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Quantification of the Metabolic and Physical Demands of the 90-Second Box Jump

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Abstract

Introduction: The goal of the 90-second box jump (BJ90) is to perform as many lateral jumps as possible onto and off of a bench within 90 seconds. We aimed to determine the physiological and biomechanical demands of the BJ90.

Methods: Sixteen trained males (age range 23–45 y) performed a cycling test to determine maximal oxygen uptake (VO_2max), three countermovement jumps (CMJ) to determine explosive leg strength and the BJ90 on 1–3 occasions. Heart rate (HR), VO_2, and ground reaction forces were recorded throughout the BJ90. Acceleration, work and power were derived from force measurements. Blood lactate and oxygen debt were measured after the test and aerobic energy contribution was estimated.

Results: Subjects performed (mean ± SD (range)) 75 ± 13 (52-94) jumps. Total work was 64.0 ± 6.3 (53–78) kJ, denoting a work rate of 711 ± 70 (590–868) W. Mean acceleration and impulse for the ground contact phase were 14.9 ± 4.3 (7.5–22.3) m/s^2 and 521 ± 94 (410–783) N·s, respectively. Maximal concentric power remained higher than in CMJ for the first 60 s but dropped over the last 30 s to values similar to CMJ. Average concentric power was always lower than in CMJ, and dropped continuously throughout the BJ90. Maximal eccentric power was of lesser magnitude than in CMJ. Peak VO_2 and HR were 93.1 ± 8.3% (77–110) and 95.6 ± 2.6% (89-102) of maxima, respectively. Metabolic intensity corresponded to 136 ± 12 (108–156)%VO_2max (80.1 ± 6.3 ml/min/kg) and aerobic contribution to total energy was 55.9 ± 4.2%. Metabolic efficiency was 34.5 ± 3.6%. Blood lactate reached 13.4 ± 1.6 (9.0-17.0) mM.

Conclusions: Physiologically speaking, the BJ90 is similar to giant slalom skiing, whereas the movement frequency corresponds to slalom racing. The faster rate of force development in the BJ90 represents the main difference from ski racing.

Keywords

Alpine skiing; Performance test; Biomechanics; Severe exercise; Energy production

Introduction

Competitive alpine skiing is a complex sport with high physiological and technical demands. Ski racing requires high leg strength, high metabolic capacity, developed motor control and coordination, and rapid reaction times [1]. In the four main disciplines, slalom, giant slalom, super G and downhill, race duration can range from around 45 seconds up to two and a half minutes. Centrifugal forces in the turns are resisted, in most part using one leg only contracting at ~60-150% of maximal voluntary isometric force [2,3], concurrent with precise modulations of pressure and bodyweight distribution. The overall metabolic work rate can range from 120 – 200% of the maximal aerobic capacity (VO_2max) [4-6]. At the same time, the almost constant high leg muscle tension, resulting from prolonged near-isometric or slow-velocity contractions, restricts blood flow and oxygen supply to mitochondria [2,7,8], which poses an additional challenge to muscle energy supply.

Since many factors can influence skiing performance, standardized physiological tests are often used to assess, in isolation, physical capacities that are important for performance. The 90-second box jump (BJ90) test is a simple indoor performance test typically used for this purpose in alpine skiing [9]. For example, the BJ90 is performed regularly by junior skiers in Switzerland [10-12], the United States [13,14], Canada [15], and other countries, for monitoring training progress and for athlete selection. The test goal is to perform as many lateral jumps as possible onto and off of a bench, alternating left to right on the jump down, within 90 seconds.

Like alpine skiing, the BJ90 apparently draws upon leg muscle power, aerobic and anaerobic capacities, and movement coordination with ensuing fatigue. Moreover performance in the BJ90 (i.e., total number of jumps onto the bench) has been shown to correlate with giant slalom racing performance times in competitive skiers [15]. Thus, using the BJ90 for tracking training progress of skiers or athlete selection seems justified. Nonetheless, the BJ90 is typically performed in a gym, sometimes in groups, and only total jumps after each 30-second segment are recorded, without consideration of additional physiological and physical data (e.g.,10). Moreover, with the exception of a study from our lab, which reports VO_2 data from nine Swiss junior alpine skiers [11], supplementary descriptive data of the BJ90 have not been published. As a result, no direct comparison of the physiological and biomechanical demands of the BJ90 and those of actual ski racing has previously been attempted. Thus, the main aim of this project was to determine the physiological and biomechanical demands of the BJ90, such that comparisons can be made to actual alpine ski racing. An additional goal was to assess possible correlations between typical physiological variables and BJ90 performance, as well as the possibility of predicting mechanical power using data more typically available in the practice setting.

Methods

Subjects

Sixteen physically active males (Table 1) participated in this study voluntarily, for which all procedures were approved by the ethical review board of the Canton of Bern, Switzerland. Subjects participated regularly (~5 d/wk, recreationally or competitively) in sports such as cycling, running game sports, strength training, and

Table 1: Subject characteristics (*n*=16, males).

Subject characteristics (*n*=16, males)				
	Age (y)	**Height (cm)**	**Weight (kg)**	**VO_2max**
Mean ± SD	32 ± 8	180 ± 6	73 ± 7	60 ± 4
Range	(23-45)	(171-192)	(64-85)	(48-69)

Note: VO_2max: maximal cycling oxygen uptake rate

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taekwondo. Prior to beginning the study, each subject provided written informed consent to participate and underwent a basic medical screening (including resting and exercising ECG) performed by a medical doctor.

Setup

For the BJ90, a wood-frame structure, which was custom-built for this study, enclosed two QuattroJump one-dimensional force plates (Kistler Instruments, Winterthur, Switzerland), each 920×920 mm, which stood directly on the floor. This frame, which was of the same height (125 mm) as the force plates, surrounded but did not contact the plates (gap between frame and plate ~10 mm). Between the two plates was a gap of 240 mm, which was spanned by a custom-built wooden bench (height 440 mm, width 500 mm, length 920 mm), whose weight was equally distributed onto the two force plates (Figure 1).

Procedures

Subjects were recruited to participate in an intervention study, which involved beta-alanine supplementation and aerobic interval training [16], for which they performed an incremental cycling test to exhaustion (starting power 70 W, 30 W increases every two minutes) on an Ergometrics 800S cycle ergometer (ergoline GmbH, Bitz, Germany) to determine peak power output (PPO), oxygen consumption (VO_2 max) and heart rate (HR_{max}), three countermovement jumps (CMJ) to determine explosive leg strength, and the BJ90 at three time points. This provided the framework for collecting data on the BJ90 in a reasonably-sized group of subjects and across a range of fitness levels and for changing test ability. Data from CMJ, which were performed immediately prior to the BJ90 on each occasion, and the incremental cycling test, which was always performed one to two days prior to BJ90, were employed in the analyses and interpretation of the BJ90 data (details below).

After at least two familiarization sessions, subjects performed trials of the BJ90 on three separate occasions, separated by 2-6 weeks. For each trial, subjects warmed up initially on a stationary bicycle for 10 minutes at a light, self-selected intensity. Next, subjects performed multiple maximal CMJ on one force plate (with the bench set to the side), each separated by 30 s. Subjects wore shoes and the only instruction given was to jump as high as possible with hands fixed at the hips. Three correct jumps between which height did not vary by more than 2 cm were recorded for analysis. Typically, this required that subjects perform 3-6 CMJ. Standard CMJ parameters (jump height, mean (cP_{avg}^{CMJ}) and maximal (cP_{max}^{CMJ}) concentric power output relative to body weight were identified by the QuattroJump software (version 1.0.9.2). Additionally, maximal eccentric power output (eP_{max}^{CMJ}) was identified manually from the 500 Hz raw data. After three correct jumps had been performed, subjects were seated and fitted with a heart rate monitor (R500, Polar Electro Oy, Kempele, Finland) and a mask. Meanwhile, the bench was set into place and both force plates, each connected to its own Dell Latitude laptop with QuattroJump software, were zeroed. Thereafter, subjects were weighed on each plate separately, and then re-seated beside the test station.

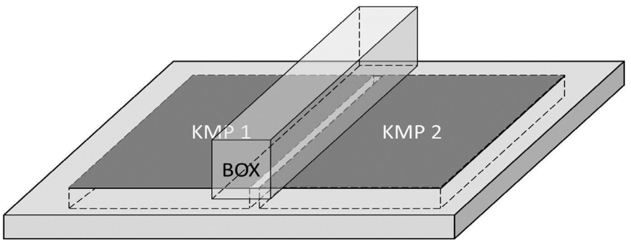


Figure 1: Design and dimensions of the custom-made test station for the 90-second box jump (BJ90). A frame and bench (BOX) were made of wood. Enclosed in the frame were two force plates, each standing on the floor and, together, supporting the weight of the bench.

Following calibration of flow and gas sensors, an Oxycon Pro respiratory gas-exchange analyzer (Erich Jaeger GmbH, Höchberg, Germany) was connected to the mask and breath-by-breath gas-exchange measurement began. During the initial two minutes, subjects remained seated and resting lactate was measured at the finger (Biosen C-line sport, EKF-diagnostic GmbH, Barleben/Magdeburg, Germany). Between 2:15 and 2:20, measurements on both force plates were initiated using the software's *other* mode. In this mode, force (F) is measure at 500 Hz for the selected amount of time, in this case 120 seconds. Once force measurements were underway, subjects stepped upon plate 1 (bench on the subject's right-hand side) and waited approximately 10 seconds for the start command, which was given at 2:30. At this point, the BJ90 began. During the test, subjects jumped laterally onto the bench, down the other side to plate 2, then back again, repeating as many cycles as possible within 90 seconds. The performance criterion was jumps onto the bench (from either side); thus each complete cycle included two counted jumps. Throughout the test, one investigator supported the Oxycon's gas tube and cable by hand, guiding it from side to side along with the subject, so that it did not interfere with jumping. Another investigator informed the subject when 30, 60 and 80 seconds had elapsed and to stop once 90 seconds had elapsed. One investigator counted jumps and informed the subject of the total jumps accumulated at 30 and 60 seconds.

Upon test conclusion, subjects were seated within 5 seconds and lactate was measured again (BLa_{post}) 30 seconds after the test termination. A final lactate measurement was made four minutes after test termination (BLa_{4min}), while heart rate and breath-by-breath gas-exchange measurements continued five minutes beyond test termination.

Biomechanical (physical) data processing

Raw data from the two force plates were inserted into a spreadsheet (Microsoft Excel 2010), where they were converted to 100 Hz, and synchronized to the nearest 0.01 s by visually identifying the initiation of the first jump. If needed, initial values were corrected manually so that F on plate 1 corresponded to the subject's weight (mean of values taken immediately before test onset on the two plates separately) and F on plate 2 was zero (occasional systematical error of <50 N). For example, for a subject weighing 685 N (69.8 kg), if F measured 690 N and 5 Non plates 1 and 2, respectively, immediately prior to test onset, these and all subsequent values were corrected by subtracting 5 N. In the same manner, if F did not return to zero during a flight phase in a later part of the test, values from that time point on were corrected so that F during flight remained zero.

Next, data from plates 1 and 2 were summed and separated into visually identified jump half-cycles (each comprising one landing on the floor and one landing on the bench). For each half-cycle, acceleration (*a*) and velocity (*v*) curves were generated as follows:

$a=F/m-g$, where m is subject body mass and $g=9.81$ m/s^2

$v=v_0+a^*t$, where $v_{0=}-{}^1/_2\cdot(v_{max}-v_{min})$

That v_0 is the inverse of half the amplitude of the jump half-cycle is based on the assumption that v at the instant of take-off from the floor (v_{max}) is of equal magnitude (but opposite direction) to v at the moment of ground contact (v_{min}). This assumption is incorporated into the QuattroJump software (version 1.0.9.2) for repeated jumping on a single plate to avoid "drift" in the data over longer recording periods (personal correspondence with Kistler technical service). Finally, power (P) curves were generated for each jump half-cycle, where P=F· v, and P was distinguished as eccentric (P<0) or concentric (P>0). In order to describe the BJ90 in terms of the typical variables taken from the more commonly employed CMJ, the analogous parameters maximal (cP_{max}^{BJ90}) and average (cP_{avg}^{BJ90}) concentric P were determined for each jump half-cycle. As well, since eccentric muscle activity is known to be especially important for skiers (who use this test perhaps the most), the maximal eccentric P (eP_{max}^{BJ90}) was determined for each jump half-cycle. Additionally, positive and negative mechanical work, (P·Δt), and ground contact time (ct) for each landing were tracked throughout the test. Total work was expressed as an absolute value ($|W_{tot}|=W_{pos}-W_{neg}$) and as the actual sum of W_{pos} and W_{neg}. In an analogous manner, P_{pos}, and P_{neg}, and total P ($|P_{tot}|$) were calculated for the complete BJ90 as P=W/90 s. Finally, the impulse (F·Δt) for each ground contact phase was determined by integrating the F data across the contact phase (i.e., mean F·ct).

The cP_{max}^{BJ90}, eP_{max}^{BJ90}, cP_{avg}^{BJ90} and ct were compiled into 15 second segments (for comparison to those in the CMJ using dependent t-tests) and 30 second segments (for use in regression analyses described below). In each case, compilation was done by averaging all jump half-cycles performed within one segment.

In order to evaluate the reliability of the force plate measurements, mechanical work registered on force plates 1 and 2 were compared using Pearson correlations. Using data from 18 familiarization trials, correlations were strong (R^2 0.998 ± 0.004, range 0.984 – 1.000) and linear regression lines on the x-y plots of plate 1 against plate 2 were close to the line of identity (slope 0.95 ± 0.06, range 0.796 – 1.035).

Physiological data processing

Breath-by-breath VO_2 data were compiled into 5-second averages. Baseline VO_2 was taken as the average VO_2 during the 30 seconds preceding the test. VO_2peak was taken as the highest 15-s average (average of three consecutive 5-s values). Further, total O_2 consumption during the BJ90 (O_2cons) as well as net O_2 consumption (integrated VO_2 above baseline VO_2) during the first five minutes following the test ($EPOC_5$) were determined.

Five minutes was used for the $EPOC_5$ because a validation study in our lab [17] revealed that, for 90 seconds cycling at a fixed intensity eliciting similar VO_2peak and HR_{peak} as the BJ90, the $EPOC_5$ provided the best estimate of the O_2-deficit, which serves as a non-invasive measurement of anaerobic energy utilization. Moreover, the O_2cons:$EPOC_5$ ratio provided an equally good estimate of aerobic and anaerobic energy contributions as did the O_2cons:O_2-deficit ratio [17]. Thus, for the current study, because O_2 demand could not be estimated beforehand as is common for cycling exercise, we used the sum of O_2cons and the $EPOC_5$ as a surrogate estimate. Considering the high intensity of the BJ90 and the fact that we recorded RER values above 1.00 in all subjects throughout the five minutes that followed the BJ90, we assumed pure carbohydrate as the energy source in the muscles and therefore multiplied O_2cons, $EPOC_5$ and their sum by 21.09 kJ/L O_2 [18] to calculate aerobic, anaerobic and total metabolic energy turnover. Metabolic efficiency was calculated as the ratio, in kJ, of mechanical work performed to total metabolic energy turnover.

Correlates of performance and regression

To help identify physiological determinants of performance, Pearson's correlation analyses were run between BJ90 performance, i.e., total jumps, and various anthropometric (weight, height) and physiological measures from the incremental cycling test (PPO, VO_2 max, maximal blood lactate concentration), the CMJ (jump height, v_{max}^{CMJ}, cP_{max}^{CMJ}, cP_{avg}^{CMJ}), and the BJ90 itself (BLa_{4min}). Because overall performance in the BJ90 changed across the three trials, all trials were included in correlation analyses (n=45). Bonferroni's correction for multiple comparisons was applied to the level of significance when interpreting these data [19].

Linear regression analyses were run to explore the predictive power of commonly available data for determining the cP_{avg}^{BJ90} and cP_{max}^{BJ90}. The cP_{avg}^{BJ90} and cP_{max}^{BJ90} values from each 30-second segment were set as the output variable (three segments in each of 45 tests, hence n=135), while total jumps (also per 30 second segment), body height, body weight, and the CMJ parameters jump height, v_{max}^{CMJ}, cP_{max}^{CMJ}, and cP_{avg}^{CMJ} served as input variables. For the regressions using CMJ input variables, two models were tested for each of cP_{avg}^{BJ90} and cP_{max}^{BJ90}. In the first of these, cP_{avg}^{BJ90} and cP_{max}^{BJ90} were expressed in W/kg; in the second, they were expressed as a percentage of cP_{avg}^{CMJ} and cP_{max}^{CMJ}, respectively. The model yielding a higher R^2 was accepted. Because overall performance changed across the three trials and because the cP_{avg}^{BJ90} and the cP_{max}^{BJ90} where changing across each segment during the test due to fatigue (see results below), we considered 30 second segments to be independent data points. That is, varying physical ability (from time point to time point) and incurring fatigue (from segment to segment) implied different conditions for each data point.

Statistical analyses

Descriptive statistics (means, standard deviations, ranges) and t-tests were performed using Microsoft Excel 2010, while correlation and regression analyses were performed using SPSS (version 20, IBM) employing the two-tailed bivariate correlation and stepwise linear regression functions, respectively. From correlation analyses, the Pearson coefficient (r) was extracted, whereas the line of identity (measured versus predicted), 95% confidence intervals (CI), and constants and coefficients from the prediction equation were extracted from the linear regression analyses. The standard alpha level was set at 0.05. However, for correlation analysis, this was divided by the number of comparisons (10), thus yielding a significance level of p=0.005.

Results

One subject incurred an injury outside the study and could only complete one trial, while another became sick and completed only two. Thus, data were gathered from a total of 45 trials performed by 16 subjects.

CMJ

Data from the CMJ are displayed in Table 2. No changes occurred between trials.

BJ90 performance

BJ90 performance improved significantly from trial to trial (trial 1: 72 ± 13, trial 2: 76 ± 12, trial 3: 80 ± 10 jumps). Jumps per 30-seconds dropped from the first to second segment and from the second to third segment significantly (both $p<0.01$) but the fatigue pattern was similar across trials. These data are displayed in Table 3.

BJ90 biomechanical parameters

Total work and power data from the BJ90 are displayed in Table 4. In the initial 15 seconds of the BJ90, the cP_{avg}^{BJ90} (18.9 ± 4.5 W/kg) was significantly lower than the cP_{avg}^{CMJ} and incurred linear decay, significant across four of five remaining 15 second segments, to a final value of 15.0 ± 4.5 W/kg (Figure 2B). The overall (90-second) P_{avg}^{BJ90} was 17.0 ± 3.1 (range within subject cohort 11.8 – 22.0) W/kg.

In the initial 15 seconds of the BJ90, the cP_{max}^{BJ90} (59.9 ± 15.7 W/kg) was significantly higher than the cP_{max}^{CMJ}. The cP_{max}^{BJ90} was maintained throughout the first three 15 second segments. Significant decreases in the cP_{max}^{BJ90} occurred in each of the last three 15 second segments, such that during the second to last (54.1 ± 14.9 W/kg) and the last segments (49.5 ± 14.8 W/kg), the cP_{max}^{BJ90} was no longer statistically different from the cP_{max}^{CMJ} (Figure 2A). The overall cP_{max}^{BJ90} was 56.1 ± 13.8 (range 33.6 – 85.0) W/kg.

The overall eP_{max}^{BJ90} was –62.1 ± –11.1 (range –39.5 to –84.7) W/kg, which was significantly higher (of lesser absolute value) than the eP_{max}^{CMJ}. The eP_{max}^{BJ90} increased *in absolute value* throughout the first minute, then sank in absolute value slightly but significantly in the last two 15 s segments. For each 15-segment, the eP_{max}^{BJ90} was larger in absolute value than the cP_{max}^{BJ90} (Figure 2C).

Ground *ct* decreased from the first to the second 15-second segment, then increased linearly until test end, such that *ct* in the final two segments was significantly greater than at test onset (Figure 2d).

Table 2: Performance measures from the countermovement jump (CMJ).

Performance measures from the countermovement jump (CMJ)			
	Trial 1 (*n*=16)	**Trial 2 (*n*=15)**	Trial 3 (*n*=14)
Jump height (cm)	47.0 ± 6.8	47.7 ± 6.8	46.7 ± 6.9
v_{max} (m/s)	2.8 ± 0.2	2.8 ± 0.2	2.8 ± 0.2
cP_{max} (W/kg)	49.4 ± 7.0	50.3 ± 7.5	49.6 ± 7.3
cP_{avg} (W/kg)	28.1 ± 3.8	28.3 ± 4.4	28.1 ± 4.3
eP_{max} (W/kg)	-102.9 ± 28.3	-102.3 ± 26.1	-99.3 ± 24.7

Note: Data presented as mean ± standard deviation. v_{max} : maximal concentric velocity. cP_{max}: maximal concentric power output. cP_{avg}: average concentric power output. eP_{max}: maximal eccentric power output

Table 3: Jumps performed per 30-second segment in three trials of the 90-second box jump (BJ90).

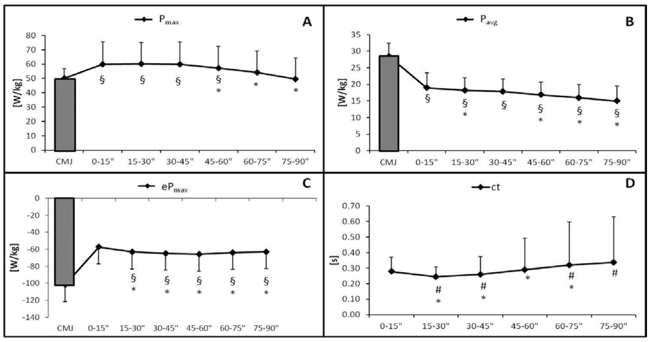
Jumps performed per 30-second segment in three trials of the 90-second box jump (BJ90)			
Segment	**Trial 1 (*n*=16)**	**Trial 2 (*n*=15)**	**Trial 3 (*n*=14)**
0 - 30"	26.0 ± 3.6	27.5 ± 4.3*	28.6 ± 3.9*
30 - 60"	23.5 ± 5.1§	25.3 ± 5.1*x	27.1 ± 3.3*§
60 - 90"	21.6 ± 5.7§	21.6 ± 5.1§	24.3 ± 4.0§

Note: Data presented as mean ± standard deviation. *Significantly different than trial 1 ($p<0.05$). §Significantly different than previous segment in same trial ($p<0.05$)

Table 4: Work and power values in the 90-second box jump (BJ90) for three trials and overall.

Work and power values in the 90-second box jump (BJ90) for three trials and overall				
	Trial 1 (*n*=16)	**Trial 2 (*n*=15)**	**Trial 3 (*n*=14)**	**All trials (*n*=45)**
W_{pos} (kJ)	40.8 ± 6.0	39.2 ± 5.4	38.9 ± 4.6	39.7 ± 5.3
W_{neg} (kJ)	−23.8 ± 4.0	−24.1 ± 3.6	−25.0 ± 4.1	−24.3 ± 3.9
W_{tot} (kJ)	17.0 ± 8.0	15.1 ± 6.6	13.9 ± 5.5	15.4 6.8
$\lvert W_{tot} \rvert$ (kJ)	64.6 ± 6.3	63.3 ± 6.4	63.9 ± 6.7	64.0 ± 6.3
P_{pos} (W)	454 ± 66	435 ± 60	432 ± 51	441 ± 59
P_{neg} (W)	−265 ± 45	−267 ± 40	−278 ± 46	−270 ± 43
$\lvert P_{tot} \rvert$ (W)	718 ± 70	703 ± 71	710 ± 74	710 ± 70
$\lvert P_{tot} \rvert$ (W/kg)	9.8 ± 0.9	9.6 ± 0.9	9.7 ± 0.8	9.7 ± 0.8
cP_{avg} (W/kg)	17.0 ± 3.3	17.2 ± 3.0	17.0 ± 2.9	17.1 ± 3.0
cP_{max} (W/kg)	56.1 ± 14.7	55.6 ± 12.7	57.3 ± 13.8	56.3 ± 13.5
eP_{max} (W/kg)	-62.4 ± 12.7	-62.0 ± 10.5	-62.0 ± 10.7	-62.1 ± 11.1

Note: Data presented as mean ± standard deviation. W_{pos}: positive work. W_{neg}: negative work. W_{tot}: total work (sum of W_{pos} and W_{neg}). $\lvert W_{tot} \rvert$: sum of absolute values of W_{pos} and W_{neg}. P_{pos}: positive power output (W/test duration, i.e., W/90 s). P_{neg}: negative power output. $\lvert P_{tot} \rvert$: total work as $\lvert W_{tot} \rvert$ /90 s. cP_{avg}: average concentric power output. cP_{max}: maximal concentric power output. eP_{max}: eccentric power output



P_{max}: Maximal concentric power output; P_{avg}: Mean concentric power output; eP_{max}: Maximal eccentric power output; ct: Ground contact time. Data points are averages of all jump half-cycles within each 15-s segment. § Significant difference to CMJ. * Significant difference ($p>0.05$) to preceding segment. # Significant difference to first segment

Figure 2: Development of biomechanical parameters during the 90-second box jump (BJ90), compared to a single countermovement jump (CMJ).

Mean acceleration during the ground contact phase was 14.9 ± 4.3 (7.5 – 23.2) m/s^2 while maximal acceleration was 39.5 ± 9.2 (18.1 – 55.7) m/s^2. Acceleration at the moment of the cP_{max}^{BJ90} was 21.0 ± 6.4 (10.9 – 32.2) m/s^2. Mean impulse of the ground contact phase was 521 ± 94 (410 – 783) N·s or, normalized to body mass, 6.9 ± 1.1 (5.9 – 10.7) m/s/kg.

Physiological parameters

Subjects attained VO_2peak of 54.7 ± 4.7 ml/min/kg or 93.1 ± 8.3% (77 – 110%) of their cycling VO_2max. Peak HR was 95.6 ± 2.6% (89 – 102%) of cycling HR_{max}. Gross O_2cons was 4925 ± 556 mL, while the $EPOC_5$ was 3909 ± 638 mL. This indicated that energy provision was 55.9 ± 4.2% aerobic and 44.1 ± 4.2% anaerobic. Calculated overall intensity, based on aerobic and anaerobic energy demand, corresponded to 136 ± 12% (range 108 – 156%) of VO_2max (i.e., 80.1

± 6.3 ml/min/kg). Metabolic efficiency was 34.5 ± 3.6%. BLa_{post} was 7.1 ± 1.6 (4.6 – 10.5) mM, while BLa_{4min} was 13.4 ± 1.6 (9.0 – 17.0) mM.

Correlates of performance and regression analysis

BJ90 performance correlated significantly with the CMJ parameters jump height (r=0.51, $p<0.001$), v_{max}^{CMJ} (r=0.46, $p=0.002$), and cP_{max}^{CMJ} (r=0.44, $p=0.002$), but not with other tested variables.

The ranges for the dependent and independent variables used in the cP_{avg}^{BJ90} and cP_{max}^{BJ90} regression analyses are displayed in Table 5. A regression using only the most easily attained input variables (total jumps, body weight, and body height), could predict the cP_{avg}^{BJ90} with an R^2 of 0.73 and residuals of −0.1 ± 1.8 (95% CI ± 3.0) W/kg (equation 1, Figure 3A). The same input variables could predict the cP_{max}^{BJ90} with an R^2 of 0.60 and residuals of 0.03 ± 9.1 (95% CI ± 14.9) W/kg (equation 3, Figure 3B). In both cases, each input variable contributed significantly ($p<0.01$) to the predictive quality of the model.

The CMJ parameters v_{max}^{CMJ}, cP_{max}^{CMJ} and cP_{avg}^{CMJ} as additional input variables each improved predictive quality for cP_{avg}^{BJ90} significantly ($p<0.01$), whereas CMJ height did not. These variables predicted the cP_{avg}^{BJ90} as a percentage of cP_{avg}^{CMJ} with the highest R^2 (0.82) and residuals of −0.5 ± 1.6 (95% CI ± 2.1) W/kg (equation2, Figure 4A). Only v_{max}^{CMJ} contributed additionally ($p<0.01$) to the model for cP_{max}^{BJ90}; the R^2 of this regression was 0.70 and residuals were 2.0 ± 8.8 (95% CI ± 16.5) W/kg (equation 4, Figure 4B).

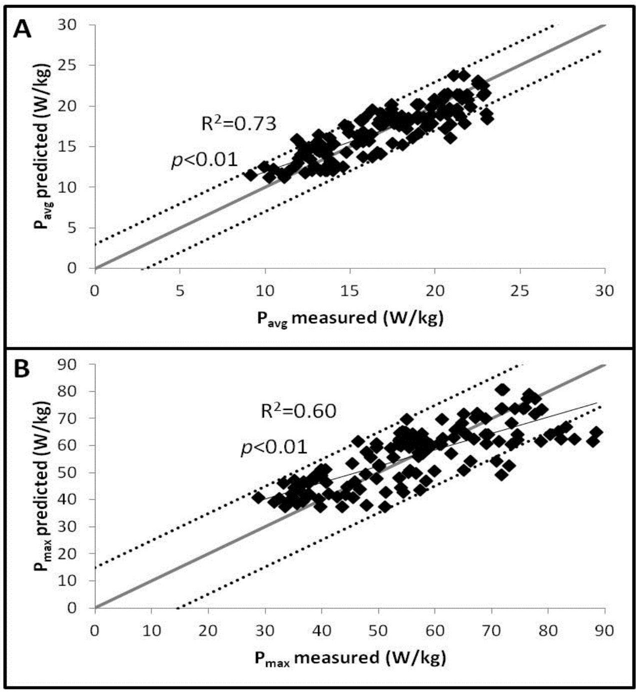
The resultant equations were for these four models were:

$$P_{avg}^{BJ90}=82.535-0.557\cdot jumps+0.568\cdot height+0.278\cdot weight \quad (R^2=0.73)$$

$$P_{avg}^{BJ90}=P_{avg}^{CMJ}\times(3.634-0.359\cdot v_{max}^{CMJ}-0.024\cdot P_{avg}^{CMJ}+0.01\cdot P_{max}^{CMJ}+0.021\cdot jumps-0.017\cdot height+0.009\cdot weight) \quad (R^2=0.82)$$

$$P_{max}^{BJ90}=307.191+1.755\cdot jumps-1.867\cdot height+0.563\cdot weight \quad (R^2=0.60)$$

$$P_{max}^{BJ90}=7.722-1.074\cdot v_{max}^{CMJ}+0.04\cdot jumps-0.029\cdot height+0.009\cdot weight \quad (R^2=0.70)$$



Predicted values were derived from regression equations using easily-attained input variables (body height, body weight and total jumps per 30-second segment in the BJ90). Grey solid line represents the line of identity (measured=predicted). Dotted lines represent the ± 95% confidence intervals of the predictions

Figure 3: Measured *vs.* predicted values for average concentric power output (P_{avg}^{BJ90}, A) and maximal concentric power output (P_{max}^{BJ90}, B) in the 90-second box jump (BJ90).

Discussion

The main aim of this project was to determine the physiological and biomechanical characteristics of the BJ90, such that comparisons can be made between this presumably ski-specific performance test and actual alpine ski racing. We were able to measure various physiological and biomechanical variables during the BJ90 in 16 active men with reasonably diverse BJ90 ability. Although this field test is commonly employed by alpine skiing federations in Switzerland [10-12], the United States [13,14], Canada [15], and other countries, there has been little mention of the BJ90 in the scientific literature. Compared to the performance values reported more than 20 years ago by Andersen et al. [15], our subjects spanned the range of abilities corresponding to club, divisional, and provincial alpine skiers. However, more recent reports suggest that BJ90 performance among competitive skiers has improved drastically over the years [10,11]; these studies report mean performance of 90 to 95 jumps in groups of junior male skiers. Thus, our subjects probably compare best to alpine skiers competing regionally in Switzerland today [12].

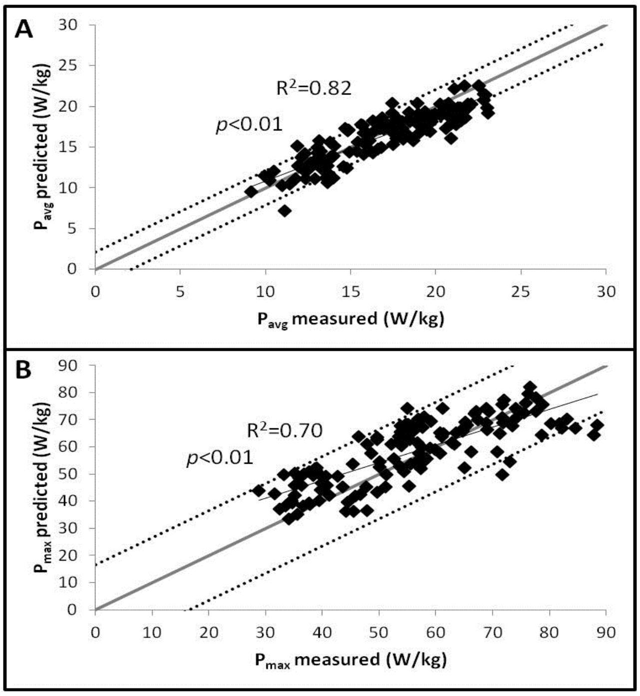
Table 5: Values used in regression analyses.

		Mean ± SD	Range
Jumps	(/30 s)	25 ± 5	(11 - 36)
Body height	(cm)	181 ± 7	(171 - 192)
Body weight	(kg)	75 ± 7	(64 - 88)
P_{max}^{CMJ}	(W/kg)	50.0 ± 7.0	(37.1 - 68.0)
P_{avg}^{CMJ}	(W/kg)	28.4 ± 4.1	(21.6 - 39.1)
v_{max}^{CMJ}	(m/s)	2.8 ± 0.2	(2.4 - 3.2)

Note: Data presented as mean ± standard deviation. Input variables for predicting average (P_{avg}^{BJ90}) and maximal (P_{max}^{BJ90}) concentric power output during 30-segments of the 90-second box jump (BJ90), including basic performance and anthropometrics measures, plus average (P_{avg}^{CMJ}) and maximal (P_{max}^{CMJ}) concentric power output and maximal velocity (v_{max}^{CMJ}) measures from a single countermovment jump (CMJ)

Our subjects performed the test in the framework of an intervention study, and their performance ability changed across the three trials (apparently also due to a learning effect). Moreover, we believe that changes were due to improved technical ability (implied by improved performance in the first 30 s) as well as aerobic condition (implied by improved performance in the last 30 s). This unique situation allowed us to collect data over a wider range of ability.

One limitation of our study is that we used one-dimensional force plates, which only capture the vertical component of jumping force. Because subjects had to jump slightly laterally upon to the bench, true force (and further parameters derived from it) was probably underestimated slightly. Another consideration is that we performed the measurements on recreationally trained subjects from various sports, rather than on competitive skiers. Skiers would have been more familiar with the test from the onset of the study and could have



Predicted values were derived from regression equations. Considering jump height, maximal concentric power output (P_{max}^{CMJ}), average concentric power output (P_{avg}^{CMJ}) and maximal velocity (v_{max}^{CMJ}) from a single countermovement jump (in addition to body height, body weight, and total jumps per 30-second segment in the BJ90) improved predictive quality by 5 – 6%. P_{max}^{CMJ}, P_{avg}^{CMJ}, and v_{max}^{CMJ} contributed significantly to the predictive quality for P_{avg}^{BJ90} (A), whereas only v_{max}^{CMJ} did so for P_{max}^{BJ90} (B). Grey solid line represents the line of identity (measured=predicted). Dotted lines represent the ± 95% confidence intervals of the predictions

Figure 4: Measured *vs.* predicted values for average concentric power output (P_{avg}^{BJ90}, A) and maximal concentric power output (P_{max}^{BJ90}, B) in the 90-second box jump (BJ90).

displayed different biomechanical behavior. Nonetheless, post-test BLa values (BLa_{4min}) appear similar to those of diverse populations of skiers spanning the BJ90 ability of our subjects [15]. Moreover, VO_2 responses were similar between our subjects and competitive junior male skiers [11].

In characterizing the test, we show that subjects were able to maintain work rates of 9.7 ± 0.8 W/kg on average, for 90 seconds. Such high power output, which would represent 194 ± 17% of cycling PPO, was possible because of a metabolic efficiency of 34.5 ± 3.6%. This value is approximately double that for cycling exercise [20] and very similar to that measured elsewhere for continuous countermovement [21] or drop jumping [21,22]. The explanation for such higher efficiency for repeated jumping is related to the storage of elastic energy during the eccentric phase of jumping [23]. The cP_{max}^{BJ90} (which occurred in the drop-jump like portion) was as much as 20% higher than, and never dropped below, that from a single maximal CMJ. On the other hand, the cP_{avg}^{BJ90} was well below the cP_{avg}^{CMJ}. Both the cP_{max}^{BJ90} and the cP_{avg}^{BJ90}, but especially the cP_{avg}^{BJ90}, clearly revealed incurring fatigue as the test progressed. Maximal eccentric power output differed to the greatest degree between BJ90 and CMJ; the eP_{max}^{BJ90} was of around only 60% of the eP_{max}^{CMJ}.

Aerobic capacity was more or less exhausted at 93% VO_2 max, while BLa_{4min} (13.4 ± 1.6 mM) indicates that anaerobic glycolysis was greatly stressed as well. That 56 and 44% of energy came from aerobic and anaerobic sources, respectively, could be expected for maximal exercise of this duration, and is within the range concluded by Gastin [24].

From a comparative standpoint, this study confirms several similarities between the demands of the BJ90 and those of competitive alpine skiing, as well as some foreseeable differences. Attaining VO_2 [25] and HR [6] above 90% of their maxima, as occurred in the BJ90, has been shown for race-like skiing situations as well. Blood lactate accumulation in the BJ90 was also similar to that measured after giant slalom runs lasting 70 seconds [5]. Furthermore, Saibene et al. [4] estimated the energy demand of giant slalom skiing over 82 seconds to be 72 ml/min/kg or 120% VO_2 max. Our measurements for the BJ90 where slightly higher, suggesting an intensity of 80 ± 6 ml/min/kg or 136 ± 12% VO_2 max.

Our subjects needed about 1.2 seconds per jump half-cycle (note, two jumping movements per half-cycle); however, high-level alpine skiers typically achieve 90 or more (counted) jumps in the BJ90 [26], and thus perform jump half-cycles in less than one second. These values correspond to ~0.6 s per jumping movement in the present subjects and ~0.5 s in high level skiers. Before the introduction of carving skis, Berg and Eiken [7] reported turn frequencies of 3.5 and 1.6 seconds for giant slalom and slalom, respectively. However, in the carving era, turning frequency has certainly increased; recent data we have gathered on elite skiers reveal average turn cycles of less than 1 second for slalom but around 4 seconds for downhill racing (unpublished). Thus, biomechanically speaking, the BJ90 mimics the movement cycle frequency of shorter slalom racing, whereas the test duration is closer to that of giant slalom, where movement cycles are longer.

Similar to skiing, the BJ90 requires good coordination during moments of high eccentric force production [1,7]. Alpine skiing has been shown to involve predominantly eccentric muscle work [7], which is necessary to overcome gravitational and centrifugal forces. This phenomenon is made possible by the elevation decrease encountered during the race, and is not mimicked in the BJ90. Depending on contraction time, eccentric muscle contractions serve different functions [27]. Faster stretch-shortening cycles, like in the BJ90, allow for storage and recovery of elastic energy because they are much closer to the optimal frequency of the muscle-tendon system, whereas slower eccentric contractions such as in skiing function like shock absorbers to dissipate energy [27,28]. In this manner, eccentric contractions function somewhat differently in the BJ90 than in skiing, whereby movement cycles in skiing rely more heavily on muscle contractile force.

It is therefore unsurprising that maximum acceleration during the ground contact phase in the BJ90 (~40 m/s^2) is much higher than in the turns of slalom racing (unpublished observations). However, mean acceleration (for our subjects ~15 m/s^2) is similar. Data we have gathered using an accelerometer from top-level skiers during slalom racing suggest peak a of ~21 m/s^2 and mean a of ~13 m/s^2 for slalom. Accordingly, due to the longer force application phase for skiing, impulse ($F \cdot \Delta t$) is greater than in the BJ90. It can, however, be said that the eccentric portion of work during the BJ90 is condensed in the drop-jump portion, and it is noteworthy that the eP_{max}^{BJ90} was consistently greater in absolute value than the cP_{max}^{BJ90}.

An additional goal was to assess possible physiological correlates of performance, and also the possibility of predicting mechanical power in the BJ90 using data more typically available in the practice setting. We show that CMJ parameters (jump height, cP_{max}^{CMJ}, and v_{max}^{CMJ}) correlate with BJ90 performance. The markers of aerobic capacity PPO and VO_2max, on the other hand, were not significantly correlated with performance.

Predicting the cP_{avg}^{BJ90} during the BJ90, or segments thereof, proved to be quite feasible. Anthropometric and performance variables alone described 73% of variation in the cP_{avg}^{BJ90}, while 82% could be described with the addition of CMJ parameters. Predictions of the cP_{max}^{BJ90} were less precise, with regression describing at most 70% of variation. This could be of interest for coaches who employ the BJ90 with athletes of higher ability than the present subjects.

Practical Applications

The BJ90 has been commonly employed in the practice of competitive alpine skiers for decades [10,11,13-15,26] but has been referred to only infrequently in the scientific literature. In the present study, we confirm that the BJ90 is an appropriate maximal performance test for aerobic and anaerobic capacity in the framework of biomechanically dynamic and coordinationally demanding movements. Moreover, metabolic characteristics show high similarity to giant slalom racing, while biomechanical characteristics show that movement cycle frequency is similar to slalom racing. The main difference relates to the rates of force development, which are much higher in the BJ90 than in any ski racing event. All things considered, the present study shows that the BJ90 mimics ski racing from a metabolic standpoint very well and from a biomechanical standpoint reasonably well, which supports the continued use of this test in practical and research settings for the assessment of competitive alpine skiers.

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