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The “velocity barrier” in giant slalom skiing: An experimental proof of concept

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Abstract

Background: Alpine skiing involves the conversion of potential energy into kinetic energy, with the “velocity barrier” (VB) at each moment corresponding to the maximal velocity at which the athlete can ski while staying within the boundaries of the gates and maintaining control. Nevertheless, this concept has never been proven by evidence. The aim of this study was to experimentally test the existence of the VB and clarify its relationship with skier’s force production/application capacities.

Methods: Fourteen skiers were equipped with ski-mounted force plates and a positional device and ran a 2-turn Giant Slalom section starting from eight different heights on the slope. Three conditions were selected for further analysis: minimal entrance velocity (v_{\min}); entrance velocity allowing the better section time (VB); maximal entrance velocity (v_{\max}). Entrance velocity, section time, mean force output, ratio of force application effectiveness, velocity normalized energy dissipation, and path length were compared between the three conditions. Moreover, skier’s mechanical energy and velocity curves were compared all along the section between the three conditions using SPM analysis.

Results: The section time was reduced in VB compared to v_{\min} ($p < 0.001$) and v_{\max} ($p = 0.002$). Skiers presented an incapacity to increase force output beyond the VB ($p = 0.441$) associated with a lower force application effectiveness ($p = 0.005$). Maximal entrance velocity was associated to higher energy dissipation ($p < 0.001$) and path length ($p = 0.005$).

Conclusion: The present study experimentally supports the existence of the VB. The force production/application capacities seem to limit the skiing effectiveness beyond the VB, associated to increased energy dissipations and path length.

KEYWORDS

biomechanics, energy dissipation, force production, performance, speed, SPM analysis, technical ability, trajectory

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1 | INTRODUCTION

Giant slalom (GS) skiing performance is defined by the race-time which differs by mere fractions of a second between skiers.¹ The specific performance determinants in alpine skiing have been widely studied. Briefly, time can be minimized by selecting and maintaining the shortest path length possible while keeping an amount of velocity as high as possible.^{2,4} Nevertheless, alpine skiing presents specificities, which make the performance a challenging trade-off between velocity and path length (trajectory). Indeed, one of the particularities of alpine skiing is the way skiers gain velocity. Contrary to sporting actions (e.g., running, jumping, change of direction), where the velocity is the consequence of the mechanical work produced by the athlete onto the ground through motor actions,⁵ the velocity of a skier results from the conversion of the potential energy the skier's center of mass at the top of the slope in kinetic energy or dissipation.⁶ Therefore, even with energy dissipation due to ski-snow frictions and air drag,⁷ skiing velocity can theoretically be very high,⁸ and overpass the velocity at which the skier is able to ski without losing control of trajectory. Hence, skiers must continuously adapt their velocity or trajectory to stay within the boundaries of the gates while dealing with numerous other constraints such as slope, snow, weather condition, and fatigue.⁹

Accordingly, Supej et al., (2011) summarized the requirement to control velocity by introducing the concept of "velocity barrier" (VB). VB is a theoretical concept which defines a velocity threshold, specific to each turn, skier, and environmental condition, above which the skier degrades his motricity (balance, postural organization, etc.) due to technical and physical capacity limitations. This degradation would imply a too large dissipation of mechanical energy, exposing the skier to errors, leading to a velocity decrease, and thus to a higher section time.⁴ Previous research has yielded some evidence in support of this concept. While numerous studies showed that higher section entrance velocity (v_{in}) leads to better section time,^{2,4,10,11} other results pointed out that skiers with higher v_{in} loose markedly more absolute velocity during a section than skiers with lower v_{in} .¹² Stated differently, the greater the skier's entrance velocity, the more kinetic energy they are likely to lose during that section. Consequently, the skier must continuously dissipate energy (modulate velocity through breaking) at specific moments throughout the run to prevent errors that would lead to a high increase in energy dissipation and a decreased performance, compared to controlled breaking.

Although the mechanisms underlying the VB have often been mentioned,^{11,13-16} no study has experimentally evidenced this concept. Theoretically, the VB is not only

dependent on the skier but is probably a result of intertwining external unmodifiable factors (e.g., course setting, slope steepness and snow quality) and internal factors (e.g., physical, technical, perceptual, trajectory targeting, and psychological).¹⁷ These factors can easily modulate the risk of exceeding VB, leading the skier to three possible situations: $v_{in} > VB$; $v_{in} = VB$ and $v_{in} < VB$. Regarding external constraints imposed to the skiers, steep slope (increasing the possibility to reach high v_{in}), reduced vertical distance and/or extended horizontal distance between the gates (theoretically reducing the VB) increase the risk of being in the $v_{in} > VB$ situation.^{13,15}

Among the internal factors, the VB could be influenced by the skier's lower limb force production capacities. Indeed, there is some evidence supporting that skiers regulate their instantaneous velocity according to the turn radii (r) of their trajectory to not exceed the maximal snow reaction forces (SRF_{max}) they can tolerate.^{15,18} According to Newton's laws of motion, turns performed at higher velocities and/or with smaller r require higher radial force output (F_r) compared to slower and/or straighter turns ($F_r = v^2/r$). Therefore, the ability to exert a greater force onto the snow in the radial direction was demonstrated to be associated with a higher skiing velocity, lower energy dissipation and enhanced performance.¹³ Improving radial force output can be achieved through two underlying mechanisms: a greater physical capacity of lower limbs to produce external total force, and/or a greater technical ability to apply a part of external force in the radial direction.¹³ Finally, knowing that alpine skiing velocities may require muscle forces exceeding the skier's capacities, the VB could be defined as the velocity threshold above which excessive radial force output will be required relative to the skier's force production capacities and force application effectiveness capabilities. In this context, there is two possible situations: (i) the skier regulates his velocity before the section (so as $v_{in} = VB$ or $v_{in} < VB$) to maintain an effective trajectory or (ii) $v_{in} > VB$ resulting in a high level of energy dissipation within the section (to reduce velocity) and/or in an increased path length (to increase r and reduce the level of F_r to sustain), or failure in completing the task (i.e., missing the gate/crash).

In summary, although there is considerable theoretical evidence supporting the concept of VB in alpine skiing, it has been usually discussed only based on its mechanical consequences (i.e., necessity to dissipate energy at specific moments along the run¹²). No study has experimentally demonstrated the existence of VB (i.e., a higher v_{in} is not necessarily associated to a better performance in the subsequent section) and its interaction with force production and trajectory. Therefore, the aims of this study were (i) to experimentally show the existence of the VB, (ii) to clarify the relationship between the VB

and the force production/application capacities and, (iii) to analyze the effect of a v_{in} exceeding the VB on energy dissipation and path length of the subsequent section. Based on previous research, our hypothesis was that the section time improves with increasing v_{in} up to a VB, beyond which the section time starts to worsen. We further hypothesized that skier's snow reaction forces increase with increasing v_{in} until the VB without any further increasing (or even a deterioration) beyond it, notably due to an alteration of force application effectiveness. Lastly, we hypothesized that, when arrived in a section with a v_{in} higher than VB, the mechanical energy is quickly dissipated to reach a velocity close to the one in VB condition to avoid any loss of control and any alteration of trajectory (notably path length). If the dissipation of energy is inadequate (too low or too high), it was assumed that the trajectory would be affected.

2 | MATERIALS AND METHODS

2.1 | Participants

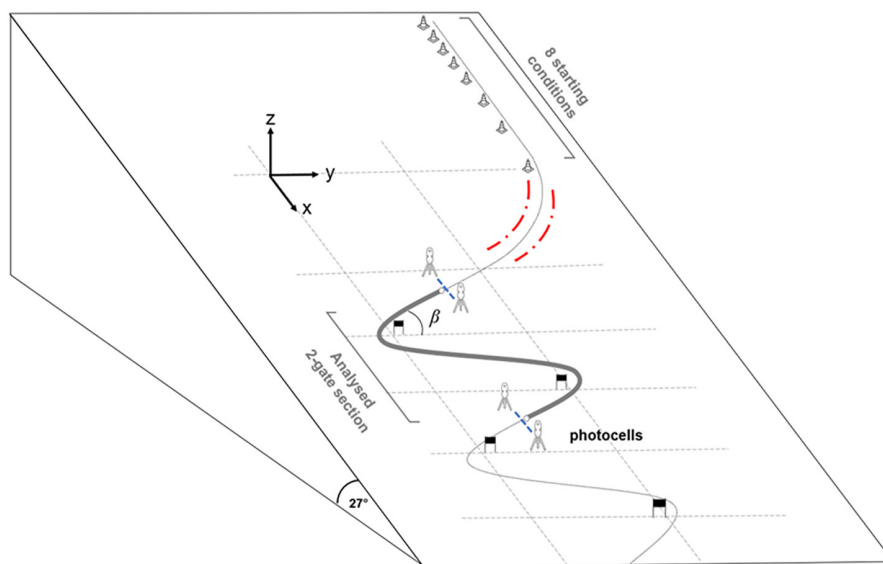
Fourteen alpine skiers (six females and eight males) participated in this study (mean \pm SD: age 21.2 ± 1.1 years, height 172.9 ± 10.4 cm, body mass 70.9 ± 11.3 kg). Participants were either ski instructors or ranked skiers (from 106 to 34 FIS points). They were free of any injuries that would affect their ability to fully participate in the study. Before the testing began, skiers were informed about the content of the study and gave their written consent to participate. The experiment was conducted under the Declaration of Helsinki and was approved by the local ethics committee of the Université Savoie Mont-Blanc (n° 2022-19-CVBSA).

2.2 | Experimental protocol data collection

To manipulate velocities in a GS section, a specific gate set up was designed including 4-GS gates preceded by eight different race starts placed at different heights on the slope. The first two gates were used for analyses (analyzed section, bold gray line in Figure 1), the following two other gates allow a representative GS trajectory at the exit of the second turn. The 4-GS gates were set up with a gate distance of 23 m and an offset of 8.5 m on a 27° inclined groomed slope. The first starting height was placed 70 m higher of the first gate with a horizontal offset of 20 m. All starting heights were defined based on the results of pre-tests to allow the skier to reach various velocity levels when entering the analyzed section (v_{in}) ranging from very slow to excessive velocities (8.74 – 23.68 m.s $^{-1}$). For all starting heights, the same lane was marked out so that the skier arrived at the first gate with a similar trajectory, that is, with a same angle (β) between instantaneous trajectory and that horizontal to the fall line (Figure 1). The skiers were also instructed to adopt a similar tuck position until the end of the lane marked by two poles to prevent them from regulating their v_{in} by modulating the air drag force before entering the analyzed run section. A rigorous protocol for installing the setup was respected in order to reproduce the experimental situation across sessions. Poles were strategically placed near the section of the grooming area under analysis, and the positions of gates were determined by measuring their distance relative to these landmark poles. This triangulation process was repeated every experimental day to locate each gate precisely.

Athletes were equipped with a positional device (Real-Time-Kinematic [RTK] systems, previously validated in skiing environment), and with an onboard

FIGURE 1 Schematic overview of the experimental setup. Thin black line corresponds to the overall path of the skier; bold gray line, the analyzed section; black cones, eight starting conditions; red dashed lines, lane marked on the snow to standardize entrance trajectory; β , angle between instantaneous trajectory of the skier and that horizontal to the fall line; photocells, time measurement device; blue dashed lines, lines linking the two entrance section cells and the two exit section cells; black flags, gates. The proportions are not representative.



validated force plates¹⁹ attached to race-boots and skis (see Figure 2). First, skiers performed three familiarization trials on the turn section by starting at three different heights (low, medium, and high), while being equipped with the various experimental devices. Once comfortable and familiar with the equipment and the different levels of velocity to manage, skiers ran the section starting from the eight different heights in a random order. The tests were separated by a passive recovery (~10 min including a 6-min chairlift) limiting neuromuscular fatigue development.²⁰ Skiers were instructed to ski as fast as possible while avoiding the risk of falling. If the skier failed to complete the entire section in one of the height conditions, a second trial was granted. Additionally, the skier was allowed to refuse to perform a starting height condition if they did not believe in succeeding. The experiments took place in the morning on a groomed slope. The snow was cleaned between each run by an experimenter to avoid any deformation of the slope. To ensure sessions comparability, the tests were only carried out in the following conditions: (i) the previous night's temperature was cold enough to freeze the snow, (ii) the temperature was lower than 0°C, (iii) the visibility was excellent. Skiers used the same pair of skis (DYNASTAR Speed Master GS —Sallanches—France; radius: 23 m, length: 185 cm) and were equipped with the same model of ski boots (SALOMON XLAB 140+



FIGURE 2 Ski-specific force plates. Devices used to collect the primary SRFs data, attached to a pair of standardized boots used during the experiment. More information available in Cross et al., (2021). Each force plate could provide force and moments in three axes (antero-posterior = x, medio-lateral = y, normal = z), but only resultant forces were examined in the present study.

WC— Annecy—France). Skiers used their own race suits and other FIS approved race clothing and protective gear (e.g., helmet, goggles, back protectors).

Athletes were equipped with a RTK compatible GNSS unit/s to record spatiotemporal data. The system was built from a high-fidelity antenna (model: ANNMB, uBlox, Thalwil, Switzerland; gain, 28 ± 3.0 dB) and RTK compatible receiver (model: M8T, uBlox), wired to a small portable computer (model: Raspberry Pi zero, Kubii) and small battery (~100g). The antenna was attached to the skiers' helmets and all other components were set in a small hip bag. The units collected positional data from all American (GPS), Russian (GLONASS), Chinese (BeiDou), and European (Galileo) satellite constellation systems at a sampled frequency of 10 Hz. Data were collected using a portable computer Raspberry Pi which uses a “carrier-based” ranging technique in combination with corrections from base-station unit placed on the top of the slope to drastically improve positioning accuracy.^{21,22} Details about RTK are available in the supplementary material of Cross et al. (2021).

Time between the start and the end of the section (bold gray line, Figure 1) was measured using a FIS approved wireless system (model: “Basic wireless solution”, Tag Heuer, La Chaux-de-Fonds, Switzerland), comprising a starting dual-beam photocell placed at the entry of the first turn and a second dual-beam photocell set at the end of the second turn. As for the gates positioning, the landmark poles placed close to the course outside of the grooming area allowed us to triangulate the time measurement device positioning at every course setting. 3D position of each cell was also measured using the RTK and were used in the data processing (see part 2.3 Data processing). The 3D SRFs (Snow Reaction Forces) were measured using an onboard validated force-plates.¹⁹ Succinctly, the system (model: ISkiSet, Sensix, Poitiers, France; see Figure 2) is composed of two cylindrical force sensors per boot each containing six full-bridge strain gauges. Cables connect each force sensor to a custom-made acquisition card (model: Jam Ingenierie) equipped with a synchronized inertial unit (model: LSM9DS1, STMicroelectronics) [more details are available in¹³]. The acquisition card was placed in the same small hip bag containing the RTK components. Raw output and 3D acceleration data were amplified and recorded at a sampling frequency of 200 Hz. Each set of boots underwent a lab-based calibration procedure (details explained in Falda-Biscuit, 2017) to provide an accurate estimate of forces and torques on each axis in the ski referential (antero-posterior = x, medio-lateral = y, normal = z). The result was a boot-specific calibration matrices that were applied to convert the raw voltage provided by the sensors into force units.

2.3 | Data processing

All data analyses were performed using MATLAB software (The MathWorks Inc, R2021b). 3D positional data were smoothed using a 2nd order Savitzky–Golay filter (window of 201 frames). Force data filtering cutoff frequency, 4 Hz, was determined via Fast-Fourier transformation, and manual observation of the power spectral density, to remove higher frequency domain data irrelevant to our analyses such as vibration.²³ A 2nd order low-pass Butterworth filter was used. To synchronize spatiotemporal and force plate data, skiers realized four fast squat movements before each run. This movement generates simultaneously four peaks of altitude variation from positional data and four peaks of vertical acceleration from the inertial unit placed in the acquisition card of the force plate. First, positional data were resampled at 200 Hz using cubic spline interpolation. Then, the double derivative of the vertical positional data was calculated to obtain vertical acceleration signal from the RTK. Force plate and RTK unit data were finally synchronized using cross-correlation algorithm to match temporally the acceleration peaks from the acquisition card of the force plate and the acceleration peaks from the RTK. The subsequent data were analyzed on the two-turn section.

2.4 | Data analysis

First, the skiers' instantaneous velocity (v) was calculated by deriving positional data from RTK system, and v_{in} was defined as v when the skier went through the starting cells. The performance indicator was defined as the section time during the two first gates (i.e., analyzed section) (T) and was measured with the photocells. In addition, following kinetic and kinematic parameters were computed. The instantaneous body-mass normalized mechanical energy was calculated at each time during the analyzed section²⁴:

$$e_{\text{mech}} = v^2 / 2 + g \cdot z \quad (1)$$

where g corresponds to the gravity acceleration (9.81 m. s⁻²) and z to the altitude difference calculated from the RTK between the start and the end of the section. Moreover, the specific mechanical energy dissipation, normalized to v_{in} , was computed for the section ($\Delta e_{\text{mech}}/v_{in}$ (Js.kg.m⁻¹)²⁵):

$$\Delta e_{\text{mech}} / v_{in} = \Delta(v^2 / 2 + g \cdot z) / v_{in} \quad (2)$$

where Δ corresponds to the change between the beginning and the end of the section. A higher $\Delta e_{\text{mech}}/v_{in}$ (less negative value) is interpreted as less energy dissipation.^{12,24} Furthermore, the path length (L_{traj}) was computed as the cumulated displacement in all axes within the analyzed section (m). To estimate the radial force (F_r), turn radii (r) was calculated by fitting three consecutive points of the trajectory (at its native frequency of 10 Hz, up sampled to 200 Hz [i.e., 60 consecutive points]) with an arc segment.²⁶ Then, F_r (N) was calculated as^{27,28}:

$$F_r = \frac{v^2}{r} \pm g \cdot \sin. \alpha \cdot \cos. \beta \quad (3)$$

with α being the mean slope relief calculated from the RTK between the start and the end of the section, and β the angle between the instantaneous trajectory and that horizontal to the fall line.

Regarding kinetic parameters, the magnitude of the resultant *SRF* for each force plate (F_{res} in Newton) was calculated as follows:

$$F_{\text{res}} = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (4)$$

with F_x , F_y , and F_z the magnitude of the force components in x, y, and z axis of each ski referential. The magnitude of the instantaneous total force applied on the snow (F) was obtained by summing the F_{res} of each force plate. Using raw data of F , average F (F_{tot}) was calculated for the section. Finally, the ratio of forces (*RF*), representing a force application effectiveness parameter¹³ was expressed as the ratio between turn-averaged F_r and F_{tot} .

2.5 | Statistical analysis

Since VB is expected to be different between subjects, three starting conditions were selected for each skier for the analysis to represent three different velocity conditions relatively to individual VB (Figure 3): the condition with the lowest v_{in} (“ v_{min} ” condition, $v_{in} < VB$), the condition with the v_{in} allowing the best section time (T) (“VB” condition, $v_{in} = VB$) and the condition with the higher v_{in} (“ v_{max} ” condition, $v_{in} > VB$).

The first part of statistical analysis was computed in JASP software (version 0.16). Normal distribution and sphericity were checked for v_{in} , T , F_{tot} , *RF*, L_{traj} and $\Delta e_{\text{mech}}/v_{in}$ data samples. Afterwards, one-way between-condition ANOVAs were computed to test v_{in} effects on the key variables. If the sphericity was violated, Greenhouse-Geisser correction was applied. When a condition effect existed,

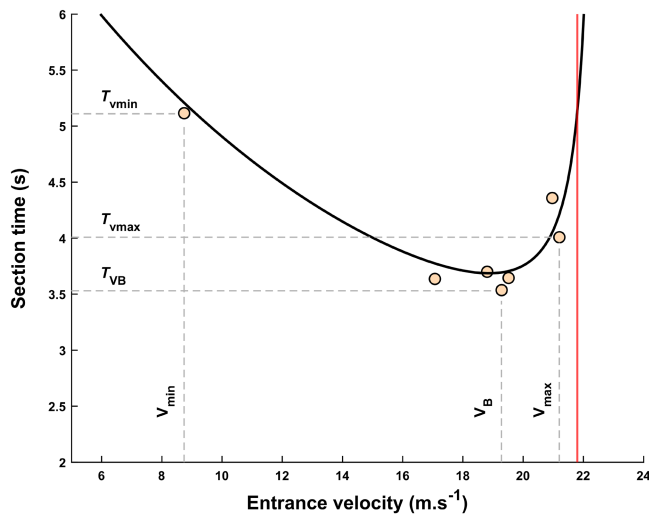


FIGURE 3 Relationship between the section entrance velocity (v_{in}) and the section time for one typical skier of the study. Orange circle points correspond to each starting condition. Red line corresponds to an unsuccessful attempt by the subject. Gray dashed line illustrates the three conditions (kept for analysis) determination. v_{min} and T_{vmin} respectively the minimal entrance velocity condition and the section time associated; VB and T_{VB} respectively the entrance velocity inducing the minimal section time and the corresponding section time; v_{max} and T_{vmax} respectively the maximal entrance velocity condition and the section time associated. Black line corresponds to an approximative modeling of the velocity-section time relationship but will not be discussed in this article.

Tukey's post hoc tests were computed to identify differences in-between conditions. The effect size was calculated using Cohen's d coefficient. The following scale of magnitude was used to interpret effect sizes: large effect for $d > 0.8$, medium effect for $0.5 < d < 0.8$, small effect for $0.2 < d < 0.5$, and trivial effect for $d < 0.2$. The significance level was set at $p < 0.05$.

The second part of the statistical analysis was computed in MATLAB R2021b using SPM-1D package (©Todd Pataky, version M 0.1) to perform Statistical Parametric Mapping²⁷ in order to compare the instantaneous changes in velocity and e_{mech} within the section between the three v_{in} conditions ($v_{in} < VB$, $v_{in} = VB$, $v_{in} > VB$). One dimensional repeated measure ANOVAs SPM{F} statistics were first performed to determine the main effects of v_{in} on the velocity and e_{mech} time series (in %section). The p -value was calculated for clusters crossing the critical threshold, with significance set at $p < 0.05$.²⁹ Thereafter, post hoc 2-sample SPM{t} (2-sided) were conducted on each vector component separately to determine the %section-specific velocity and %section-specific e_{mech} differences in-between conditions. A p -value with Bonferroni correction for three comparisons was calculated with statistical significance set at 0.05.

3 | RESULTS

3.1 | Effect of entrance velocity condition on section time

The different kinematic and kinetic variables (v_{in} , T , F_{tot} , RF , L_{traj} and $\Delta e_{mech}/v_{in}$) obtained during the three conditions are presented in Table 1. The repeated-measures ANOVAs showed condition effects in all variables. In the first instance, v_{in} was significantly greater in the v_{max} condition compared to the VB condition ($+1.49 \pm 1.27 \text{ m.s}^{-1}$, $p = 0.006$) and v_{in} was greater in the VB condition compared to the v_{min} condition ($+8.62 \pm 2.32 \text{ m.s}^{-1}$, $p < 0.001$). Regarding section performance, T was significantly lower in the VB condition compared to the v_{max} ($-0.296 \pm 0.198 \text{ s}$, $p = 0.002$) and the v_{min} ($-0.978 \pm 0.334 \text{ s}$, $p < 0.001$) condition.

3.2 | Effect of entrance velocity condition on force production/application capacities

F_{tot} in VB condition was significantly greater than in v_{min} condition ($+153.7 \pm 158.1 \text{ N}$, $p = 0.001$) but not different than in v_{max} ($-30.8 \pm 126.3 \text{ N}$, $p = 0.441$). Moreover, RF was significantly greater in the VB condition compared to v_{max} ($+0.09 \pm 0.09$, $p = 0.005$) and v_{min} ($+0.1 \pm 0.09$, $p = 0.001$).

3.3 | Effect of entrance velocity condition on path lengths and $\Delta e_{mech}/v_{in}$

Concerning kinematic differences, L_{traj} was significantly shorter in VB condition compared to v_{max} condition ($-0.57 \pm 0.68 \text{ m}$, $p = 0.008$) but there was no L_{traj} difference between VB and v_{min} ($-0.02 \pm 0.48 \text{ m}$, $p = 0.915$). Finally, $\Delta e_{mech}/v_{in}$ was significantly deteriorated in v_{max} condition compared to VB condition ($-1.36 \pm 0.96 \text{ J.kg.m}^{-1}$, $p < 0.001$) and in VB condition compared to v_{min} condition ($-2.06 \pm 1.65 \text{ J.kg.m}^{-1}$, $p < 0.001$).

3.4 | Effect of entrance velocity condition on instantaneous mechanical energy and velocity

There was a significant main effect of entrance velocity condition on e_{mech} —normalized time (%) time series ($p < 0.001$, $F = 6.562$). The post hoc SPM analysis showed a significant higher e_{mech} in VB compared to v_{min} between 0 and 29% of the section ($p < 0.001$) (Figure 4A). Moreover, the e_{mech} was higher in v_{max} compared to VB between 0

TABLE 1 Kinematic and kinetic variables calculated for the three entrance velocity conditions: minimal entrance velocity (v_{\min}), entrance velocity allowing the better section time (VB) and maximal entrance velocity (v_{\max}). Descriptive data are displayed as mean \pm standard deviation. Within subject effects are described by the p-value (p). Post hoc comparisons are represented by p and Cohen's d with Holm correction. v_{in} , correspond to the velocity measured at entry of the section; T , two-turn section time; F_{tot} , averaged total force output; RF , ratio of radial force to averaged force; $\Delta e_{\text{mech}}/v_{\text{in}}$, change in specific mechanical energy relative to entry velocity; L_{trag} , section cumulated path length.

Variable	Results (mean \pm SD)			Post hoc comparisons (Cohen's d)										
	1. v_{\min}		2. VB	3. v_{\max}		Within subject effects		1 vs. 2		1 vs. 3		2 vs. 3		
	mean	\pm SD	mean	\pm SD	mean	\pm SD	p	p	p	d	p	d	p	d
v_{in} ($\text{m}\cdot\text{s}^{-1}$)	10.58	0.91	19.20	2.09	20.69	1.59	<0.001	<0.001	<0.001	1.84	<0.001	1.91	0.006	0.75
T (s)	4.720	0.436	3.74	0.569	4.038	0.628	<0.001	<0.001	<0.001	1.39	<0.001	1.08	0.002	0.49
F_{tot} (BW)	1.426	0.435	1.626	0.453	1.687	0.442	<0.001	<0.001	0.001	0.45	<0.001	0.58	0.441	0.13
RF	0.585	0.186	0.688	0.218	0.602	0.151	<0.001	<0.001	0.001	0.50	0.518	0.1	0.005	0.45
$\Delta e_{\text{mech}}/v_{\text{in}}$ (Js/kg/m)	-10.70	1.84	-12.76	1.12	-14.12	1.08	<0.001	<0.001	<0.001	1.13	<0.001	1.50	<0.001	1.1
L_{trag} (m)	59.47	3.59	59.45	3.69	60.01	3.30	0.003	0.003	0.915	0.03	0.008	0.08	0.008	0.11

and 6.7% of the section ($p=0.016$) (Figure 4B) and compared to v_{\min} between 0 and 27% of the section ($p<0.001$) (Figure 4C). The e_{mech} was also higher in VB compared to v_{\max} between 31% and 93% ($p<0.001$) (Figure 4B).

There was a significant main effect of entrance velocity condition on velocity - normalized time (%) time series ($p<0.001$, $F=6.504$). The post hoc SPM analysis showed a significant higher velocity in VB compared to v_{\min} between 0 and 55% of the section ($p<0.001$) (Figure 4D). Moreover, the velocity was higher in v_{\max} compared to VB between 0 and 7.3% of the section ($p=0.016$) (Figure 4E) and compared to v_{\min} between 0 and 35% of the section ($p<0.001$) (Figure 4F). Finally, the velocity was higher in VB compared to v_{\max} between 39% and 94% ($p<0.001$) (Figure 4E).

4 | DISCUSSION

The purpose of the present study was to experimentally demonstrate the existence of the VB in alpine skiing turns and understand its relationship with skier's force production/application capacities. To our knowledge, this study is the first to provide experimental evidence of the VB's existence. Overall, the main results showed that a velocity higher than VB leads to worse performances in the subsequent turns. Overtaking the VB resulted in a quick over-dissipation of mechanical energy leading to a quick loss of velocity and an increased path length. This VB seems to be limited by both the skiers "force" production capacities and force application effectiveness.

First and foremost, the study had to test entrance velocities ranging from very slow to excessive to highlight the VB phenomenon. Thus, the main purpose of the present experimental design was to induce various v_{in} for a given turn section while stabilizing the other parameters (entrance trajectory, snow characteristics, course setting). Regarding this requirement, all the three starting heights kept for analysis induced significantly different v_{in} , with a mean optimal velocity (VB) which was $44.9 \pm 12.1\%$ higher compared to the mean minimal velocity condition (v_{\min}), and $7.7 \pm 6.6\%$ lower compared to the mean maximal velocity condition (v_{\max}). All these differences were characterized by a large effect ($d>0.9$) confirming very different velocity turn entrance conditions. The v_{in} in the VB condition ranged from 15.1 to 21.7 $\text{m}\cdot\text{s}^{-1}$ (mean: 19.2 $\text{m}\cdot\text{s}^{-1}$) and corresponds to typical entrance velocities previously observed in GS.^{4,11,15,30,31} The v_{in} in the v_{\min} condition was logically much lower compared to these studies and represents a condition with the intent of gaining speed during the turn. On the contrary, the v_{in} in the v_{\max} condition was slightly higher compared to the common observed velocities and could allow to analyze the

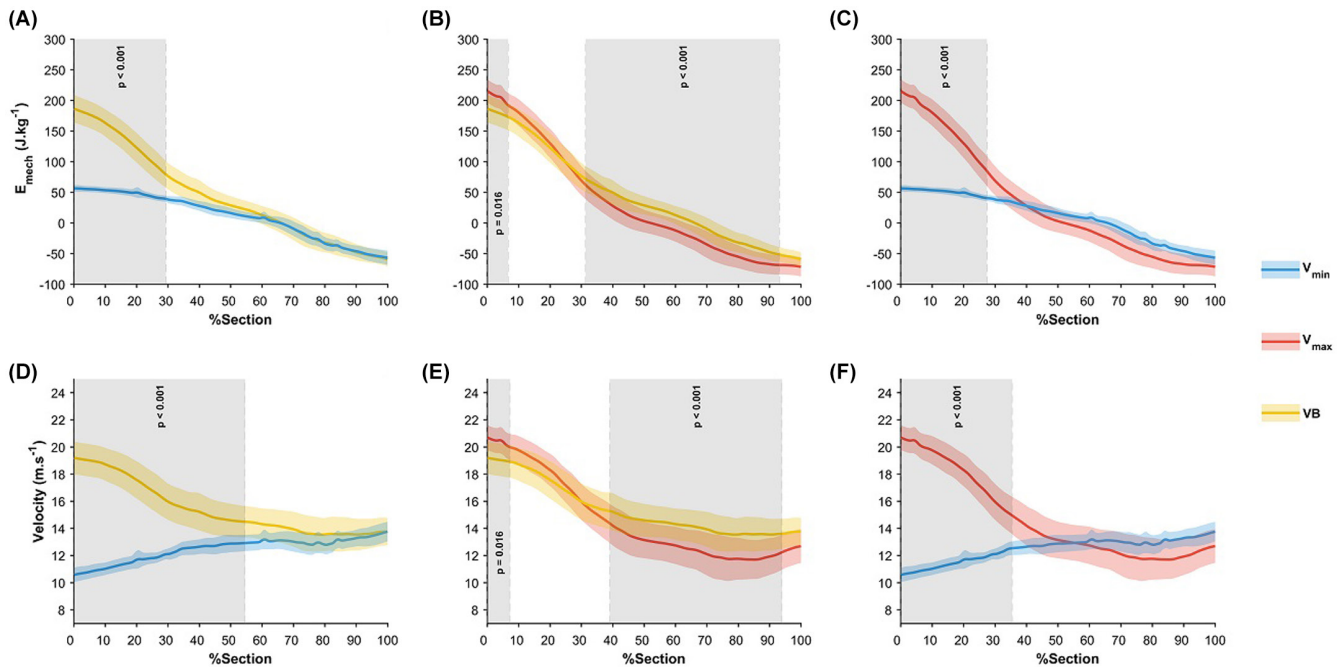


FIGURE 4 2×2 comparisons of the skiers' instantaneous velocity during the section depending on the entrance velocity condition with: (A) v_{min} versus VB; (B) v_{max} versus VB; (C) v_{min} versus v_{max} and 2×2 comparisons of the skiers' instantaneous e_{mech} during the section depending on the entrance velocity condition with: (D) v_{min} versus VB; (E) v_{max} versus VB; (F) v_{min} versus v_{max} . Blue line (mean) and blue shade area (SD), the v_{min} condition; Red line (mean) and red shade area (SD), the VB condition; Green line (mean) and green shade area (SD), the v_{max} condition. Gray shade area separated by gray dashed line, the SPM range of statistical difference between the two curves. 100% of the section refers to entire 2-GS gates section.

consequences of a slight excess of velocity on performance over the subsequent turns. It is worth noting that it is difficult to induce velocities much higher than VB for safety reasons, but also because some skiers decline to attempt the turn section at higher entrance velocities due to their apprehension or fear. Finally, these results demonstrate that the experimental protocol allowed to induce different entrance turn velocities, while stabilizing the other parameters: entrance trajectory, snow characteristics and course setting.

As expected on the basis of previous studies,^{11,16} we evidenced that skiers' performance is conditioned by an individual VB. Indeed, the section time improves with increasing entrance velocity (T significantly decreased in VB compared to v_{min}) up to a VB beyond which the section time starts to worsen (T significantly increased in v_{max} compared to VB). Below the VB, skiers need to transform as much as possible of potential energy into kinetic energy, to improve their time on the turn section.^{11,24} As exposed in Figure 4D, velocity increases throughout the turn section in the v_{min} condition while being lower from 0 to 55% of the section compared to the VB condition. Note that two turns seem sufficient to catch up the markedly lower v_{in} of the v_{min} condition (no more velocity difference at the end of the two turns section between VB and v_{min} conditions, see Figure 4D).

Nevertheless, an excessive v_{in} induces a deterioration of the performance. If the skiers do not regulate accurately their velocity before the start of the turn, there is a risk of excess mechanical energy being dissipated over the subsequent turn, thus explaining the negative consequence on performance.¹² Indeed, the higher turn entrance velocity in the v_{max} condition is quickly lost (higher velocity only from 0 to 7,3% of the analyzed section) leading to lower velocity compared to VB condition from 39% to 94% of the section (Figure 4E). Interestingly, the optimal v_{in} is only $\sim 7\%$ slower than the maximal velocity observed (v_{max}). This result highlights the need for the skiers to reach high velocity to perform² but also the impossibility of testing excessive velocities for safety reasons.

Regarding the total magnitude of force applied onto the snow, F_{tot} was higher in both VB and v_{max} compared to the v_{min} condition (respectively 15.4% and 18.5% higher) but was not different between VB and v_{max} conditions. Thus, skiers increased the F_{tot} between slow velocity (v_{min}) and high velocity (VB and v_{max}) conditions. This phenomenon is mainly related to the higher F_r output required as the velocity increases.¹³ Another possibility is that skiers must generate force in response to targeted dissipation and transient vibrations (increasing with velocity),³² that might otherwise disrupt the motion of skiers to maintain optimal skiing technique. Nevertheless, skiers were

unable to increase F_{tot} beyond their VB. Thus, the physical ability of lower limbs to produce external total force could be a limiting factor to effectively maintain high velocity with the same trajectory. It is also possible that the skier can physically increase F_{tot} output further but that ski-snow interactions do not allow him to increase its F_{tot} without skidding (i.e., edge angle too small to stay in carving mode³³). Furthermore, F_{tot} at the VB condition is very close to F_{tot} observed at the self-selected velocity in a previous study (1.63 BW vs. 1.60 BW in¹³). Therefore, we can postulate that skiers always deal with their physical limits and cannot effectively support velocity higher than their VB. Hence, further technical capacities, improving the total magnitude of force, seems of primary importance to have a high VB, and thus, high performance as previously demonstrated.^{13,34}

Regarding the force application effectiveness (RF , corresponding to the average ratio between F_r and F_{tot}), it appears that RF is higher in the VB compared to the v_{min} (+14.9%) and the v_{max} (+12.5%) conditions. The lower RF in the v_{max} compared to VB condition indicate an altered skiing effectiveness beyond the VB: the skiers were unable to orient F_{tot} onto the snow as efficiently as in VB condition. Given that skiers are unable to increase their F_{tot} above the VB, the lower RF indicate a lower F_r produced during the turn, that can be the cause of either a markedly velocity diminution or an increased turn radii during the section. Finally, the RF at the VB condition is close to the RF at the self-selected velocity observed in a previous study (0.69 vs. 0.68 in Cross et al., 2021). Thus, we can hypothesize that high-level skiers always deal with their technical limits and cannot apply enough F_{tot} in the radial direction to ski effectively beyond the VB.

Given that optimum physical (F_{tot}) and technical (RF) abilities or maximal ski-snow interaction are reached at the VB, the skiers need to reduce the external constraints when they exceed their VB. One of their strategies may be to dissipate energy (using lateral skidding³⁵) to reduce their velocity, and thus, the requiring level of F_r for a given turn radii. Our results showed that an increase of 7.7% in v_{in} above the skier's VB generates a 10.7% deterioration in $\Delta e_{\text{mech}}/v_{\text{in}}$. Indeed, the higher e_{mech} from 0 to 6.7% of the section in v_{max} condition (Figure 4B) is quickly and markedly loss leading to lower e_{mech} from 31% to 93% of the section compared to VB. This energy dissipation leads to the high velocity loss observed on the Figure 4E. Interestingly, and in contrast to v_{max} , the higher initial level of mechanical energy in VB became equal to the one of v_{min} at 29% of the section (Figure 4A), indicating a more accurate energy dissipation (there is no over-dissipation of mechanical energy). Conversely to the first strategy, the skiers can also reduce external constraints by increasing their turn radii for a given velocity. Indeed, while there is no L_{traj}

difference between VB and v_{min} , the L_{traj} was significantly higher in v_{max} condition compared to VB and v_{min} (respectively +57 cm and +55 cm). A higher path length in v_{max} compared to v_{min} and VB probably being the consequence of later turn initiation and an increased turn radii, as can be observed on the Figure 5.

Finally, the VB condition seems characterized by a high level of mechanical energy in the first part of the turn section though allowing to keep a high level of mechanical energy and a short path length in the rest of the turn section. The increased energy dissipation and L_{traj} above the VB illustrates the two strategies skiers use to match external constraints with their capabilities: (i) either skiers quickly over-dissipate their excessive mechanical energy by skidding to reduce their velocity and thus the requiring level of F_r for a given turn radii, and/or (ii) they increase their turn radii to reduce the requiring level of F_r at his velocity. Since the L_{traj} and energy dissipations both increase above the VB, it is possible that these two behaviors occur simultaneously or that the higher L_{traj} is the consequence of skidding.

5 | LIMITATIONS

In this study, the VB is approximate due to the measurement accuracy of the experimental protocol and may not exactly represent the actual VB for each participant. Indeed, the gap between each starting heights must have been large enough to induce velocities higher and lower

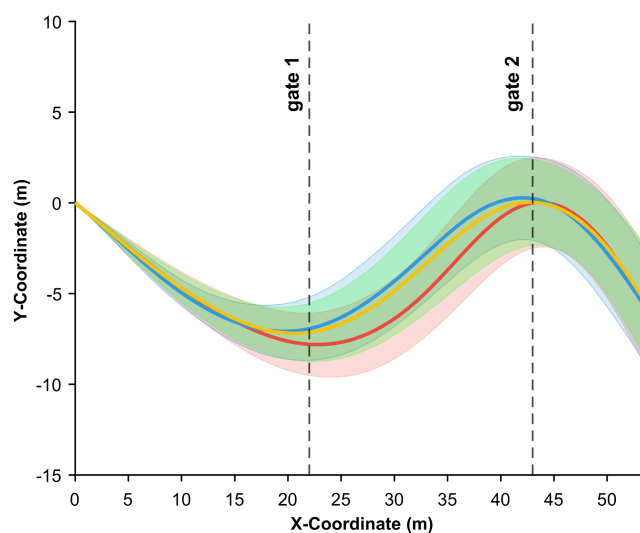


FIGURE 5 Comparisons of the skiers' mean trajectory during the section depending on the entrance velocity condition. 100% of the section refers to the entire section. Blue line (mean) and blue shade area (SD), the v_{min} condition; Red line (mean) and red shade area (SD), the VB condition; Green line (mean) and green shade area (SD), the v_{max} condition.

than the VB. Conversely, an accurate assessment of the VB (for a given slope and gate set up) would require lots of small increments around the common velocities observed in GS [$\sim 16\text{--}20\text{ m}\cdot\text{s}^{-1}$].^{4,12,15,30,31} Despite this limitation, the v_{in} in the VB condition was congruent with those previously observed in GS, which supports the results of this experiment. Moreover, there were no turns before the turn analyzed section which makes our experimental section set up not totally similar to a race situation. Nevertheless, this specificity is linked to one of the key points of this protocol: inducing different v_{in} while maintaining a similar entrance trajectory. To alleviate this potential limit, the angle between instantaneous trajectory and the horizontal to the fall line was standardized to induce representative turn entrance condition (see Figure 1). Finally, our experimental set up represent only one specific situation and the magnitude of our results could be different in other situations (different slope steepness and gate set up¹⁶ but also other environmental condition such as temperature, humidity, wind and visibility that may change the ability to reach high velocity). However, the specific situation of this study was chosen to represent the most common situation in which the VB may be exceeded (steep slope¹³ and relatively small vertical distance between gates^{15,16}) and is relevant to assess the effect of exceeding the VB in the conditions in which it may appear.

6 | PERSPECTIVES

The present study experimentally highlights the existence of the VB in GS alpine skiing. The main findings are that (i) there is a VB above which the turn time starts to worsen, (ii) the VB is limited by skiers' lower limbs capability to produce external total force but also by their technical force application effectiveness (iii) above the VB, skiers use two strategies to match external constraints with their capabilities: either they quickly over-dissipate the excessive mechanical energy by skidding to reduce their velocity and thus the requiring level of radial force for a given turn radii and/or they increase their turn radii to reduce the requiring level of radial force. In coaching, the training should be focused on the development of lower limbs force production capacities but also in the force application effectiveness (e.g., through improving the technical ability to manipulate the edge angle to avoid skidding when radial force increases) to reach higher VB and enhance performance in stressful sections.

AUTHOR CONTRIBUTIONS

MC, FH, CD, PS and BM conceptualized the study design and contributed to interpretation of results. MC and FH conducted the data collection. MC, CD and MB

contributed to the data analysis. MC drafted the manuscript. All authors revised it critically, approved the final version, and agreed to be accountable for all aspects of this work.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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