclined position (Figure 1 panel **b**). Mechanically, this extension motion reduces the moment of inertia and consequently increases the skier's rotational kinetic energy and speed, assuming conservation of angular momentum. In their model, the increase in rotational kinetic energy from this motion is proportional to the amount of work exerted against the centrifugal force (from the skiers' frame of reference); thus, a larger extension movement results in a greater increase in rotational kinetic energy. Extending toward the axis of rotation can therefore potentially increase speed on flat terrain.

Yet, researchers have previously thought that the contribution of pumping to increase velocity is minimal and that it is a negotiable mechanism to increase speed and improve race times in slalom (Supej et al., 2001; Supej, 2008). The critics are directed towards that Lind and Sander's model neglects friction and that it should only work at low speeds (Supej, 2008; Supej & Holmberg, 2010). Despite this, several studies have reported quantitative evidence that elite alpine skiers gain additional kinetic energy at the exit of the turn to—an increase that cannot be accounted for solely by their available potential energy preceding that moment (Reid, 2010; Supej, 2008; Supej et al., 2015; Supej & Holmberg, 2010). Thus, pumping appears to be a mechanism that skilled skiers already exploit to increase velocity to some extent.

In two recent experiments, we have also provided evidence that skilled skiers can greatly improve their race times when performing the pumping strategy (Magelssen et al., 2022, 2024). In Magelssen et al. (2022), the skiers' were challenged to ski three slalom courses in a shorter time than if they skied straight down the hill from start to finish. If skiers could use a shorter time to ski the slalom course than skiing straight down (meaning a longer path length), they must have increased their kinetic energy beyond the amount of potential energy available at the top of the slope, which could be linked to pumping. In that study, we reported that skiers significantly improved their slalom course times compared with their straight-down gliding times over the course of the training sessions. For three of the ski teams participating in the study, we monitored the skiers using a local positioning system in a five gate long section in the middle of the course. Here we ask whether we could explain this improvement in one of the slalom courses (which was most representative for a typical slalom course) through changes in kinematics. Because race time in alpine ski racing is a function of speed and path length, there are two ways in which these kinematic changes can manifest: alteration in speed or path length. Therefore, the aim of this study was to investigate which of these explanations is most likely given our data and to explore the characteristics of these kinematic changes. We would expect that pumping would exert greater impact on the velocity than on the path length.

Methods

Participants

The participants in this study were eighteen alpine ski racers (mean age = 16.7 years, SD = 1.1; 7 females, 11 males) from three ski academies in Norway. These eighteen skiers formed a subset of a larger sample (66 skiers) from which we have already published results from a learning experiment that tested the contextual interference effect (Magelssen et al., 2022). These skiers were included because we had the local positioning system at the upper section of the course for these skiers. With the exception of three skiers, all skiers had previously raced Fédération Internationale de Ski (FIS) races, with FIS points recorded (M = 115, SD = 31) in slalom. Their FIS points, however, may not accurately reflect their skill levels due to the challenges of organizing races during the COVID-19 pandemic, which limited opportunities to accumulate FIS points.

Setup

The experiment took place on a 250-meter-long flat section of the race hill at the indoor ski hall in Oslo (https://snooslo.no/). Before each ski academy was tested, we watered this flat section to create a hard yet grippy snow surface, ensuring the most equal and consistent conditions throughout the intervention. Across the hill, we set up three slalom courses (courses A, B, and C) with the purpose of testing the contextual interference effect (Magelssen et al., 2022). See Supplementary **B** for an overview and illustration of how we set the courses. Here, we report only data from Course B (hereafter referred to as the slalom course) because it resembled a typical slalom course the most. This course featured a 1.7-meter gate offset and a 10-meter vertical distance (Figure 1 panel **e**).

We used a standardized starting procedure to minimize variation in entry speed. That is, the skiers started 20 meters before the first gate from a stationary position with the forebinding placed behind the start gate. Upon receiving clearance to start, skiers lifted their poles from the snow and skied straight down 10 meters from the hill until crossing the first photocell, which started the timer. Subsequently, skiers continued down the course. For the purposes of this study, a trial concluded when skiers crossed the second intermediate split (Figure 1 panel **d**), although they continued skiing the rest of the course. The race time data were recorded using a wireless photocell timing system (HC Timing wiNode and wiTimer; Norway).

In addition to the timing system for recording times, we used a local positioning system to record the skiers' positions as they skied the course section. To this end, we used Catapult ClearSky T6 (Catapult Sports; Australia). The local positioning system was set up to cover the area from the first photocell (gate G-4) until the second intermediate split (Finish), which covered an area of approximately 90 m (length) and 30 m (width). See Figure 1 panels **d** and **e** for an illustration of this section. For the setup, we placed ten nodes on each side of the hall. One node served as the master node and was positioned on the skier's right side of the course. Unfortunately, due to the narrowness of the ski hall in the upper part of the course, the wall was too close to the nodes, creating a signal interference that destroyed the data quality and that did not improve until the skiers descended further down where the hall widened. Consequently, we only have data from the local positioning system for a smaller section of the course (Gate 1 to Finish). In Supplementary **C**, we elaborate on this challenge in more detail. Each skier wore a manufactured-supplied vest that supported a lightweight (28 g) mobile node (firmware version: 1.40), measuring L: 40 mm × H: 52 mm × D: 14 mm. The local positioning system provided positional data as skiers descended through the course section (sampling frequency ˜10 Hz), enabling us to compute their speed and path length. Compared to motion capture systems, the local positioning system has been found to operate within the range of 0.21-0.35 m of error in distance for short agility test courses with an optimal setup (but much worse with a suboptimal setup) (Luteberget et al., 2018). This error might be too high for skiing, but it was the only system we could use to record this amount of data at the time we undertook the study.

Design and procedure

The original study consisted of a five-day learning experiment with a three-day learning intervention on learning to pump in slalom (Figure 1 panel **c**). On day 1, the skiers underwent a baseline test comprising a total of 9 runs (3 runs in the slalom course reported in this study), during which they received instructions to ski as quickly as possible down the course. During these runs, the skiers did not see their race times. Before and after the 9 runs in the slalom courses, the skiers performed a straight gliding run, where they descended the section straight down without any turns. Straight gliding was conducted in an upright, stationary posture to ensure a consistent drag area for each run (Figure 1 panel **a**).

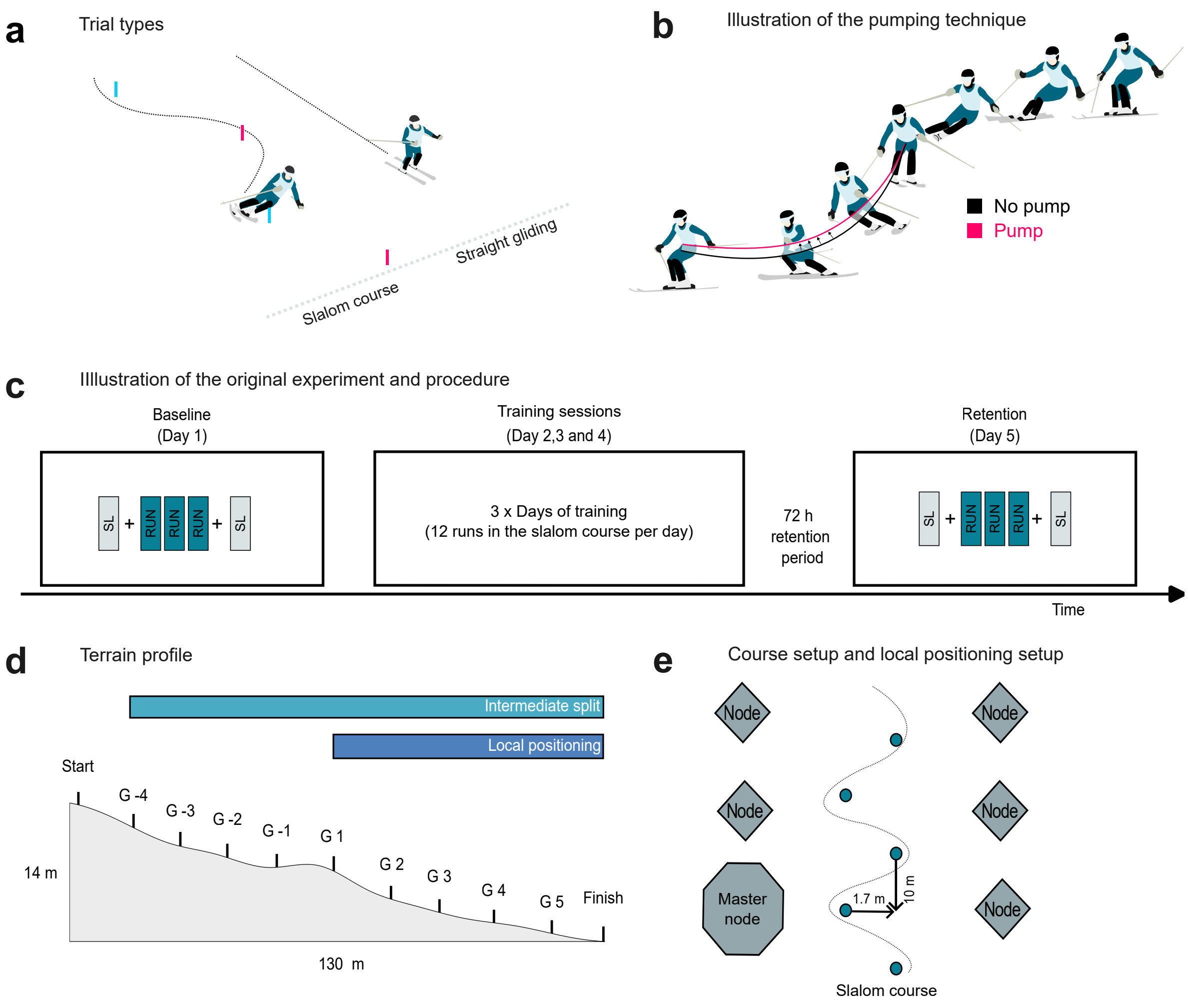

Figure 1: Illustration of the setup, experimental design and procedure. **a.** Illustration of the task and performance measures used in the study. The skiers' task was to ski faster in the slalom course than in straight gliding, which was also the measure used in our study. **b.** Illustration of the pumping technique. Skiers can achieve the pumping effect by extending their legs to move their center of mass closer to the rotation axis of the turn (from the black to the pink line). **c.** Illustration of the experiment and procedure. The data analyzed in this study are from course B in the original experiment. We analyzed only baseline and retention data but showed the training sessions to provide a complete illustration of the training intervention. See Magelssen et al. (2022) for a complete overview of the design and procedure **d.** Illustration of the course profile and the two analyzed sequences. **e.** Illustration of the setup of the local positioning system and the slalom course we have analyzed in this study.

After the baseline test, all skiers gathered for a workshop where the principle of pumping was explained, and quantitative evidence of its effect was presented. Following this, the skiers underwent three days of training on this pumping strategy (12 trials per day, of which four were in the course reported in this study). During these sessions, the skiers received race times as feedback after each trial, expressed as the difference between course time and straight gliding run time. In the original learning experiment, we assigned the skiers to two learning groups. However, since no evidence for a treatment effect was found, we combined the groups in our analysis and henceforth only described the overall procedure. Further specifics of the experiment and procedure can be found in the original study (Magelssen et al., 2022)

After the three training sessions (days 2, 3, and 4), the skiers had a three-day break during which they did not ski (retention interval). Following this break, skiers underwent a retention test (same as baseline) consisting of a total of 9 runs (3 runs in the slalom course reported in this study). During this test, they received instructions to ski as quickly as possible down the courses, with no timing provided as feedback, similar to the baseline procedure.

Analysis

Local positioning system data collection and processing

To use the local positioning system for studying kinematics in skiing, we had to perform additional processing as the system is designed for use on horizontal planes, such as in football and handball. In these applications, the vertical component of the position output is projected onto a horizontal plane, setting the vertical position to a fixed value. Because the ski slope was inclined, we projected the position output onto a virtual plane that was parallel to the average slope incline. This virtual plane was created using tachymetry measurements (Leica Builder 509 Total Station, Leica Geosystems AG, Switzerland) of the start and finish of the course and the local positioning system nodes placed along the course. The position measurements of the nodes were also used to calibrate the local positioning system. Since skiers did not ski in that virtual plane but rather along the snow surface, where the snow surface shape was not uniform, the two-dimensional local positioning system positions of the virtual plane of the skiers were projected onto the snow surface in the normal direction to the virtual plane. The snow surface onto which the virtual plane positions were projected was also captured using the tachymeter by measuring points approximately every meter where the terrain was uniform and more often when the terrain was changing (in terrain transitions). The measured points on the snow surface were triangulated and smoothed on a rectangular grid using cubic spline functions (Gilgien et al., 2013).

To calculate the kinematic variables adressed in this study, we used the following procedure. First, we filtered the skier position data with a cubic spline function since the skier trajectory resembles a harmonic motion. In this filtering, we gave each 3D position equal weights and set the tolerance factor (lambda) to 0.5 for the horizontal and vertical components, consistent with a previous study (Gilgien et al., 2013). Then, we calculated the instantaneous speed and acceleration norm from the spline filtered position and time data. The speed and acceleration were derived as the first and second position-time derivatives using the finite central difference formulae (Gilat & Subramaniam, 2013). The acceleration norm along the velocity vector was calculated as the projection of the acceleration on the velocity vector. The speed and acceleration norms were filtered with a second-order Butterworth filter at 4 Hz for speed and 3 Hz for acceleration to remove white noise. This data processing step was performed in MATLAB.

Following this procedure, the data were imported to R (in long format) for analysis via Python using the SciPy (Virtanen et al., 2020) and pandas (McKinney, 2011) packages. During this import, some trials caused import problems in Python because they were not part of the experimental protocol (warm-up runs or freeski runs). In addition, in a few cases, the quality of the data from the local positioning signal was poor, preventing the calculations in MATLAB from proceeding. In both error cases, we manually removed the runs from the MATLAB file. After this processing step, the remaining data underwent two manual screening processes to verify the quality of the local positioning data. The first screening process involved removing all runs that did not match the experimental procedure, such as warm-up runs or runs where a skier did not finish (DNF) the run. In the second screening process, all runs were visually inspected to identify errors in the local positioning data. To aid in this detection, the race times in the section, the position coordinates, and the velocities of all the ski racers were plotted. All the runs we removed are documented, along with the reasons for their removal. An extensive report of this cleaning and validation process can be found at the Open Source Framework (OSF) (https://osf.io/egbpr).

General statistical strategies and models

Our general statistical approach was to leverage multilevel modeling due to the hierarchical data structure of our data. This hierarchy was due to two sources: each skier had three runs in the slalom course on baseline and retention (by design), and the skiers were nested within three different ski academies that conducted the learning experiment together. We employed a Bayesian estimation approach because our goal was to describe the changes and interpret their effects rather than testing any hypothesis (Kruschke & Liddell, 2018), where we incorporated this multilevel information in our models. To determine the random effects structure, we used a design-driven approach where our choice of random effects was determined by the design of the experiment (Barr et al., 2013; Barr, 2021). This design-driven model formula failed to converge with the ski academy as a random effect (that is, varying intercept, slope or smooth) due to few varying levels. Therefore, we opted for a simpler model that excluded this multilevel information. To fit the models, we used the brms (Bürkner, 2017) package in R (R Core Team, 2022). We used weakly informative priors and performed prior predictive check simulations to inform our decisions. All models (including the priors) are reported in Supplementary **D** and the codes are available at OSF. To extract and visualize the draws from the model, we used the Tidybayes package (Kay, n.d.). We chose to report the average mean and contrast for a typical skier (that is, setting the random effects to zero when making posterior predictions).

We used multilevel generalized additive models (GAMs) (Pedersen et al., 2019; Wood, 2017) for most of our analyses. The reason for our choice is that GAMs allow greater flexibility in modeling nonlinear shapes in data and therefore better allow us to model our kinematic data.

In general, a GAM model takes the form of $Y \sim \beta_0 + S(x)$, where β_0 represents an intercept term, and $S(x)$ is a smooth function of the predictor x. The smooth function $S(x)$ in the model is in turn composed of several simple basis functions (K), each with an estimated coefficient derived from the data. Researchers can model more complex shapes by adding many basis functions (K) to the data. With this approach, risk looms such that the model overfits the sample data and therefore leads to poor out-of-sample generalization. This risk is counteracted in the GAM by penalizing the coefficients of the basis functions such that the model effectively negotiates the tradeoff between the wiggly smoothers and generalizability.

Race time

To analyze the race times, we conducted two statistical analyses. In the first model, we examined the time it took from the start to the second intermediate time, which was positioned just after the finish of the local positioning section (intermediate section in Figure 1 panel **d**). In this model, we predicted race time (measured as the time behind straight gliding in the respective session), with session (baseline, retention) as a fixed effect, and a random intercept and slope for skiers. We coded session (baseline, retention) with an index coding approach to place equal uncertainty for both levels and to ease the process of setting sensible priors (McElreath, 2018).

For the second model, we analyzed the local positioning (Figure 1 panel **d**) with the data from the local positioning system to determine whether the skiers also improved in this small section. These data were normalized to ensure an equal number of data points between the gates in the sequence. To model the race times in this section, we employed the difference between the time in the slalom course and the time straight down for the entire length of the section. We modeled this difference with a multilevel generalized additive model (GAM) as an average global smooth plus random smooth for each skier (Pedersen et al., 2019). We allowed the skiers to have their own random smooth because we know that kinematic data can vary significantly both between and within skiers (Federolf, 2012; Reid, 2010; Supej et al., 2015).

Speed

To model speed, we used the difference between the speed in the slalom course and the speed when the skiers performed straight gliding. To model this difference, we used a multilevel generalized additive model (GAM), incorporating an average smooth function along with group-level smoothers (random smooths) for each skier (Pedersen et al., 2019). We allowed the skiers to have their own smooths because velocity can be erratic and vary significantly between skiers (Federolf, 2012; Reid, 2010; Supej et al., 2015).

Acceleration

To model acceleration, we used the difference between the acceleration in the slalom course and the acceleration when the skiers performed straight gliding. Similar to the speed model, we modeled this using a multilevel generalized additive model (GAM) with an average smooth function and with group-level smoothers (random smooths) for each skier because acceleration can be erratic and vary significantly between skier (Federolf, 2012; Reid, 2010; Supej et al., 2015). We also conducted a secondary analysis for acceleration, where we summed the total acceleration for each skier between each gate in the section. We predicted this total acceleration with session (baseline, retention) as a fixed effect and a random intercept and slope for skiers, again using the index coding approach

Path length

Finally, to calculate path length, we applied the Pythagorean theorem for each incremental change in X, Y, and Z for the course section. We then summarized the total path length for each skier between each gate per run. To model this, we predicted path length with session (baseline, retention) as a fixed effect and a random intercept and slope for skiers, again coding session (baseline, retention) with an index coding approach.

Results

Race time

We analyzed the skiers' race time from the section's start to its end (intermediate section) and the race time in the section covered by the local position system (local positioning section). We performed these two analyses to provide quantitative evidence that the skiers also improved in the top section of the slalom course so that we had a basis for further in depth kinematic analyses to explain this improvement. Our analysis revealed that the skiers on average improved their race time by -0.17 sec. (95% credible intervals (CI)[-0.33, 0.01]) from the baseline to the retention session on the intermediate section. Therefore, the expected mean difference overlaps only by a small amount, suggesting that they were largely different. Zooming into the local positioning section, we found that the skiers on average improved their race time by -0.1 sec. (95% CI[-0.1, -0.09]). This provided evidence that this section was instrumental for skiers' overall improvement in race time and as a basis for further kinematic analysis. Figure 2 shows the estimated race times for baseline and retention and their differences for the two analyzed sections.

Speed

If the improvement in the skiers' race times can be attributed to the pumping mechanism, we would expect skiers to increase their speed around or immediately after gate passage, at the time when the extension movement occurs. Figure 3 panel **a** shows the speed profiles for the local positioning system section during baseline and retention. We will first describe the average speed trend at baseline and then the contrast between baseline and retention.

In the baseline test, the skiers' speed almost declined for each gate in the local positioning system section compared to their speed during straight gliding. With the exception of a slight speed increase of 0.05 m/s (95% CI[-0.08, 0.17]) from gate 1 to gate 2, the speeds decreased on average by -0.06 m/s (95% CI[-0.19, 0.07]) from gate 2 to gate 3 and by -0.12 m/s (95%

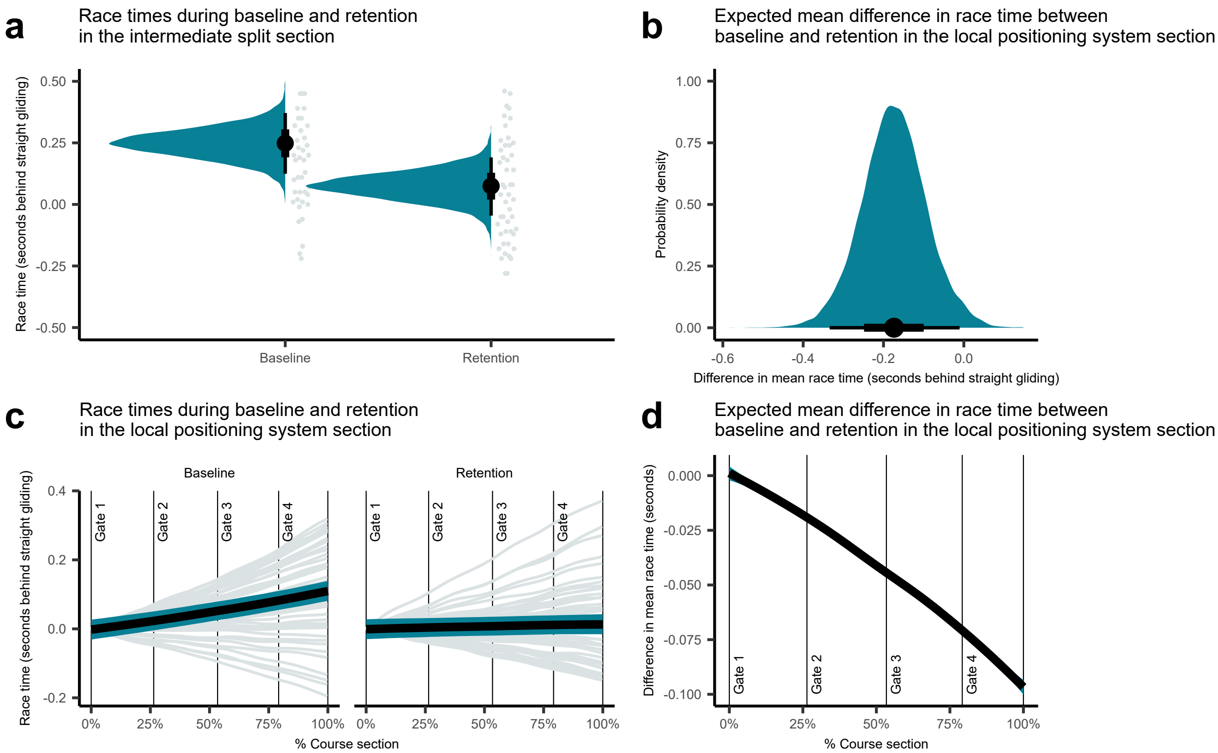

Figure 2: Race times for both the intermediate time section and the local positioning system section. **a**. Estimated race times during baseline and retention for the intermediate time section. **b**. Estimated differences (contrast) between baseline and retention for the intermediate time section. **c**. Estimated race times during baseline and retention for the local positioning section. **d**. Estimated differences (contrast) between baseline and retention for the local positioning section. The black lines denote the expected mean or differences in mean, with the shaded area representing their 95% credible interval (CI). Each gray point or line represents one run trial by a skier.

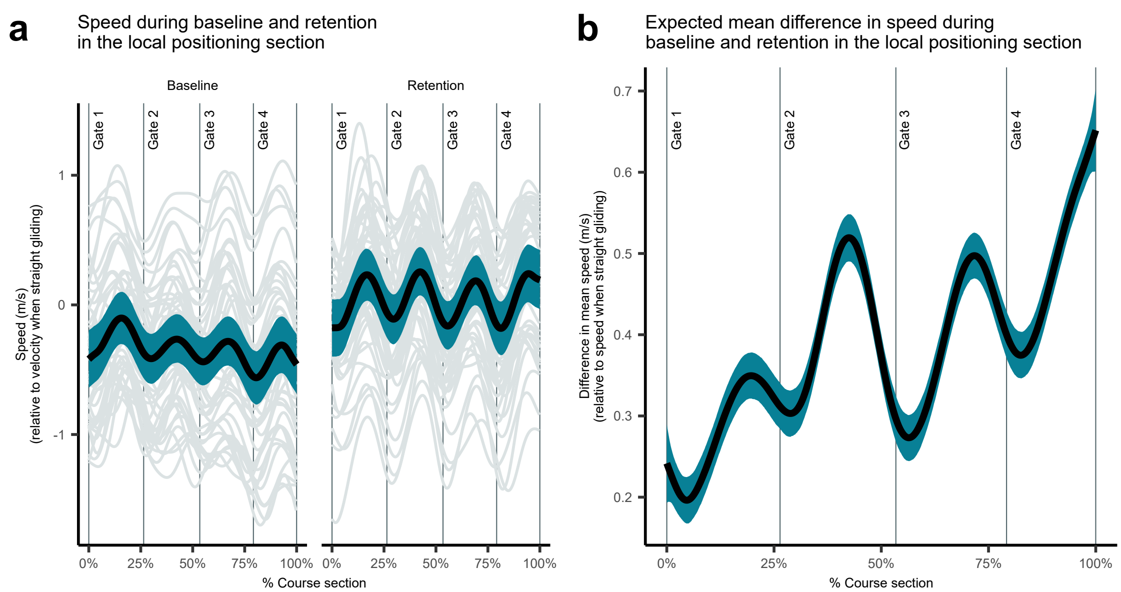

Figure 3: Speed in the local positioning system section. **a.** Estimated speed during baseline and retention for the local positioning section. **b.** Estimated differences (contrast) between baseline and retention for the local positioning section. The black lines denote the expected mean or differences in mean, with the shaded area representing their 95% credible interval (CI). Each gray line represents one run trial by a skier.

CI[-0.25, 0]) from gate 3 to gate 4 compared to straight gliding times. We focused only on comparisons at the gates because the gates mark a fixed reference point.

After the training intervention, skiers increased their entry speed into the local positioning section (gate 1) by an average of 0.24 m/s (95% CI[0.19, 0.29]) compared to the baseline speed. From here, the skiers also tended to increase their speed throughout the section. Specifically, the skiers increased their speed on average by 0.07 m/s (95%CI [0.01, 0.12]) from gate 1 to gate 2, followed by a slight decrease of -0.02 m/s (95% CI[-0.05, 0.02]) from gate 2 to gate 3. Subsequently, the speed of the skiers increased again by 0.1 m/s (95% CI[0.06, 0.14]) from gate 3 to gate 4. Therefore, the speed of the skiers increased almost incrementally from gate to gate. Besides, the speed profiles appeared wavier, as depicted in Figure 3 panel **b**. In general, the pattern of these waveforms was that skiers increased their speed after gate passage and continued to rise until the skier was about mid-way between two gates. After that, the speed decreased to gate 6 before it rose again.

Acceleration

We continued to study the acceleration through the turns to analyze the speed changes more closely.As shown in Figure 4 panel **a**, the acceleration exhibited fluctuating waves, with skiers increasing their acceleration up to about the switch between two turns that began just before or around the gate passage. After this switch, the skiers decelerated until just before the gate.

During the baseline, we found that the skiers' acceleration decreased on average by -0.91

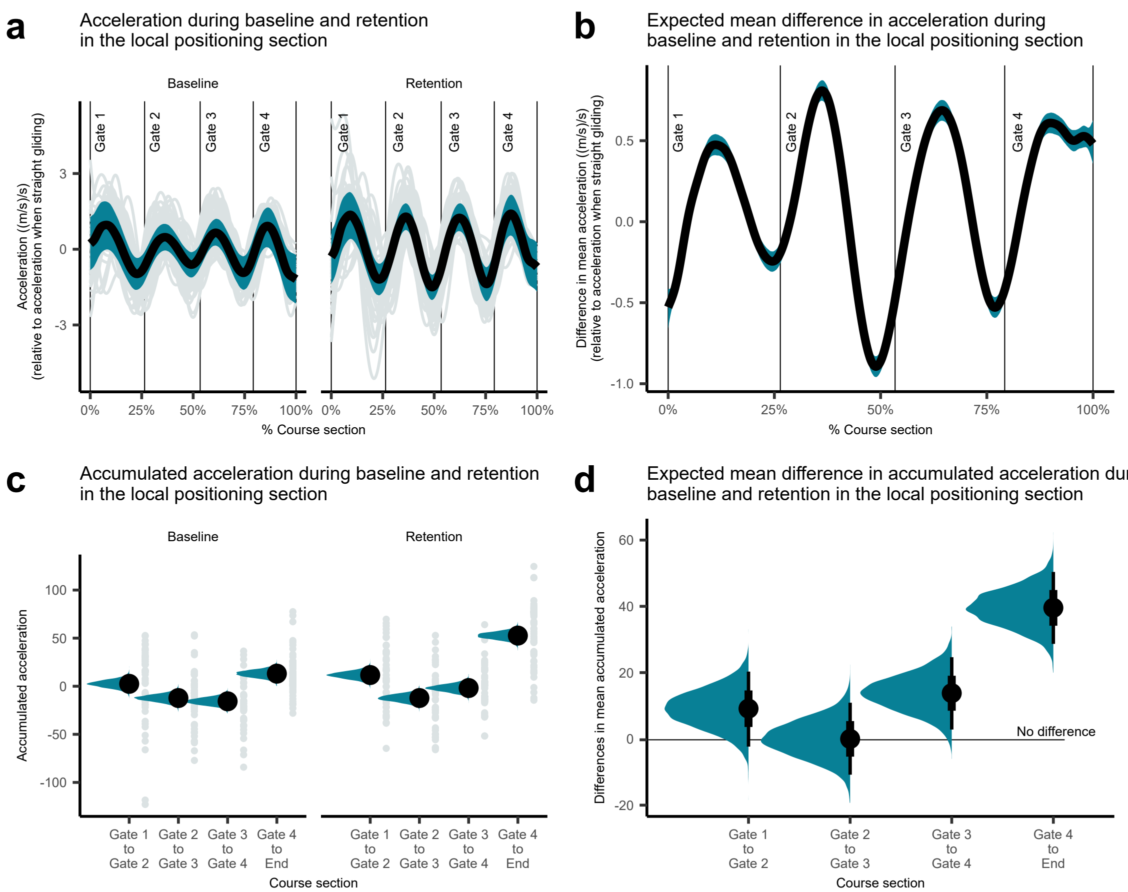

Figure 4: Acceleration in the local positioning system section.**a.** Estimated acceleration during baseline and retention for the local positioning section. **b**. Expected mean difference between baseline and retention in the local positioning section.**c.** Estimated total gate-to-gate acceleration during baseline and retention in the local positioning section. **d**. Expected mean difference between baseline and retention in the local positioning section. The black lines denote the expected mean or differences in mean, with the shaded area representing their 95% credible interval (CI). Each gray point or line represents one run trial by a skier

m/s^2 (95% CI[-1.71, -0.05]) from gate 1 to gate 2, followed by an increase of 0.42 m/s^2 (95% CI[-0.40, 1.31]) from gate 2 to gate 3 and then a marginal increase of 0.01 m/s^2 (95% CI[-0.84, 0.79]) again from gate 3 to gate 4, compared to the acceleration during straight gliding.

Following the intervention, the skiers developed a more variable acceleration profile with a larger range. Compared to the baseline, the acceleration increased just before the gate passage and continued to increase until reaching its peak during the transition between two turns before declining just before the gate (ending up lower than the acceleration during the baseline period). We performed a gate-to-gate analysis, which revealed that acceleration was lower at gate 1 by -0.53 m/s^2 (95% CI[-0.66, -0.41]), at gate 2 by -0.19 m/s^2 (95% CI[-0.26, -0.13]), at gate 3 by -0.48 m/s^2 (95% CI[-0.54, -0.42]), and at gate 4 by -0.42 m/s^2 (95% CI[-0.48, -0.36]) compared to the baseline. Figure 4 panel **b** shows the expected mean difference between baseline and retention.

To better understand how the acceleration changed between baseline and retention in each turn, we computed the total acceleration from gate to gate through the local positioning sequence. From this model, we found that the expected difference in total acceleration was 9.13 m/s^2 (95% CI[-2.33, 20.3]) from slalom gate 1 to slalom gate 2, -0.01 m/s^2 (95% CI[-10.8, 10.9]) between gate 2 and gate 3, 13.8 m/s^2 (95% CI[2.83, 24.6]) from gate 3 to gate 4, and 39.6 (95% CI[28.7, 50.4]) from gate 4 to the end of the sequence. Therefore, the skiers appears to have had a positive overall acceleration in most of the gates in the sequence. Figure 4 panel **c** and **d** show the total acceleration during each gate in the local positioning section.

Path length

Finally, we analyzed the path length, which we expected not to undergo massive changes according to our measurements from the local positioning system. At the baseline test, we found that the total path length from gate 1 to gate 2 was 10.00 m (95% CI[9.97, 10.10]), 10.7 (95% CI[10.70, 10.80]) from gate 2 to gate 3, and 10.10 m (95% CI[10.10, 10.10]) from gate 3 to gate 4, while it was 8.19 m (95% CI[8.15, 8.23]) from gate 4 to the end of the section. Notably, the reason for the lower estimate from gate 4 to the end is that this section was shorter than the other gate sections because the section ended before gate 5. Figure 5 panel **a** shows the total path length during each gate in the local positioning section.

Overall, we found no clear systematic differences in path length from baseline to retention across the gates. Surprisingly, the expected mean difference was 0.17 m (95% CI[0.06, 0.28]) longer from gate 1 to gate 2 in retention. This expected mean difference did not overlap with the estimated mean at baseline. Conversely, the expected mean difference overlapped considerably between baseline and retention for gate 2 to gate 3 (-0.02 m, 95 % CI[-0.14, 0.10]) and for gate 3 to gate 4 (0.02 m, 95 % CI[-0.02, 0.06]). In contrast, we observed an increased path length in retention from gate 4 to the end of the section (0.08 m, 95 % CI[0.04, 0.13]). Therefore, we found no consistent systematic mean differences across all gates. Figure 5 panel **b** shows the expected mean difference in the total path length for each gate in the local positioning section.

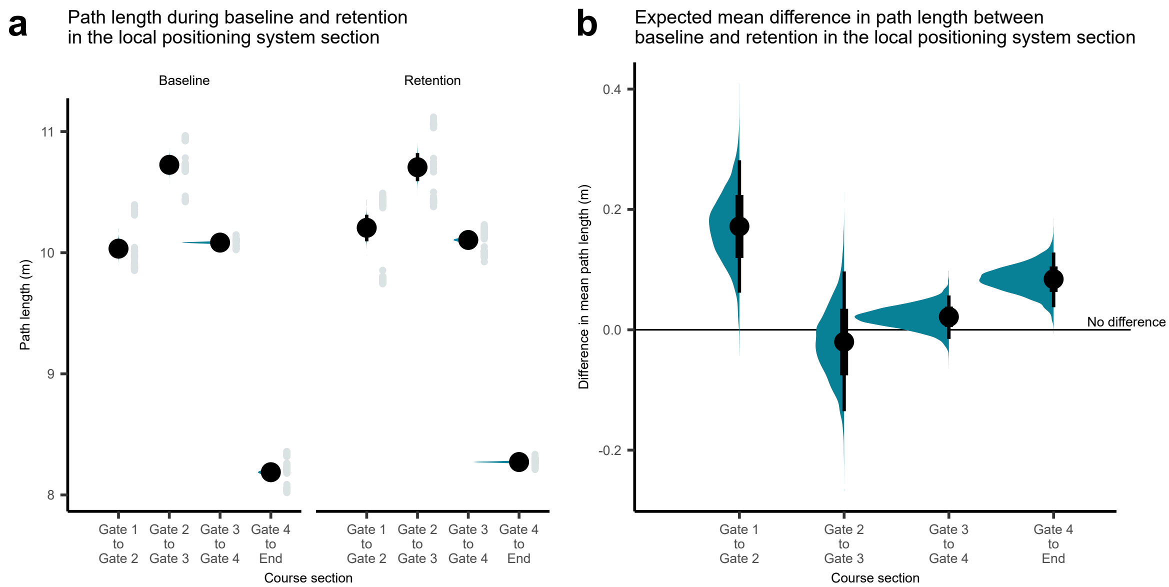

Figure 5: Total gate-to-gate path length in the local positioning system section.**a.** Estimated gate-to-gate path length during baseline and retention for the local positioning section. **b**. Expected mean difference in gate-to-gate path length between baseline and retention in the local positioning system section. The black lines denote the expected mean or differences in mean, with the shaded area representing their 95% credible interval (CI). Each gray point represents one run trial by a skier.

Discusson

Slalom racers rely on effective strategies to bring them down the course in the shortest amount of time possible. One strategy that skiers can employ to achieve this goal is to pump themselves to higher velocities by extending their center of mass closer to the axis of rotation during turns (Lind & Sanders, 2004). However, researchers previously believed that these extension movements had little or negligible impact on skiers' race times. However, this view has been challenged by conflicting evidence in recent years (Magelssen et al., 2022, 2024; Reid, 2010; Supej, 2008; Supej et al., 2015; Supej & Holmberg, 2010). In a previous training intervention (Magelssen et al., 2022), we trained skiers on this pumping strategy and found that they greatly improved their race time in the slalom course. This improvement could in principle be driven by two kinematic changes: either by skiing a shorter path length or by increasing the speed. Since our intervention focused on pumping, our expectation was that the change would exert the greatest influence on the skier's speed rather than the path length. Here, we asked which of these best served as a plausible explanation of our data and examined the kinematic changes following the intervention. For this purpose, we employed a Bayesian estimation approach. We found that the training intervention likely exerted a greater impact on the skiers' speed and acceleration through the turns than on the total path length.

To begin, the skiers' speed and acceleration turn profiles fluctuated during both the baseline and retention sessions, with their speed and acceleration increasing roughly at the gate passage, peaking around the switch to the next turn, before declining until the next turn. These wavy profiles closely align with previous observations of elite slalom racers skiing flat courses (Supej et al., 2015) and therefore seem to characterize skilled performers skiing slalom on flat terrain. In the retention test, we found notable shifts in the skiers' acceleration profile. This expected shift was a higher range of acceleration, with an increased acceleration just before the gate passage. This acceleration continued to increase until reaching its peak during the transition between two turns before declining just before the gate (ending up lower than the acceleration during the baseline period). And yet, the skiers' total acceleration and speed from gate to gate were positive for almost every gate. Although we cannot provide quantitative data on the movements of skiers, the changes in speed and acceleration profile are consistent with the principles of pumping to increase velocity. According to these mechanics, when the skiers move their center of mass closer to the axis of rotation of the turn while the skis are edged and provide support, we would expect them to increase their rotational kinetic energy, which would positively affect their tangential velocity out of a turn (Lind & Sanders, 2004). This effect is likely observed in the speed and acceleration curves.

In contrast, we found no consistent differences in path length from baseline to retention across the gates. For two of the gate sections (gate 1 to gate 2 and gate 4 to the end), we found that the path length was longer at retention than at baseline. Yet, we want to add that the distribution of the expected mean difference was wide in the two first gate sections and that the estimate of the expected difference is uncertain. We can only speculate why we found a longer path length at retention than at baseline for these two gate sections. One possible explanation is that pumping increases the path length because the extension movement exerted more force on the skis, causing them to bend and turn more. Since the courses had to be re-set for each test day, minor variations in course setup could have impacted the path length. Additionally, measurement errors from the local positioning system could have contributed to these results, but we cannot quantify this with our data. Despite these factors, the differences in path length are relatively small. Overall, our results are consistent with previous studies indicating that velocity through turns is a crucial performance factor (Federolf, 2012; Lešnik & Žvan, 2007; Spörri, Kröll, Schwameder, & Müller, 2012; Supej, 2008) and that the intervention's effect on pumping likely operated through this me

Our findings may have important practical implications for coaches. Based on this and prior studies (Magelssen et al., 2024), pumping could be a crucial strategy for increasing velocity on flats in slalom. The great challenge for coaches lies in guiding skiers to understand when pumping is an appropriate strategy and when it is not, so they can instruct skiers in using it in the right situations (Supej et al., 2015).

Limitation

A limitation of the study is the low sampling frequency of the local positioning system, which is much lower than the minimum recommendation for studying the skiing technique in alpine skiing (10 Hz versus the 50 Hz that is suitable for skiing; Federolf (2012)). Notably, the speed of the skiers in our study was in the lower range of a typical outdoor race course in slalom. Therefore, the system's accuracy may have been adequate for the conditions in this study. Another limitation of the data is that the local positioning system only records data in two dimensions (X and Y). However, alpine skiing involves a third dimension (Z), the slope of the terrain and vertical actions of the skiers. We addressed the former of these issues by measuring the snow surface and modeling the skiers' vertical position as their projection on the snow surface. Consequently, this strategy excluded the skiers' vertical position, which is an important part of the pumping motion from the analysis. However, the effect of pumping is well reflected in the propagation of the skiers (speed and acceleration) along the snow surface.

the altitude position of the gates and interpolating values between them. It is possible that this solution resulted in a loss of important data precision. Last, we encountered challenges in using the local positioning system in the ski hall due to the narrow space in the ski hall that made the nodes come too close to the walls. Due to this proximity, we lost over half of the turns and the upper part of the course. Only when the ski hall opened did we get data of sufficient quality for which we could analyze. Nevertheless, we observed several spikes in the signals, which we have openly and transparently reported. Despite these issues, the data from the study were deemed important to report. We recommend that other researchers exercise caution and carefully consider whether and how to use local positioning systems in alpine skiing.

Conclusion

To conclude, we found that a training intervention aimed at pumping was more likely to impact the velocity profiles of skiers and, to a lesser extent, their path length. Based on this and previous studies (Magelssen et al., 2024), skiers can benefit greatly from pumping to achieve a higher velocity in situations where the available potential energy is low. However, there is a point where the slope becomes too steep and pumping might become an inefficient strategy based on general observations of skiers. Assisting skiers in linking the right strategy to the right situation is crucial for helping them develop expertise (Krakauer et al., 2019).

Supplementary documents

A. Courses and local positioning system

Here we show the setup of the courses and the local positioning system

B. Course setting

This appendix describes how we set up the slalom courses for data collection. We began by laying out a 50-meter long rectangular square. This was consistently extended from a fixed reference point at the top of the course, ensuring that the starting position remained constant. The placement of the square along the course was performed through visual aiming with a fixed reference point on the ceiling. Once we had found the right position and angle, we placed the rectangular square down on the snow surface. For every 10 meters of the rope, we had a tape mark on both ends of the rope to indicate the vertical distance of the course. Then, we lay a

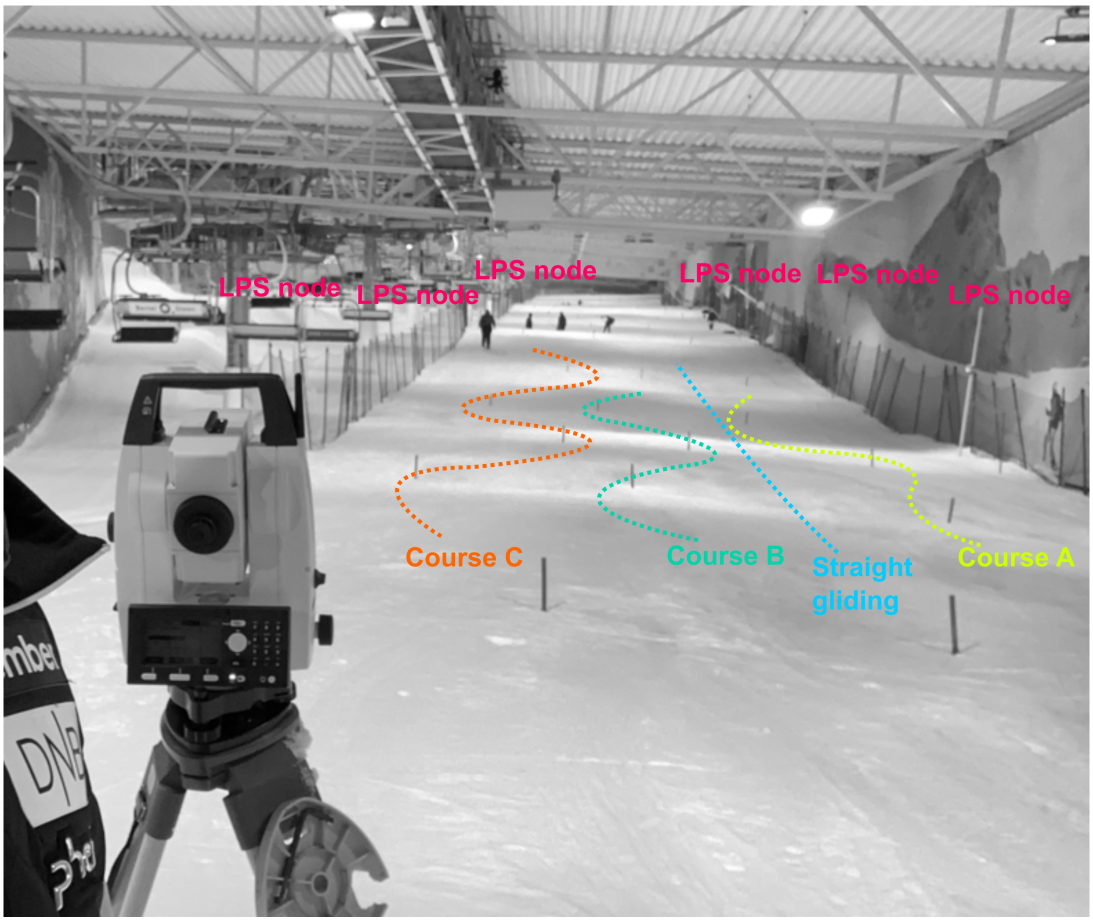

Figure 6: Illustration of the course and the local positioning system setup

second rope between these two tape points with tape points where to set the different courses (that is, their offset). Figure 7 shows an illustration of how this process worked.

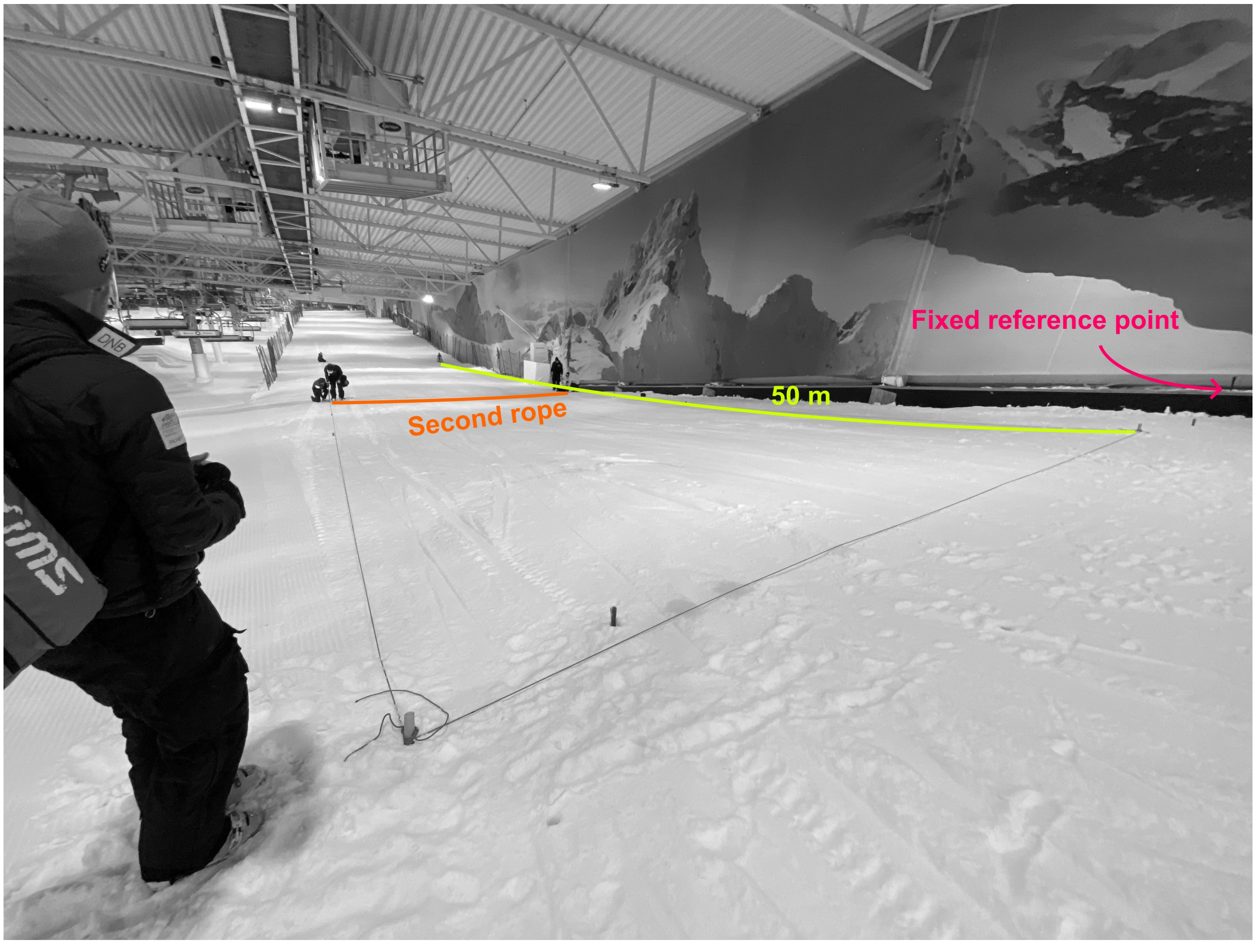

Figure 7: Illustration of the course setting. This is an image from one of the training session with the staff

C. Challenges with the local positioning system

We encountered challenges with local positioning system in the ski hall, especially in the upper part of the course. Only when the hall opened up, increasing the distance between the node and the wall, did we receive a signal strong enough to provide us with analyzable data. However, we still faced some signal issues. We have thoroughly analyzed and plotted all the data, and this overview is available as both a quarto and html file at (https://osf.io/egbpr).

D. Details of statistical models

Model 1: Race times during baseline and retention in the intermediate section

```
brm(formula = racetime ~ 0 + session +
          (0 + session | skier),
```

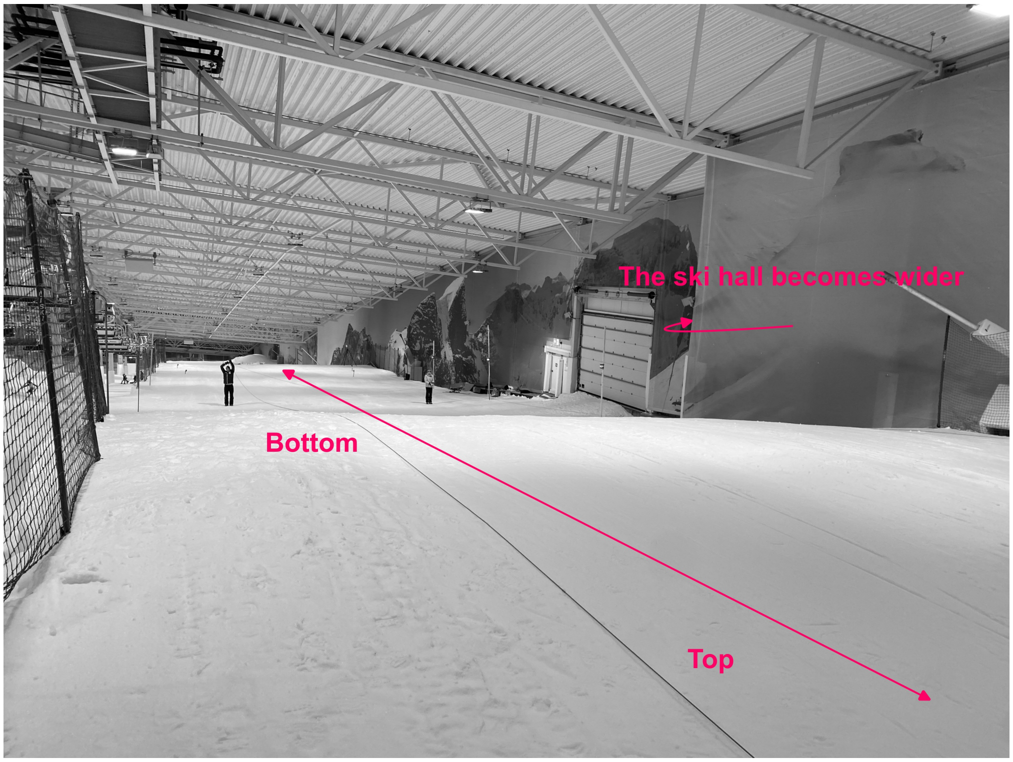

Figure 8: Illustration of the course setting. This is an image from one of the training session with the staff

```
    prior = c(prior(normal(0, 1), class = b),
          prior(exponential(1), class = sigma),
          prior(exponential(1), class = sd)),
    control = list(adapt_delta = 0.95),
    family = gaussian)
```

Model 2: Race times during baseline and retention in the local positioning section

```
brm(formula = bf(racetime ~ 1 + session +
                 s(sectionlength, by=session) +
                 s(sectionlength, skier, bs="fs", m=1)),
    prior = c(prior(student_t(10, 0, 1), class=Intercept),
              prior(student_t(10, 0, 1), class = b),
              prior(student_t(10, 0, 1), class = sds),
              prior(exponential(1), class = sigma)),
    control = list(adapt_delta = 0.95))
```

Model 3: Velocity during baseline and retention in the local positioning section

```
brm(bf(velocity ~ 1 + session +
       s(sectionlength, by=session, k=40) +
       s(sectionlength, skier, bs="fs",m=1, k=10)),
       prior = c(prior(student_t(10, 0, 1.5), class = Intercept),
                 prior(student_t(10, 0, 1.5), class = b),
                 prior(student_t(10, 0, 1), class = sds),
                 prior(exponential(1), class = sigma)),
    control = list(adapt_delta = 0.95),
    family = gaussian())
```

Model 4: Total path length during baseline and retention in the local positioning section

```
brm(family = gaussian(),
    formula = pathlength ~ 0 + gate:session +
            (0 + gate:session | skier),
    prior = c(prior(normal(10, 3), class = b),
              prior(exponential(1), class = sigma),
              prior(exponential(1), class = sd)),
    control = list(adapt_delta = 0.95),
    family = gaussian())
```

Model 5: Acceleration during baseline and retention in the local positioning section

```
brm(bf(acceleration ~ session +
       s(sectionlength, by=session, k=45) +
       s(sectionlength, skier, bs="fs",m=1, k=10)),
    prior = c(prior(student_t(10, 0, 1.5), class = Intercept),
              prior(student_t(10, 0, 2), class = b),
              prior(student_t(10, 0, 1.5), class = sds),
              prior(exponential(1), class = sigma)),
    control = list(adapt_delta = 0.8),
    family = gaussian())
```

Model 6: Total acceleration during baseline and retention in the local positioning section

```
brm(formula = totalacceleration ~ 0 + acc_gate:session +
              (0 + acc_gate:session | skier),
    prior = c(prior(normal(0, 100), class = b),
```

```
            prior(exponential(1), class = sigma),
            prior(exponential(1), class = sd)),
    control = list(adapt_delta = 0.95),
    family = gaussian())
```

Contributions

Substantial contributions to conception and design: Christian Magelssen, Per Haugen, Matthias Gilgien; Acquisition of data: Christian Magelssen, Live Steinnes Luteberget, Petter Jølstad; Matthias Gilgien; Analysis and interpretation of data: Christian Magelssen, Per Haugen; Drafting the article or revising it critically for important intellectual content: Christian Magelssen, Per Haugen, Petter Jølstad, Live Steinnes Luteberget; Final approval of the version to be published: Christian Magelssen, Live Steinnes Luteberget, Petter Jølstad; Matthias Gilgien, Per Haugen, Robert Reid.

Acknowledgements

We thank SNØ (https://snooslo.no/) and Igloo Innovation (https://iglooinnovation.no/) for allowing us to use the indoor ski hall and facilities for testing. We thank the skiers and coaches who participated in the project. We thank Mai-Sissel Linløkken, Katrine Groth Eggar, Erland Vedeler Stubbe, Johan Ansnes, Tor-Magnum, Kjersti Mejdell Styrmoe, Einar Witteveen, Kasper Sjøstrand, Pernille Lindman and Tim Gfeller for helping with watering the hill and/or assisting during the data collection. The first author would also like to give special thanks to Gavin Simpson, Cameron Patrick, Isabella R. Ghement, Stephen Wild, and James Steele for their methodological and statistical discussions.

Data and Supplementary Material

Data and code can be found at https://osf.io/6s4g8/

References

Barr, D. J. (2021). Learning statistical models through simulation in R: An interactive textbook. Version 1.0.0. In *Learning statistical models through simulation in R: An interactive textbook. Version 1.0.0*. https://psyteachr.github.io/stat-models-v1.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Bürkner, P.-C. (2017). Brms: An R Package for Bayesian Multilevel Models Using Stan. *Journal of Statistical Software*, *80*(1), 1–28. https://doi.org/10.18637/jss.v080.i01

Federolf, P. A. (2012). Quantifying instantaneous performance in alpine ski racing. *Journal of Sports Sciences*, *30*(10), 1063–1068. https://doi.org/10.1080/02640414.2012.690073

Gilat, A., & Subramaniam, B. (2013). *Numerical methods for engineers and scientists*. Wiley & Sons Inc.

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., & Müller, E. (2013). Determination of External Forces in Alpine Skiing Using a Differential Global Navigation Satellite System. *Sensors*, *13*(8), 9821–9835. https://doi.org/10.3390/s130809821

Hébert-Losier, K., Supej, M., & Holmberg, H.-C. (2014). Biomechanical factors influencing the performance of elite alpine ski racers. *Sports Medicine*, *44*, 519–533. https://doi.org/10.1007/s40279-013-0132-z

Howe, J. (2001). *The new skiing mechanics*. McIntire Publishing. https://books.google.no/books?id=aUkAPgAACAAJ

Joubert, G. (1978). *Le Ski: Un Art, Une Technique*. Arthaud.

Joubert, G., & Vuarnet, J. (1967). *How to Ski the New French Way*. Dial Press.

Kay, M. (n.d.). *Tidybayes: Tidy Data and Geoms for Bayesian Models*. https://doi.org/10.5281/zenodo.1308151

Krakauer, J. W., Hadjiosif, A. M., Xu, J., Wong, A. L., & Haith, A. M. (2019). Motor Learning. *Comprehensive Physiology*, *9*(2), 613–663. https://doi.org/10.1002/cphy.c170043

Kruschke, J. K., & Liddell, T. M. (2018). The bayesian new statistics: Hypothesis testing, estimation, meta-analysis, and power analysis from a Bayesian perspective. *Psychonomic Bulletin & Review*, *25*(1), 178–206. https://doi.org/10.3758/s13423-016-1221-4

LeMaster, R. (1999). *The skier's edge*. Human Kinetics.

LeMaster, R. (2010). *Ultimate Skiing*. Human Kinetics.

Lešnik, B., & Žvan, M. (2007). The best slalom competitors-kinematic analysis of tracks and velocities. *Kinesiology*, *39*(1.), 40–48.

Lind, D. A., & Sanders, S. P. (2004). *The physics of skiing: Skiing at the triple point* (2nd ed.). Springer Science & Business Media.

Luginbühl, M., Gross, M., Lorenzetti, S., Graf, D., & Bünner, M. J. (2023). Identification of optimal movement patterns for energy pumping. *Sports*, *11*(2). https://doi.org/10.3390/sports11020031

Luteberget, L. S., Spencer, M., & Gilgien, M. (2018). Validity of the Catapult ClearSky T6 local positioning system for team sports specific drills, in indoor conditions. *Frontiers in Physiology*, *9*, 330987.

Magelssen, C., Gilgien, M., Tajet, S. L., Losnegard, T., Haugen, P., Reid, R., & Frömer, R. (2024). Reinforcement learning enhances training and performance in skilled alpine skiers compared to traditional coaching instruction. *bioRxiv*, 2024.04.22.590558. https://doi.org/10.1101/2024.04.22.590558

Magelssen, C., Haugen, P., Reid, R., & Gilgien, M. (2022). Is there a contextual interference effect for sub-elite alpine ski racers learning complex skills? *Frontiers in Bioengineering and Biotechnology*, *10*. https://doi.org/10.3389/fbioe.2022.966041

McElreath, R. (2018). *Statistical rethinking: A Bayesian course with examples in R and Stan*. Chapman; Hall/CRC.

McKinney, W. (2011). Pandas: A foundational Python library for data analysis and statistics.

Python for High Performance and Scientific Computing, *14*(9), 1–9.

Mote, C. D., & Louie, J. K. (1983). Accelerations induced by body motions during snow skiing. *Journal of Sound and Vibration*, *88*(1), 107–115. https://doi.org/10.1016/0022-460X(83)90682-X

Müller, E. (1994). Analysis of the biomechanical characteristics of different swinging techniques in alpine skiing. *Journal of Sports Sciences*, *12*(3), 261–278.

Pedersen, E. J., Miller, D. L., Simpson, G. L., & Ross, N. (2019). Hierarchical generalized additive models in ecology: An introduction with mgcv. *PeerJ*, *7*, e6876.

R Core Team. (2022). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Reid, R. C. (2010). *A kinematic and kinetic study of alpine skiing technique in slalom* [{PhD} {Thesis}]. Norwegian School of Sport Sciences.

Reid, R. C., Gilgien, M., Moger, T., Tjørhom, H., Haugen, P., Kipp, R., & Smith, G. (2009). *Turn characteristics and energy dissipation in slalom*. na.

Spörri, J., Kröll, J., Schwameder, H., & Müller, E. (2012). Turn characteristics of a top world class athlete in giant slalom: A case study assessing current performance prediction concepts. *International Journal of Sports Science & Coaching*, *7*(4), 647–659.

Spörri, J., Kröll, J., Schwameder, H., & Müller, E. (2018). The role of path length- and speed-related factors for the enhancement of section performance in alpine giant slalom. *European Journal of Sport Science*, *18*(7), 911–919. https://doi.org/10.1080/17461391.2018.1453870

Spörri, J., Kröll, J., Schwameder, H., Schiefermüller, C., & Müller, E. (2012). Course setting and selected biomechanical variables related to injury risk in alpine ski racing: An explorative case study. *British Journal of Sports Medicine*, *46*(15), 1072. https://doi.org/10.1136/bjsports-2012-091425

Supej, M. (2008). Differential specific mechanical energy as a quality parameter in racing alpine skiing. *Journal of Applied Biomechanics*, *24*(2), 121–129. https://doi.org/10.1123/jab.24.2.121

Supej, M., & Cernigoj, M. (2006). Relations between Different Technical and Tactical Approaches and Overall Time at Men's World Cup Giant Slalom Races. *Kinesiologia Slovenica*, *12*, 63–69.

Supej, M., Hébert-Losier, K., & Holmberg, H.-C. (2015). Impact of the steepness of the slope on the biomechanics of world cup slalom skiers. *International Journal of Sports Physiology and Performance*, *10*(3), 361–368. https://doi.org/10.1123/ijspp.2014-0200

Supej, M., & Holmberg, H.-C. (2010). How gate setup and turn radii influence energy dissipation in slalom ski racing. *Journal of Applied Biomechanics*, *26*(4), 454–464. https://doi.org/10.1123/jab.26.4.454

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., Kipp, R., & Holmberg, H.-C. (2011). Mechanical parameters as predictors of performance in alpine World Cup slalom racing. *Scandinavian Journal of Medicine & Science in Sports*, *21*(6), e72–e81. https://doi.org/10.1111/j.1600-0838.2010.01159.x

Supej, M., Kugovnik, O., Nemec, B., & Šmitek, J., 1916-. (2001). Doba smučanja s sledenjem telesa - Tekmovalna slalomska tehnika z vidika biomehanike = [Slalom racing technique from the viewpoint of biomechanics]. *Šport*.

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., & Bright, J. (2020). SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nature Methods*, *17*(3), 261–272.

Wood, S. N. (2017). *Generalized additive models: An introduction with R*. chapman; hall/CRC.