Original Research Article

International Journal of Sports Science & Coaching

International Journal of Sports Science & Coaching
1–10

DOI: 10.1177/17479541261479190
journals.sagepub.com/home/spo
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In-season resistance training intervention improves strength and power characteristics in academy freestyle freeski athletes – a quasi-experimental study

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Abstract

Resistance training (RT) is recognized for enhancing strength and power in athletes, yet its application and effects in freestyle freeski athletes remain underexplored. This study examined the impact of an in-season RT intervention on lower-body strength and power characteristics in freeski athletes. Twenty-four male athletes (mean ± SD; age 17.5 ± 1.3 years, height 177.2 ± 3.9 cm, mass 71.9 ± 4.4 kg) participated in a nonrandomized controlled study. Participants were assigned to two groups: 13 freeski athletes formed the RT group, 11 sports athletes served as historical control. A repetitions in reserve RT approach (including knee and hip dominant exercises) were performed twice per week. Assessments, CMJ height, drop jump (DJ) height, DJ contact time, reactive strength index (RSI), absolute peak force (PF_{abs}), and relative PF, were conducted pre-and post-intervention. Differences were analysed using repeated measures MANOVA Wilks' lambda (Λ), magnitude of effect with partial-eta squared (ηp2), and pairwise comparisons with Cohen's d. Within-group pre-to-post changes were assessed using paired sample t-tests. A significant effect between timepoint and group was found (Wilks' Λ=0.3, $F(8,15) = 4.33$, $p < 0.007$, ηp^2=0.7), indicating changes over time (pre vs. post) differed significantly between the RT intervention and control groups. There was a significant main effect of group (Wilks' Λ=0.4, $F(8,15) = 2.65$, $p = 0.049$, ηp^2=0.6), highlighting differences across all dependent variables. Timepoint effect was significant (Wilks' Λ=0.15, $F(8,15) = 10.3$, $p < 0.001$, ηp^2=0.8), reflecting considerable changes across dependent variables. The RT group demonstrated significant improvements in all dependent variables ($p < 0.05$). A 10-week in-season RT intervention twice per week elicited significant improvements in lower-body strength and power characteristics in freeski athletes.

Keywords

Athlete monitoring, autoregulation, on-snow season, physical fitness, technical skills

Reviewer: Brendon Ferrier (Edinburgh Napier University, UK)

Introduction

Freestyle freeski is a rapidly growing winter sport recognized for its recent inclusion of slopestyle, big air, and halfpipe events in the Winter Olympics. Freeski demands a comprehensive set of technical, tactical, and psychobiological skills.[1] Furthermore, freeski athletes often perform potentially high-injury-risk tricks near the limits of their technical proficiency and physical capacity, placing substantial demands on arousal regulation during both training and competition[2] making their long-term and short-term preparation unique and challenging.[3] To perform these tricks safely, freeskiers must maintain the strength and coordination required to propel themselves into the air and adapt to variable transitions, features and take-offs and landings on uneven surfaces.[4]

Freeski is often characterized by early specialization, as evidenced by the average age of 17.5 years of the top 20 athletes at the Sochi 2014 Winter Olympics when they first

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reached international podium success. Consequently, freeski athletes and coaches often prioritize on-snow skill acquisition, trick refinement and retention, and mental performance development,[5,6] often at the expense of consistent physical conditioning, especially during the on-snow season.[3]

Although not clearly defined, qualitative data from a small sample of elite freeski coaches indicate that a basic level of general fitness and musculoskeletal balance is viewed as essential for reducing injury risk and enhancing performance progression.[1,7] However, quantitative data on other potentially important physiological capacities, such as muscular strength, are quite rare.[8] While not exceptional, the strength and force production capacities of freeski athletes are well-developed[8–10] and comparable to those found in alpine ski racers.[11] This lack of research and evidence poses challenges for decision-making in long-term athlete development within the broader context of holistic training and development at the academy-elite level.

There is compelling evidence that success across numerous sports often relies heavily on an athlete's ability to utilize high levels of lower-body strength to generate large forces quickly.[12–15] Notably, studies in snowboard cross[16] and alpine skiing[17] highlight the significance of greater lower-body strength in these disciplines, showing that maximum isometric force is strongly associated with speed-related performance metrics.[17] While freestyle snowboard athletes are known to be exposed to impact forces equal to approximately 4.1 body weight (e.g., ∼2816 newtons for a 70 kg athlete) when landing from jumps spanning 7.5 to 15 meters.[18] Moreover, since freeski athletes carry high momentum during landing and have limited time to reduce ground reaction forces,[19] they may often need to generate high levels of force quickly while simultaneously adopting technically effective positions for successful landings. These brief durations necessary to land effectively may approach maximal contractile capacity,[20] yet further research is needed.

While freeski performance is strongly influenced by technical skill,[1,7] young athletes with underdeveloped physical capacities may still experience junior success due to their technical proficiency. However, as the training intensity and volume of more technically demanding tricks on larger jumps and rail features increase, addressing underdeveloped strength and power characteristics may become an increasingly important consideration for youth athletes to help reach their full athletic potential.[21–23]

Freeski athletes appear to be at increased risk of injury,[24] and the inclusion of resistance training in an athlete program could help in terms of injury prevention.[25,26] According to recent injury prevention observational research, technical errors in the take-off and landing phases can result in falls, collisions, and non-contact injuries.[27,28] In the 2016 and 2020 Youth Winter Olympic Games, freeski athletes suffered the highest percentage of injuries.[27,28] Assuming high compliance, integrating physical training into freeski academy programs could mitigate the risks of acute and overuse injuries[29–31] likely by enhancing the structural resilience of bones, ligaments, tendons, and cartilage,[32] and improving muscle recruitment and activation patterns.[33] However, comprehensive year-round freeski injury surveillance data are still needed.[34]

There currently is limited research on resistance training practices and their impact on the long-term physical development of freeski athletes, partly due to the sport's relative infancy and the remote locations of many academies. The challenge of implementing effective resistance training during the competitive on-snow season adds to the complexity, as it must be balanced with the athletes' performance and recovery needs.[3,34] Accordingly, the aim of this study was to investigate the effects of a 10-week in-season resistance training intervention on lower body maximum strength and power performance in academy freestyle freeski athletes. A secondary aim was to provide applied coaching perspectives on the complexities of integrating sport science principles within freeski coaching practice, highlighting practical considerations and challenges faced in real-world academy environments.

Materials and methods

Participants and study design

Twenty-four male student athletes provided informed consent to participate in a non-randomized parallel group study with repeated measures to investigate the effects of resistance training on freeski athletes (Figure 1) (mean ± SD; age 17.5 ± 1.3 years, height 177.2 ± 3.9 cm, mass 71.9 ± 4.4 kg). All participants were enrolled at the Vuokatti-Ruka Sports Academy, Ruka-Kuusamo, Finland, and had a minimum of 6 months of resistance training background. The participants were divided into two groups: 13 Freeski Academy athletes formed the resistance training intervention group, and 11 male Sports Academy athletes participating in sports other than freeski (snowboard, freeride/alpine skiing, and ice-hockey) formed the historical control group. This quasi-experimental allocation method was chosen because conducting the study within a real-world youth development academy system made randomization impractical because of the limited pool of freeski athletes and the necessity of avoiding negative interference with the existing training regimes. Additionally, the time intervals between measurements differed between groups (2021 and 2023) because of COVID-19 and scheduling conflicts. The study was approved by the Ethical Committee of the University of Jyväskylä and was conducted according to the provisions of the Declaration of Helsinki.

Data collection

All participants were familiarized with the testing procedures as part of their regular training and testing protocols.

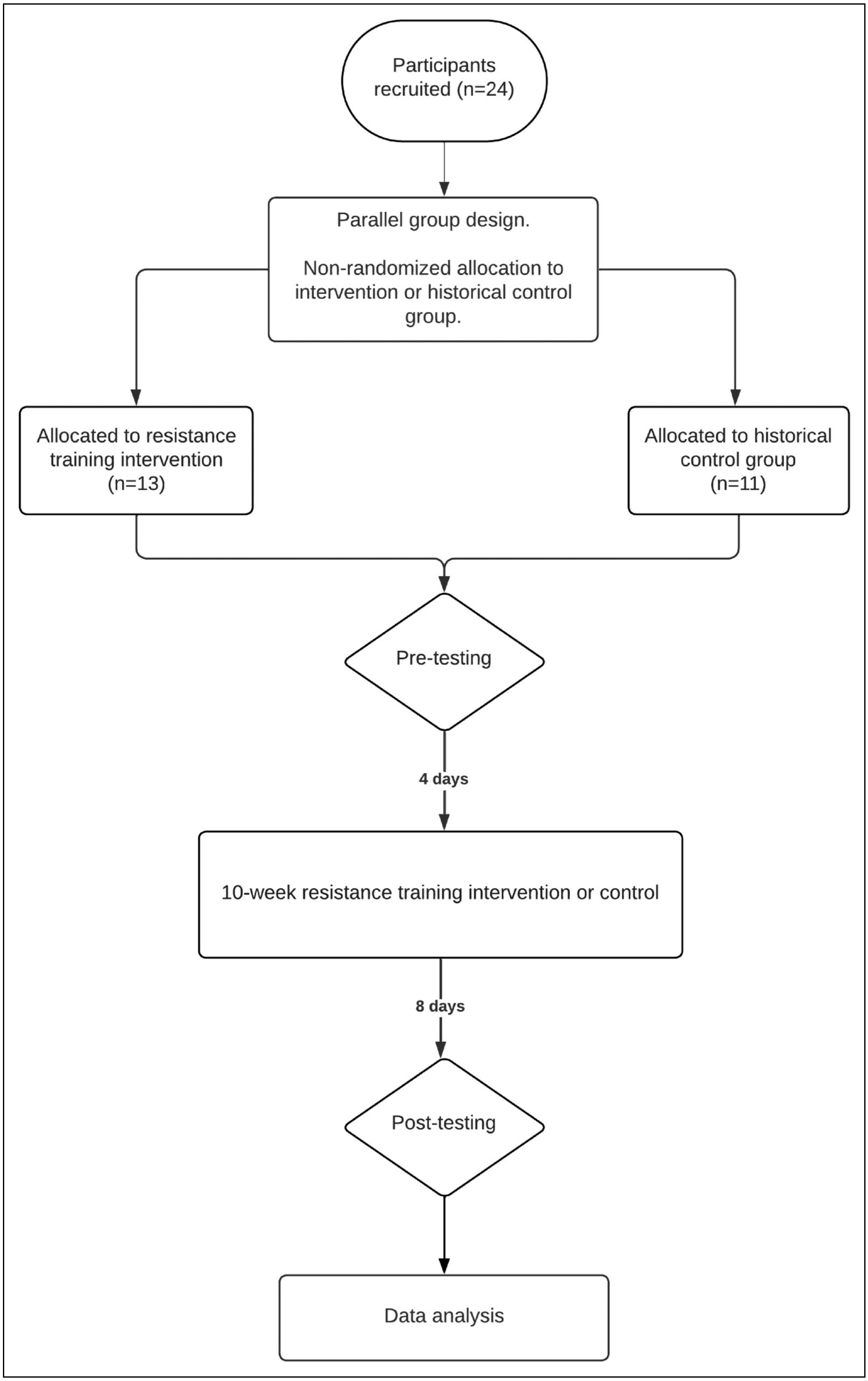

Figure 1. Study design.

Table 1. 10-week resistance training program.

Resistance training session 1				
Exercise	**Load**	**Sets**	**Reps**	**Rest**
Barbell back squat	1–2 RIR	4	5	3–4 min
Barbell unilateral calf raises	1–2 RIR	3	10	1–2 min
Barbell bent over row	1–2 RIR	3	8	2–3 min
Nordic hamstring curl	MMF	2–3	5	2–3 min
Resistance Training Session 2				
Exercise	**Load**	**Sets**	**Reps**	**Rest**
Hex bar/trapbar deadlift	2–3 RIR	3	5	3–4 min
Pull ups	1–2 RIR	4	8	3–4 min
Push back lunge	1–2 RIR	4	5	2–3 min
Unilateral Romanian deadlift	1–2 RIR	3	8	2–3 min

RIR = repetitions in reserve; MMR = momentary muscle failure.

The participants did not perform any strenuous physical activity in the 48–72 h prior to testing. Data collection for the pre-intervention measurements occurred 4 days before the intervention commenced, while post-intervention testing occurred 8 days after the final resistance training session. Figure 1 shows the design for the study.

During both sessions, participants wore normal training clothes, including trainers, and all testing took place at the same time of day and in the following order: countermovement jumps (CMJ), drop jumps (DJ) and a unilateral (single leg) isometric maximal voluntary contraction test. The duration of testing for each participant was ∼45 min. For each testing session, participants first performed a 15-min standardized dynamic warm-up consisting of 5 min of jogging and skipping, 2 min of dynamic stretching, 3 sets of 8 repetitions of linear bilateral and unilateral ankle pogo jumps, 2 sets of 8 linear and lateral hop and hold tasks, 1 set of 4 squat jumps, and 1 set of 4 bilateral and unilateral CMJ jumps.

Testing was conducted using a force plate (1000 Hz, HUR labs, Finland). The force plate was zeroed before each independent test. The force plate was securely embedded into the ground of a weightlifting platform to ensure that it was flush with the floor, avoiding any elevation above the surface. For the CMJ and DJ assessments, participants placed their hands on their hips throughout the entire jump to prevent upper-body interference.[35] For the CMJ, the trials were performed with a self-selected knee flexion angle depth of ∼90°. The participants were instructed to descend rapidly and immediately perform a jump with maximum effort. For the DJ task, instructions were given to the participants to eliminate any initial upwards movement, descend from a box 30 cm in height and then execute a jump aiming for the minimal ground contact time and maximal jump height.[36] The participants performed three trials of both the CMJ and DJ with a 15–30 s rest between each trial. A trial was considered invalid if the hands left the hips at any point.

For the unilateral isometric maximal voluntary contraction assessment, participants positioned themselves for a unilateral hex bar deadlift test,[10] ensuring a knee angle of 115° flexion, as assessed using a handheld goniometer. To accommodate taller participants, blocks were placed beneath the weights to maintain the prescribed knee angle. Once correctly positioned, participants raised the uninvolved, non-weight-bearing limb backwards off the ground while keeping their trunk stable. A brief 2–3 s pause was followed by warm-up trials at 70%, 80%, and 90% of perceived maximum effort. Each limb underwent three trials, separated by 60-s rest periods. The participants were then instructed to apply maximal force for 4 s, "pulling against the bar and pushing into the ground as hard as possible." Furthermore, rate of force development (RFD) was not analyzed in the current study, as attempting to assess both maximal force and RFD within the same contraction may lead to suboptimal measurement of each parameter.[37,38]

The unilateral hex bar configuration was selected over the more traditional isometric midthigh pull (IMTP) test due to equipment constraints (a fixed rig was not available) and the test not being suitable for context. Additionally, the 115° knee angle was chosen to reflect a freeski-specific joint position typically observed during high-force phases, such as takeoff and landing from jumps. This setup therefore provided a practical and sport-relevant alternative for assessing unilateral force production in freeski athletes.

Resistance training intervention

The participants in the resistance training intervention group were required to complete a 10-week training program (Table 1) that involved two 60–90-min training sessions per week. The intervention focused predominantly on the lower limbs, with knee- and hip-dominant exercises selected. A repetition in reserve (RIR) autoregulation resistance training approach[39] was implemented and the training schedule was planned and supervised by a sport scientist in conjunction with technical freeski coaches, with additional input from a sports physiotherapist and life coach (responsible for daily living and linking academic and athletic programs). Training sessions were conducted at a training center and were performed either in the morning (8.30–10.00) or afternoon (15.30–17.00). Throughout the duration of the intervention, the participants in the resistance training group maintained 3–5 on-snow freeski training sessions per week (90–120 min per session). The participants in the historical control group did not participate in any resistance training throughout the intervention period but continued their 3–5 physical education classes per week which included activities ranging from indoor games such as volleyball, floorball and ice-hockey to skiing and snowboarding.

Data analysis

For unilateral isometric assessment, unfiltered force-time data were analyzed using the Coachtech online measurement and feedback system (University of Jyväskylä, Finland). For each trial and limb, the absolute peak force (PF_{abs}) was defined as the point of maximum force from initiation, and the relative peak force (PF) was defined as the PF_{abs} divided by body mass. The individual limb data were classified as left or right. The trial with the highest value was used for statistical analysis. For both the CMJ and DJ, the jump height was calculated using the impulse method.[40] The reactive strength index (RSI) was calculated for each DJ, by dividing the jump height by the ground contact time.[41] The best jump height from each assessment was used for analysis.

Statistical analysis

All the statistical analyses were performed in SPSS (version 28, IBM Corporation, Armonk, USA). Descriptive statistics, including means and standard deviations, were calculated for all dependent variables in the study. Additionally, 95% confidence intervals (CIs) were computed where applicable. To address our study aim, repeated measures multivariate analyses of variance (MANOVA) employing Wilks' lambda (Λ) were conducted to evaluate the impact of the intervention over time, and between groups. Test assumptions, including multivariate normality, were checked before the outcomes were interpreted. These tests were performed across the physiological variables, with 'group' (intervention and control) as the between-subject factor and 'timepoint' (pre-and post-testing) as the within-subject factor, with their interaction (group × time). Partial eta squared (ηp2) was used to quantify the magnitude of effect, with predefined qualitative thresholds of small, moderate, and large as $\eta p2 < 0.01$, <0.06 and <0.14, respectively.[42] Effect size threshold values of <0.2 (trivial), 0.2–0.5 (small), 0.5–0.8 (moderate), and >0.8 (large) were used.[42] To evaluate within-group pre-to-post performance changes, paired sample t-tests were applied. Alpha was set at $\alpha=0.05$ for all tests.

Results

Descriptive statistics for strength and power characteristics in the freeski intervention and control groups are presented in Table 2. There was a large interaction effect between timepoint and group (Wilks' $\Lambda=0.3$, $F(8,15) = 4.33$, $p < 0.007$, $\eta p^2=0.7$), indicating that the changes over time (pre vs. post) differed significantly between the intervention and control groups. Additionally, there was a significant main effect of group (Wilks' $\Lambda=0.4$, $F(8,15) = 2.65$, $p = 0.049$, $\eta p^2=0.6$), demonstrating significant differences between the intervention and control groups across all dependent variables. The effect of timepoint was significant (Wilks' $\Lambda=0.15$, $F(8,15) = 10.3$, $p < 0.001$, $\eta p^2=0.8$), indicating changes over time across all dependent variables. Follow-up paired sample t tests revealed that the intervention group achieved significant pre-to-post training improvements in: CMJ height (small effect size), DJ height (moderate effect size), DJ contact time (small effect size), DJ RSI (trivial effect size), left limb PF_{abs} (moderate effect size), right limb PF_{abs} (moderate effect size), relative left PF (moderate effect size), and relative right PF (moderate effect size). In the control group, no significant pre-to-post changes were found.

Discussion

The main findings of this investigation were that the inclusion of a 10-week resistance training intervention performed twice per week during the initial stage of the freeski on-snow season elicited significant improvements in lower body maximal strength and power characteristics in academy freestyle freeski athletes. This suggests that resistance training can be integrated into the in-season period to enhance physical qualities, although its effect on technical on-snow skill development remains unknown and warrants further investigation.

The timepoint effect explained 80% of the variance in the strength and power variables, suggesting that the changes in strength and power characteristics over time (from pre- to post-training intervention) were significant with a large effect in academy freestyle freeski athletes. In contrast, there was no timepoint effect in the control group. This suggests that the resistance training and on-snow activities performed by the athletes within the freeski intervention group significantly impacted the improvements observed compared with those in the historical control group. Likewise, the interaction effect between timepoint and group explained 70% of the variance in the strength and power variables, also indicating a large effect size. Furthermore, with regards to the specific strength and power characteristic performance measures included in our study, the intervention group experienced significant pre-to-post training improvements in CMJ height, DJ height, DJ contact time, DJ RSI, left limb PF_{abs}, right limb PF_{abs}, relative left PF, and relative right PF while the historical control group did not show any significant pre-to-post changes. The significant improvements in strength and power characteristics, along with the high proportion of explained variance, demonstrate that the 10-week in-season resistance training intervention had a meaningful effect on the lower body maximum strength and power performance of the freeski athletes compared with the historical control group.

Our findings support numerous studies that have reported similar changes in lower body strength in academy athletes following adherence to a resistance training program.[43–47] However, to our knowledge, this is the first study to provide practical data on freeski athletes, an underrepresented population in the literature. During the initial phases of a training intervention, the mechanisms attributed to

Table 2. Strength and power characteristics pre-and post- intervention.

Variables	Intervention group (N = 13) *mean ± SD*		Paired samples t test p value (Cohen's *d*)	Control group (N = 11) *mean ± SD*		Paired samples t test p value (Cohen's *d*)
	Pre	Post		Pre	Post	
CMJ height (cm)	41.1 ± 4.7	45 ± 2	<0.001** (0.21)	39.9 ± 2.8	40.4 ± 2.5	0.486 (1.8)
DJ height (cm)	36.4 ± 5.7	40.1 ± 6.8	0.004* (0.29)	32.1 ± 3.1	32.9 ± 3.3	0.349 (2.5)
DJ contact time (ms)	180 ± 18.2	168.8 ± 20.9	0.040* (0.32)	193 ± 13.5	198 ± 10	0.311 (0.95)
RSI (au)	2.06 ± 0.4	2.4 ± 0.5	<0.001** (0.12)	1.65 ± 0.2	1.62 ± 0.2	0.689 (0.59)
PF_{abs} left limb (N)	1590 ± 212	1767 ± 174	<0.001** (0.60)	1434 ± 164	1493 ± 150	0.074 (0.72)
PF_{abs} right limb (N)	1633 ± 199	1788 ± 168	<0.001** (0.62)	1459 ± 183	1517 ± 160	0.064 (0.59)
Relative PF, left limb ($N \cdot kg^{-1}$)	22.2 ± 2.3	24.7 ± 2	<0.001** (0.59)	19.7 ± 2.2	20.5 ± 2.1	0.078 (0.81)
Relative PF, right limb ($N \cdot kg^{-1}$)	22.8 ± 2	25 ± 1.9	<0.001** (0.63)	20.1 ± 2.4	20.9 ± 2.3	0.063 (0.67)

*SD = standard deviation; CMJ = countermovement jump; DJ = drop jump; RSI = reactive strength index; au = arbitrary unit; PF = peak force; PF_{abs} = absolute peak force. * $p < 0.05$. ** $p < 0.001$.*

strength increases are largely due to neuromuscular adaptations, as opposed to muscular hypertrophy.[48] Potential neural adaptations may include an increase in the number and firing rate of motor units with increased nerve conduction velocity,[48,49] improved intermuscular coordination and an enhanced motor unit recruitment strategy,[50] increased excitability of the Hoffman reflex (H-reflex),[49] alterations in muscle architecture,[51] and heightened tendon stiffness.[52] Conversely, no significant changes between pre and post-tests were observed in the control group. This is unsurprising since the student athletes in the control group did not participate in any resistance training while they continued their physical education classes.

However, it is plausible that the same magnitude of improvement would not have occurred during the mid-late stages of the season, characterized by elevated freeski on-snow training volume, transatlantic travel and heightened competition congestion. Using a customized athlete monitoring system[53,54] to explore individual variations in the tested variables alongside valid subjective and psychometric measures[2,55] throughout a season could offer a more comprehensive understanding of the biopsychosocial status of freeski athletes.[34] The collection of such data could help coaches determine whether resistance training adaptations can continue season-long or if physiological plateaus or detraining occur despite the possibility of increased skill acquisition through intensified freeski training. Moreover, while strength may be retained for up to 3–4 weeks of inactivity,[56] coaches should also be aware that short-term detraining may specifically affect eccentric strength and the size of type II muscle fibers,[57] which could have negative consequences for freeski athletes in certain circumstances.

Despite these findings supporting the implementation of resistance training programs for improving lower body strength and power characteristics in freeski athletes, it is unclear to what extent the freeski on-snow skill acquisition practice contributed to or hindered such improvements. For this, a deeper understanding of the specific neurological responses to resistance training and motor skill acquisition at the corticospinal level would be needed for optimizing sports performance.[58] However, quantifying the extent to which improvements in strength and power account for the variance in on-snow freeski settings is a complex challenge.[59]

Despite methodological challenges of controlling variables in on-snow environments, these insights are particularly relevant given that despite observed gains in maximal strength and power, it is still uncertain whether such adaptations enhance freeski performance or reduce injury risk. This uncertainty underscores the need for freeski specific injury prevention frameworks and surveillance systems.[34,60] Investigating whether physical training can influence kinetics, kinematics, and muscle activation patterns during critical freeski maneuvers, both planned and unplanned, such as during in-run compression, take-off during jumps, and during the landing phase is needed. This could shed light on the nuanced relationship between physical training adaptations and the biomechanical aspects of on-snow.[61] It is unclear how elements such as the level of trick complexity, individual differences in technique, body composition ranges, and equipment influence the overall demands placed on freeski athletes during competition and training. For example, improvements in knee and hip strength may help limit angular motion during high-impact landings, mitigating ground reaction and shear forces[62] and reduce the risk of certain overuse injuries.[30] Moreover, technical errors such as poor take-off mechanics or misjudged approach speed can lead to unfavorable landing positions including hitting the knuckle or overshooting into a deep landing zone of a jump. When combined with insufficient strength and limited capacity to attenuate the impact of ground reaction forces, these situations may increase mechanical load and reduce the athlete's ability to maintain control. A compromised landing can also disrupt approach speed into the next feature in slopestyle, affecting trick execution and potentially injury risk.

It is important to recognize that maintaining the same volume and intensity of resistance training across various stages of the season may not be universally suitable and could, in certain circumstances prove counterproductive from biopsychosocial[63] and skill acquisition perspectives.[64] This could be particularly relevant for athletes who may find resistance training less engaging,[65] especially during the on-snow season, believing that it may interfere with skill acquisition. By adapting resistance training to accommodate the varying demands and stressors experienced during different stages of the season,[66] coaches can attempt to better support the overall well-being and athletic development of their freeski athletes.

If a traditional repetition maximum (RM) or %RM approach[67] is not feasible, several viable in-season resistance training methods can be considered. Depending on the desired adaptation outcome goal and individual needs, these include an autoregulation approach[37,68] as adopted in this study, a minimal dose strategy,[69] isometric training,[70] increasing rest intervals between sets[71] or a cluster sets approach.[72] Nonetheless, the current findings provide evidence that freeski coaches could deliver effective in-season resistance training, and coaches should select methods that are appropriate for their context and consider a well-rounded holistic approach to youth athletic development.

The main limitation of this study is the lack of randomization due to the use of a non-randomized parallel groups approach and the absence of a control group comprising freeski athletes. Conducting the study within a real-world youth development academy system made randomization impractical because of the limited pool of athletes and the need to avoid disrupting existing training regimens.[73] This reflects the broader challenges of implementing context-specific and cost-effective sports injury prevention programs in real-world settings.[74,75] Consequently, owing to the absence of a true control group and the small sample size, the results should be interpreted with caution. However, the fact that the intervention was implemented in a real-world academy environment is also a strength, as it enhances ecological validity and provides insights and discussion points that are directly relevant to applied coaching practice and future research in this area. Moreover, it is important to acknowledge that small sample sizes are often an unavoidable reality in freeski academy and national team research, where the entire population may consist of only a limited number of athletes, as exemplified in this study. The inability to control the intensity and volume of on-snow slope training poses a further limitation and highlights the need for further research and understanding of this complex multi-factorial topic area. Another limitation of the study could be the slightly lower physical fitness of the athletes in the control group at the beginning of the study compared to those in the intervention group, which can be observed for all tested variables. Accordingly, the comparability of the groups could be limited in principle, even if this is unlikely to have had any influence on the relative changes observed within the groups; the differences in performance levels were probably not large enough for such an influence.

A further limitation of this study is the absence of detailed monitoring of individual training loads, progression, and the effectiveness of the autoregulation approach. While the intervention structure and supervision were standardized, we did not systematically record the actual loads lifted or total training volume over the 10-week period. This limits the ability to evaluate the relationship between specific loading parameters and performance adaptations. Furthermore, we were unable to quantify concurrent training exposures outside the intervention, such as on-snow sessions, physical education, or informal sport activity. Academic stress related to school was also not measured, yet it may influence recovery and overall adaptation.[76]

Conclusions

This study demonstrated that the inclusion of a 10-week in-season resistance training program elicited significant improvements in lower body maximal strength and power characteristics in academy freeski athletes. These improvements suggest that underlying neural and morphological adaptations were induced by the resistance training intervention. While developing and retaining technical skills in freeski will often have the greatest effect on performance, coaches could consider implementing physical training during the on-snow season to help support their athletes. Further research, including year-round athlete monitoring and injury surveillance, is needed to better understand the impact of resistance training on the overall development of freeski athletes for both the performance enhancement and injury prevention purposes.

Acknowledgments

The authors would like to thank the coaches of the Vuokatti-Ruka Sports Academy, Finland who supported the project, along with all the athletes who participated in this study.

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Ethical considerations

This study received ethical approval from the University of Jyväskylä Ethical Committee (Jyväskylän yliopiston eettinen toimikunta). The Committee reviewed and approved the research protocol titled “Erilaisten voima- ja tehotestien luotettavuuden vertailu alppi- ja freeski-hiihtäjillä” on 12 February 2019, confirming that the study meets the standards of the Finnish National Board on Research Integrity (TENK) and the University of Jyväskylä’s guidelines for good scientific practice.

The committee determined that the study does not fall under the Finnish Medical Research Act (488/1999 and 794/2010) and therefore does not require review by a medical research ethics committee. Ethical approval was granted on the basis that the research involves healthy volunteer athletes and includes minimal risk physical performance testing.

Approval reference: University of Jyväskylä Ethical Committee, 12.2.2019.

Consent to participate

All participants were informed about the study procedures, risks, benefits, and voluntary nature of participation in writing and verbally. Written informed consent was obtained from all participants prior to testing. For participants under the age of 18, written consent from a parent or legal guardian was also obtained.

Consent for publication

All participants provided written informed consent for the use of their anonymized data for research and publication purposes. For participants under the age of 18, written consent for publication was obtained from a parent or legal guardian.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data availability

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

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