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Kinematics and Kinetics of Squats, Drop Jumps and Imitation Jumps of Ski Jumpers

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Abstract

Pauli, CA, Keller, M, Ammann, F, Hübner, K, Lindorfer, J, Taylor, WR, and Lorenzetti, S. Kinematics and kinetics of squats, drop jumps and imitation jumps of ski jumpers. *J Strength Cond Res* 30(3): 643–652, 2016—Squats, drop jumps, and imitation jumps are commonly used training exercises in ski jumping to enhance maximum force, explosive force, and sport-specific skills. The purpose of this study was to evaluate the kinetics and kinematics of training exercises in ski jumping and to find objective parameters in training exercises that most correlate with the competition performance of ski jumpers. To this end, barbell squats, drop jumps, and imitation jumps were measured in a laboratory environment for 10 elite ski jumpers. Force and motion data were captured, and the influence of maximum vertical force, force difference, vertical take-off velocity, knee moments, knee joint power, and a knee valgus/varus index was evaluated and correlated with their season jump performance. The results indicate that, especially for the imitation jumps, a good correlation exists between the vertical take-off velocity and the personal jump performance on the hill ($R = 0.718$). Importantly, however, the more the athletes tended toward a valgus knee alignment during the measured movements, the worse their performance ($R = 0.729$ imitation jumps; $R = 0.685$ squats). Although an evaluation of the athletes' lower limb alignment during competitive jumping on the hill is still required, these preliminary data suggest that performance training should additionally concentrate on improving knee alignment to increase ski jumping performance.

Key Words performance, ski jumping, movement analysis

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Introduction

Ski jumping has been an Olympic sport since the winter games of 1924 and it still attracts the attention of spectators and the media alike (24,30). The introduction of new techniques such as the V-style in 1987 (30), optimized training methods, new materials, and increased training infrastructure over the years have led to large improvements in the performance of athletes, including greater jump distances (20). However, although the availability of training facilities has been enhanced, ski jump training on the hill remains extremely time consuming. High-quality performance training in other environments is therefore a key factor for improving competitive performance.

A ski jump is composed of 4 main phases: in-run, take off, flight, and landing (8,16), although only the first 3 are considered to be essential for jump distance (21). Together with the quality of the skis and their preparation (21), an optimal tucked position during in-run should reduce drag and help increase the jumpers' take-off velocity (31). After take off, the aerodynamic abilities of the athletes can be decisive for jump distance and therefore the outcome of a competition. However, it is the rapid knee extension during take off, the second phase of the ski jump, that is thought to be the key factor for jump performance in competitive jumping, and one that can also be improved by training strength, timing, coordination, and speed (21).

The take-off velocity on the hill, composed of the in-run velocity and the vertical take-off velocity, reaches its peak approximately 0.3 seconds after the beginning of the take off (17,23,28,42). The explosive strength needed for a large vertical component of the take-off velocity is especially important on smaller hills with jump distances of less than 95 minutes (6), where a high rate of force development increases the take-off velocity (31). The performance training to enhance the take off typically includes exercises such as squats, drop jumps, and imitation jumps (3,27,46,47). However, it remains unclear which parameters during these exercises have a primary influence on the performance of the athletes on the hill.

The squat is one of the most popular exercises for performance training to strengthen the muscles of the lower extremities, involving multiple joints and a variety of muscles (1,11,18,19). Although there are no studies to date that have compared the biomechanics of squats with the performance of ski jumping, it is plausible that training the maximum force in the lower extremities could improve the vertical take-off velocity and with it performance on the hill. Whether it is strength or other factors that are important for jump performance remains to be investigated.

When drop jumping from an elevated platform, immediately followed by a jump over a hurdle, the stretch-shorten cycles of the quadriceps and gluteus maximus are specifically trained. During landing, these muscles are loaded eccentrically, followed by a concentric muscle contraction for the take off (3). Although this exercise is not predominantly sport specific, improvements in jumping skills due to higher muscle force and power output have been shown (3) and therefore the drop jump has been integrated into ski jump training. Bobbert (4) and Walsh et al. (45) came to the conclusion that a sport-specific technique should be chosen for drop jumps in performance training to improve the desired parameters. Importantly, excessive internal or external rotation of the knee resulting from the eccentric-concentric loading cycle can lead to injuries of the passive structures such as the anterior cruciate ligament (3,12,13,26). As it remains unclear which aspects of this training exercise are correlated with the final jumping performance on the hill, it is not yet possible to reduce the highest risk elements without reducing the efficacy of the training.

Although parameters of movement in the sagittal plane have more often been measured during competition than in a laboratory environment (30), 3D parameters of jump take-off kinematics that include e.g., limb alignment during hill jumps are hardly available. Despite differences in comparison with hill jumps, the knee valgus/varus during take off can be evaluated during imitation jumps (30). Starting from a squatting position on the ground, the athletes simulate the take-off jumping action and are held in the air by the trainer to mimic the actual take-off motion on the hill as closely as possible (40). To better understand the process, Virmavirta and Komi (41) investigated the kinetics of imitation jumps in a laboratory environment. Although the largest forces were indeed observed in the vertical direction, as would be expected for a large take-off velocity, forces in anteroposterior direction were also observed for all athletes, which is not possible on the hill due to the low friction between the skis and in-run track. In addition, Müller (24) suggested a sufficiently high vertical take-off velocity of at least 2.5 $m \cdot s^{-1}$, but further increases in the take-off velocity, which can only be achieved by extreme effort, might be less important than optimized take-off movements (24). The force during take off should be applied vertically (16,41) and symmetrically for an effective take off. The knee is seen as the joint with the highest power production during jumps (29). However, which kinetic and kinematic parameters during training exercises correlate with performance on the hill remain unknown. An evaluation of those parameters in the training of elite ski jumpers and an associated correlation with the performance is required for a reduction of injury risk and an optimal focus on the most decisive parameters for ski jumping performance in strength and jumping exercises.

To this end, the objective of this study was to determine kinetic and kinematic parameters of ski jumpers during performance training and to correlate these biomechanical parameters with their jump performance during competitions in the summer season 2012. Especially the maximum vertical force, force difference between the legs, knee valgus/varus index, and joint moments in the knee of ski jumpers were analyzed during squat. In addition to these parameters, the vertical take-off velocity and joint power in the knee were determined during drop jumps and imitation jumps. With regard to earlier studies of biomechanical parameters in this field and expertise in ski jumping, it is hypothesized that normalized kinetic parameters maximum force, knee moments and power, as well as the vertical take-off velocity and the knee valgus/varus index, correlate positively with the athletes' performance, whereas lower force differences between the legs result in better performance and therefore show a negative correlation with jumping performance.

Methods

Experimental Approach to the Problem

Each athlete performed 2 sets of squats and 1 set of drop jumps and imitation jumps. The extra load on the barbell during squats corresponded to the athletes' actual training weight and 70% of their 1 repetition maximum (1RM). Ground reaction forces and motion data were used to analyze the maximum vertical force, force differences between the legs with respect to the maximum vertical force, the maximum knee joint moments, and the knee valgus/varus index during all 3 exercises, and the maximum vertical take-off velocity and knee joint power during drop jumps and imitation jumps. The knee valgus/varus index was analyzed in terms of minimum values and their values at the maximum knee flexion angle. The evaluated biomechanical parameters were determined at the beginning of the winter season and correlated with the ski jumping performance in competitions during the previous summer season 2012. All measurements were completed during a single visit at the movement analysis laboratory of the Institute for Biomechanics (IfB) at the ETH Zurich.

Subjects

The subjects in this study represented the top end of ski jumpers in Switzerland. Here, 1 female and 9 male subjects with a mean age of 23 ± 4 years (range, 19–31), an average height of 179 ± 5 cm, and an average weight of 64.6 ± 4.8 kg participated in this study. The 7 elite ski jumpers and 3 elite Nordic combined (ski jumping and cross-country skiing) athletes were all members of the national performance center of the Swiss Ski Federation in Einsiedeln (Switzerland), and were all experienced in strength training. All athletes were free of injuries and health problems at the time of the study. The study was approved by the Ethics Committee of the ETH Zurich, and written informed consent to participate in the study was obtained from all subjects after receiving detailed information about the measurement procedures.

Procedures

Kinetic data was measured using 2 Kistler force plates (Type 9286AA; Kistler Instrumente AG, Winterthur, Switzerland) with a sampling frequency of 2000 Hz (2). An optoelectronic measurement system (Vicon V612; Oxford metrics, Oxford, United Kingdom) with 12 cameras (MX40; 8 fixed, 4 mobile; resolution 2353 × 1728 pixels) (2) and a sampling frequency of 100 Hz was used to capture the motion during the exercises. Seventy-seven skin markers based on the IfB marker set of List et al. (18), with 6 additional markers on the arms were then fixed to the subjects by the same examiner.

After an individual warm-up and the equipping with the skin markers, the measurements including squats, drop jumps, and imitation jumps were conducted. The first set of squats composed of 5 repetitions and an extra load corresponding to the subjects' actual training weight was followed by a set of 5 repetitions with an extra load of 70% of the estimated 1RM of each athlete (Table 1). The 1RM was estimated as follows: First, an isometric maximum force with maximum voluntary contraction (MVC) test for the squat position was performed at the Swiss Federal Institute of Sports Magglingen, Switzerland. This test is part of the typical performance diagnostics for ski jumpers and is conducted on a regular basis during their noncompetitive phase. Compared with 1RM testing, this approach ensures a higher safety standard and lower risk of injury. Subjects pushed maximally against a bar, fixated at a 70° ski jump–specific knee angle position, which was controlled by a goniometer. The subjects' feet were placed on a force plate (MLD Test Evo 2; SPSport, Innsbruck, Austria). Total ground reaction force (sum of both legs) and knee angle data were collected and saved in a database. The conversion factors for MVC to 1RM of 71.3% for male and 67.1% for female subjects were based on a study by Duss and Hobi (7), who investigated the correlation between MVC and 1RM in different knee angles for 12 male and 7 female highly-trained ski alpine athletes. Instructions given for the squats were similar to a previous study conducted at the Institute (19) (Table 2). As a measure of reproducibility, the typical coefficient of multiple correlation values for the lower extremity motion during squatting were about 0.97 (sagittal plane) and 0.8–0.85 (frontal-/transverse plane) (18).

The subjects performed the drop jumps starting from an upright position on a platform with a height of 74 cm, with the tips of their shoes flush with the platform edge. They were instructed to drop from the platform and immediately rebound over a hurdle (whose height and distance they were

Table 1. Weights for squats (kg).

Subject No.	First set training weight	Second set 70% 1RM
S01	90	80
S02	80	80
S03	90	75
S04	93	93
S05	90	93
S06	85	85
S07	85	92.5
S08	90	80
S09	95	87.5
S10	70	72.5

Table 2. Instructions for execution of squats (19).

1	Stand upright with your feet approximately shoulder width apart
2	Point the feet slightly outward, following the natural divergence of the feet
3	Put the barbell on the trapezius muscle and hold it with a comfortable hand position
4	Lift the thorax to a natural spinal position
5	Hold tension in the core muscles during execution of the squat
6	Breathe out during the ascent
7	Perform the squat explosively

Table 3. Calculation of points for international competitions (34).

International competitions	Points
World Cup (Men), World Championships, Olympic games	+6
Junior World Championships, Continental Cup (Men)	+4
FIS-Cup/Alpen-Cup	+2
World Cup (Women)	0
Continental Cup (Women)	−1
FIS-Cup/Alpen-Cup (Women)	−3
Example: Continental Cup	
Achieved points in competition (2 jumps)	247.5 Points
Division by 10	24.75 Points
Points for competition (+4)	28.75 Points

free to choose) while keeping the ground contact time as short as possible. For all subjects, the hurdle was higher than the dropping height. Six valid trials were required from each athlete, which involved both feet landing completely on the force plates and no loss of markers before clearance of the hurdle.

Finally, 10 imitation jumps without additional weight were conducted with the help of a trainer, in the same manner as they are executed during training. The subjects were allowed sufficient, individually chosen rest periods between trials.

Cycle Definition

Start and end time points of the movements were defined for all 3 exercises as follows. A squat repetition was defined as starting in an upright position, moving down to the lowest position achieved during the squat and returning upward to the original posture. The start and end points of the cycle were defined by the vertical velocity of the barbell ($v_{barb} < 0.04\ m \cdot s^{-1}$) tracked by 2 markers attached to the ends of the barbell (18).

The evaluation of the knee valgus/varus index at the position of the maximum knee angle of the drop jumps was determined during the movement starting when the data from at least 1 force plate had exceeded 2% of the subject's body weight (BW). Accordingly, the end point occurred when the force on both plates was again lower than 2%BW. The remaining variables were determined from the starting point of the drop jump defined as the lowest crouched position of the athletes, derived from the average of the markers fixed to the acromia, to the end point derived from the data of the force plates as described above.

Finally, the imitation jumps started from where the take-off velocity, calculated from force data, became and remained >0 until the point when the maximum velocity was reached.

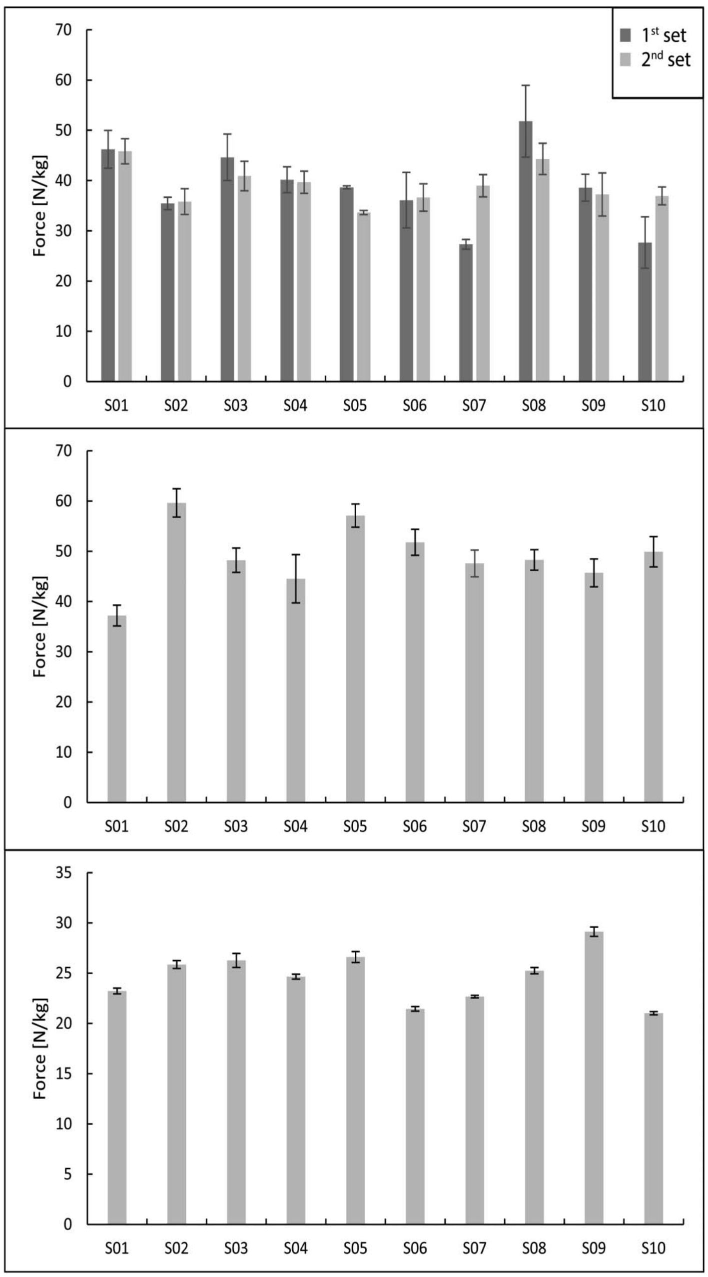

Figure 1. Maximum vertical forces F_{max} ($N \cdot kg^{-1}$)–normalized mean and *SD* for all subjects (squats–top, drop jumps–middle, imitation jumps–bottom).

Kinetics

The maximum vertical force for the stance phase of each repetition of the different exercises was determined as the sum of forces for both legs, normalized to BW. As a measure of asymmetry, the force production from both legs was

Table 4. ΔF_{max} [$\%F_{max}$]—mean and *SD* for all subjects.

Subject No.	Squats	Drop jumps	Imitation jumps
S01	7.9 ± 8.1	2.8 ± 1.9	3.1 ± 0.6
S02	9.5 ± 6.1	1.4 ± 0.9	1.2 ± 0.5
S03	10.9 ± 6.5	2.2 ± 1.2	2.0 ± 0.6
S04	8.0 ± 5.8	3.2 ± 1.6	1.0 ± 0.7
S05	8.3 ± 5.3	1.0 ± 0.6	1.2 ± 0.8
S06	9.4 ± 6.3	1.4 ± 1.2	1.3 ± 0.5
S07	8.0 ± 4.0	2.5 ± 1.5	0.9 ± 0.4
S08	9.5 ± 7.6	1.7 ± 1.1	1.0 ± 0.5
S09	7.4 ± 6.6	2.1 ± 1.3	3.0 ± 1.3
S10	9.1 ± 12.0	0.7 ± 0.6	2.6 ± 1.0
Mean ± *SD*	8.8 ± 1.1	1.9 ± 0.8	1.7 ± 0.9

evaluated using the absolute difference in maximum vertical force for each foot as a percentage of the total maximum vertical ground reaction force (equation 1).

$$\Delta F_{max} = \frac{\left|F_{max,\ left} - F_{max,\ right}\right|}{F_{max}} \cdot 100, \qquad (1)$$

where ΔF_{max} [$\%F_{max}$] is the difference between maximum vertical force of the left and right foot; $F_{max,\ left}$ [N] is the maximum vertical force under the left foot; and $F_{max,\ right}$ [N] is the maximum vertical force under the right foot. The maximum of the vertical component of the take-off velocity for drop jumps and imitation jumps was determined from the vertical force data (equation 2):

$$v(t) = \int_{t_{start}}^{t_{end}} \frac{F_{GRF}(t) - F_g}{m} \mathrm{d}t, \qquad (2)$$

where v [$\mathrm{m \cdot s^{-1}}$] is the velocity of the subject's center of mass; F_{GRF} [N] is the vertical ground reaction force; F_g [N] is the bodyweight; and m [kg] the subject mass. Knee joint moments (normalized to BW) were calculated using functionally determined joint centers from basic motion tasks (18). The maximum values are derived from the average of both legs. The normalized joint moments M [$\mathrm{N \cdot m \cdot kg^{-1}}$] and the joint angular velocity ω [$\mathrm{s^{-1}}$] in the knee, also reported as the average of both legs, were combined to calculate the normalized maximum of the joint power, P [$\mathrm{W \cdot kg^{-1}}$] in the knee (equation 3).

$$P = M \cdot \omega. \qquad (3)$$

Kinematics

The index for knee valgus/varus, Δd^*, was calculated using equation 4:

$$\Delta d^* = \frac{k - a}{a} \qquad (4)$$

where k is the distance between knee joint centers; and a is the distance between ankle joint centers. $\Delta d^* = 0$ indicates straight leg alignment, whereas $\Delta d^* < 0$ indicates a knee valgus and $\Delta d^* > 0$, a knee varus. The distances k and a were assessed at the lowest body position (i.e., largest knee flexion angle) during the squat and drop jump exercises (Δd^*_{knee}), similar to the study of Herrington and Munro (12). Starting from a crouched position at the maximum knee flexion angle during the imitation jumps, Δd^*_{knee} was calculated as the average of Δd^* during the first 10% of the exercise. Differing from (12), the distances were derived from 3D motion data and were therefore an extension of a planar analysis. Additionally, the lowest value of Δd^* during the execution of the 3 exercises was evaluated (Δd^*_{min}). The joint centers were calculated from the marker data, where normal standing was considered as the reference for a neutral posture, defining the knee angle of 0°. The angle was then calculated as the relative motion of the lower limb relative to the upper limb.

Performance

The evaluation of ski jumping performance was based on the points achieved during a competition season. To directly compare different competitions under different environmental conditions, expertise and weighting was required, as shown in major sport rating systems (33). Similar to the calculation of alpine FIS points (10), Swiss Ski (35) uses a scoring table (Table 3) that has been adapted thoroughly by ski jumping trainers over the years. The ranking is based on the average of the best 6 Swiss Ski points during a competition period, where the points are

Table 5. Maximum moments *M* and power *P* in the knee for drop jumps and imitation jumps.

Parameters	Squats	Drop jumps	Imitation jumps
M_{max} ($\mathrm{N \cdot m \cdot kg^{-1}}$)	2.61 ± 0.38	6.18 ± 0.58	3.21 ± 0.49
P_{max} ($\mathrm{W \cdot kg^{-1}}$)	–	52.35 ± 10.36	39.09 ± 7.77

Table 6. Δd^*–mean and *SD* for all exercises ($\Delta d^* < 0$: knee valgus; $\Delta d^* > 0$ knee varus).

Parameters	Squats	Drop jumps	Imitation jumps
Δd^*_knee	0.14 ± 0.09	−0.12 ± 0.20	0.02 ± 0.11
Δd^*_min	−0.12 ± 0.08	−0.21 ± 0.15	−0.22 ± 0.11

calculated as follows: The points achieved during a competition, resulting from jump length and the judges' notes, are divided by 10 and weighted for different competition types using specific extras and deductions (Table 3). This scoring method was used in the present study for evaluating the jumping performance of each athlete on the hill in the summer season of 2012, which was shortly before the investigation was conducted.

Statistical Analyses

The mean values and *SD*s over the valid trials were determined for each parameter and each athlete. The Shapiro-Wilk method was used to test the trials of each athlete and the parameters as the averaged values of the athletes for normal distribution. As this could be shown for 90% of the tests, normal distribution was adopted for all parameters. A correlation analysis was conducted for the parameters F_{max}, ΔF_{max}, v, Δd^*, M_{max}, and P_{max} with the jumping performance. The IBM software package SPSS Statistics version 22 (IBM Corp., Armonk, NY, USA) was used for all analyses with an alpha level of 5% ($p \leq 0.05$).

Results

Kinetics

Within 1 set, most of the athletes conducted the squats regularly with a relative *SD* of less than 5%, whereas some varied up to 18% with maximum forces of $38.7 \pm 7.7\ N \cdot kg^{-1}$ (first set) and $39 \pm 3.8\ N \cdot kg^{-1}$ (second set) (Figure 1). While performing drop jumps, maximum forces of $49 \pm 6.3\ N \cdot kg^{-1}$ were shown with a relative *SD* below 7% for 90% of the athletes. The imitation jumps, as a sport-specific exercise, were conducted very regularly, resulting in low relative *SD*s for the individual subjects (<2% for 80% of the athletes) and an average maximum force of $24.6 \pm 2.5\ N \cdot kg^{-1}$.

The interlimb force variability, ΔF_{max} for the imitation jumps was below 1% for some of the subjects, whereas others exhibited interlimb differences of up to 3% (Table 4). Similar values were found for the drop jumps, but mean force differences between the legs of up to 11% were shown for the squats.

The highest knee joint moments were achieved during the drop jumps. Relative *SD*s of up to 16% for squats and drop jumps are in contrast to values of less than 5% for all athletes during the imitation jumps (Table 5). Similar to the maximum moments, the maximum knee joint power was higher during drop jumps than during imitation jumps.

Taking advantage of the stretch-shortening cycle during drop jumps, average vertical velocities of $3.35 \pm 0.30\ m \cdot s^{-1}$ were achieved compared with $2.95 \pm 0.23\ m \cdot s^{-1}$ during imitation jumps.

Kinematics

At the lowest point of the squats, 90% of the athletes showed a tendency toward knee varus (Table 6), which was in accordance with the anatomical conditions (9). Although the mean value during imitation jumps indicated a knee varus alignment at maximum knee angles, a tendency toward knee valgus was found for 60% of the athletes. However, the average minimum Δd^* was negative for all 3 exercises. Within the imitation jumps, this shows a knee valgus alignment during take off. Similarly, this was also the case for the drop jumps, for which the average values at the lowest position in the exercise exhibited a knee valgus alignment.

Performance

Each athlete's jumping performance during the summer season of 2012 was available as a basis for the statistical evaluation (Figure 2).

Correlations

Although the vertical take-off velocities were indeed correlated with the athletes' jumping performance on the hill ($r = 0.647$ for the drop jumps and $r = 0.718$ for the imitation jumps), no significant correlation could be found for the maximum vertical forces within the exercises (Table 7). The highest correlation with the jumping performance was shown in the minimum Δd^* during the imitation jumps

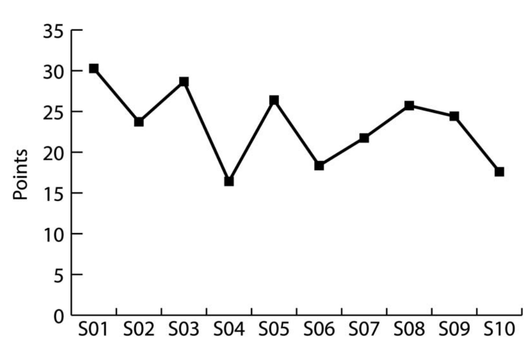

Figure 2. Ski jumping performance during the summer season of 2012 for each subject (35).

TABLE 7. Correlation (*r*) and the corresponding *p*-values of performance with maximum vertical force, force difference, vertical take-off velocity, Δd^* as well as maximum moment and power in the knee.

Parameters	Squats		Drop jumps		Imitation jumps	
	r	*p*	*r*	*p*	*r*	*p*
F_{max} ($N \cdot kg^{-1}$)	0.592	0.072	−0.179	0.620	0.477	0.163
ΔF_{max} ($\%F_{max}$)	0.125	0.730	0.110	0.763	0.331	0.350
v_{max} ($m \cdot s^{-1}$)	–	–	0.647*	0.043	0.718*	0.019
Δd^* (knee)	0.502	0.139	0.570	0.085	0.399	0.253
Δd^* (min)	0.685*	0.029	0.555	0.121	0.729*	0.017
M_{max} (knee) ($N \cdot m \cdot kg^{-1}$)	0.632*	0.050	0.318	0.370	0.540	0.107
P_{max} (knee) ($W \cdot kg^{-1}$)	–	–	0.607	0.063	0.637	0.065

*Significant correlation for squats, drop jumps, and imitation jumps.

($r = 0.729$). Similarly, jumping performance was correlated with the performance during squats ($r = 0.685$), whereas no significant correlation could be shown for the drop jumps in minimum Δd^*. Although the maximum knee moments during squats are slightly correlated with ski jumping performance on the hill, no significant correlation could be found for the remaining parameters within the exercises.

DISCUSSION

Coaches often rely on experience when providing feedback to ski jump athletes during performance training, where take-off force and take-off velocity are commonly measured during exercises to provide a key training goal. For the first time, this study reveals a connection between the take-off velocity and the athletic performance, but at the same time does not find any link with take-off force. However, the investigation further found that the vertical take-off velocity was not the only important parameter: knee valgus during squats and imitation jumps seem to be highly correlated with performance on the hill. This effect is likely to be related to the efficiency with which power can be transferred at take off, suggesting that take-off technique can play a more important role for performance than raw power alone. This information can help coaches to know where to focus during training sessions to maximize the benefits of an athlete's jump training.

Separating the push-off propulsion phase from the landing during drop jumps allows the comparison of biomechanical parameters during take off with other sport-specific exercises. Interestingly, using the average weight of Viitasalo's et al. (36) triple jumpers to calculate the normalized vertical forces in the propulsion phase of a drop jump from a box 6 cm higher than the one used in the present study suggests that the maximum values are lower than those achieved by the ski jumpers. In contrast, Virmavirta and Komi (41) measured imitation jumps in the laboratory of 10 Finnish elite jumpers. The relative *SD*s of their maximum forces were clearly higher than those observed in our study. Their measurements on the hill (39) yielded forces that were slightly below those measured in our investigation, but this could be due to the technical set up, including the lack of slope in the laboratory.

As a reflection of performance-determining parameters during take off, the early flight phase is seen as a crucial phase in ski jumping (37). To avoid a leaning position during the early flight phase, it is known that athletes should push with approximately the same force for both legs during take off. Because the subjects in this study represent the top end of ski jumpers, only small differences in the maximum force between the left and right legs were expected, especially for the imitation jumps. The results of this study indicate that if additional load acts on the athlete during the squatting or drop jump training, either from the weight of the barbell or because of the drop from the box, subjects have difficulties balancing the force on both legs. In contrast, the imitation jumps can be well prepared for, and the athlete can choose the moment of take off and there is no additional load. However, even under these conditions, some athletes had problems to distribute the force equally. It seems that despite requiring a bilateral movement in their sport, ski jumpers still develop a dominant leg under some conditions. This supports the findings in (25), where significant strength imbalances between the dominant and nondominant leg could be shown, even for bilateral movements. As a remaining question in Newton et al. (25), whether imbalances result from sport-specific training or other parameters, the present study showed that the interlimb force variability as a similar parameter to the calculated imbalance in Newton et al. (25) was lower for sport-specific exercises than for common training exercises.

Jumpers in this study achieved average vertical take-off velocities during drop jumps that were higher than those presented by Walsh et al. (45). In agreement with Schwameder et al. (32), the imitation jumps resulted in an average vertical take-off velocity of 2.95 ± 0.23 $m \cdot s^{-1}$. According to Virmavirta et al. (38), only approximately 72–85% of this velocity can be applied during jumps on the hill. The resulting velocity of 2.12–2.51 $m \cdot s^{-1}$ on the hill is close to the 2.5 $m \cdot s^{-1}$, which according to Müller (24), is necessary for a good jump distance and is a sign for good explosive force. The only other study that measured imitation jumps showed lower take-off velocities (41). Especially when wearing jumping boots during imitation jumps, only 91.6% of the take-off velocity could be achieved compared with imitation jumps when wearing training shoes (41). Furthermore, these authors summarized that the take-off velocity of jumps on the hill ranged from 2.33 $\pm$ 0.10 $m \cdot s^{-1}$ (43) up to 2.85 $m \cdot s^{-1}$ (15), depending on the size of the hill and the ability level of the ski jumpers (14). Because of the fact that the take-off velocities for hill jumps are similar to imitation jumps, even with different shoes, it seems that the take-off situation during training is indeed similar to the real jumps, although the slope and the lift are generally missing in laboratory environments.

As a result of the additional loads used in this study, which exceeded the BW of the athletes, the knee moments during squatting were higher than the moments reported in (19) for restricted and unrestricted squats. Slightly lower average values were found for the push-off phase during drop jumps in (5), providing normalized values for the maximum moments in the knee. However, it must be noted that the platform from which the drop jumps were performed was 10 cm lower than in our study. Although kinetic parameters seem to be essential in ski jumping performance, joint moments during hill jumps were evaluated based on motion data (29) and show differing results to the present study. Similarly, the knee joint power during imitation jumps in our study differs from the findings of Sasaki et al. (29), as their values, derived from hill jumps, are markedly higher. The calculation of the kinetic parameters from video data in Sasaki et al. (29) might explain these differences and can therefore not be seen as an appropriate comparison with analyses of imitation jumps in a laboratory environment, for which kinetic data are measured accurately using force plates.

Performing exercises correctly is a key factor for safety in strength training (48). In fitness centers in Switzerland, 21.1% of injuries are due to incorrect execution of the exercise and 45.6% to overloading (22). The alignment of the lower limbs can be seen as one factor critical for correct execution. A straight leg axis or a tendency to knee varus for the lowest position during squats and the starting point during imitation jumps (Table 5) seems plausible. When flexing the knee, an internal rotation of the hip joint leads to a valgus alignment (13). If the foot is not fixed, it is normal that a tibial internal rotation occurs during knee flexion, whereas an external rotation occurs during knee extension (9). During the execution of squats, however, since the foot is fixed, there is an external rotation of the femur when flexing the knee, which also causes the tibia to rotate externally (9). Despite these anatomical relationships, this study could show that during squats as well as drop jumps and imitation jumps, the knees tend toward a valgus position within the exercises. The trend for a knee valgus during the drop jumps might be explained by the short time required for landing and thus insufficient time for the musculature to react appropriately (13). The leg axis during imitation jumps that shows knee valgus alignment during take off, seems to result from a lack of focus or an inability to control the limb axis, which would support the findings of Wallace et al. (44), who suggested that a lack of neuromuscular control could be the reason for knee valgus position.

List et al. (18) and Lorenzetti et al. (19) looked at the impact of anteroposterior knee motion during unrestricted and restricted executions of squats. If the knee motion is restricted, there is a reduced load on the lower extremities but more load on the lower back, than for unrestricted performance. Therefore, it makes sense that ski jumpers do not restrict their knee movement during take off as the effect on the muscles of the lower extremities will be greater than with restricted squats and the load on the lower back will be lower.

The scale used to rate the ski jump performance during the best 6 competitions of the summer season (35) not only includes the personal performance but also a correction factor, which is based on the type of competition. This factor allowed the comparison of performance throughout an extended period and effectively reduced the influence of single exploits. As a required comparison of different competition types, this method was seen as appropriate for the analysis of ski jumping performance, as it includes, among others, ranks of jump length that might be markedly different between the compared competitions.

The results of this study indicate that the maintenance of limb alignment during take off during the squat and imitation jump training exercises is correlated with ski jumping performance and should therefore be a dominant parameter for the efficacy of the take-off training in ski jumpers (Table 7). Thus, it seems plausible that knee valgus should be avoided not only at the lowest point of, but throughout the whole training exercises. The magnitude of the knee valgus/varus index for the minimum values indicates that a knee valgus alignment should be noticeable by eye during the training exercises.

Our data support the findings of Müller (24), who suggested a nonlinear behavior of the force-velocity relationship, including little improvement in the velocity for further increases in maximum force, and that only a certain amount of maximum force is needed. A slight correlation between the maximum vertical forces and the corresponding jump lengths on the hill was shown in Virmavirta and Komi (39), whereas we did not observe any significant correlation for a score of the ski jumping performance and therefore this hypothesis has been rejected. However, considering take-off velocity and its effect on jump length, we were able to support the findings of Müller (24) by showing a significant correlation between vertical take-off velocity and the ski jumping performance on the hill. Although the effect of imbalances and the hypothesized relation to ski jumping performance could not be shown in the present study, it seems important for the imitation jumps to exert an equal force with both legs during the take off. Deviations may not have a direct effect in the laboratory or during training, but if the athletes are not balanced during take off, they may have to correct their position during the early flight phase and therefore not reach stable flight as quickly, or even be forced into a less stable or less aerodynamic position during the early phases of flight until correction can occur. Besides the significant correlation of the normalized moments in the knee during squats, no further relation between the power and moments in the knee with the performance could be shown. As these parameters are assumed to be crucial in ski jumping, the magnitude of the differences between elite athletes might be too small for significant correlations. Furthermore, a multivariant interaction of all decisive parameters should be considered.

The parameters that were not significantly correlated with performance in this study, but have been seen as important factors in the literature, should be considered during training exercises as they are a basis for the take off, which further influences the phases of flight during ski jumping. The hypothesis was rejected for the evaluated parameters except the vertical take-off velocity, minimum knee valgus/varus index and the normalized moments in the knee for the mentioned exercises. However, it is assumed that the parameters are related to performance if lower level athletes would be considered. In addition to the underlying generic ability of athletes to reach elite level, it is therefore reasonable that subject-specific characteristics and training focus on e.g., limb alignment are required for practicing and perfecting jumping performance.

Practical Applications

Squats, drop jumps, and imitation jumps conducted by ski jumpers were biomechanically analyzed in this study. The maximum vertical forces, force differences, vertical take-off velocities, as well as the knee valgus/varus index, the maximum knee moments and joint power and their correlation with the performance on the hill were calculated. The results not only indicate that it is essential to have a good force basis, but also that a high vertical take-off velocity seems to be much more important than the maximum vertical force. If the athlete shows a knee valgus during the take off, the force can probably not be converted optimally into a high take-off velocity. This would explain why the knee position during take off in the imitation jumps has the highest correlation with the performance on the hill. One reason for a knee valgus can be instability in the knee joint. For trainers and athletes, this means that proper knee alignment is important during performance training and the magnitude of the values indicates that valgus alignment can be monitored during training without the requirement of motion capture technology. Although no significant correlation of the interlimb force variability for the sport-specific exercise imitation jumps with the performance could be shown, this parameter seems to be crucial for an optimal early flight phase and should therefore not be neglected during performance training. As the top end of ski jumpers was measured and no significant correlation with the most parameters could be found, this indicates that ski jumping performance cannot be estimated by performance in training exercises at the elite level. Even though those parameters are the basis of the take off and provide reference values for coaches, measurements during the time-consuming training on the hill and the athletes' abilities in the flight phases seem to be required for the evaluation of ski jumping performance. Another parameter that should not be forgotten is the force difference between the left and right leg. This may not have a direct impact on the performance for the squats and drop jumps but more on imitation or hill jumps as sport-specific exercises. To enhance performance during competition (and to reduce the injury risk during training), trainers should ensure the correct execution of all exercises during performance training.

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