Sports Med (2014) 44:519–533
DOI 10.1007/s40279-013-0132-z

SYSTEMATIC REVIEW

Biomechanical Factors Influencing the Performance of Elite Alpine Ski Racers

Kim Hébert-Losier · Matej Supej · Hans-Christer Holmberg

Abstract

Background Alpine ski racing is a popular international winter sport that is complex and challenging from physical, technical, and tactical perspectives. Despite the vast amount of scientific literature focusing on this sport, including topical reviews on physiology, ski-snow friction, and injuries, no review has yet addressed the biomechanics of elite alpine ski racers and which factors influence performance. In World Cup events, winning margins are often mere fractions of a second and biomechanics may well be a determining factor in podium place finishes.

Objective The aim of this paper was to systematically review the scientific literature to identify the biomechanical factors that influence the performance of elite alpine ski racers, with an emphasis on slalom, giant slalom, super-G, and downhill events.

Methods Four electronic databases were searched using relevant medical subject headings and key words, with an additional manual search of reference lists, relevant journals, and key authors in the field. Articles were included if they addressed human biomechanics, elite alpine skiing, and performance. Only original research articles published in peer-reviewed journals and in the English language were reviewed. Articles that focused on skiing disciplines other than the four of primary interest were excluded (e.g., mogul, ski-cross and freestyle skiing). The articles subsequently included for review were quality assessed using a modified version of a validated quality assessment checklist. Data on the study population, design, location, and findings relating biomechanics to performance in alpine ski racers were extracted from each article using a standard data extraction form.

Results A total of 12 articles met the inclusion criteria, were reviewed, and scored an average of 69 ± 13 % (range 40–89 %) upon quality assessment. Five of the studies focused on giant slalom, four on slalom, and three on downhill disciplines, although these latter three articles were also relevant to super-G events. Investigations on speed skiing (i.e., downhill and super-G) primarily examined the effect of aerodynamic drag on performance, whereas the others examined turn characteristics, energetic principles, technical and tactical skills, and individual traits of high-performing skiers. The range of biomechanical factors reported to influence performance included energy dissipation and conservation, aerodynamic drag and frictional forces, ground reaction force, turn radius, and trajectory of the skis and/or centre of mass. The biomechanical differences between turn techniques, interdependency of turns, and abilities of individuals were also identified as influential factors in skiing performance. In the case of slalom and giant slalom events, performance could be enhanced by steering the skis in such a manner to reduce the ski-snow friction and thereby energy dissipated. This was accomplished by earlier initiation of turns, longer path length and trajectory, earlier and smoother application of ground reaction forces, and carving (rather than skidding). During speed skiing, minimizing the exposed frontal area and positioning the arms close to the body were shown to reduce the energy loss due to aerodynamic drag and thereby decrease run times. In actual races, a consistently good performance (i.e., fast time) on different sections of

---

K. Hébert-Losier (✉) · H.-C. Holmberg
Department of Health Sciences, Swedish Winter Sports Research Centre, Mid Sweden University, Kunskapens väg 8, Hus D, 83125 Östersund, Sweden
e-mail: kim.hebert-losier@miun.se

M. Supej
Department of Biomechanics, Faculty of Sport, University of Ljubljana, Ljubljana, Slovenia

the course, terrains, and snow conditions was a characteristic feature of winners during technical events because these skiers could maximize gains from their individual strengths and minimize losses from their respective weaknesses.

Limitations Most of the articles reviewed were limited to investigating a relatively small sample size, which is a usual limitation in research on elite athletes. Of further concern was the low number of females studied, representing less than 4 % of all the subjects examined in the articles reviewed. In addition, although overall run time is the ultimate measure of performance in alpine ski racing, several other measures of instantaneous performance were also employed to compare skiers, including the aerodynamic drag coefficient, velocity, section time, time lost per change in elevation, and mechanical energy behaviours, which makes cross-study inferences problematic. Moreover, most studies examined performance through a limited number of gates (i.e., 2–4 gates), presumably because the most commonly used measurement systems can only capture small volumes on a ski field with a reasonable accuracy for positional data. Whether the biomechanical measures defining high instantaneous performance can be maintained throughout an entire race course remains to be determined for both male and female skiers.

Conclusions Effective alpine skiing performance involves the efficient use of potential energy, the ability to minimize ski-snow friction and aerodynamic drag, maintain high velocities, and choose the optimal trajectory. Individual tactics and techniques should also be considered in both training and competition. To achieve better run times, consistency in performance across numerous sections and varied terrains should be emphasized over excellence in individual sections and specific conditions.

1 Introduction

In highly competitive alpine ski racing, the difference between first and second place is often measured in mere fractions of a second. For example, at the 2013 Alpine World Ski Championships in Schladming, Austria, the average difference between first and second place across events was less than half a second (~0.6 %) [1], even though the difference in time during racing between the top six World Cup contenders can be as great as 10 % on short sections of a course [2]. More than one-tenth of the total medals at the upcoming Sochi 2014 Winter Olympics will be awarded to alpine skiers, which illustrates the increasing international recognition and prestige associated with this sport.

These small winning margins highlight the need for a deep understanding of the factors which influence alpine skiing performance. Previous reviews have focused on the impact of physiology [3–5], strength and conditioning [6], and ski-snow friction [7] on performance, with numerous other papers focusing on the incidence [8], trends [9, 10], causes [11, 12], underlying mechanisms [13, 14], and preventive strategies [15, 16] of injuries to alpine skiers. However, to this day, only a single paper has reviewed the biomechanics of alpine skiing to compare the characteristics of the classic-parallel and modern-carving turn techniques [17]. This review was well warranted by virtue of the significant changes in the pattern of movement of skiers that resulted from the introduction of carving skis into the market in 1997/1998 [18] and into World Cup events in 1999/2000 [19], with specifications formulated by the International Ski Federation (FIS) in 2002/2003 [2]. Nonetheless, despite providing insight into the biomechanics of the modern ski-turn technique, this review by Müller and Schwameder [17] does not offer a comprehensive understanding of the currently known biomechanical features that contribute to the success of elite alpine skiers.

Researchers have examined alpine ski racing performance employing a range of methodologies that have included using wind tunnels to quantify the impact of position and/or aerodynamic drag on run times [20] and sophisticated video analyses of World Cup races [21] or field-based studies [22] to characterize the technical and tactical abilities of the most successful international skiers. In addition, various mathematical models have been developed, validated and applied to alpine skiers to characterize performance parameters at various time points [21, 23–25]. However, in spite of these advances in alpine skiing research, the biomechanical and functional parameters that promote the performance of the elite athlete are still not completely understood [22].

Accordingly, the aim of the present systematic review is to identify the biomechanical factors that impact elite alpine skiing performance from the currently available evidence, with a particular focus on slalom, giant slalom, super-G, and downhill events. It is expected that such an overview will help optimize the performance and training of the elite alpine ski competitor, as well as guide future research in the field.

2 Methods

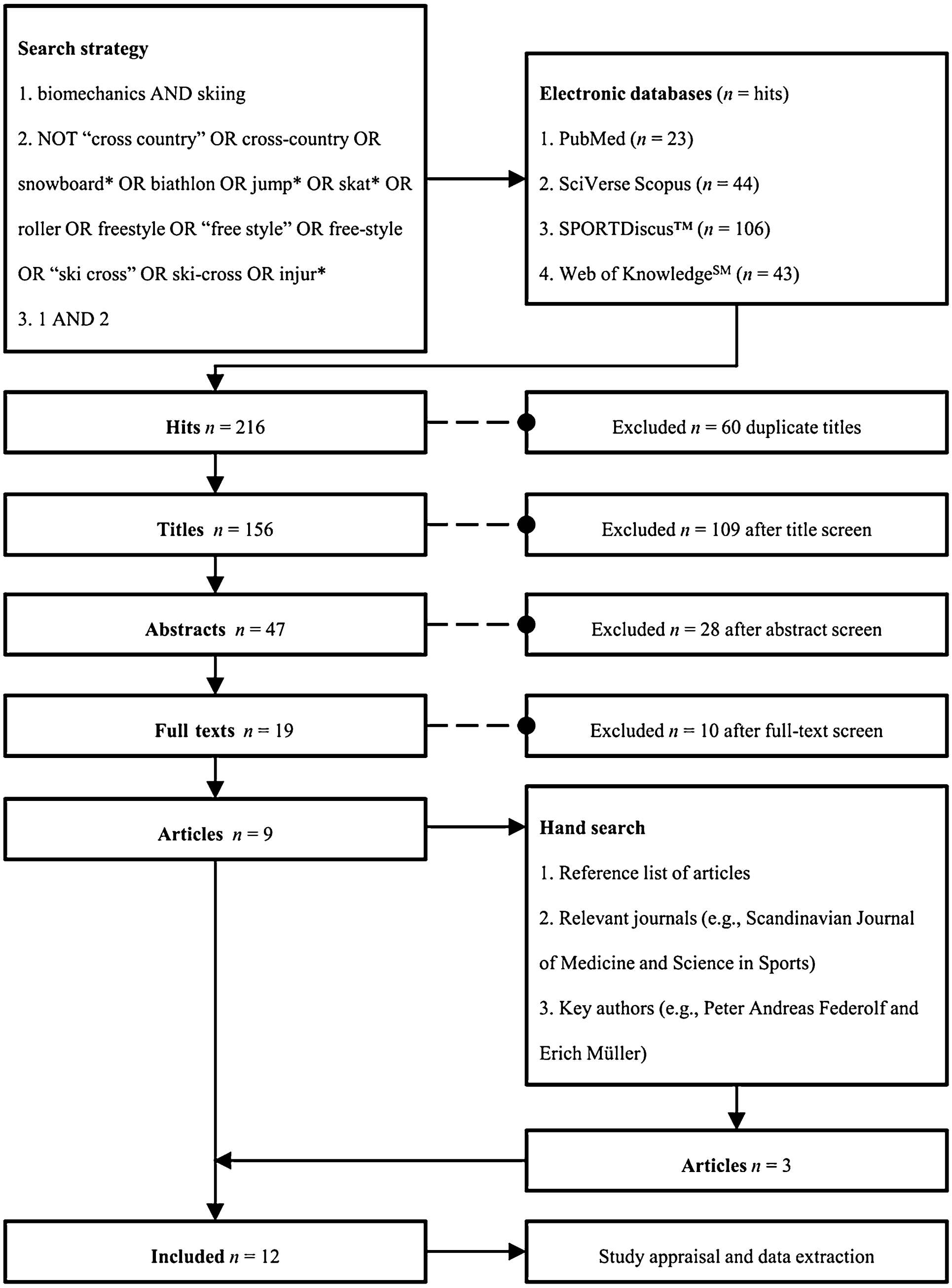
2.1 Data Sources and Search Strategy

Four electronic databases were systematically searched on April 5th 2013 using relevant medical subject headings, key words, Booleans, and truncation symbols. The databases searched were PubMed, SciVerse Scopus, SPORTDiscus$^{\mathrm{TM}}$, and Web of Knowledge^{SM}. The following search strategy was employed: (biomechanics AND skiing) AND NOT (“cross country” OR cross-country OR snowboard* OR biathlon OR jump* OR skat* OR roller OR freestyle OR “free style” OR free-style OR “ski cross” OR ski-cross OR injur*). In addition, the reference lists in all of the articles subsequently included in this systematic review were manually searched, as were relevant journals (e.g., the Scandinavian Journal of Science and Medicine in Sports) and key researchers in alpine skiing (e.g., Peter Andreas Federolf and Erich Müller). The search strategy and article selection process are illustrated in Fig. 1.

2.2 Inclusion and Exclusion Criteria

Only articles concerning the biomechanics of human motion during competitive alpine ski racing were included in the formal review process and not those focused on equipment and/or course layouts and/or environmental conditions. For an article to be included, the subjects needed to include elite alpine ski racers (i.e., World Cup, European Cup, national team, and top-level competitive ski racers) and the analyses had to relate at least one biomechanical measure to the performance or rank of the skier. Only original research published in peer-reviewed (abstract

Fig. 1 Flow diagram of the search strategy and article selection process



available) journals and the English language were considered. Articles on cross-country skiing, roller-skiing, biathlon, snowboarding, ski jumping, ski-cross, freestyle skiing, and mogul skiing were excluded, as were those pertaining to skiing injuries or modelling and optimization without an experimental component. Letters to the Editor, reports from symposia, conference abstracts, special technical publications, books, expert opinions, and literature reviews were also excluded.

2.3 Study Selection Process

Duplicate articles from the electronic database search were removed first. After eradication of potentially identifiable information (i.e., authors, affiliations, country of origin, and source of publication) by an anonymous third party; two independent reviewers screened all titles, abstracts, and full texts of the articles sequentially for inclusion and exclusion criteria. Results from the two independently performed screening processes were compared and, if there was disagreement on the inclusion/exclusion of a given article, a third reviewer helped reconcile differences in opinion. The study selection process was repeated for articles that were included through the manual search described above until no additional publications of interest were identified.

2.4 Study Appraisal

The Downs and Black Quality Assessment Checklist [26] can be used to provide an overall quality score of articles with different research designs, where articles with higher scores are considered as being of superior quality. The original checklist contains 27 items that appraise the quality of a study on the basis of its reporting, external validity, internal validity (bias and confounding), and power. This checklist exhibits high internal consistency (Kuder–Richardson 20 = 0.89), test–retest reliability ($r = 0.88$), inter-rater reliability ($r = 0.75$), and criterion validity when compared with Global Scores from the Standards of Reporting Trials Group ($r = 0.90$) [26, 27].

Modified versions of the original checklist have been employed to appraise the quality of articles in several research areas, including biomechanics [28, 29], sports [16, 30], and elite sports performance [31]. The following amendments to the Downs and Black Quality Assessment Checklist [26] were applied for the purpose of this review. The term ‘patient’ was replaced with ‘subject’ and ‘treatment’ interpreted in the context of ‘testing’. In questions 10–12, 18, 21–23, 25, and 27, ‘Not applicable’ (question excluded) was added as a fourth scoring option. Question 27 was answered with ‘Yes’ (1 point—statistical significance reached), ‘No’ (0 points—statistical significance not reached), or ‘Not applicable’ (question excluded—no statistical analyses) rather than a 5-point scale. When an article reported or referenced the levels of accuracy of a measurement system, question 20 was scored ‘Yes’. Questions 4, 8, 9, 14, 15, 17, 19, 24, and 26 were excluded during all quality scoring since they were not applicable for any of the studies as none were intervention studies. In answering questions 5 and 25, sex, age, and level of competition were deemed as being *core* confounders, whereas weight, skiing discipline, and country of origin were defined as being *other* confounders. To score two points on question 5, all core confounders and at least one other confounder needed to be stated in the article. To score one point, three confounders, including at least two core confounders, had to be reported. A score of zero was given when one or no core confounders were given, or when two core confounders but no other confounders were stated. Questions scored as ‘Not applicable’ were not considered when calculating the final quality score of an article, which was expressed as a percentage: [(total number of points/total number of applicable points) × 100 %].

Finally, since the quality scores did not depend on study designs, standard classification schemes [32, 33] were employed to classify the study design of each article first as being experimental, quasi-experimental, or non-experimental, and then as having a case study, case series, or repeated-measures design. No article was excluded on the basis of its quality score or study design.

The two reviewers who screened the articles for inclusion/exclusion also independently assessed the quality and classified the design of all articles. In presence of disagreement in quality scores between the two reviewers, a third reviewer was consulted to reconcile differences in opinion. At this stage, the articles still lacked potentially identifiable information to reduce assessment bias.

2.5 Data Extraction, Synthesis, and Analysis

Data concerning the study aims, population, location, procedures, key results, and biomechanical parameters examined (along with their relationships to or implications for the performance of elite alpine skiers) were extracted using a standard form. At the same time, the area(s) of study addressed by articles—i.e., aerodynamics, kinematics, and/or kinetics—were identified. Data extraction was performed by the same two reviewers who performed the quality assessment of articles. First, each reviewer independently extracted data from half of the articles that were allocated in a randomized fashion. For data validation, the two reviewers then exchanged articles and data collection sheets to verify that the data extraction was accurate and complete.

Data were managed and analysed using Microsoft Excel® 2010 (Microsoft Corporation, Redmont, WA, USA). Descriptive statistics for the data were expressed using means and standard deviations (mean ± SD), minimum to maximum ranges (min to max), counts (*n*) and/or percentages (%).

3 Results

As shown in Fig. 1, the initial electronic database search yielded 216 hits in total, with 156 titles undergoing screening after the removal of duplicates. A further 147 articles were excluded following screening of titles, abstracts, and full texts. A total of nine articles from the electronic search met the inclusion criteria and an additional three were identified during the manual search. Accordingly, 12 articles were retained for review with two articles published before 1990 and the remaining 10 from 2004 onward.

3.1 Quality Score and Research Design

A summary of the quality scores, research designs, subjects, biomechanical variables examined, and key findings of each article meeting inclusion is presented in Table 1. The average quality score of the 12 articles was 69 ± 13 % (40–89 %) on the basis of scoring using our modified Downs and Black Quality Assessment Checklist. The main quality issues were failure to report: subject characteristics, confounding variables, actual probability scores (e.g., 0.035 rather than <0.05), subject selection processes, representativeness of subjects to the source population, and time period of recruitment/testing.

Eight studies (67 %) were classified as quasi-experimental [20, 22, 23, 34–38] and the remaining four (33 %) as non-experimental [2, 19, 21, 24], with none categorized as experimental (i.e., designed to examine the effect of an intervention on a selected outcome or to compare outcomes between experimental and control groups). Half of the studies included ($n = 6$) had a case series design [2, 19, 21, 23, 24, 37], a third ($n = 4$) employed a repeated-measures design [20, 34, 35, 38], and two (17 %) were case studies including several repeated trials of a single subject [22, 36]. All studies attempted to directly relate at least one biomechanical factor to changes, differences, or improvements in the performance of elite alpine ski racers.

3.2 Subjects and Experimental Protocols

The articles had a mean sample size of 8 ± 6 (range 1–18) and altogether comprised 99 subjects representing 11 different countries (Table 1). Sixty-four of these subjects (64 %) were males, four (4 %) were females, and the remaining thirty-one subjects (31 %) were of unspecified sex (i.e., articles did not report whether subjects were male or female).

The majority of subjects were described as being World Cup ski racers [2, 19, 21, 24] or Champion ski racers [22] (62 %), followed by national team members [20, 34, 36, 37] (22 %), top-level ski racers [35, 38] (10 %), and European Cup skiers [23] (6 %). Only two articles explicitly reported their skiers' FIS points [23, 34], and only five articles reported the age of their subjects [2, 23, 34–36]. The youngest, oldest, and mean age of skiers weighted on the basis of sample size of these five articles was 16, 37, and 24.5 years, respectively.

Five articles (42 %) focused on giant slalom [2, 22, 24, 34, 36], four (33 %) on slalom [19, 21, 23, 35] and three (25 %) on downhill [20, 37, 38] events. Aerodynamics was the main topic of these last three articles [20, 37, 38], which employed data exclusively from (indoor) wind tunnel experiments and discussed their findings in the context of downhill skiing, although were also applicable to super-G and speed skiing. Kinematics were investigated in most articles reviewed, with five performing experimentations on ski slopes [22, 23, 34–36] and four employing films from World Cup races [2, 19, 21, 24] for kinematic analyses. One study reported outdoor kinematics together with indoor aerodynamics data [34], while another investigated both kinetics and kinematics simultaneously outdoors using fusion motion capture [36].

3.3 Biomechanical Factors with Influence on Performance

A range of biomechanical factors were reported to influence or relate to elite alpine ski racing performance (Table 1), which were computed, assessed, or quantified in various ways. Logically, because the winner of an alpine skiing event is the racer with the fastest time, all the studies employed time as an indicator of performance with the exception of one that used the aerodynamic drag coefficient instead [20]. However, many of the articles reported one or more measures of instantaneous performance (i.e., performance at a certain point in time or space) on the race course or on a short section of the course (i.e., one or few gates) to compare faster and slower skiers (see Biomechanical parameters in Table 1). To name a few, these measures included the aerodynamic drag coefficient [20, 38], time lost or distance travelled per change in elevation [23], velocity (including control of entrance velocity, average velocity, and relative velocity in wind tunnels) [19, 22, 23, 38], and mechanical energy behaviours (including specific mechanical energy, energy dissipation, differential mechanical energy, and relative energy dissipation)

Table 1 Summary of the reviewed articles ($n = 12$) with the key biomechanical parameters examined and findings with implications for performance in elite alpine ski racers

Study Quality score (%)	Study design	Subjects	Experimental protocol	Biomechanical parameters	Findings with implications for performance
Barelle et al. [20] 56 %	Quasi-experimental Repeated-measures	$n = 4$ Country: France Level: National team	Discipline: DH Site: wind tunnel Study: aerodynamic, force plate and still photograph data	SCx Reduced amplitude Frontal area	SCx varies with frontal area and is related to the positions of the limbs and trunk Frontal area and reduced amplitude show a linear relationship SCx is directly proportional to reduced amplitude
Brodie et al. [36] 58 %	Quasi-experimental Case study	$n = 1$ Sex: male Age: 20 years Country: New Zealand Level: National team	Discipline: GS Site: ski slope Study: kinematics and kinetics data using fusion motion capture, combining inertial sensors, video, GPS and plantar pressure data Note: pilot use of fusion motion capture with accuracy of this system not yet known	Course and gait times Force vectors CoM trajectory Air drag, friction, GRF, gravitational and total kinetic energies (work)	Split times, CoM trajectory and force vectors reflect good turning technique Faster turns had an apex well before the gate, allowing a greater acceleration from the gate and straighter skiing after the gate, despite a longer CoM trajectory The horizontal component of the GRF (pointed in the direction of skiing) was applied earlier, was smoother and kept for relatively longer, resulting in acceleration
Federolf [23] 79 %	Quasi-experimental Case series	$n = 6$ Sex: male Age range: 17–20 years Country: Norway Level: European Cup FIS points mean ± SD: 22 ± 8	Discipline: slalom Site: ski slope Study: kinematics based on video data	Time difference Change in elevation Change in distance Elevation Instantaneous performance Velocity	$p \approx$ time loss per change in elevation and depends on v and the distance travelled per change in elevation p varies more with change in v than change in the distance travelled p differences between skiers at the start of turns persist until the end of turns
Lešnik and Žvan [19] 65 %	Non-experimental Case series	$n = 18$ Level: WC	Discipline: slalom Site: Kranjska Gora WC, Slovenia Study: kinematics based on video data	Mean distance between ski and fall lines ($y = 0$) Mean velocity of skis Trajectory of the point closest to the gate	Insignificant negative correlation between the distances of the skiing lines for two consecutive turns Significant negative correlation between the average skiing velocity and distance between the line of skiing and the fall line during two consecutive turns Skiers further away at the first turn are generally closer at the second turn Skiing velocity generally increases as the skiing line decreases

Table 1 continued

StudyQuality score (%)	Study design	Subjects	Experimental protocol	Biomechanical parameters	Findings with implications for performance
Luethi and Denoth [37] 40 %	Quasi-experimental Case series	$n = 8$ Country: Switzerland Level: National team	Discipline: DH Site: Wind tunnel Study: Aerodynamic, force plate and video data	Aerodynamic drag and lift coefficients Mass Frontal area Anthropometric code number	The factors that exert the most impact on DH times are the drag coefficient (49 %), mass (29 %), frontal area (21 %) and lift coefficient (1 %) Performance is better with a higher anthropometric code number (i.e., ↓ drag coefficient, ↑ mass, ↓ frontal area, and ↓ lift coefficient)
Spörri et al. [22] 67 %	Quasi-experimental Case study	$n = 1$ Level: WC (World Champion)	Discipline: GS Site: ski slope Study: Kinematics based on video data	CoM line (i.e., trajectory) path length, radius, velocity, and traverse angle Total mechanical energy Energy dissipation ($\Delta e_{\mathrm{mech}}/v_{\mathrm{in}}$) Entrance and exit velocities Turn and section times Skid angle Path of quickest decent	Fast in comparison to slow turns: ↑ CoM trajectory length, ↑ CoM radius, ↓ CoM traverse angle, ↑ v_{in}, ↑ v_{out}, ↓ energy dissipation pre-gate, ↑ energy dissipation post-gate, ≈total energy dissipation, ↓ skid angle pre-gate, ↑ skid angle post-gate, ↓ total skid angle Fast turns are initiated farther from and completed closer to the gates (*x* and *y*), with a longer initiation and pre-gate section The differences in CoM line characteristics and turn cycle structure between slow and fast turns increase as the gate offset is reduced
Supej and Cernigoj [2] 80 %	Non-experimental Case series	$n = 8$ Sex: male Age range: 26–37 years Country: Austria, Canada, Finland, Italy, Sweden, United States Level: WC	Discipline: GS Site: Sölden WC, Austria Study: kinematics based on video data	Time from the first gate Section time Time behind the fastest skier in a section Section time (%) relative to the theoretical fastest section time Sum of all section time differences behind the fastest section times	Performance differences among top WC racers on given sections can be as much as 10 % Individual abilities are influenced by the terrain, course configuration and snow conditions
Supej [24] 67 %	Non-experimental Case series	$n = 16$ Sex: Male Level: WC	Discipline: GS Site: Kranjska Gora WC, Slovenia Study: kinematics based on video data	Specific mechanical energy (e_{mech}) Differential specific mechanical energy [diff(e_{mech})] Trajectory of the ski	Efficient use of potential energy reflects the technical ability to reduce ski-snow friction and aerodynamic drag Energy dissipation is cyclic (i.e., highest at the gates and lowest during weight transitions) Energy dissipation is lower in smooth carving than side-skidding turns Better skiers started turns earlier with high intensity (short radius) Short radius turns close to the gates (most direct line) increase energy dissipation and lower performance

Table 1 continued

StudyQuality score (%)	Study design	Subjects	Experimental protocol	Biomechanical parameters	Findings with implications for performance
Supej et al. [21] 76 %	Non-experimental Case series	$n = 18$ Sex: Male Level: WC	Discipline: slalom Site: Kranjska Gora WC, Slovenia Study: kinematics based on video data	e_{mech} Diff(e_{mech}) v_{in} and v_{out} Radius, velocity and acceleration of the CoM during turns Radius of the trajectory of the skis GRF	Higher compared with lower performing skiers: ↓ diff(e_{mech}), ↓ Δ e_{mech}/v_{in}, ↑ v_{out}, ↑ v_{in}, ↑ CoM v with a similar range of energy dissipation No difference in the turn radius or acceleration of the CoM, ski turn radius and GRF Positive correlation between diff(e_{mech}) and ski turn radius <15 m; between diff(e_{mech}) and acceleration of the CoM; and between diff(e_{mech}) and GRF with radius <15 m High GRF coincides with low diff(e_{mech}) and high energy dissipation A 'hysteresis' and phase transition is observed in [GRF/ski turn radius] at a 15 m radius, with highest GRF at the smallest turn radius Acceleration of the CoM is inversely proportional to the GRF Short ski turn radius and high GRF need to be lowered to maintain energy and improve performance
Supej and Holmberg [35] 82 %	Quasi-experimental Repeated-measures	$n = 8$ (4, 4) Sex: male, female Age mean ± SD: 22 ± 4 years, 23 ± 5 years Level: top-level skiers	Discipline: slalom Site: ski slope Study: kinematics based on GNSS and photocells (timing gates) data	An intermediate, intermediate-to-final and final time Shortest time from start to each gate Time differences relative to the fastest time (lag) Gate-to-gate times	Largest absolute difference between skiers at the start, in the transition phases, and in the regions close to and after the hairpin bends Slight differences in intermediate lag times Large differences in final cumulative lag times Skiers performed considerably differently on various sections of the course Much care must be taken preceding a flat section to maintain good entry velocity, so that time losses on this section are minimized

Table 1 continued

StudyQuality score (%)	Study design	Subjects	Experimental protocol	Biomechanical parameters	Findings with implications for performance
Supej [34] 89 %	Quasi-experimental Repeated-measures	$n = 9$ Sex: male Age mean ± SD: 20 ± 4 years Country: Sweden Level: National team FIS points mean ± SD: 19 ± 11	Discipline: GS Site: wind tunnel and ski slope Study: aerodynamics, force plate and video data; and on slope kinematics/kinetics and aerodynamics based on data from GNSS, videos and anemometers	Drag and friction coefficients Aerodynamic drag and friction force E_t E_d Relative energy dissipation due to aerodynamic drag (E_d E_t) Sectional energy based on entry velocity (E_t/v_{in}) Turn time, velocity and CoM trajectory	Drag coefficient is significantly correlated with shoulder height Aerodynamic drag is minimal during weight transfer and is maximal near the start gates (mostly noise from ski-pole push-off) The correlation between E_d and E_t was poor and insignificant for most turns Largely insignificant relationships between E_d and E_t, between E_t/v_{in} and E_d, and between E_t/v_{in} and average drag coefficient On averaging all turns, the only significant correlations were between E_t/v_{in} and E_d/E_t, between v and E_d, and between v and E_d/E_t The E_d/E_t per turn was ~15 %, indicating that E_t is due primarily to ski-snow friction and poor guidance of the skis A more pronounced contribution of E_d to E_t is correlated with better performance, suggesting that reduction in E_t from sources other than E_d will improve performance
Watanabe and Ohtsuki [38] 69 %	Quasi-experimental Repeated-measures	$n = 2$ Sex: male Country: Japan Level: top-level skiers	Discipline: DH Site: wind tunnel Study: aerodynamics using data from wind tunnel, force plates and photographs	Aerodynamic drag and lift coefficients Relative velocity Drag and lift area	The aerodynamic drag and lift forces are minimal when the relative velocity and postures are minimized Drag forces increase as the centre of gravity is raised and the arms are extended The increase in drag with arm extension is relatively great and independent of trunk position The ability to ski with tight arms is a key factor in DH performance Slight postural changes can greatly influence the relative velocity and, thus, the distance covered in any given time

CoM centre of mass; *Diff(e_{mech})* differential specific mechanical energy, *DH* downhill, E_d energy dissipation due to aerodynamic drag, E_t total energy dissipation, e_{mech} specific mechanical energy, *FIS* International Ski Federation, *GNSS* global navigation satellite system, *GPS* global positioning system, *GRF* ground reaction force, *GS* giant slalom, p instantaneous performance, *SCx* aerodynamic drag coefficient, v velocity, v_{in} entrance velocity, v_{out} exit velocity, *WC* World Cup

[21, 22, 24, 34]. Other factors recurringly reported to influence ski racing performance were posture [20, 37, 38], frictional forces and ground reaction forces (GRFs) [21, 36], the trajectories of the skis and/or centre of mass [19, 21, 22, 24, 34, 36], turning technique and radius [21, 22, 24, 36], previous turn performance [19, 21, 23, 36], and individual traits [2, 19].

Adopting postures that minimized the skier's exposed frontal area was a key factor in reducing aerodynamic drag [20, 38], increasing the average skiing velocity [38], and reducing overall run times [37, 38]. This was true particularly when skiing downhill or in a straight line, under which conditions wind tunnel measurements support that the variation in aerodynamic drag accounted for almost 50 % of the differences in time required to complete 300-m computer-simulated runs [37]. Minimal aerodynamic drag was observed when skiing in an egg shape with arms close to the trunk [20, 38]. In the case of giant slalom, however, aerodynamic drag was reported to account for only 15 % (range 5–28 %) of the total energy loss per turn and the authors thus concluded that this factor was not a major determinant of giant slalom performance [34].

In general, initiating slalom and giant slalom turns higher up on the slope and/or well before the gate resulted in a smoother and more rapid turn. Despite the increase in the length of the skiing trajectory [22, 24, 36], such turns had lower or equal net negative work with a more favourable distribution of the GRF and energy dissipation. However, upon observing two consecutive turns, one article reported an alternate relationship, where the average skiing velocity fell as the average distance between the line of skiing and the fall line increased [19]. Nevertheless, instantaneous performance during alpine ski racing (defined as the time lost per change in elevation) was more strongly correlated to change in skiing velocity than change in distance travelled, suggesting that a higher velocity is more advantageous than a shorter trajectory [23].

Typically, more energy is dissipated during the pre-gate than the post-gate section of a turn of an elite skier [22]. However, when comparing the fastest and the slowest trial of the same elite skier, the difference between the average energy dissipated on the pre-gate section and on the post-gate section was found to be smaller in the fastest than the slowest trial, while the total average amount of energy dissipation was identical [22]. The ability to use potential energy effectively (i.e., to minimize the ski-snow friction and optimize the guidance of skis while turning) was employed to define a well performed turn, which was achieved more easily when the elite skier utilized a carving rather than a skidding or pivoting technique to turn [24]. Minimizing high instantaneous GRFs was proposed to reduce ski-snow friction and energy dissipation during turns, thereby lowering the time required to cover short sections of a giant slalom course [21]. During well executed turns, the horizontal component of the GRF (i.e., the component pointed in the direction of skiing) was applied earlier, maintained over a relatively longer proportion of the turn, and contributed to acceleration [36].

The inter-dependency of performance in successive turns was signalled in several articles [19, 21, 23, 36], one of which emphasized that the conditions of entry into and exit from any given turn are closely related to the conditions of exit from the previous turn and entry into the following turn, respectively [21]. The importance of capitalizing on individual strengths and reducing the impact of weaknesses was also highlighted, since the performance times of elite skiers vary according to the turn, course, terrain, and environmental conditions [2, 35].

4 Discussion

This review has attempted to identify the biomechanical factors that influence the performance of elite alpine ski racers, particularly during slalom, giant slalom, super-G, and downhill events. The main factors found were aerodynamic drag, turn characteristics (notably velocity, turn radius, and trajectory), mechanical energy dissipation behaviours, and individual skiing techniques. The intricate interactions between these biomechanical factors under different conditions are used by elite skiers to minimize their descent times. In summary, the effective use of potential energy reflects a skier's technical ability to reduce ski-snow friction and aerodynamic drag, the latter being particularly influential during downhill events or in straight line skiing, in combination with the capacity to maintain high velocities and the skill to select the optimal line of skiing [24].

In actual fact, identifying the biomechanical factor(s) that exerts the greatest impact on the performance of elite alpine ski racers is a considerable challenge in light of the wide variety of approaches employed to examine this topic. As presented in the results, in addition to turn, section, and course times [2, 22, 34–36], several researchers have used instantaneous performance in their attempt to compare faster and slower elite skiers [19, 21–23, 39].

The motivation for using such parameters to define skiing performance was justified in one paper on the basis that the time required to complete sections comes with several limitations [21]: (1) it is influenced by the skier's initial velocity, position, and orientation; (2) an error made close to the end of the section observed exerts only minimal impact on the time measured, but may affect the performance in the next section due to a reduction in the exit velocity; (3) the skier's position and orientation at the end of the section in relation to the following gate will exert only a marginal impact on the section time, but may influence performance in the next section; and (4) a high exit velocity will have only a small influence on the time measured, despite its potential to contribute to performance in the subsequent section. On the other hand, another paper stated that using a skier's velocity and/or energy state was also limited in quantifying ski racing performance because actual performance was also dependent on the path chosen by a skier [23].

Indeed, one parameter in isolation cannot explain *why* one skier is faster than another. While instantaneous performance parameters are practical to measure and compare, it is their interaction with other factors that determines cumulative run times and ultimately the outcome of a race. From a mechanical viewpoint, the kinematic parameters may be perceived as reflecting the outcomes of performance (i.e., differences in motion without reference to causes) and the kinetic parameters more reflective of the causes that explain these differences in performance (i.e., the integrals of forces and their effects on motion). Both are needed to comprehend and improve alpine ski racing performance.

The considerable impact of aerodynamic drag on alpine ski racing performance summarized here [20, 34, 37, 38] appeared to depend on both the skiing event and biomechanical measure under consideration. For example, in straight sections and during downhill events, the effects of aerodynamic drag are minimal when skiing in the egg-shaped posture with the arms close to the trunk [20, 38]. However, in more technical sections and events when such positions are not feasible, effective aerodynamic position is suggested to more strongly depend on the ability of a skier to adopt a posture that minimizes the exposed frontal area without compromising the balance or line of skiing [20]. At certain time points, such as on flat sections or during flight, aerodynamics is one of the only factors under a skier's control and can thus be optimized to enhance performance. In light of the small winning margins at the 2013 Alpine World Ski Championships [1], aerodynamic may well be a decisive factor in determining podium place finishes, particularly in speed events.

All the laboratory studies reviewed here acquired data relevant to performance in wind tunnels, whereas a diversity of methods was employed on snow. Analysis of video films was the most common [2, 19, 21–24], but global navigation satellite systems with and without timing gates [34, 35] and fusion motion capture [36] were also utilized. In this last case, Brodie et al. [36] introduced a prototype system that combined data from global position, inertial, and plantar pressure sensors. Using this approach, the researchers tracked the whole-body and single-limb motions of one elite skier along an entire giant slalom course. Similar to observations from some of the other studies [22, 24], Brodie et al. found that the fastest turns had apexes well before the gate that allowed greater acceleration from the gate and straighter skiing after the gate, which more than compensated for the longer distance travelled. The horizontal component of the GRF (pointed in the direction of skiing) that results in acceleration was also increased earlier, generally smoother and maintained for a relatively longer period of time.

Full-body inertial measurements on alpine skiers are useful for research [40] and have proven to provide reasonably accurate kinematic values on field [39]. In contrast to conventional analyses of video films; inertial motion sensors, global navigation satellite systems, and fusion motion capture allow recording of skiing performance over a relatively larger volume, during several turns or even throughout an entire race course. However, only Brodie et al. [36] have reported applying fusion motion capture systems in an elite alpine ski racing situation and because they only piloted the use of such methods in one national skier from New Zealand, their findings are difficult to generalize and need further validation. Studies have investigated the accuracy and validity of inertial motion sensors [39], global navigation satellite systems [35, 41], and their combination [40] in analysing alpine skiing mechanics, although not for the particular prototype system employed by Brodie et al. [36]

Most of the other on-snow studies computed a series of parameters designed to quantify the performance of turns in giant slalom [2, 22, 24, 34] and slalom [19, 21, 23, 35] using video films, including variables that define the trajectory of the centre of mass and/or skis, radius and/or initiation point of turns, entrance and/or exit velocities, skid and/or traverse angles, and amount of carving and/or skidding during turns. To assess the relationship between these factors and skiing performance, several equations and models were employed, some of which included the principle of differential mechanical energy. Using such approaches, Supej et al. [21, 24] reported that the greatest dissipation of energy in slalom occurs in the vicinity of the gates (during steering) and in turns with a short radius (<15 m), whereas the lowest dissipation of energy occurs during weight transition (prior to initiation). In fact, during turns with a short radius, the difference in specific mechanical energy is directly related to the turn radius [21], suggesting that a longer turn radius may be beneficial to ski racing performance despite the longer distance travelled, as discussed above and also consistent with the findings by Spörri et al. [22].

On the other hand, Lešnik and Žvan [19] reported a negative correlation between the average skiing velocity and the average distance between the line of skiing and the fall line during two consecutive turns. Altogether, the evidence appears to indicate a trade-off between instantaneous skiing velocity and trajectory length that ultimately determines the time taken to complete a turn. Although tighter turns permit a more direct line of skiing, wider turns enable faster velocities. With respect to this trade-off, Federolf [23] found that instantaneous velocity was more influential than the choice of line or turning radius (i.e., distance travelled). These findings are consistent with others that quantify performance on the basis of mechanical energy principles according to which changes in kinetic energy are determined by the velocity squared [21, 24].

On this topic, the ability of skiers to maintain high velocities was seen as an important determinant of ski racing performance that did not only rely upon the skiing trajectory chosen, but also on the skiing technique and approach to turn execution. Indeed, three studies demonstrated that more rapid turns were initiated further from the gate, completed closer to the gate, and were longer [22, 24, 36]. Since such turns generally allow a greater acceleration from the gate and straighter skiing after the gate [36], the entrance velocities into the subsequent turns should be higher and the overall performance thus improved.

However, research has revealed that this is not necessarily the case since the entrance velocity is negatively correlated to the change in velocity during a turn [21, 22]. This negative correlation suggests that performances worsen when skiers enter turns at excessively high velocities [21, 34] and skiers confront a maximal velocity above which avoiding mistakes and falls become a great challenge. Indeed, the elite alpine ski racer cannot only seek to minimize energy loss by reducing aerodynamic drag and frictional forces, since this might also lead to a loss in control of skiing velocity and trajectory, particularly in connection with technical events.

These considerations are reflected in the analysis of World Cup events, which reveal that the fastest racers do not always post the best times on all sections [2]. Instead, these skiers exhibit a more consistent performance (i.e., constantly short section times) and are able to minimize energy dissipation and maximize velocity. To this effect, avoiding turns characterized by a small turn radius, skidding, and high GRFs, particularly at the end of turns, has been proposed to be an effective means to reducing energy loss, frictional drag, and forces counteracting the downhill motion of the skier [21, 22, 24]. Energy dissipation was lower and performance enhanced when elite skiers used the carving technique of turning because it allowed high velocities to be maintained and negative impacts of ski-snow friction and high GRFs to be reduced [21, 22, 24, 34]. On the other hand, energy dissipation was higher and performance lower when the guiding of skis was imprecise and skidding or pivoting techniques of turning were used [21, 22, 24, 34].

At the same time, the influence of GRFs on the performance of elite skiers remains relatively unclear. A few attempts have been made to record and compare the GRFs of ski testers, ski instructors, and recreational skiers [42–44], but only one article fulfilling our inclusion criteria measured these forces directly in a national team member skier [36]. Employing pressure insoles, Brodie et al. [36] reported that during giant slalom turns, their skier could utilize GRFs to increase turning velocity either by leaning effectively during the entry phase (i.e., thereby increasing the distance between the trajectories of the centre of mass and skis in the horizontal plane) or by generating greater GRFs in the vicinity of the apex of the turn to reduce forces during the transition phase.

On the other hand, applying Newton's second law of motion to kinematic data, Supej et al. [21] found indications that the distribution of GRFs between higher and lower performing elite slalom skiers did not differ remarkably, but that the highest GRFs coincided with lowest differential specific mechanical energy (i.e., highest energy dissipation) and were detrimental to the instantaneous performance of all skiers, particularly during turns of short radius ($<$15 m). Collectively, these findings suggest that the appropriate timing of GRFs, more than their magnitude, may enhance performance. However, more direct investigations of forces in a relatively large cohort of internationally competitive alpine skiers are required to confirm these relationships.

None of the articles reviewed here directly examined the effect of a skier's posture and motion on ski-snow friction and straight-line gliding times, which is of particular relevance for downhill and super-G events. Elite ski racing competitions inherently include low-speed gliding sections wherein minimizing ski-snow friction can make a substantial difference to overall performance. Research in non-elite skiers [45, 46] suggest that a skier's posture and anterior-posterior position along the ski axis do not significantly impact ski-snow friction and gliding times. More precisely, well trained skiers exhibit similar ski-snow friction coefficients in egg-shape and erect standing postures [45], and professional ski testers show similar gliding times in neutral, forward, and backward leaning tucked positions. On the other hand, the latter group exhibits quicker gliding times with flat compared with (inside) edged skis, suggesting that edging of skis increases ski-snow friction [45]. Accordingly, to improve performance in straight sections, the elite skier should restrict edging motions to minimize ski-snow friction and adopt egg-shape postures to minimize aerodynamic drag, with no major concern regarding anterior-posterior body positioning over skis. Future studies should confirm the validity of these suggestions applied to internationally competitive skiers because they are currently derived from well trained, but non-competitive, skiers.

The setting of a course also appears to be an important consideration when analysing the relative effect of various biomechanical factors on performance. For instance, in a case study involving a World Champion in giant slalom, Spörri et al. [22] showed that the negative correlation between entrance velocity and turning time was stronger when the gate offset was reduced by 2 m [22]. Although the difference in time required to complete the fastest and slowest turns was smaller when this offset was reduced, the characteristics of these turns became more distinct. In a separate report that focused on injury prevention, the same authors observed that such gate changes exerted a considerably large effect on the (i) deceleration at the end of a turn, (ii) centripetal forces during the initiation and the completion of a turn, (iii) degree of inward lean post-gate, (iv) position of the centre of mass in relationship to the ankles post-gate, and (v) structure of the turn cycle [47]. Accordingly, the biomechanical factors leading to success in one race may differ significantly from those most prominent on a course with a different setting, with evidence to support this statement in both slalom [48] and giant slalom [22, 47] disciplines.

Although this review identified biomechanical factors of general relevance to the performance of elite alpine ski racers, attention to individual differences is essential considering that technical and tactical abilities of the best international competitors vary considerably [2, 19]. In fact, the relationship between any given biomechanical factor and performance exhibited by a group of World Cup alpine skiers was not demonstrated by all the individual members constituting this group [19]. The key to success appears to be more closely related to a skier's ability to maintain a consistently high level of performance and select the optimal turning technique and line of skiing on various courses, terrain, and snow conditions than to a skier's ability to achieve the fastest time or highest velocity under a given circumstance. Accordingly, training of elite skiers should focus not only on maximizing time gain on strong sections, but also on minimizing time loss on weak ones.

Moreover, the differences in section times between skiers tend to differ to a greater extent on specific areas of the race course. In the slalom event, for example, time differences between competitors are greatest at the start of the race, during transitional phases, around hairpin bends and when entering or negotiating flat sections [35]. Enhancing performance on such sections may prove to be of great benefit to overall race time.

On the basis of the present review, certain recommendations for the coaching and training of elite alpine skiers can be made. There was clear evidence supporting the importance of appropriate ski guidance with consequent reduction of ski-snow friction and energy dissipation. In the case of slalom and giant slalom, one should encourage (i) earlier initiation of turns (despite the increase in the distance travelled) [22, 24, 36], (ii) achievement of earlier and smoother application of GRFs when turning by leaning more effectively (i.e., increasing the distance between the trajectories of the centre of mass and skis in the horizontal plane) during the entry phase [36], and (iii) use of carving rather than skidding or pivoting techniques for turning [21, 22, 24, 34]. For speed events, but also technical ones, skiers should practice adopting and maintaining positions that reduce the exposed frontal area [20, 34, 37, 38]. None of the studies reviewed here examined relationships between downhill or super-G performance and turn characteristics or trajectories or manoeuvres, thus restricting suggestions for training for such events.

A common limitation in research on performance of elite sports is the small number of subjects available, which is reflected in the articles evaluated here. However, individual tactics and techniques are also aspects of importance in top-level sports performance and coaching. Therefore, single subject analyses are also likely to contribute to the identification of biomechanical factors that lead to the quickest alpine skiing descent. The greater concern is the low number of females, who represented less than 4 % of all the subjects examined. It is difficult to generalize the current findings to the elite female skier as she differs physiologically [49], morphologically [50], and with respect to injury [51–53] from her male counterpart. Clearly, further biomechanical studies on internationally competitive female skiers and comparisons of female and male skiers are warranted. Similarly, differences in the level of skills between juniors and seniors and between rankings by different nations must be taken into consideration prior to the integration of research findings to practice.

A second limitation discerned in several of these articles was that skiing performance was examined over two to four gates only and generalization of findings to an entire race course must be made with caution. For instance, for a slalom course consisting of 56 gates, two gates represent a mere 3.6 % of the entire course. Therefore, it is important to determine whether performance in a restricted number of turns accurately reflects performance of an elite skier across a series of gates and, moreover, whether high instantaneous performance can be maintained throughout an entire race. In biomechanical field studies; video-based systems presumably provide higher accuracy for analysing a skier's position in the order of centimetres, but limit the maximum number of analysable turns and become less accurate when considering derivative parameters, such as accelerations and angular velocities, compared with purpose-built sensors. On the other hand, global navigation satellite systems and inertial sensors may enlarge the capture volume and increase the number of analysable turns, but simultaneously limit accuracy in the local coordinate system. The simultaneous use of several systems might hence be necessary to further advance research in this area.

As for speed disciplines, the level of specificity of findings derived from wind tunnels to downhill or super-G events is not clear, nor are the effects of posture and skier action on ski-snow friction.

The present review is limited to articles published in English in peer-reviewed scientific journals, indicating that articles in other languages and/or in books were not included. Nonetheless, we believe that the essential information currently available in this field was covered. A further consideration is that this review focused exclusively on elite alpine skiers and the biomechanical factors that influenced performance. Consequently, studies on ski instructors, testers, amateurs or regional competitors, or that described without comparing the biomechanical traits of elite skiers (e.g., principal component [25] or electromyography [54] analyses to describe patterns of movement) were excluded. However, the characteristics of international elite sportspeople differ from those of national, regional, and non-elite athletes [49, 55, 56] and we chose to focus specifically on the former to help improve competitive alpine ski racing performance. Rather than being a limitation, the specificity of the search strategy and inclusion criteria strengthens the relevance of findings towards the population of interest. The systematic methods, quality appraisal tools, and strategies for reducing potential bias (e.g., article blinding and input from independent reviewers) employed here contribute to the rigour of our results and conclusions.

5 Conclusions

Identifying the biomechanical factors that determine the performance of elite alpine ski racers is a challenging goal. The present review indicates that performance is enhanced by minimizing energy dissipation while maintaining high velocity and an optimal trajectory. In this context, reduction of the exposed frontal area, longer turn radius, earlier initiation of turns, avoidance of high GRFs (particularly in the latter part of turns), and employment of carving instead of skidding or pivoting techniques of turning are all proposed to improve the performance of elite skiers.

The timing and application of GRFs also differ when comparing fast to slow turns, whereas the magnitude does not. Although individual tactics and techniques are obviously important, performing well consistently on all sections was more advantageous than being best on given sections. Moreover, certain biomechanical factors are of greater significance in connection to speed (downhill and super-G) than technical (giant slalom and slalom) events.

In summary, the efficient use of potential energy in skiers reflects their ability to minimize ski-snow friction and aerodynamic drag, which is particularly important in speed events and on flat sections of a technical course. However, in the case of slalom and giant slalom, such minimization of energy dissipation is not sufficient to ascertain the shortest overall descent time. In elite skiers, the ability to achieve such minimization in a manner that allows maintenance of high velocities and optimal line choice on all sections also exerts a considerable impact on race outcomes. To fully comprehend the biomechanical factors determining alpine skiing performance, future research must focus more on the performance over an entire race course, on the influence of the skiers' movement patterns on performance-related biomechanical factors, as well as on the elite female skier and different skill levels.

Acknowledgements The authors acknowledge contribution from Laura Nevala and Ben Stocks in the systematic review process. This review was supported financially by the Swedish National Centre for Research in Sports, without any relevant conflicts of interest to declare.

References

1. International Ski Federation. Events & Places: Schladming Results. 2013. http://www.fisalpine.com/venues/calendar-archive.html?page=2. Accessed 03 May 2013.
2. Supej M, Cernigoj M. Relations between different technical and tactical approaches and overall time at men's world cup giant slalom races. Kinesiol Slov. 2006;12(2):59–68.
3. Turnbull JR, Kilding AE, Keogh JWL. Physiology of alpine skiing. Scand J Med Sci Sports. 2009;19(2):146–55.
4. Andersen RE, Montgomery DL. Physiology of alpine skiing. Sports Med. 1988;6(4):210–21.
5. Ferguson RA. Limitations to performance during alpine skiing. Exp Physiol. 2010;95(3):404–10.
6. Hydren JR, Volek JS, Maresh CM, et al. Review of strength and conditioning for alpine ski racing. Strength Cond J. 2013;35(1):10–28.
7. Colbeck SC. A review of the friction of snow skis. J Sports Sci. 1994;12(3):285–95.
8. Flørenes TW, Nordsletten L, Heir S, et al. Injuries among World Cup ski and snowboard athletes. Scand J Med Sci Sports. 2012;22(1):58–66.
9. Chissell HR, Feagin JA Jr, Warme WJ, et al. Trends in ski and snowboard injuries. Sports Med. 1996;22(3):141–5.
10. Hagel B. Skiing and snowboarding injuries. Med Sport Sci. 2005;48:74–119.
11. Bouter LM, Knipschild PG. Causes and prevention of injury in downhill skiing. Phys Sportsmed. 1989;17(11):81–94.
12. Natri A, Beynnon BD, Ettlinger CF, et al. Alpine ski bindings and injuries: current findings. Sports Med. 1999;28(1):35–48.
13. Pressman A, Johnson DH. A review of ski injuries resulting in combined injury to the anterior cruciate ligament and medial collateral ligaments. Arthroscopy. 2003;19(2):194–202.
14. Hunter RE. Skiing injuries. Am J Sports Med. 1999;27(3):381–9.
15. Koehle MS, Lloyd-Smith R, Taunton JE. Alpine ski injuries and their prevention. Sports Med. 2002;32(12):785–93.
16. Hébert-Losier K, Holmberg HC. What are the exercise-based injury prevention recommendations for recreational alpine skiing and snowboarding? A systematic review. Sports Med. 2013;43(5):355–66.

17. Müller E, Schwameder H. Biomechanical aspects of new techniques in alpine skiing and ski-jumping. J Sports Sci. 2003;21(9):679–92.
18. Burtscher M, Gatterer H, Flatz M, et al. Effects of modern ski equipment on the overall injury rate and the pattern of injury location in alpine skiing. Clin J Sport Med. 2008;18(4):355–7.
19. Lešnik B, Žvan M. The best slalom competitors: kinematic analysis of tracks and velocities. Kinesiology. 2007;39(1):40–8.
20. Barelle C, Ruby A, Tavernier M. Experimental model of the aerodynamic drag coefficient in alpine skiing. J Appl Biomech. 2004;20(2):167–76.
21. Supej M, Kipp R, Holmberg HC. Mechanical parameters as predictors of performance in alpine World Cup slalom racing. Scand J Med Sci Sports. 2010;21(6):e72–81.
22. Spörri J, Kröll J, Schwameder H, et al. Turn characteristics of a top world class athlete in giant slalom: a case study assessing current performance prediction concepts. Int J Sports Sci Coach. 2012;7(4):647–60.
23. Federolf PA. Quantifying instantaneous performance in alpine ski racing. J Sports Sci. 2012;30(10):1063–8.
24. Supej M. Differential specific mechanical energy as a quality parameter in racing alpine skiing. J Appl Biomech. 2008;24(2):121–9.
25. Federolf P, Reid R, Gilgien M, et al. The application of principal component analysis to quantify technique in sports. Scan J Sci Med Sports. 2012. doi:10.1111/j.1600-0838.2012.01455.x.
26. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. J Epidemiol Community Health. 1998;52(6):377–84.
27. Andrew E, Anis A, Chalmers T, et al. A proposal for structured reporting of randomized controlled trials. J Am Med Assoc. 1994;272(24):1926–31.
28. Mills K, Hunt MA, Ferber R. Biomechanical deviations during level walking associated with knee osteoarthritis: a systematic review and meta-analysis. Arthr Care Res. 2013;65(10):1643–65.
29. Hall JL, Barton C, Jones P, et al. The biomechanical differences between barefoot and shod distance running: a systematic review and preliminary meta-analysis. Sports Med. 2013;43(12):1335–53.
30. Cummins C, Orr R, O'Connor H, et al. Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. Sports Med. 2013;43(10):1025–42.
31. Costa MJ, Bragada JA, Marinho DA, et al. Longitudinal interventions in elite swimming: a systematic review based on energetics, biomechanics, and performance. J Strength Cond Res. 2012;26(7):2006–16.
32. Hurley WL, Denegar CR, Hertel J. Research methods: a framework for evidence-based clinical practice. Baltimore: Lippincott Williams & Wilkins; 2010.
33. Berg KE, Latin RW. Essentials of research methods in health, physical education, exercise science, and recreation. 3rd ed. Baltimore: Lippincott Williams & Wilkins; 2008.
34. Supej M, Sætran L, Oggiano L, et al. Aerodynamic drag is not the major determinant of performance during giant slalom skiing at the elite level. Scand J Med Sci Sports. 2013;23(1):e38–47.
35. Supej M, Holmberg H-C. A new time measurement method using a high-end global navigation satellite system to analyze alpine skiing. Res Q Exerc Sport. 2011;82(3):400–11.
36. Brodie M, Walmsley A, Page W. Fusion motion capture: a prototype system using inertial measurement units and GPS for the biomechanical analysis of ski racing. Sports Technol. 2008;1(1):17–28.
37. Luethi SM, Denoth J. The influence of aerodynamic and anthropometric factors on speed in skiing. Int J Sport Biomech. 1987;3(4):345–52.
38. Watanabe K, Ohtsuki T. Postural changes and aerodynamic forces in alpine skiing. Ergonomics. 1977;20(2):121–31.
39. Krüger A, Edelmann-Nusser J. Application of a full body inertial measurement system in alpine skiing: a comparison with an optical video based system. J Appl Biomech. 2010;26:516–21.
40. Supej M. 3D measurements of alpine skiing with an inertial sensor motion capture suit and GNSS RTK system. J Sports Sci. 2010;28(7):759–69.
41. Gilgien M, Spörri J, Chardonnens J, et al. Determination of external forces in alpine skiing using a differential global navigation satellite system. Sensors. 2013;13(8):9821–35.
42. Vaverka F, Vodickova S, Elfmark M. Kinetic analysis of ski turns based on measured ground reaction forces. J Appl Biomech. 2012;28(1):41–7.
43. Nakazato K, Scheiber P, Müller E. A comparison of ground reaction forces determined by portable force-plate and pressure-insole systems in alpine skiing. J Sports Sci Med. 2011;10(4):754–62.
44. Scheiber P, Seifert J, Müller E. Relationships between biomechanics and physiology in older, recreational alpine skiers. Scand J Med Sci Sports. 2012;22(1):49–57.
45. Watanabe K, Ohtsuki T. The effect of posture on the running speed of skiing. Ergonomics. 1978;21(12):987–98.
46. Federolf P, Scheiber P, Rauscher E, et al. Impact of skier actions on the gliding times in alpine skiing. Scand J Med Sci Sports. 2008;18(6):790–7.
47. Spörri J, Kröll J, Schwameder H, et al. Course setting and selected biomechanical variables related to injury risk in alpine ski racing: an explorative case study. Br J Sports Med. 2012;46(15):1072–7.
48. Supej M, Holmberg HC. How gate setup and turn radii influence energy dissipation in slalom ski racing. J Appl Biomech. 2010;26(4):454–64.
49. White AT, Johnson SC. Physiological comparison of international, national and regional alpine skiers. Int J Sports Med 1991;12(4):374–8.
50. Haymes EM, Dickinson AL. Characteristics of elite male and female ski racers. Med Sci Sports Exerc. 1980;12(3):153–8.
51. Stevenson H, Webster J, Johnson R, et al. Gender differences in knee injury epidemiology among competitive alpine ski racers. Iowa Orthop J. 1998;18:64–6.
52. Ekeland A, Dimmen S, Lystad H, et al. Completion rates and injuries in alpine races during the 1994 Olympic Winter Games. Scand J Med Sci Sports. 1996;6(5):287–90.
53. Bere T, Flørenes TW, Nordsletten L, et al. Sex differences in the risk of injury in World Cup alpine skiers: a 6-year cohort study. Br J Sports Med. 2013. doi:10.1136/bjsports-2013-092206.
54. Berg HE, Eiken O. Muscle control in elite alpine skiing. Med Sci Sports Exerc. 1999;31(7):1065–7.
55. Lorenz DS, Reiman MP, Lehecka BJ, et al. What performance characteristics determine elite versus nonelite athletes in the same sport? Sports Health. 2013;5(6):542–7.
56. Eynon N, Ruiz JR, Oliveira J, et al. Genes and elite athletes: a roadmap for future research. J Physiol. 2011;589(13):3063–70.