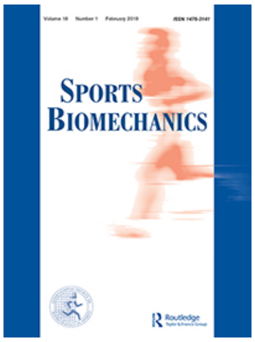

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Conditioning exercises in ski jumping: biomechanical relationship of squat jumps, imitation jumps, and hill jumps

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ABSTRACT

As hill jumps are very time-consuming, ski jumping athletes often perform various imitation jumps during training. The performed jumps should be similar to hill jumps, but a direct comparison of the kinetic and kinematic parameters has not been performed yet. Therefore, this study aimed to correlate 11 common parameters during hill jumps (Oberstdorf Germany), squat jumps (wearing indoor shoes), and various imitation jumps (rolling 4°, rolling flat, static; jumping equipment or indoor shoes) on a custom-built instrumented vehicle with a catch by the coach. During the performed jumps, force and video data of the take-off of 10 athletes were measured. The imitation and squat jumps were then ranked. The main difference between the hill jumps and the imitation and squat jumps is the higher maximal force loading rate during the hill jumps. Imitation jumps performed on a rolling platform, on flat ground were the most similar to hill jumps in terms of the force–time, and leg joint kinematic properties. Thus, non-hill jumps with a technical focus should be performed from a rolling platform with a flat inrun with normal indoor shoes or jumping equipment, and high normal force loading rates should be the main focus of imitation training.

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Ski jumping performance; kinetics and kinematics; jump training

Introduction

The goal of the Olympic discipline of ski jumping is to score as many points as possible, with points being awarded for jumping distance and a clean execution. Over the last few years, changes in technique, material and training methods have led to a considerable increase in achieved ski jumping distance (Muller, 2009). As the take-off has been found to be the most important phase in ski jumping (Schwameder, 2008), it is one of the key priorities of the training. As training on the hill is very time-consuming, coaches resort to different training methods such as imitation jumps and various strength exercises for the lower extremities (Ettema, Hooiveld, Braaten, & Bobbert, 2016; Müller, 2012). Thereby, the kinematics as well as the kinetics of the imitation jumps and strength exercises should

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resemble the hill jumps as much as possible to achieve the highest transfer from training to competition (Schmidt & Lee, 1988).

Training exercises that have already been investigated include imitation jumps from a fixed platform, imitation jumps from a rolling platform with different inclination angles, squats, squat jumps, and drop jumps (Ettema et al., 2016; Fritz, Lindinger, & Schwameder, 2015; Pauli et al., 2016). For an imitation jump, the athlete stands on the platform in a squatting position and then mimics the take-off of a hill jump by jumping into the arms of the coach, who holds the athlete in the air to imitate the flight phase. Obvious differences between these imitation jumps and hill jumps include the take-off velocity, air resistance, friction, and shear forces. Nevertheless, imitation jumps are relevant exercises for ski jumping training as they resemble hill jumps enough to be a valuable training method (Ettema et al., 2016; Müller, 2012).

Pauli et al. (2016) found significant correlations between the vertical take-off velocity ($r = 0.718$) as well as the valgus/varus index ($r = 0.792$) during imitation jumps and the performance of 10 athletes during competition. Virmavirta et al. (2009) found a correlation ($r = 0.628$) between the official inrun velocity during hill jumps and jumping distance of 50 athletes. Zanevskyy and Banakh (2010) found significant correlations between the foot angle ($r = -0.614$), knee angle ($r = -0.596$), hip angle ($r = 0.437$), body angle ($r = -0.556$) and ankle-shoulder joint angle ($r = -0.402$) at the take-off of a hill jump and jumping distance of 33 athletes. A direct comparison of the same parameters obtained during imitation and hill jumps was, however, not performed in these studies. One study compared the same parameters during hill jumps and imitation jumps performed with indoor shoes and with jumping boots (Virmavirta & Komi, 2001a). In this study, only the plantar pressures and muscle activity were measured, without any other kinetic or kinematic parameters. Therefore, a comparison of those parameters from a biomechanical perspective is still lacking and should be performed to obtain knowledge about the relationship between hill jumps and the different jumps performed during training.

An important aspect that has not received enough attention is athletes' clothing when performing imitation jumps. Whereas the athletes are equipped with their helmet, jumpsuit, jumping boots and wedge during hill jumps, they usually wear a normal t-shirt, shorts and indoor shoes during training sessions (Ettema et al., 2016; Pauli et al., 2016). While ski jumping boots do not allow any motion in the ankle, movements in all directions are possible for the ankle with indoor sport shoes. Schwameder, Müller, Raschner, and Brunner (1997) and Virmavirta and Komi (2001b) found significant differences between the parameters measured during static imitation jumps performed with indoor shoes and those with jumping boots, whereupon the former concluded that jumping boots should be worn during imitation training. Given that neither of these studies compared the results with those obtained during hill jumps, their findings should be confirmed by doing so.

To the authors' knowledge, a direct comparison of the different kinematic and kinetic parameters between hill and imitation jumps as well as squat jumps has not yet been performed. However, to provide training recommendations on which jumps to perform in training for the best outcome in competition, the differences and similarities between these jumps should be known. Therefore, the aim of this study was to compare hill jumps with imitation jumps from a rolling platform with two different inclination angles, imitation jumps from a fixed platform, and squat jumps. It was hypothesised that by ranking the imitation jump types, it would be possible to identify those which are most suitable for training.

Methods

Participants

Ten healthy male members of a ski jumping squad (age 21.2 ± 4.9 years, weight 62.1 ± 4.1 kg) participated in this study. Their proficiency level ranged from the Alpen Cup and Fédération Internationale de Ski Cup levels up to Olympic champion. The study was approved by the ethics committee of the Swiss Federal Office of Sport, Magglingen. All participants provided written informed consent to participate in the study.

Experimental approach to the problem

All participants performed hill jumps (Hill_E) as well as squat jumps (SJs) and imitation jumps under different conditions (I_{SL}, I_{SL}_E, I_{FL}, I_{FL}_E, I, I_E; see Table 1).

For the first three Hill_E, the athletes could choose their starting gate individually, while the last two were performed as competition jumps and the jumping distance was measured. To ensure similar conditions and inrun speed, the starting gate was standardised. The distance points were corrected for the wind influence according to regulations of the Fédération Internationale de Ski (Fédération Internationale de Ski, 2012). All six imitation jumps and the SJs were performed as in a normal training session. The order of these jumps was randomised, while Hill_E was either performed beforehand or the day after. The imitation jumps on the slanted (I_{SL}, I_{SL}_E) and flat surface (I_{FL}, I_{FL}_E) were performed from a custom rolling instrumented vehicle; for the static imitation jumps (I, I_E), the vehicle was still. The imitation jumps were performed twice: once with indoor shoes and once with complete personal jumping equipment. For the slanted surface, the athletes were only accelerated by the downhill-slope force whereas for the flat surface, one single experienced coach accelerated all athletes. Force data were measured for all jumps, and the jumps were recorded with video cameras for a kinetic as well as a kinematic analysis later on.

Procedures

The forces at the take-off of Hill_E were measured with integrated force plates over 14 m on the HS 106 hill in Oberstdorf (ETEC Ceram Tec, Lohmar, Germany) at a frequency of 2 kHz. Each force measuring element has a length of 0.7 m and two OBU 250 force sensors (Mess- und Sensortechnik GmbH Althen Germany), which is mounted under the track element via a steel plate. The measuring error is <1%. The inrun speed was determined by

Table 1. Summery of various jump types performed.

Jump		Equipment	Abbreviation	Number of performed jumps
Hill jump		Ski jumping equipment*	Hill_E	5
Imitation jump	Slope (4°)	Indoor shoes	I_{SL}	3
		Ski jumping equipment*	I_{SL}_E	3
	Flat	Indoor shoes	I_{FL}	3
		Ski jumping equipment*	I_{FL}_E	3
	Static	Indoor shoes	I	3
		Ski jumping equipment*	I_E	3
Squat jump		Indoor shoes	SJ	3

Notes: E = equipped, I = imitation jump, SL = slope, FL = flat, SJ = squat jump.
*The complete ski jumping equipment of the athletes consisted of their helmet, jumping suit, jumping boots, and wedge.

standardised photoelectric switches (1 kHz) at the entrance and exit of the radius of the inrun. For the calculation of the kinetic parameters for Hill_E, the centrifugal force, based on the inrun speed, was subtracted from the measured force on the hill. The forces of the imitation jumps and the SJs were measured with an instrumented vehicle at a frequency of 1.2 kHz and with a Quattro Jump force plate (type 9290AD, Kistler, Switzerland) at a frequency of 500 Hz, respectively. All jumps were recorded with two video cameras. One of these (LEGRIA HF R66, Canon, Japan) provided a frontal plane view at a frequency of 50 Hz, which allowed assessment of the athletes' body position maximally 0.02 s after take-off. The other camera (type Bosch, Germany) provided a sagittal plane at a frequency of 50 Hz. Force data were smoothed using a Savitzky–Golay filter with a window of 25 frames and used to calculate the following parameters at the take-off: maximal vertical force (F_{max}), impulse (p_{max}), maximal vertical take-off velocity (v_{max}), maximal power (Pow_{max}), maximal force loading rate (LR_{max}), take-off time (t), and vertical force ratio of the right to the left foot ($FR_{r/l}$). For LR_{max}, a window of 50 ms was used. The extra weight of the equipment was taken into account. The knee valgus/varus index (Δd^*) at take-off was read out of the recorded videos from the frontal plane according to the methods of (Pauli et al., 2016). Three body angles (lower body angle (LBA), upper body angle (UBA) and knee joint angle (KJA)) were determined at the take-off from the sagittal plane videos (definitions see Figure 1). The angles and Δd^* were extracted from the video data at the first frame in which the athletes left the ground (take-off) with Kinovea (version 0.8.15, Joan Charmant & Contrib., https://www.kinovea.org/). The parameters were calculated for all jumps except $FR_{r/l}$, which could not be calculated for the squat jumps.

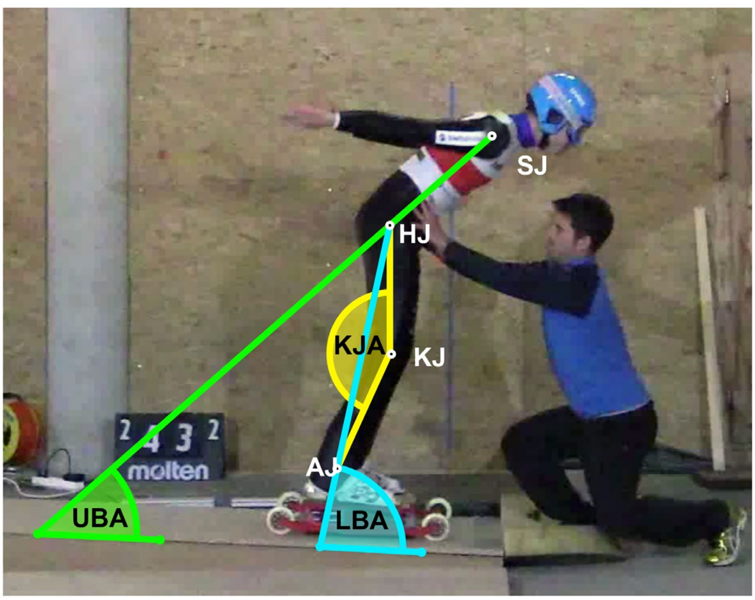

Figure 1. Definition of body and joint angles in the first frame after take-off.
Notes: LBA = lower body angle, UBA = upper body angle, KJA = knee joint angle, SJ = shoulder joint, HJ = hip joint, KJ = knee joint, AJ = ankle joint. LBA corresponds to the angle enclosed by the connecting line from HJ to AJ and the line parallel to the ground. UBA corresponds to the angle enclosed by the connecting line from SJ to HJ and the line parallel to the ground. KJA corresponds to the angle enclosed by the connecting line from HJ to kJ and the connecting line from AJ to KJ.

Statistical analysis and ranking of the jumps

For the statistical analysis, for each participant, the competition Hill_E with the best distance points and the imitation jumps and SJs with the greatest take-off velocity were included in the analysis. The parameters of Hill_E, for each participant individually, were compared to the parameters of the imitation jumps and SJ using correlation and root-mean-square error (RMSE). The correlations intend to provide a measure of individual performance variations between hill jumps and the imitation jumps, whereas the RMSE indicate the sum of individual differences for each parameter.

Subsequently, the six imitation jumps and the SJ were ranked based on the principles of Langville and Meyer (2012) from one (best) to seven (worst) according to their correlation or RMSE, for each parameter separately. Insignificant correlations were all given seven points. The sums of both rankings were calculated for each jump to establish two overall rankings, where fewer points meant a better placement.

All calculations were performed using Excel (Microsoft Excel for Mac 2011, Microsoft Corporation, Redmond, WA, USA), and all statistical analyses were performed using IBM SPSS software (IBM SPSS Statistics for Windows, IBM Corp. Version 22.0. Armonk, NY, USA).

Results

Parameters

The highest values of LR_{max}, $FR_{r/l}$ and Δd^* (valgus) as well as the lowest value of the KJA were all obtained with Hill_E, while the values of the other Hill_E parameters seemed to be within the same range as the imitation jumps (see Table 2). During Hill_E, jumping distance and v_{max} ranged from 61.6 to 80.4 m and 2.41 to 3.30 m/s, respectively. The standard deviations are rather high compared to the differences between Hill_E and the other jumps (see Table 2). The parameters that showed the most consistently high correlations for all jumps were p_{max}, Pow_{max} and F_{max}, whereas t and $FR_{r/l}$, did not show any significant correlations (see Table 3). The highest correlation could be observed between the p_{max} values of Hill_E and of the I_{FL} jumps (see Table 3). Overall, 35 parameters correlated significantly with Hill_E (28 kinetic and 7 kinematic parameters, see Table 3). The RMSEs of the parameters seemed to be within the same ranges for the different jumps, with some exceptions (see Table 4).

Ranking

For both the correlation and the RMSE, a ranking of the jumps was established that shows the training exercises that best resembles Hill_E when all evaluated parameters are taken into account (see Tables 5 and 6, respectively). In both cases, I_{FL}_E, I_{FL} and I_{SL}_E ranked first, second, or third, while I and I_E ranked among the last positions (see Tables 5 and 6). No difference in ranking larger than two places was observed between the two methods. I and I_E were never ranked better than fifth.

Force–time correlation

A typical force–time correlation for all performed jumps is displayed in Figure 2 for one participant. The LR_{max} as well as the overall force increase rate are the highest for Hill_E (see Table 2 and Figure 2).

Table 2. Mean ± standard deviation of all evaluated parameters for Hill_E, imitation jumps and SJs.

	Hill_E	I_{SL}	I_{SL}_E	I_{FL}	I_{FL}_E	I	I_E	SJ
F_{max} [N]	1,431 ± 118	1,404 ± 120	1,406 ± 109	1,420 ± 110	1,420 ± 107	1,436 ± 124	1,456 ± 131	1,374 ± 118
p_{max} [Ns]	188 ± 26	193 ± 22	166 ± 20	188 ± 17	176 ± 18	179 ± 21	168 ± 20	195 ± 19
v_{max} [m/s]	2.6 ± 0.3	3.1 ± 0.2	2.8 ± 0.2	3.0 ± 0.2	2.7 ± 0.2	2.9 ± 0.2	2.6 ± 0.2	3.1 ± 0.2
Pow_{max} [W]	3,197 ± 482	3,782 ± 509	3,720 ± 489	3,853 ± 603	3,712 ± 441	3,561 ± 513	3,428 ± 496	3,798 ± 454
LR_{max} [N/s]	11,020 ± 1,633	6,324 ± 1,753	6,132 ± 1,597	5,667 ± 2,096	5,844 ± 1,376	5,093 ± 1,518	5,354 ± 2,371	7,396 ± 1,712
t [s]	0.32 ± 0.02	0.40 ± 0.03	0.37 ± 0.02	0.39 ± 0.03	0.37 ± 0.03	0.43 ± 0.04	0.41 ± 0.04	0.37 ± 0.03
$FR_{r/l}$	1.85 ± 4.12	−0.05 ± 1.81	−0.71 ± 2.34	0.03 ± 1.82	−0.38 ± 1.52	0.84 ± 2.25	0.12 ± 1.78	n.a.
Δd^*	−0.16 ± 0.05	−0.15 ± 0.06	−0.12 ± 0.06	−0.14 ± 0.08	−0.08 ± 0.11	−0.13 ± 0.05	−0.11 ± 0.07	−0.10 ± 0.07
LBA [°]	90 ± 2	79 ± 3	79 ± 2	84 ± 2	80 ± 3	77 ± 3	75 ± 3	88 ± 2
UBA [°]	31 ± 3	49 ± 8	47 ± 7	50 ± 5	48 ± 7	42 ± 7	41 ± 6	71 ± 7
KJA [°]	142 ± 5	181 ± 7	171 ± 6	183 ± 5	170 ± 5	182 ± 6	168 ± 5	180 ± 7

Notes: F_{max} = maximal vertical force, p_{max} = impulse, v_{max} = maximal vertical take-off velocity, Pow_{max} = maximal power, LR_{max} = maximal force loading rate, t = take-off time, $FR_{r/l}$ = force ratio of the right to the left foot, Δd^* = valgus/varus index, LBA = lower body angle, UBA = upper body angle, KJA = knee joint angle, Hill_E = hill jump with jumping equipment, I_{SL} = imitation jump slope with indoor shoes, I_{SL}_E = imitation jump slope with jumping equipment, I_{FL} = imitation jump flat with indoor shoes, I_{FL}_E = imitation jump flat with jumping equipment, I = imitation jump static with indoor shoes, I_E = imitation jump static with jumping equipment, SJ = squat jump with indoor shoes, n.a. = not applicable.

Table 3. Correlations comparing Hill_E with imitation jumps and SJs.

	I_{SL}	I_{SL}_E	I_{FL}	I_{FL}_E	I	I_E	SJ
F_{max}	0.715*	0.815*	0.795*	0.670*	0.756*	0.778*	0.790*
p_{max}	0.836*	0.844*	0.946*	0.870*	0.815*	0.796*	0.809*
v_{max}	0.694*	0.782*	0.788*	0.739*	0.666*	0.623	0.733*
Pow_{max}	0.864*	0.921*	0.903*	0.837*	0.903*	0.869*	0.945*
LR_{max}	0.310	0.425	0.390	0.692*	0.096	0.017	0.570
t	0.204	0.310	0.370	0.196	−0.033	0.126	0.349
$FR_{r/l}$	−0.027	0.079	0.227	0.226	−0.096	−0.015	n.a.
Δd*	0.693*	0.436	0.730*	0.534	0.275	0.077	0.486
LBA	0.435	0.209	0.304	0.661*	0.303	0.442	0.327
UBA	0.522	0.359	0.529	0.643*	0.458	0.337	0.529
KJA	0.784*	−0.208	0.673*	0.225	0.449	0.43	0.689*

Notes: F_{max} = maximal vertical force, p_{max} = impulse, v_{max} = maximal vertical take-off velocity, Pow_{max} = maximal power, LR_{max} = maximal force loading rate, t = take-off time, $FR_{r/l}$ = force ratio of the right to the left foot, Δd^* = valgus/varus index, LBA = lower body angle, UBA = upper body angle, KJA = knee joint angle, I_{SL} = imitation jump slope with indoor shoes, I_{SL}_E = imitation jump slope with jumping equipment, I_{FL} = imitation jump flat with indoor shoes, I_{FL}_E = imitation jump flat with jumping equipment, I = imitation jump static with indoor shoes, I_E = imitation jump static with jumping equipment, SJ = squat jump with indoor shoes, n.a. = not applicable.
*Correlation is significant at the 0.05 level.

Table 4. RMSE comparing Hill_E with imitation jumps and SJs.

	I_{SL}	I_{SL}_E	I_{FL}	I_{FL}_E	I	I_E	SJ
F_{max} [N]	73.1	55.4	60.8	75.7	70.7	77.7	84.2
p_{max} [Ns]	14.3	17.4	10.7	15.0	17.3	25.1	15.9
v_{max} [m/s]	0.511	0.222	0.416	0.194	0.334	0.208	0.530
Pow_{max} [W]	635	554	703	561	420	332	619
LR_{max} [N/s]	5,062	5,156	5,710	5,301	6,258	6,280	3,911
t [s]	0.092	0.056	0.083	0.060	0.124	0.103	0.058
$FR_{r/l}$	4.71	5.04	4.30	4.45	4.74	4.62	n.a.
Δd*	0.044	0.064	0.056	0.116	0.063	0.090	0.086
LBA [°]	11.5	11.8	6.9	10.6	13.0	15.7	2.9
UBA [°]	19.3	16.4	19.0	17.6	12.3	11.1	40.1
KJA [°]	39.3	30.8	41.5	29.2	41.1	27.4	39.0

Notes: F_{max} = maximal vertical force, p_{max} = impulse, v_{max} = maximal vertical take-off velocity, Pow_{max} = maximal power, LR_{max} = maximal force loading rate, t = take-off time, $FR_{r/l}$ = force ratio of the right to the left foot, Δd^* = valgus/varus index, LBA = lower body angle, UBA = upper body angle, KJA = knee joint angle, I_{SL} = imitation jump slope with indoor shoes, I_{SL}_E = imitation jump slope with jumping equipment, I_{FL} = imitation jump flat with indoor shoes, I_{FL}_E = imitation jump flat with jumping equipment, I = imitation jump static with indoor shoes, I_E = imitation jump static with jumping equipment, SJ = squat jump with indoor shoes.

Discussion and implications

As the training of Hill_E is very time-consuming, imitation jumps and SJs are popular and well-established training methods in a ski jumping training session. To achieve the greatest success, the performed imitation jumps should be similar to Hill_E in terms of kinetics and kinematics (Schmidt & Lee, 1988). Nevertheless, to the authors' knowledge, this study was the first to perform a direct comparison of the kinematic and kinetic parameters between Hill_E and SJs as well as imitation jumps under different conditions.

Parameters

Even though the comparison with other studies is difficult, as the definition of the measured parameters often differs, some comparisons could be made.

Table 5. Rankings of the imitation jumps and SJs based on correlations with Hill_E.

	I_{SL}	I_{SL}_E	I_{FL}	I_{FL}_E	I	I_E	SJ
F_{max}	6	1	2	7	5	4	3
p_{max}	4	3	1	2	5	7	6
v_{max}	5	2	1	3	6	7	4
Pow_{max}	6	2	3	7	3	5	1
LR_{max}	7	7	7	1	7	7	7
t	7	7	7	7	7	7	7
$FR_{r/l}$	7	7	7	7	7	7	7
Δd^*	2	7	1	7	7	7	7
LBA	7	7	7	1	7	7	7
UBA	7	7	7	1	7	7	7
KJA	1	7	3	7	7	7	2
Sum	59	57	46	50	68	72	58
Ranking	5	3	1	2	6	7	4

Notes: F_{max} = maximal vertical force, p_{max} = impulse, v_{max} = maximal vertical take-off velocity, Pow_{max} = maximal power, LR_{max} = maximal force loading rate, t = take-off time, $FR_{r/l}$ = force ratio of the right to the left foot, Δd^* = valgus/varus index, LBA = lower body angle, UBA = upper body angle, KJA = knee joint angle, I_{SL} = imitation jump slope with indoor shoes, I_{SL}_E = imitation jump slope with jumping equipment, I_{FL} = imitation jump flat with indoor shoes, I_{FL}_E = imitation jump flat with jumping equipment, I = imitation jump static with indoor shoes, I_E = imitation jump static with jumping equipment, SJ = squat jump with indoor shoes.

Table 6. Rankings of the imitation jumps and SJs based on RMSE to Hill_E.

	I_{SL}	I_{SL}_E	I_{FL}	I_{FL}_E	I	I_E	SJ
F_{max}	4	1	2	5	3	6	7
p_{max}	2	6	1	3	5	7	4
v_{max}	6	3	5	1	4	2	7
Pow_{max}	6	3	7	4	2	1	5
LR_{max}	2	3	5	4	6	7	1
t	5	1	4	3	7	6	2
$FR_{r/l}$	4	6	1	2	5	3	7
Δd^*	1	4	2	7	3	6	5
LBA	4	5	2	3	6	7	1
UBA	6	3	5	4	2	1	7
KJA	5	3	7	2	6	1	4
Sum	45	38	41	38	49	47	50
Ranking	4	1	3	1	6	5	6

Notes: F_{max} = maximal vertical force, p_{max} = impulse, v_{max} = maximal vertical take-off velocity, Pow_{max} = maximal power, LR_{max} = maximal force loading rate, t = take-off time, $FR_{r/l}$ = force ratio of the right to the left foot, Δd^* = valgus/varus index, LBA = lower body angle, UBA = upper body angle, KJA = knee joint angle, I_{SL} = imitation jump slope with indoor shoes, I_{SL}_E = imitation jump slope with jumping equipment, I_{FL} = imitation jump flat with indoor shoes, I_{FL}_E = imitation jump flat with jumping equipment, I = imitation jump static with indoor shoes, I_E = imitation jump static with jumping equipment, SJ = squat jump with indoor shoes.

The F_{max} values relative to the average bodyweight and the v_{max} values during the imitation jumps are comparable to those obtained by (Pauli et al., 2016). The F_{max} values reported by Virmavirta and Komi (2001b) divided by the average body weight of the participants are also similar, although the v_{max} during their imitation jumps was slightly smaller compared to the values of the present study. The KJA measured at the take-off during Hill_E by Virmavirta and Komi (1993a) seemed to be a few degrees smaller than our KJA for Hill_E and the 141° reported by Virmavirta et al. (2009). Additionally, their angle of the trunk to the horizontal, which corresponds to our UBA minus 11° (which corresponds to the inclination of the take-off table) seemed to be a few degrees less than in our study and the reported angle of 31° by (Virmavirta et al., 2009). These deviations to the position reported by Virmavirta and Komi (1993a) might arise from the fact that only measured two participants, so their values may not be generalised to larger populations of ski jumpers. Additionally, there were

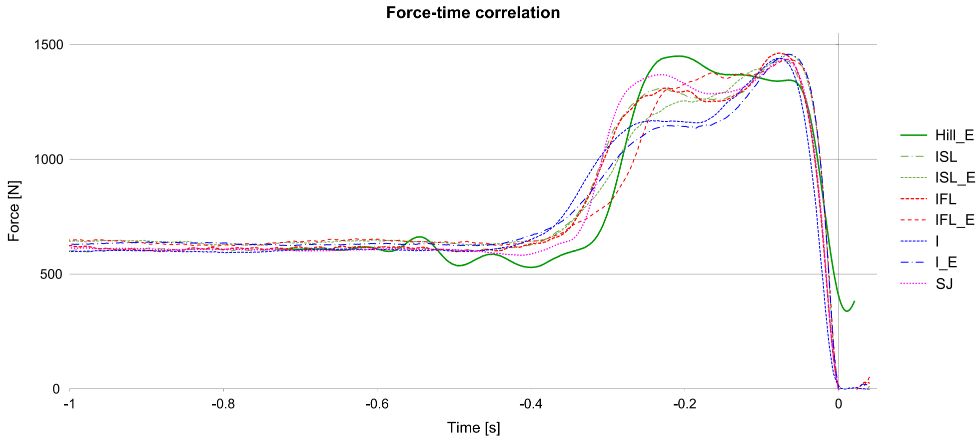

Figure 2. Typical force–time curves of one participant for all performed jumps.

27 years between the data acquisition of Virmavirta and Komi (1993a) and ours, a time during which inrun position has changed markedly (Janura, Cabell, Elfmark, & Vaverka, 2010). As a different body position for the inrun of a ski jump leads to a different body position at take-off Virmavirta, Kivekas, and Komi (2001), the take-off position may also have changed over the years, and thus different angles at the take-off between Virmavirta and Komi (1993a, 1993b) and the present study are confirmed.

The main difference between Hill_E and the imitation jumps as well as the SJs is the higher LR_{max} during Hill_E due to the aerodynamic lift. Thus, high LR_{max} values should be a main focus of the training. However, as the inrun velocity during imitation jumps cannot be increased enough to markedly increase the aerodynamic lift, the reduction in bodyweight needs to be imitated by elastic bands supporting the take-off. According to Pauli et al. (2016), the Δd^* during the imitation jumps positively correlates with the performance of Hill_E. Therefore, a valgus alignment (which corresponds to negative Δd^* values) during Hill_E should be avoided to obtain better performance. As the present work shows, this is rather difficult to achieve, as the knee valgus alignment was the largest in Hill_E. As the $FR_{r/l}$ was also the largest in Hill_E, it may be assumed that here the highest coordinative skills are required compared to the imitation jumps and SJs, and thus a further focus in training should be the inter-limb coordinative skills. This is in accordance with (Pauli et al., 2016), who also concluded that inter-limb coordinative skills should not be disregarded in training. The high standard deviations that were detected in the present work might be explained by the differences in the proficiency levels of the participants that participated (ranging from Alpen Cup and Fédération Internationale de Ski Cup levels up to Olympic champion).

Ski jumping equipment vs. indoor shoes

The ski jumping equipment might cause some restrictions to the athletes compared to normal indoor shoes. The most important restriction is the limited movement in the ankle when wearing ski boots when compared to indoor shoes, which allow full ankle range of motion. It is certainly conceivable that the equipment worn by the athletes during any type of jump influences the take-off. Schwameder et al. (1997) are one of the few who have investigated the differences between static imitation jumps performed with indoor shoes and those with jumping boots. They found significant differences in the measured parameters and concluded that jumping boots should be worn during technique-specific imitation training. However, a comparison of the values with those obtained during Hill_E or any comparison to the performance during Hill_E is missing in their work. Virmavirta and Komi (2001a) compared EMG and plantar pressure data between imitation jumps and hill jumps. Virmavirta and Komi (2001b) compared imitation jumps performed with and without jumping boots, but they did not compare the obtained parameters of the imitation jumps to Hill_E. They found some differences between the parameters obtained with and without jumping boots, but a final recommendation on whether to wear jumping boots during imitation jumps was not made.

Both of the rankings of the present study showed that the imitation jumps performed with a flat inrun were ranked better than those with a slanted inrun or a static start. No clear difference was observed regarding the jumping equipment. This is only partially in accordance with Schwameder et al. (1997), but as mentioned previously, they drew their conclusion based on imitation jumps only, without a comparison to Hill_E, in contrast to this study. This leads to the conclusion that imitation jumps or other jumps performed for training should be performed with a flat inrun and with or without the complete jumping equipment.

Correlation and RMSE – rankings

When comparing the correlations of the kinematic and the kinetic parameters, it is remarkable that the kinetic parameters overall have much more significant correlations (28 significant correlations) than the kinematic parameters (7 significant correlations). Thus, the kinematics of the imitation jumps and SJs do not really resemble those of Hill_E. It would certainly be beneficial for the athletes if there was an imitation jump that resembled Hill_E in both the kinetics and the kinematics so that the transfer of the jumps performed in training to Hill_E is as great as possible. The parameter that had the most significant correlations was p_{max}, followed by Pow_{max}, F_{max} and then v_{max}. This is not surprising, since power is closely connected to F_{max} and v_{max}. Different studies showed correlations of different parameters during the imitation jumps with the performance during Hill_E and, in accordance with the present study, the parameters that correlated the most were the take-off force and the take-off velocity or components thereof (Pauli et al., 2016),(Virmavirta & Komi, 1993a), (Virmavirta & Komi, 1993b),(Fritz et al., 2015).

The results of the rankings show that the two methods (correlation and RMSE) are rather robust in detecting the jumps that resemble Hill_E the most and the least. If all examined parameters are taken into account, I_{FL}_E resembles Hill_E the most and I_{FL} and I_{SL} the second-most. Not surprisingly, both of these imitation jumps are performed from a rolling platform, which decreases the possibility and the need to create shear forces just as in Hill_E, and this might be an explanation of why these jumps resemble Hill_E the most.

Force–time relationship

The force–time curves for the participant shown in Figure 2 resemble those that were measured in other studies (Ettema et al., 2016; Müller, Kreibich, & Seibel, 2015; Virmavirta &

Komi, 1993a, 1993b, 2001b).It should be kept in mind that this curve only resembles the typical values of one participant, and, as Virmavirta and Komi (1993b) and Müller et al. (2015) found, the characteristics of the force–time curves can differ significantly between different participants. However, the authors believe that the main findings based on the force–time relationship of this participant can be applied to most of the ski jumping population.

It can clearly be observed that the maximal force peak in Hill_E is achieved earlier than in all other jumps. While the force decrease rates are quite similar for all jumps, the force increase rates differ noticeably. This is probably due to the varying inrun conditions, especially differences in aerodynamic lift, during all of the performed jumps. It is important that emphasis be placed on this phase of the take-off during training so that the imitation jumps or other imitation jumps imitate Hill_E as much as possible with respect to the force–time relationship.

Conclusion

According to our results, it is possible to identify suitable jump types. Imitation jumps are best performed from a rolling platform with a flat inrun with normal indoor shoes or complete ski jumping equipment. The main focus should be on achieving a high force loading rate and on good coordination between the left and the right leg so that both exert the same force and a parallel alignment of the legs is maintained during take-off.

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