

Research article

## The 2 Minute Loaded Repeated Jump Test: Longitudinal Anaerobic Testing in Elite Alpine Ski Racers

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### Abstract

This study investigated the 4-year development of anaerobic power and capacity in Austrian elite female alpine ski racers and examined the relationship between the 2-minute loaded repeated jump test (LRJT) results and ski racing performance (International Ski Federation (FIS) points). Ten Austrian elite female ski racers were tested prior to four racing seasons. The LRJT consisted of 48 loaded countermovement jumps (LCMJs) with barbell load equivalent to 20% bodyweight. Before the LRJT, maximal body mass normalized average power of a single LCMJ ( $P_{MAX}$ ) was determined. The mean jump power was calculated across all jumps in the test ( $P_{0-120}$ ). Anaerobic power ( $P_{MAX}$ ) in season 2 ( $32.3 \pm 2.3 \text{ W}\cdot\text{kg}^{-1}$ ) significantly improved over season 1 ( $30.5 \pm 2.3 \text{ W}\cdot\text{kg}^{-1}$ ) ( $p < 0.05$ ) but there were no further differences between seasons, with season 3 at  $33.5 \pm 3.4 \text{ W}\cdot\text{kg}^{-1}$  and season 4 at  $33.6 \pm 3.0 \text{ W}\cdot\text{kg}^{-1}$ . Anaerobic capacity ( $P_{0-120}$ ) increased up to season 3 by 9.2% ( $27.1 \pm 2.8$  to  $29.6 \pm 2.4 \text{ W}\cdot\text{kg}^{-1}$ ), but was significantly higher only when comparing season 4 to seasons 1 and 2 ( $p < 0.05$ ). FIS points changed significantly ( $p < 0.05$ ), from  $18.1 \pm 8.2$  in season 1 to  $8.4 \pm 4.8$  in season 4 (lower FIS points indicates better racing results). FIS points had a positive relationship with  $P_{MAX}$  ( $r = -0.73$ ,  $p < 0.05$ ) and  $P_{0-120}$  ( $r = -0.64$ ,  $p < 0.05$ ) only in season 4. Improvements in FIS points from year to year did not correlate with seasonal increases in LRJT results. In conclusion, anaerobic power improved only after season 1, and anaerobic capacity changes were evident only in season 4. Ski racing performance (FIS points) correlated with LRJT test results in only season 4. The LRJT can monitor a ski racer's anaerobic power and capacity, but does not correlate with ski racing performance.

**Key words:** Alpine skiing, female, anaerobic power and capacity, jump test.

### Introduction

The regular monitoring of physical fitness and sport-specific performance is important in elite sports to increase the likelihood of success in competition (Chaabene et al., 2018). There is no consensus regarding the influence of physiological parameters on alpine ski racing performance (Maffioletti et al., 2006; Neumayr et al., 2003; Turnbull et al., 2009). Therefore, sport scientists have difficulty predicting ski racing performance.

Anaerobic metabolism plays a large role in alpine ski racing, as it is a high intensity sport (Gross et al., 2014; Polat, 2016; Veicsteinas et al., 1984; Vogt et al., 2003). Skeletal muscle fatigue is a limiting factor in skiing performance (Ferguson, 2010) and can be a risk factor in ski racing injuries (Spörri et al., 2012). Therefore, anaerobic

power and capacity of ski racers should be regularly monitored (Patterson et al., 2014).

Tests assessing anaerobic power and capacity are not measuring metabolism, but power output (Chamari et al., 2010). Anaerobic power is the maximal power developed during all-out, short-term effort and reflects the energy-output capacity of intramuscular high-energy adenosine triphosphate and phosphocreatine (ATP and PCr) and/or anaerobic glycolysis. Anaerobic capacity is the maximum amount of ATP resynthesized via anaerobic metabolism during a specific mode of short-duration maximal exercise (Green and Dawson, 1993).

Jump tests have been used by a number of investigators to determine anaerobic power and capacity in alpine skiers (Bosco, 1997; Bosco et al., 1994; Breil et al., 2010; Emeterio and González-Badillo, 2010; Karlsson et al., 1978; Nikolopoulos et al., 2009; Patterson et al., 2009; Patterson et al., 2014; White and Johnson, 1991). Bosco (1997) evaluated the anaerobic capacity (measured with repeated jumps) of alpine ski racers. He showed that the most successful individual male and female slalom and giant slalom racers at that time (both Olympic champions) had the highest anaerobic capacity and that seven of eight international female ski racers did not increase their anaerobic capacity over 5 years. Bosco proposed that anaerobic capacity correlated with ski racing performance but did not statistically prove this. The results of a 30 s version of Bosco's test did correlate with racing performance in Spanish male adolescent ski racers (Emeterio and González-Badillo, 2010).

Patterson and coworkers (2014) introduced the 2.5 minute loaded repeated jump test (LRJT) as an evaluation tool of anaerobic power and capacity in male ski racers. This test was standardized, repeatable and portable, allowing for testing at training camps as well as in a laboratory. The test was 2.5 minutes long and the athletes performed 60 loaded countermovement jumps (LCMJs). The test mirrors the duration of the longest International Ski Federation (FIS) World Cup (WC) men's downhill, and the number of gates in the technical events of slalom and giant slalom.

The 2.5 minute LRJT was modified for women, and has been used to test the Austrian women's alpine ski team since 2006. The longest women's WC race in the 2012/2013 season was the Lake Louise downhill at almost 2 minutes (winning time 1:52.61). Women's FIS WC slalom races normally have about 60 turning gates, and giant slalom races about 50 gates. The women's LRJT requires 48 LCMJs with a barbell loaded with a weight equivalent to 20% of the athlete's bodyweight and is 2 minutes long.

The original version of the test is reliable, and sensitive enough to detect adaptations in anaerobic power and capacity during a pre-season-training phase (Patterson, et al., 2014). It has not been explored if and to what extent anaerobic power and capacity measures made with the LRJT improve in world class ski racers from season to season or over several seasons, or if these measures are related to ski racing performance.

Thus, a multi-season standardized and repeatable evaluation of anaerobic power and capacity assessed with the LRJT in elite alpine ski racers would provide insights into the longitudinal physical development of alpine ski racers and also determine if the test has predictive value for racing performance.

Therefore, this study has two aims: first, to determine if anaerobic power and capacity would improve in female world class ski racers over 4 seasons; and secondly, to investigate the relationship between LRJT results and ski racing performance.

The hypotheses were that LRJT results measuring anaerobic power and capacity would improve over 4 seasons; and that the results of the LRJT would correlate with ski racing performance.

## Methods

### Participants

The same ten female Austrian national alpine ski team athletes were tested prior (August – October) to each of the 2010, 2011, 2012 and 2013 FIS alpine ski racing seasons. Seven had achieved at least a top 10 placing in a FIS WC race prior to or during the seasons examined, and collectively this group had won 60 FIS WC, 5 FIS world championship and 3 Olympic medals. The mean age, height, weight and Body Mass Index for the athletes are presented in Table 1.

All skiers tested were experienced with weight training, particularly in squatting. A physician medically screened each athlete before each season to ensure that there were no contraindications to participation in ski racing or any physical activity with the team. The athletes gave informed consent before the testing. The parents of athletes who were minors at the beginning of the study gave informed signed consent. An institutional review committee (Department of Sport Science, University of Innsbruck) and the Sport Science Committee of the Austrian Ski Federation gave prior approval for the testing and testing was performed according to the Declaration of Helsinki.

### Data collection equipment

The hardware (MLD-Station Evo2) and software (MLD 3.2—Muskel-Leistungs-Diagnose 3.2) from SPSport (SP Sportdiagnosegeräte GmbH, Trins, Austria) were used to

collect data. The vertical ground reaction forces were measured with two separate force platforms. The sampling rate was 1000 Hz. The transducer signal was directly amplified in the platforms to reduce interference. The reliability of the single LCMJ analysis (ICC:  $r = 0.944 - 0.981$ ) (Patterson et al., 2009) and the 2.5-minute LRJT parameters (ICC:  $r = 0.881 - 0.987$ ) of the MLD system has been reported elsewhere (Patterson et al., 2014).

### Calculation of power output and countermovement depth

The ground reaction force record obtained from the force platforms was used to calculate power output. The ground reaction force impulse was determined by calculating the area under the force–time curve by numerical integration, as described by Linthorne (2001). At the bottom of the countermovement, the subject's velocity of body center of mass ( $v$ ) was zero ( $v_0 = 0$ ). This point was defined as time zero ( $t_0$ ). The impulse–momentum theorem was applied to the concentric phase of the jump, from  $t_0$  through to the time point where maximum velocity of body center of mass was reached ( $t_f$ ) which was assumed to be the takeoff velocity ( $v_f$ ). The impulse on the subject was:

$$\int_{t_0}^{t_f} (F_{GRF} - mg) dt = m(v_f - v_0)$$

Where  $F_{GRF}$  was the ground reaction force,  $m$  was the total mass of the subject and the loaded barbell, and  $g$  was the gravitational acceleration.

$P_{mean}$  was the average power over the concentric phase of the countermovement jump, or from  $t_0$  to  $t_f$ . Power was derived from:

$$P = F \cdot v$$

Where  $P$  was power and  $F$  was force. So  $P_{mean}$  was calculated with the following formula:

$$P_{mean} = \frac{\int_{t_0}^{t_f} (F_{GRF} - mg) \cdot v(t) dt}{t_f - t_0}$$

To calculate the depth of the countermovement, the displacement–time record was obtained by numerically integrating the velocity–time record (Linthorne, 2001). The velocity–time record was obtained by dividing the resultant force–time record by the combined mass of the subject and the barbell to give the acceleration–time record, and then numerically integrating with respect to time using the trapezoid rule. The displacement–time record was obtained by numerically integrating the velocity–time record, again using the trapezoid rule.

$$s_f - s_0 = \int_{t_0}^{t_f} v(t) dt$$

Where  $s_f$  was the position of the center of mass at time of takeoff ( $t_f$ ) and  $s_0$  was the position of the center of mass at time point at the bottom of the countermovement ( $t_0$ ).

**Table 1. Physical characteristics of the ski racers (mean  $\pm$  SD), n = 10.**

Season	Age (yr)	Height (cm)	Body mass (kg)	Body Mass Index (kg·m <sup>2</sup> )
2010	20.0 $\pm$ 2.7	167.3 $\pm$ 3.5	66.3 $\pm$ 4.0	23.7 $\pm$ 2.2
2011	21.1 $\pm$ 2.7	167.3 $\pm$ 3.5	67.0 $\pm$ 4.6	24.1 $\pm$ 2.2
2012	22.0 $\pm$ 2.6	167.3 $\pm$ 3.5	66.5 $\pm$ 4.6	23.9 $\pm$ 1.8
2013	23.1 $\pm$ 2.7	167.3 $\pm$ 3.5	65.4 $\pm$ 5.3	23.6 $\pm$ 2.3

## Procedures

The testing conditions for the Austrian Ski Federation were controlled and remained very similar for each testing session. Coaches instructed athletes regarding activity and diet before the tests so that testing conditions were standardized. The LRJT was part of a battery of tests used to evaluate the Austrian Ski Federation alpine ski teams (Raschner et al., 2013), and was the last test in the battery. Before the LRJT, the subjects completed 1–2 series of squats with a weight of their choice.

The subjects performed single LCMJs with a loaded barbell (20% bodyweight). In order to allow comparisons between jumps, a consistent countermovement depth was necessary. The subjects were instructed to perform a fast downward movement (to approximately 90° knee flexion) immediately followed by a fast upward movement, jumping as high as possible. The athlete was instructed to increase or decrease the depth of the countermovement until a satisfactory depth was found. The countermovement depth from the reference jump was used to standardize the countermovement depth for the LRJT. Every jump was controlled for countermovement depth and jumps with a countermovement depth of less than 90% of the reference jump depth were not used in the data.

Subjects were given feedback regarding their technique, power, and the countermovement depth of the LCMJ. When the subject's technique was satisfactory, 3–5 individual LCMJs were performed (single jumps with rests between) to determine the reference LCMJ to compare with the LRJT jumps. The single 20% LCMJ that produced the highest average power relative to body mass with an appropriate depth was used as the reference power ( $P_{MAX}$ ) for the LRJT. After establishing the  $P_{MAX}$ , the athlete then took a rest of at least 3 minutes.

The LRJT was again described and explained, and when the subject was ready, the LRJT was performed. The test was 2 minutes long and the load was 20% body mass. The subject jumped every 2.5 s, (48 LCMJ) pausing briefly between jumps to avoid reactive jumps. A computer monitor in front of the athlete assisted in LCMJ timing with a visual countdown for each jump.

## Ski racing performance analysis

Ski-racing performance was based on FIS points. FIS points were organized so that the best in the world in each discipline had 0 points and the 31st in the world had 6 points. Occasionally everyone's FIS points were adjusted to ensure that this was the case. Thus, a racer's FIS points were a measure of how he / she compared with the rest of the world. A racer's FIS points were the average of the racer's best 2 races in that discipline in the last 13 months. Lower FIS points indicated better performance. For each season, the discipline with the lowest FIS points was used for each athlete.

## Data treatment

The software calculated the power of all jumps for each athlete. Each jump was numbered, and the power values for all valid jumps were recorded. Data sets were created for each athlete with missing values in the cases of invalid jumps. In the event of missing jumps, a regression line was

fit to the jump data so that missing data points could be interpolated. Each athlete then had power values for 48 CMJs. A mean power for the complete test ( $P_{0-120}$ ) was also calculated from the 48 values.

The first valid LCMJ ( $LCMJ_{rel}$ ) of the LRJT was compared to  $P_{MAX}$  (percentage of  $P_{MAX}$ ) as a control that the test was performed with maximal effort.

$P_{MAX}$  was defined as the measurement of anaerobic power,  $P_{0-120}$  as the measurement of anaerobic capacity, and fatigue index (FI) as the indicator of anaerobic fatigue.

FI as a control parameter was determined by taking the percentage difference between  $P_{MAX}$  and the average of the relative power of the last 12 jumps (30 seconds duration) of the LRJT ( $P_{120}$ ).

$$FI = \left[ \frac{P_{MAX} - P_{120}}{P_{MAX}} \right] \times 100$$

The seasons 2010, 2011, 2012 and 2013 were designated as season 1, season 2, season 3 and season 4.

The changes between seasons in the measures of  $P_{MAX}$ ,  $P_{0-120}$  and FIS points were also assessed, eliciting six season differences (1 and 2, 1 and 3, 1 and 4, 2 and 3, 2 and 4, and 3 and 4).

## Statistical analysis

Differences between seasons were calculated for all outcome measures. The linear relationship between the outcome measures and the seasonal differences in the outcome measures were assessed using Pearson correlation coefficients for each season and each season-to-season comparison. Analysis of variance (ANOVA) with repeated measures (SPSS 18.0 for Windows) was performed to detect differences. Pairwise comparisons were made using student t-tests. Scatter plots were made for each season to compare the following:  $P_{MAX}$  with FIS points,  $P_{0-120}$  with FIS points, changes in  $P_{MAX}$  with changes in FIS points and changes in  $P_{0-120}$  with changes in FIS points. Statistical significance was set at  $\alpha = 0.05$ .

## Results

Each athlete completed the test duration of 2 minutes and at least 48 LCMJ in every testing session.  $LCMJ_{rel}$  remained stable from year to year (between 96% and 98%  $P_{MAX}$ ), ensuring consistent test intensity. FI remained stable over the four years. The FI for seasons 1, 2, 3 and 4 were  $14.8 \pm 5.8$ ,  $17.3 \pm 7.6$ ,  $15.9 \pm 7.8$  and  $16.3 \pm 5.2$  respectively.

$P_{MAX}$  improved significantly from season 1 to season 4 [ $F(3,27) = 7.923$ ,  $p < 0.05$ ], with season 1 being significantly less than all other seasons. Pairwise comparisons between the other 3 seasons showed no differences [season 1:  $P_{MAX} = 30.5 \pm 2.3 \text{ W}\cdot\text{kg}^{-1}$ ; season 2  $P_{MAX} = 32.3 \pm 2.3 \text{ W}\cdot\text{kg}^{-1}$ ; season 3  $P_{MAX} = 33.5 \pm 3.4 \text{ W}\cdot\text{kg}^{-1}$ ; season 4  $P_{MAX} = 33.6 \pm 3.0 \text{ W}\cdot\text{kg}^{-1}$ ](see Figures 1 and 2). The pairwise comparisons revealed that the  $P_{MAX}$  change between season 1 and all other seasons was significant.

$P_{0-120}$  [ $F(3,27) = 4.019$ ,  $p < 0.05$ ] increased by 9.2% up to season 3 ( $27.1 \pm 2.8$  to  $29.7 \pm 3.4 \text{ W}\cdot\text{kg}^{-1}$ ) and was unchanged from season 3 to 4.  $P_{0-120}$  in season 4 ( $29.6 \pm 2.4 \text{ W}\cdot\text{kg}^{-1}$ ) was significantly higher than seasons 1 and 2.

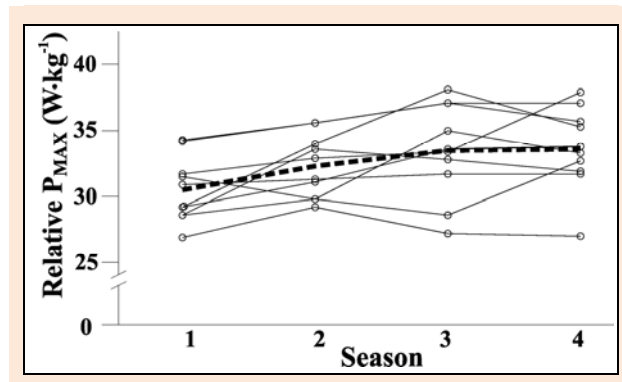
FIS points decreased significantly (racing perfor-

mance improved) [ $F(3,27) = 11.020, P < 0.05$ ], from  $18.1 \pm 8.2$  in season 1 to  $8.4 \pm 4.8$  in season 4. Pairwise comparisons revealed that FIS points in seasons 2, 3 and 4 were significantly lower than in season 1 (see Table 2).

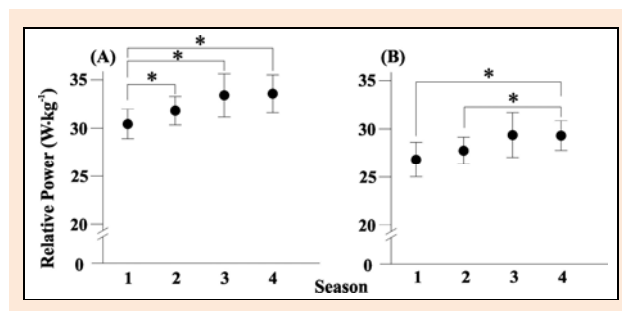
**Table 2.** FIS points for the ski racers for the best individual discipline (mean  $\pm$  SD),  $n = 10$ .

Season	FIS points	Range
2010*	$15.2 \pm 5.6$	5.1 – 20.4
2011	$10.9 \pm 6.3$	4.1 – 23.1
2012	$8.8 \pm 4.2$	1.2 – 15.5
2013	$8.4 \pm 4.8$	2.5 – 16.1

\* 2010 > 2011, 2012, 2013



**Figure 1.** Individual reference LCMJ ( $P_{MAX}$ ) over four seasons for all subjects. The thick broken line shows group mean  $P_{MAX}$  over 4 seasons.

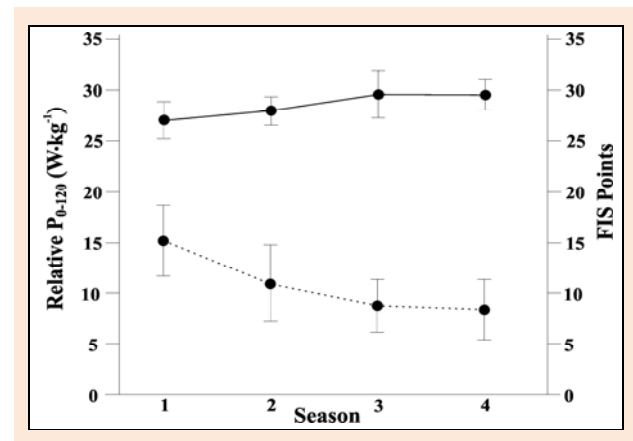


**Figure 2.** (A) Group  $P_{MAX}$  means with 95% confidence intervals for seasons 1 - 4. (B) Group  $P_{0-120}$  means with 95% confidence intervals for seasons 1 - 4. \*  $p < 0.05$

A statistically significant correlation between jump power variables and FIS points occurred only in season 4.  $P_{MAX}$  [ $r = -0.73$ ] and  $P_{0-120}$  [ $r = -0.64$ ]. Jump power variables were negatively related to FIS points, meaning higher anaerobic power and capacity both correlated positively to ski racing performance (see Figures 3, 4, 5, 6, 7 and 8).

Figures 7 and 8 illustrate the relationships between changes in anaerobic measures and the changes in performance. Values below the horizontal axis (negative) indicate that FIS points decreased (enhanced performance), and values to the right of the vertical axis (positive) indicate that the anaerobic measure increased. There were no significant positive correlations between increases in  $P_{MAX}$  and performance progression from season to season. The relationship between  $P_{0-120}$  development and the FIS points progress from season 1 to season 3 was positive ( $r = 0.64$ ,

$p < 0.05$ ), indicating that as anaerobic capacity increased, racing performance decreased.



**Figure 3.** Group mean longitudinal progression of  $P_{0-120}$  and FIS points over 4 seasons.  $P_{0-120}$  development is represented with the solid line; FIS points changes with the dotted line.

## Discussion

The first aim of this study to determine if anaerobic power and capacity would improve over 4 seasons produced inconclusive results. Anaerobic power improved from season 1 to season 2 but subsequently plateaued. Anaerobic capacity enhancements were only evident when comparing season 4 to seasons 1 and 2. There was no continuous improvement in either anaerobic power or capacity so the hypothesis that anaerobic power and capacity would improve in female world class ski racers over the four seasons was only partially confirmed.

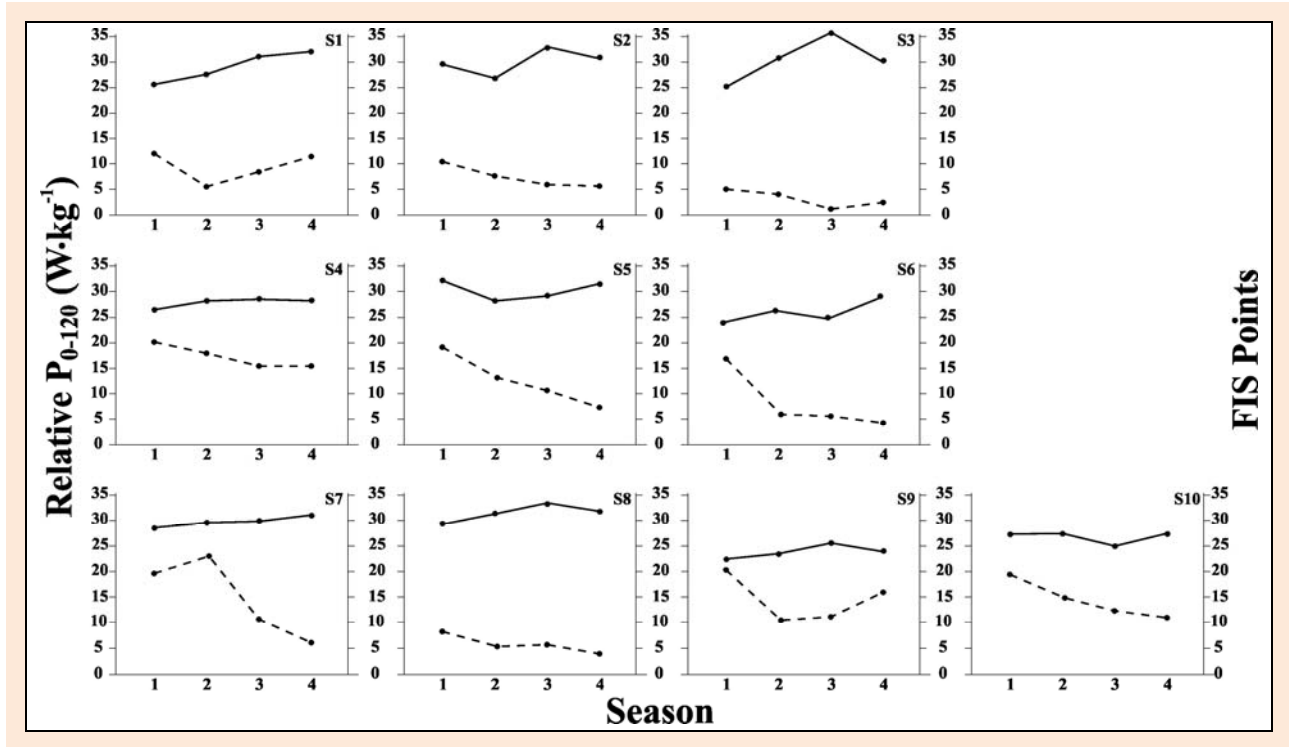
The increase in  $P_{MAX}$  results from season 1 to 2 was evident during testing. Training in the preseason leading up to season 2 may have influenced the test results, but training was not controlled in this study so training effects cannot be ascertained. Nine of the athletes had their best anaerobic capacity results in season 3 or 4 but only season 4 was greater than seasons 1 and 2. In a study of female Olympic medal winners, women peaked in their mid-twenties (Elmshawy et al., 2015). The athletes investigated in this paper had an average age of 20 in season 1, so enhanced LRJT results with each season were expected, but positive anaerobic power and capacity development was evident mainly when comparing season 1 to the other three seasons.

Bosco (1997) conducted a 45 s jump test with eight female international alpine ski racers and found that jump test results were not altered over five years (1989 to 1994) with seven women. This is a similar time span as the four years presented here, but reasons for little or no changes in anaerobic power and capacity in both groups cannot be determined without knowledge of the training programs. Bosco's (1997) subjects were described as national team athletes, but it is not known what level of competition they raced at during the study. The Austrian women in this study were not all skiing WC races over the entire study period, so as the lower level racers advanced in their ski careers

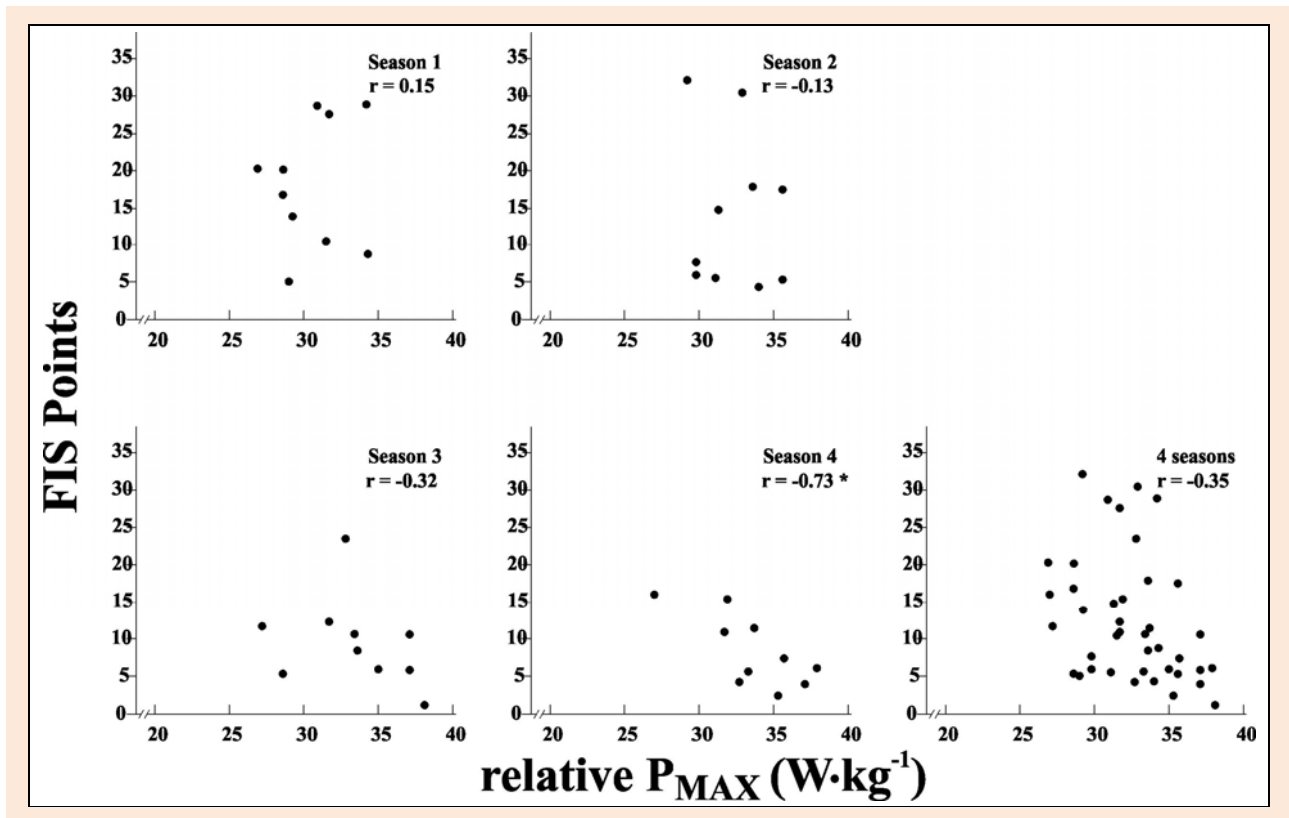


better anaerobic power and capacity coupled with more racing success would be expected. Comparisons of anaerobic test results between Bosco's study and this investigation are tenuous, as the methodologies were different. In the LRJT, the athletes jumped 48 times every 2.5 s (two minutes test duration) to avoid reactive jumps. Bosco's test

required 60 consecutive jumps, at the rate of about 1 Hz, so the 60 jumps were reactive and faster, creating a higher intensity and requiring more coordination, causing an earlier onset of fatigue. Bosco measured jump height with a contact pad and the LRJT measured ground reaction forces to calculate power.



**Figure 4.** Individual longitudinal progression of  $P_{0-120}$  and FIS points over 4 seasons for all subjects.  $P_{0-120}$  development is represented with the solid line; FIS points changes with the dotted line.



**Figure 5.** Scatter plots of  $P_{MAX}$  and FIS points for each of 4 seasons for each subject. \*  $p < 0.05$

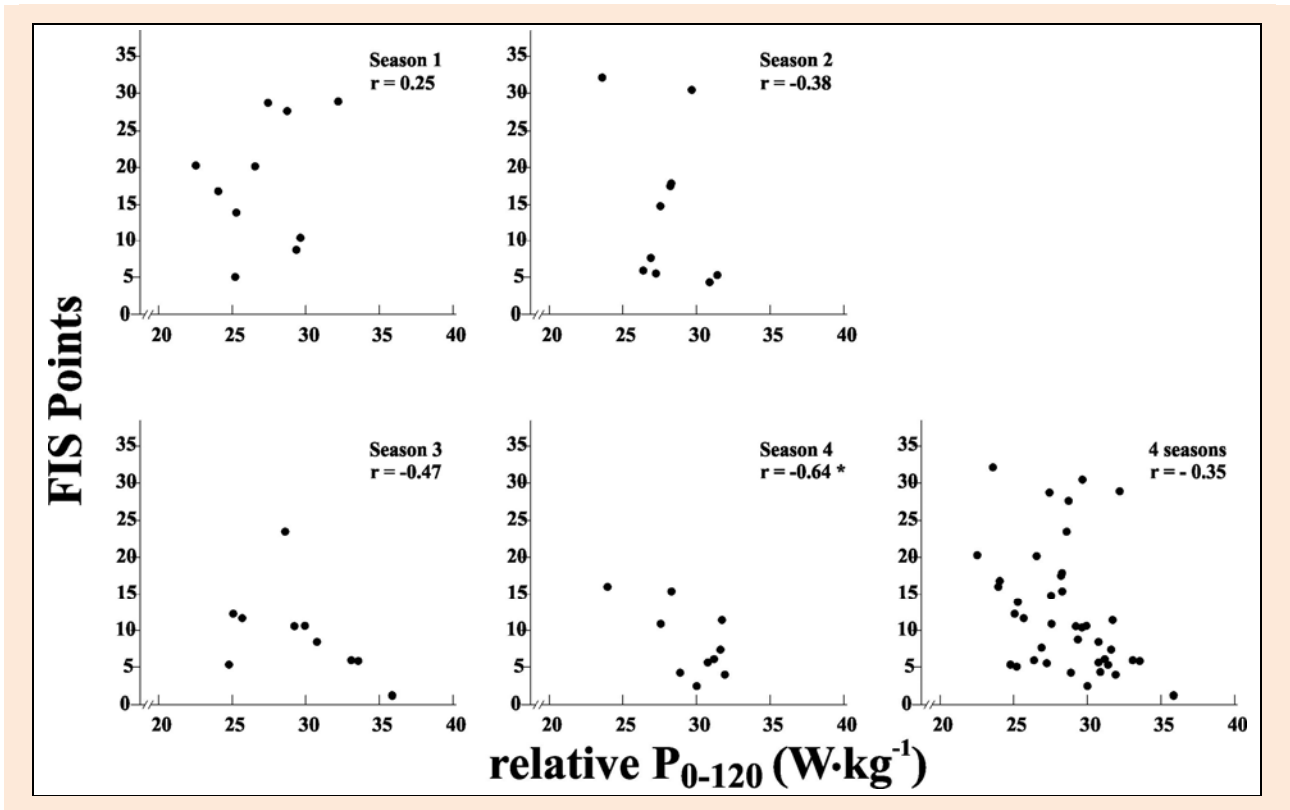


Figure 6. Scatter plots of P<sub>0-120</sub> and FIS points for each of 4 seasons for each subject. \*  $p < 0.05$

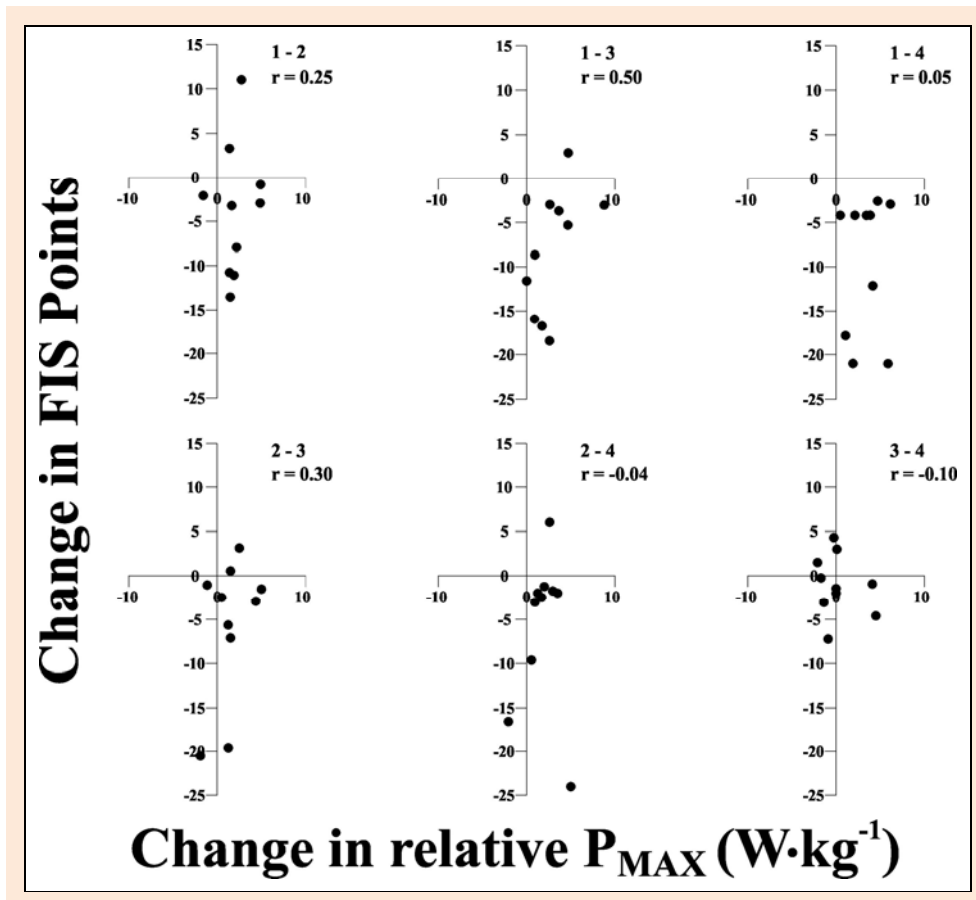
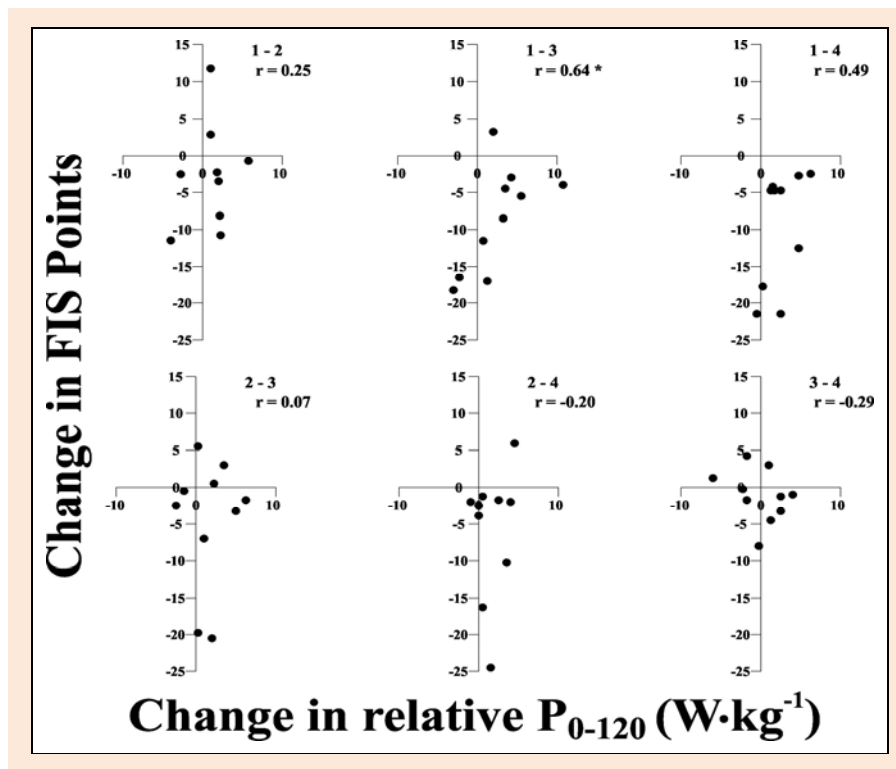


Figure 7. Scatter plots of the comparisons of season-to-season changes in P<sub>MAX</sub> and FIS points for each of 4 seasons for each subject. \*  $p < 0.05$



**Figure 8.** Scatter plots of the comparisons of season-to-season changes in  $P_{0-120}$  and FIS points for each of 4 seasons for each subject.

Karlsson and coauthors (1978) stated that fatigue in alpine skiing is not fully understood and more research is needed to examine the potential mechanisms of fatigue and thus develop better training techniques. Coaches and sport scientists agree that superior fitness is a factor that can reduce risk of injury (Spörri et al., 2012), but the relationship between anaerobic measures and performance is not clear.

The second aim of the study, to investigate the relationship between LRJT results and ski racing performance indicated a weak relationship. LRJT results correlated with performance only in season 4. The anaerobic power increase from season 1 to 2 did not correlate with the decrease in FIS points. Anaerobic capacity was higher in season 4 when compared to seasons 1 and 2, but these  $P_{0-120}$  changes had no relationship to FIS points differences.  $P_{0-120}$  increases between season 1 and season 3 negatively correlated with the change in skiing performance for the same period. Therefore, the hypothesis that anaerobic power and capacity would correlate with ski racing performance was rejected.

The younger athletes in the study may have influenced the positive correlation between both anaerobic measures and performance in season 4. After four seasons in the national program, the younger athletes had progressed in their ski racing and had started to stabilize their performance. Perhaps racers need a threshold level of technical competence and racing experience before they are able to capitalize on enhanced anaerobic power and capacity.

A single case example in this study (with no statistical support) revealed that one participant achieved the best racing performance concurrently with the highest recorded anaerobic capacity ( $P_{0-120}$ ) in season 3. This finding agrees with other case examples in the scientific literature

where two top ski racers (one male and one female Olympic champion) possessed the highest anaerobic capacity levels (Bosco, 1997). However, case examples do not represent evidence of a causal relationship between anaerobic capacity assessed with vertical jumps and alpine ski racing performance. Results of a 30 s variation of Bosco's test correlated with racing performance in Spanish male adolescent ski racers (Emeterio and González-Badillo, 2010), but the predictive power of anaerobic tests for ski racing success was not corroborated by the current study. This supports the premise of Turnbull et al. (2009) that no singular factor can predict ski racing success.

A more specific physiological measurement of WC skiers is needed (Turnbull et al., 2009). Jump tests have attempted to simulate the physical demands of ski racing (Bosco, 1997; Bosco et al., 1994; Breil et al., 2010; Emeterio and González-Badillo, 2010; Karlsson et al., 1978; Nikolopoulos et al., 2009; Patterson et al., 2009; 2014; White and Johnson, 1991). Blood lactate after ski races and training runs has been reported to have been 7 to 13  $\text{mmol}\cdot\text{L}^{-1}$  (Vogt et al., 2000; White and Johnson, 1991). Unpublished work by the authors has shown that lactate after the LRJT with men has been between 6 and 11  $\text{mmol}\cdot\text{L}^{-1}$ . The LRJT may simulate the metabolic demands of the sport, but jumping is not specific to skiing.

An athlete should fully extend at the hips, knees and ankles to maximize power in a jump, but explosive leg extension at the end of a turn can lead to skis losing contact with the snow. Loss of snow contact is disadvantageous in ski racing (Supej et al., 2011). Kröll et al (2015) measured maximal knee angles in slalom and giant slalom of  $132 \pm 6^\circ$  and  $138 \pm 8^\circ$  respectively during an on-snow kinematic study.

Berg and Eiken (1999) demonstrated that eccentric

muscle actions were dominant in slalom, giant slalom and super G skiing. Ferguson (2010) concluded that alpine skiing is characterized by isometric and eccentric muscular contractions. The LRJT requires both eccentric and concentric muscle actions during jumping, but currently only concentric power is used as a test parameter.

Ski racers need high levels of leg strength, as maximal forces can range between two to four times body-weight (Gilgien et al., 2013, Reid et al., 2012). However, as opposed to many racing sports, athletic strength or power is not the driving force for skiing velocity. In sprinting and swimming athletes create the needed forces for speed, and power tests can predict performance. Jump tests correlated with 100m sprint times (Loturco et al., 2015) and muscular power assessed in laboratory tests was an important determinant in swimming (Hawley et al., 1992).

Gravity propels the ski racer down the hill (Stöggl et al., 2016, Supej et al., 2011) and the racer must efficiently use this potential energy. Supej et al. (2011) found that high-level WC ski racers better controlled the dissipation of potential energy, and could more effectively reduce ground reaction forces compared to low-level performers. These aspects involve refined technical skills and are not determined purely by the racer's strength. There is still "a lack of functional and biomechanical understanding of the performance relevant parameters" in ski racing (Spörri et al., 2012). More work must be done to develop physical tests for ski racers.

The MLD platforms used in this study are portable, allowing for LRJT evaluations at a ski or dryland camp. The 2-minute LRJT presented here simulates the metabolic demands of women's ski racing and is appropriate for female alpine ski racers who can safely perform squats and LCMJs. A jump does not perfectly simulate a ski turn, but both actions involve eccentric and concentric muscle actions of the lower body. At this time, jumping may be the best choice for testing. Further investigations with larger sample sizes are needed.

### Limitations

The small sample size is a problem, but conducting a longitudinal study with high performance ski racers is difficult due to the nature of ski racing. It had been noted in other studies that small sample sizes are often a problem when working with world-class ski racers (Haaland et al., 2016; Kröll et al., 2017). The use of FIS points to evaluate performance may also be a problem. FIS points are based on only two results per season, and there is no general rating for athletes racing well in multiple disciplines (Maisano et al., 2015). Also, errors may have been introduced by the linear interpolation of missing jumps. Preseason fitness tests may not reflect in-season fitness, and thus may not be an accurate indicator of anaerobic power and capacity during racing.

### Conclusion

The present investigation showed that anaerobic power and

capacity improved to a limited degree during the four-season study duration, as evidenced by results of the LRJT. Anaerobic power and capacity measures derived from the LRJT did not correlate with ski racing performance. Further investigations are necessary to create testing protocols that simulate the physiological demands on alpine ski racers.

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### Key points

- The 2-minute loaded repeated jump test (LRJT) simulates the duration and number of gates in a World Cup ski race, and can be used to quantify and compare an alpine ski racer's anaerobic power and capacity.
- Over the 4-year duration of the study, the Austrian alpine ski racers in this study improved their ski racing performance as anaerobic fitness increased.
- Testing anaerobic fitness in ski racers is critical because it correlates with ski racing performance, and the high speeds in racing require maintaining high levels of strength until a racer has safely arrived in the finish area.

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