KINEMATICS AND KINETICS OF SQUATS, DROP JUMPS AND IMITATION JUMPS OF SKI JUMPERS

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The purpose of this study was to find objective factors in athleticism training which influence the performance of ski jumpers on the hill. Therefore, barbell squats, drop jumps and imitation jumps were measured in a laboratory environment for ten ski jumpers. Force and motion capture data was gathered and forces, velocities as well as an index for the knee valgus were calculated. The results show that especially for the imitation jumps there is a good correlation of the take-off velocity with the performance on the hill. What surprised more is that the more the athletes tended to a knee valgus during all measured movements, the worse the performance. Therefore, athleticism training should concentrate more on improving the knee stability.

KEY WORDS: performance, ski jumping, movement analysis

INTRODUCTION: Ski jump training on the hill is extremely time-consuming, hence high quality athleticism training is important for a good preparation. To train the explosive and plyometric strength for an effective take-off, squats, drop jumps and imitation jumps are used in athleticism training (Blackwood & Graham, 2005). Although squats are commonly implemented in training, to our knowledge, there is no study so far connecting the biomechanics of squats with the performance of ski jumping. Kinematic parameters of squats were compared to the landing phase of vertical jumps (Wallace et al., 2008). The knee movement during the squat could not predict the behaviour during the landing of a jump. This was explained by the short time a landing takes compared to the slow movement of a squat.
Some material can be found for drop jumps, executed in performance diagnostic tests with ski jumpers. Rønnestad (2013) also reported a correlation between the relative peak isometric squat strength and percentage change in vertical jump height from pre-season to the end of the competition season. Bobbert (1990) as well as Walsh et al. (2004) come to the conclusion that a sport specific technique should be chosen for drop jumps in athleticism training in order to get the best result. Special attention should also be paid to the high impact forces acting on the body during drop jump landings. Increased knee internal and external rotation can lead to injuries of the passive structures such as the ACL (anterior cruciate ligament) (Blackwood & Graham, 2005; Herrington & Munro, 2010; Hewett et al., 2005).
The determination of kinetic parameters directly on the hill causes difficulties with the measuring equipment which explains the lack of publications. Therefore, imitation jumps are measured in the laboratory (Schwameder, 2008). Virmavirta and Komi (2001) discovered that the subjects produced horizontal forces during the imitation jumps, which does not match the conditions on the hill as the friction between the skis and the in-run track is too low. A minimum take-off force is needed in order to achieve a sufficiently high take-off velocity of at least 2.5 m/s (Müller, 2009). If the take-off velocity can be increased by 0.1 m/s the jump distance is augmented by 1.2 m (Müller, 2009). A high training effort would only lead to little additional improvements.
The objective of this study was to find factors during squats, drop jumps and imitation jumps influencing the performance of ski jumpers on the hill.

METHODS: Data acquisition: *Setup:* Kinetic data was measured using two KISTLER force plates (Type 9286AA, Kistler Instrumente AG, Winterthur) with a sampling frequency of 2000 Hz. An opto-electrical measuring system from Vicon (V612, Oxford metrics, UK) was available with 12 MX40 cameras that had a resolution of 2353 x 1728 Pixels and a sampling frequency of 100 Hz. The subjects were equipped with 77 skin markers based on the IfB marker set of List et al. (2013).

Subjects: One female and nine male subjects with a mean age of 23 ± 4 years took part in the study. The seven ski jumpers and three nordic combined athletes were all members of the national performance center of Swiss Ski in Einsiedeln (CH). They showed a mean height of 179 ± 5 cm and a mean mass of 64.6 ± 4.8 kg. The subjects disposed of at least 5 years experience in performing the exercises evaluated in this study. They were informed about the measurement procedure and gave their written informed consent to participate in the study. The study was approved by the local Ethics Committee.

Measuring process: The measurements included squats, drop jumps and imitation jumps. The squats were conducted using a barbell with the currently used training weight (1st set) and 70% of the estimated 1RM (2nd set). Instructions were similar to a previous study conducted at the Institute (Lorenzetti et al., 2012). The starting position of the drop jumps was an upright position with the tip of the shoes flush with the border on a box with a height of 74 cm. The athletes were instructed that ground contact time should be held as short as possible. Afterwards, the athletes jumped over a hurdle, whose height and distance they were free to choose. Finally, ten imitation jumps were carried out with the help of a trainer. Imitation jumps should mimic real take-offs from the ground (Virmavirta & Komi, 2001). Between all trials the subjects had appropriate breaks of about 3-5 minutes.

Data processing: *Cycle definition:* "The start and end points of an entire squat cycle were defined by the vertical velocity of the barbell (v_{barb} > 0.04 m/s) tracked by two markers attached to the ends of the barbell (List et al., 2013)." For the kinetic evaluation of the drop jumps the force on at least one of the force plates had to exceed 0.02%BW. Finally, the imitation jumps started from where the total take-off velocity became positive until the point when the maximum velocity was reached.

Kinetics: The maximum force which occurred during the execution of the different exercises was calculated. Furthermore, the take-off velocity was determined out of the force data, using equation (1):

$$(1)\quad v(t) = \int \frac{(F_{measured} - F_G)}{m}\, dt$$

where v : total center of mass velocity [m/s]; $F_{measured}$: total measured ground reaction force [N]; F_G : body weight [N]; m : body mass [kg].

Knee valgus / varus: The index for knee valgus/varus Δd* was defined by equation 2:

$$(2)\quad \Delta d^{*} = \frac{k-a}{a}$$

where: *k*: distance between the knee joint centers [mm]; *a*: distance between the ankle joint centers [mm]. Δd* = 0 stands for straight leg axes whereas a Δd* < 0 indicates a knee valgus, Δd* > 0 a knee varus. The distances were taken at the lowest point during the exercise (Δd*_knee) as in the study of Herrington and Munro (2010). Additionally, the lowest value of Δd* was calculated during the execution of the exercises (Δd*_min).

Performance: In order to compare different competitions with different environmental conditions among each other, Swiss Ski has worked out a scoring table (Table 3). The ranking used in this study originates from the summer season 2012.

Table 3: Calculation of scoring points (SwissSki, 2012)

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

Statistics: A correlation analysis for the parameters maximum force, take-off velocity and Δd* with the performance was performed using the IBM software package SPSS Statistics v20.

RESULTS AND DISCUSSION: Kinetics: The average maximum forces during the three exercises are listed in table 1. Some of the athletes conducted the squats very regularly with a standard deviation of less than 100 N, while others varied up to 450 N within a set. Newton et al. (2001) measured drop jumps from a box of 75 cm height with two different execution methods. The mean of 5111 N obtained in this study is between their values of 4400 and 7300 N. The standard deviations for the drop jumps are clearly higher than for the squats and the imitation jumps. Virmavirta and Komi (2001) measured imitation jumps in the laboratory as well. They observed a mean maximum force of 1400 N which is almost within the standard deviation of this study. Their measurements on the hill (Virmavirta & Komi, 1989) yielded forces of 1766 N (1st round) and 1815 N (2nd round), which is a bit higher. The imitation jumps were conducted very regularly with very low standard deviations for the individual subjects.

Table 1: Maximum Forces F_{max} [N] – mean and SD for all subjects

Subject	Squats		Drop Jumps	Imitation Jumps
	1st set	2nd set		
S01	2790 ± 228	2771 ± 148	5603 ± 1004	1415 ± 16
S02	2316 ± 79	2335 ± 165	4033 ± 218	1690 ± 25
S03	2878 ± 291	2642 ± 192	4369 ± 643	1702 ± 41
S04	2864 ± 185	2834 ± 155	5756 ± 834	1777 ± 19
S05	2450 ± 21	2140 ± 27	4784 ± 303	1700 ± 33
S06	2480 ± 379	2515 ± 185	4752 ± 632	1481 ± 15
S07	2002 ± 73	2853 ± 161	5597 ± 310	1662 ± 9
S08	3228 ± 448	2767 ± 191	6261 ± 875	1585 ± 21
S09	2270 ± 155	2188 ± 251	5146 ± 572	1719 ± 25
S10	1707 ± 308	2266 ± 251	4807 ± 622	1300 ± 11
mean ± SD	**2498 ± 454**	**2531 ± 279**	**5111 ± 688**	**1603 ± 155**

The take-off velocity could only be calculated for the drop jumps and the imitation jumps. Walsh et al. (2004) sorted five drop jumps according to the contact time and got velocities from 2.16 m/s (shortest contact) to 2.57 m/s (longest contact). The jumpers in this study achieved a mean take-off velocity of 2.75 ± 0.34 m/s with a mean ground contact time of 244 ± 32 ms. The imitation jumps even resulted in a mean take-off velocity of 3.09 ± 0.25 m/s. According to Virmavirta et al. (2001), only about 72 - 85% of this velocity can be applied during jumps on the hill. The resulting velocity of 2.22 - 2.63 m/s on the hill is close to the 2.5 m/s, which according to Müller (2009) is necessary for a good jump distance and is a sign for a good explosive force. The only other study which measured imitation jumps showed a lower velocity of just 2.78 m/s (Virmavirta & Komi, 2001).

Δd:* When flexing the knee, an internal rotation of the hip joint most certainly leads to a valgus (Hewett et al., 2005). If the foot is fixed though, there is an external rotation of the femur when flexing the knee and an internal rotation for extension (Escamilla, 2001). Therefore, it makes sense that for the lowest position of the squats (Δd*_knee = 0.14 ± 0.09) and the starting position of the imitation jumps (Δd*_knee = 0.02 ± 0.11) the leg axis is straight or shows a tendency to a knee varus. The trend for a knee valgus during the imitation jumps (Δd*_min = -0.22 ± 0.11) and the drop jumps (Δd*_knee = -0.12 ± 0.20, Δd*_min = -0.20 ± 0.15) could be explained with the short time in which the movement takes place. Even during the execution of the squats the athletes show a slight knee valgus (Δd*_min = -0.11 ± 0.08). The athletes are not focussed on or able to control their leg axis, which would support the findings of Wallace et al. (2008).

Statistics: Knee stability seems to be more important than any of the other factors measured in this study (Table 2). In all three exercises, Δd*_min shows the biggest correlation with the performance. The take-off velocity seems to be important as well, but not the maximum force.

Table 2: Correlation (R^2) of performance with maximum force, take-off velocity and Δd*

	Squats	Drop Jumps	Imitation Jumps
F_{max}	0.093	-0.001	0.011
v_{max}	N/A	0.200	0.499
Δd*_knee	0.243	0.327	0.171
Δd*_min	0.446	0.341	0.566

CONCLUSION: Although one would think the maximum force during the take-off is important in ski jumping, this study shows a different result. It is certainly essential to have a good force basis; howevera high take-off velocity is much more important. 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 the take-off has the biggest correlation with the performance on the hill. For trainers and athletes this means that the improvement of knee stability should be brought more into focus during their athleticism training.

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