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Biomechanical agreement between different imitation jumps and hill jumps in ski jumping

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Even though the take-off in ski jumping is decisive, athletes only have a very limited number of training trials on the actual ski jump to practice under real ski jump conditions. Hence, various imitation jumps aiming to mimic the hill jump are performed during daily training. These imitation jumps should therefore mimic the kinematic pattern of hill jumps appropriately. This study aimed to identify imitation jumps that resemble hill jumps regarding four performance-related biomechanical criteria: maximal vertical take-off velocity, maximal knee extension velocity, maximal forward-directed angular momentum and anterior shift of the center of mass. Therefore, a three-dimensional analysis of the take-off during six different modalities of imitation jumps as well as hill jumps for validation was carried out in nine professional ski jumpers. Imitation jumps from a rolling platform show better agreement than stationary jumps and three out of the four parameters were best resembled via an imitation jump that included ski jumping boots. Thus, non-hill take-off training should be performed with complex imitation jumps to mimic the actual ski jump. Except for the vertical take-off velocity, we could identify one imitation jump type that is not statistically different to the hill. Consequently, the individual deficiencies of the athletes can be addressed and specifically trained using the appropriate imitation jump. These information about the similarity between imitation jumps and real hill jumps are highly relevant for trainers and athletes in order to effectively design their training programs.

KEYWORDS
3D kinematics, hill jumps and imitation jumps, ski jumping, take-off

1 | INTRODUCTION

In ski jumping, the take-off is thought to have the highest relevance for the athlete's success (ie, jump distance) as it sets the initial conditions for the subsequent flight phase. Due to the high velocities at the end of the inrun, athletes only have a very short period of time to execute the actual take-off, making this phase of the jump highly challenging.[1] This is why the take-off has received a lot of attention in biomechanical studies. It was for example shown that elite ski jumpers demonstrate a significant higher knee extension velocity during the take-off compared to athletes of a lower performance level[2] as well as compared to nordic combined athletes[3] resulting in a faster vertical acceleration of the center of mass (CoM). The vertical impulse accelerating the CoM is required to be adequately timed.[4] Moreover, using a multiple regression model, Schwameder and Müller[5] showed that not only the knee extension velocity but also other parameters such as maximal vertical take-off velocity, relative torque as well as the angle between the body longitudinal axis and the ski after 20 m of the flight phase strongly correlated with the jump distance. Other studies have additionally shown that the vertical CoM take-off velocity in particular contributed to a long ski jump distance.[2,4,6] Aside from rapidly elevating the CoM, the take-off creates a forward-directed angular momentum counterbalancing the backward-directed angular momentum created by the aerodynamic forces during and immediately after the take-off.[1] To vertically jump as high as possible, the position of the CoM needs to be in alignment with the ground reaction force vector. In order to create a large forward-directed angular momentum, however, the ground reaction force has to act posterior to the CoM. Therefore, the athlete must constantly shift the CoM in the anterior-posterior direction to control the angular momentum as the CoM position strongly influences the rotational component of the ground reaction force leading to changes in angular momentum.[1] The importance of the CoM position during take-off was highlighted by Janura et al,[7] who compared this forward-orientated shift of the CoM between elite and poor jumpers during competition on the hill. They showed that the shift was more pronounced in elite jumpers throughout the entire take-off which is in line with the findings of Jost and Janez.[8] The forward shift appears to be of importance not only during the take-off but also in the flight phase as it keeps aerodynamic drag forces small.[9] Measuring the angular momentum, however, is challenging and there are very few studies that have investigated this parameter on the hill,[2,5] although Virmavirta[10] describes this as one of the most relevant issues for future biomechanical investigations. A direct comparison between the angular momentum obtained during imitation and hill jumps was not assessed in these studies. However, as the angular momentum is decisive for ski jumping performance,[11] one must know whether or not it is replicable in imitation jumps. Since jumps on the hill are time-consuming and infrastructural demanding, the athletes can only occasionally train on the actual ski jump.[1] Therefore, athletes use imitation jumps such as squat jumps from on a stationary platform or from rolling devices. Even though these imitation jumps are designed to mimic certain aspects of the take-off on the ski jump, Schwameder[1] pointed out that there are considerable differences between the take-off during imitation jumps and hill jumps. For example, the horizontal take-off speed, air resistance, friction, and shear forces between the athlete and the surface are different.[12] This results in a lower vertical take-off velocity and shorter take-off duration on the hill compared to imitation jumps.[13,14] In addition, plantar pressure and activation patterns of the ankle extensors/flexors and knee extensors/flexors differ between the hill and imitation jumps.[15] So far, there are only very few investigations that have examined the relation of kinematic parameters of imitation jumps and the jump performance (jumping distance) on the hill. For example, Pauli et al[16] collected three-dimensional data of imitation jumps and reported of significant correlations ($r = 0.72$) between the take-off velocity in imitation jumps with the world-cup performance on the ski jump. To identify suitable imitation jumps for training, only the study by Lorenzetti et al[17] directly compared different imitation jumps with actual hill jumps regarding both kinetic and kinematic factors. They found that the imitation on a rolling platform and with a flat inrun showed the closest accordance with the hill in terms of its force-time relation and leg joint kinematics. It needs to be highlighted, however, that in the latter study, only the vertical take-off velocity was assessed while other, previously described performance-limiting factors (knee extension velocity, angular momentum, shift forward), were not reported. Additionally, the study by Lorenzetti et al[17] did not differentiate between imitation jumps where the trainer supports the athlete after the take-off or not. Finally, and most importantly, to our knowledge, no study could be found which compared distinct kinematic parameters during imitation jumps and during an elite championship in the same athletes. A further aspect that has not yet been sufficiently addressed is the influence of the equipment and trainer support. During daily training, athletes often wear no or ordinary indoor shoes,[12,16] although ski jumping boots are much stiffer, thus limiting plantar flexion which results in a lower take-off velocity.[18,19]

So far, no study has ultimately differentiated and directly compared the characteristics of verifiably performance-limiting parameters in ski jumping between imitated and competitive hill jumps. In order to provide recommendations which imitation jumps should be applied in training to mimic distinct characteristics of hill jumps, the similarities and differences to hill jumps need to be identified. Therefore, the purpose of this study was to investigate the biomechanical differences between imitation jumps and real jumps on the hill and furthermore to examine whether there is one imitation form for which the jumping kinematics are the same as on the ski jump. The imitation jumps assessed in this study are regularly used in training routines and were systematically modified: with/without ski jumping boots to limit plantar flexion. With/without trainer support to simulate aerodynamic effects after the take-off, which should affect CoM displacement during the take-off. With/without inrun approach on a rolling device to simulate friction on the ski jump. This limits the possibility to generate shear propulsion forces which affects the way the ground reaction force vector runs with respect to the CoM and therefore directly influences angular momentum.

2 | MATERIALS AND METHODS

2.1 | Subjects

Nine professional ski jumpers were measured during hill jumps and imitation jumps in the laboratory setting (age 20.9 ± 4.1 years, mass 62.3 ± 4.9 kg, height 177 ± 7 cm, proficiency level: national A- and B-squad). At the time of the study, all participants were healthy and free of injuries. Subjects participated in this study after giving informed consent. The study was approved by the ethics committee of the University of Freiburg and in accordance with the declaration of Helsinki.

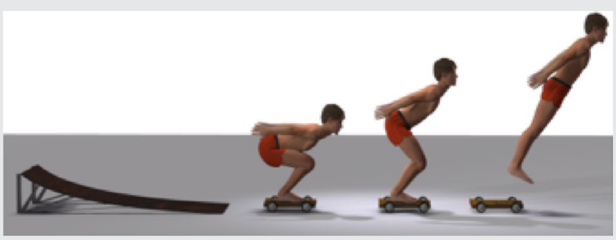
2.2 | Experimental approach to the problem

The hill jumps were recorded during the national championships where each athlete performed two jumps. Nine of these athletes additionally performed six different imitation modalities in a laboratory setting two days prior to the championship. Biomechanical features of these imitation jumps were compared with those recorded from the two hill jumps. All imitation jumps were performed from the typical inrun position either barefooted or with the athlete's individual ski jumping boots. In addition to a stationary execution, jumps were also performed on a custom-made rolling device built into the laboratory with a gradient of 5.2°. For this condition, an additional distinction was made between trials where the trainer caught the athletes and where the athletes were required to land on their feet. Due to the trainer support, the aerodynamic effects after the take-off on the hill can be better simulated. Table 1 shows the different conditions and ranks their complexity.

2.3 | Procedure

The three-dimensional kinematics of the take-off in the laboratory as well as on the actual hill were recorded by a video-based motion capturing system (Simi Reality Motion Systems GmbH, Unterschleißheim, Germany) with six synchronized high-speed cameras (mvBlueCOUGAR-XD, Matrix Vision GmbH, Oppenweiler, Deutschland). Four cameras were equipped with a 16 mm lens and the two sagittal plane cameras with a 6 mm lens. The trials in the laboratory were sampled at 200 Hz while the hill jumps were recorded at 250 Hz. Due to the high inrun velocities on the hill such a high sample rate is required. Because of the light conditions, a higher sample rate in the laboratory was not possible. The measurements were started by a triggered signal coming from a light barrier mounted 1 m prior to the take-off space in the laboratory and 10 m

TABLE 1 Summary of the six imitation jumps sorted by increasing complexity

	Equipment	Abbreviation
Imitation jump (Imi)	None	Imi
	Ski jumping boots	Imi_S
Imitation jump from rolling device (Slope)	None	SL
	Trainer support	SL_T
	Ski jumping boots	SL_S
	Trainer support + ski jumping boots	SL_{T_S}

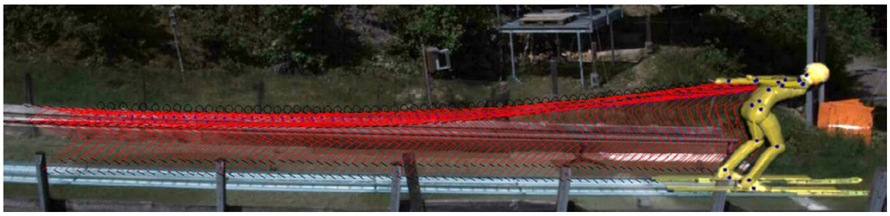


FIGURE 1 The athlete's silhouette is tracked by a three-dimensional model (marked yellow). The blue dots indicate the segments from a simple skeleton overlay

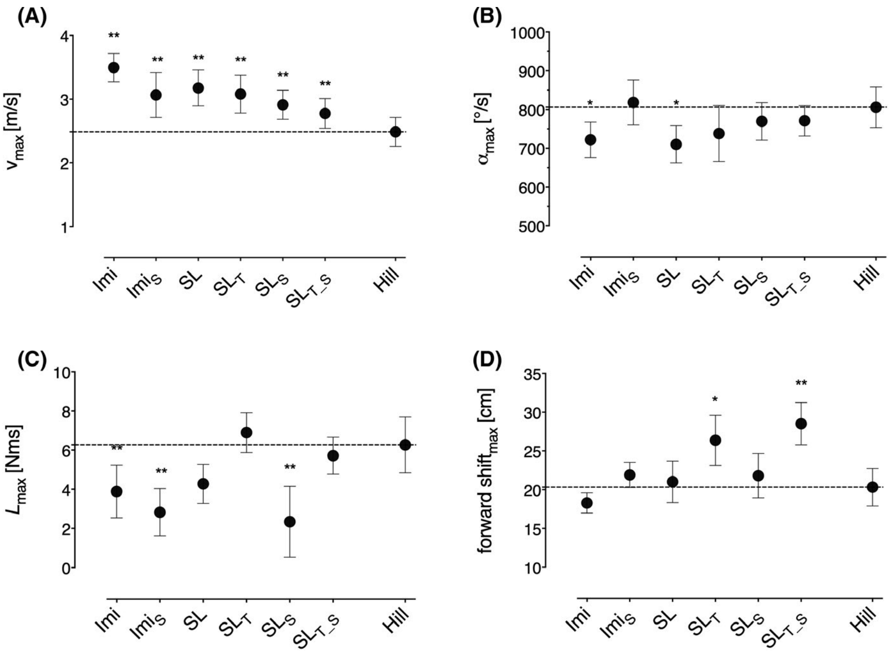


FIGURE 2 Mean ± SD for (A) maximal vertical take-off velocity, (B) maximal knee extension velocity, (C) maximal angular momentum, and (D) maximal forward *shift* over the different imitation conditions. Imi = imitation jump; Imi$_S$ = imitation jump with ski jumping boots; SL = imitation jump from slope on a rolling platform; SL$_T$ = imitation jump from slope on a rolling platform with trainer support; SL$_S$ = imitation jump from slope on a rolling platform with ski jumping boots; SL$_{T_S}$ = imitation jump from slope on a rolling platform with trainer support and ski jumping boots. Statistical differences always refer to the hill. * $P < .05$, ** $P < .01$

before the end of the take-off platform on the ski jump. Using Simi Shape, a three-dimensional rigid model with 16 segments (27 degrees of freedom) was constructed that can be scaled and shaped according to the size of the ski jumper (Figure 1). Based on the video images, the model automatically adapts to the athlete's silhouette and tracks the entire take-off. During the laboratory measurements, the participants wore an orange morphsuit to increase the background contrast and thus simplify the tracking process. By applying inverse kinematics, the orientations of the model's segments could be calculated in Simi Motion. Furthermore, the athlete's CoM was computed from the model. The following parameters were calculated from the motion data: vertical take-off velocity of the CoM (v_{max}) in m/s, knee extension velocity (α_{max}) in °/s, forward-orientated angular momentum (L_{max}) in Nms and forward shift of the CoM relative to the center between the ankles (*forward shift$_{max}$*) in cm. The maximal values of each parameter in the course of the take-off are presented and taken into the analysis. Prior to the imitation measurements, the subjects performed a self-selected warm-up. In every condition, the distance between the feet equalled to the track width on the hill. The different imitation jumps were performed in a randomized order. For each imitation jump, three jumps rated as good by the trainers were evaluated and taken into further analysis.

2.4 | Statistics

For the statistical analysis, the mean of the three jumps per imitation modality from each participant was included in the analysis. All variables were tested for normal distribution using the Kolmogorov-Smirnov Test. Because of missing values, the data was analyzed by fitting a mixed model rather than a repeated measures ANOVA. The mixed-effect model uses the maximum likelihood method and was calculated to compare the imitation jumps with the hill jumps. For significant F tests showing main effects, Bonferroni-corrected Post-hoc tests were calculated. Due to the small sample size, we analyzed the agreement between imitation jumps and hill jumps via a Bland-Altman analysis for each parameter. This method can be used to quantify the agreement between two quantitative measurements by constructing limits of agreement. Here, this refers to the different imitation jumps and the

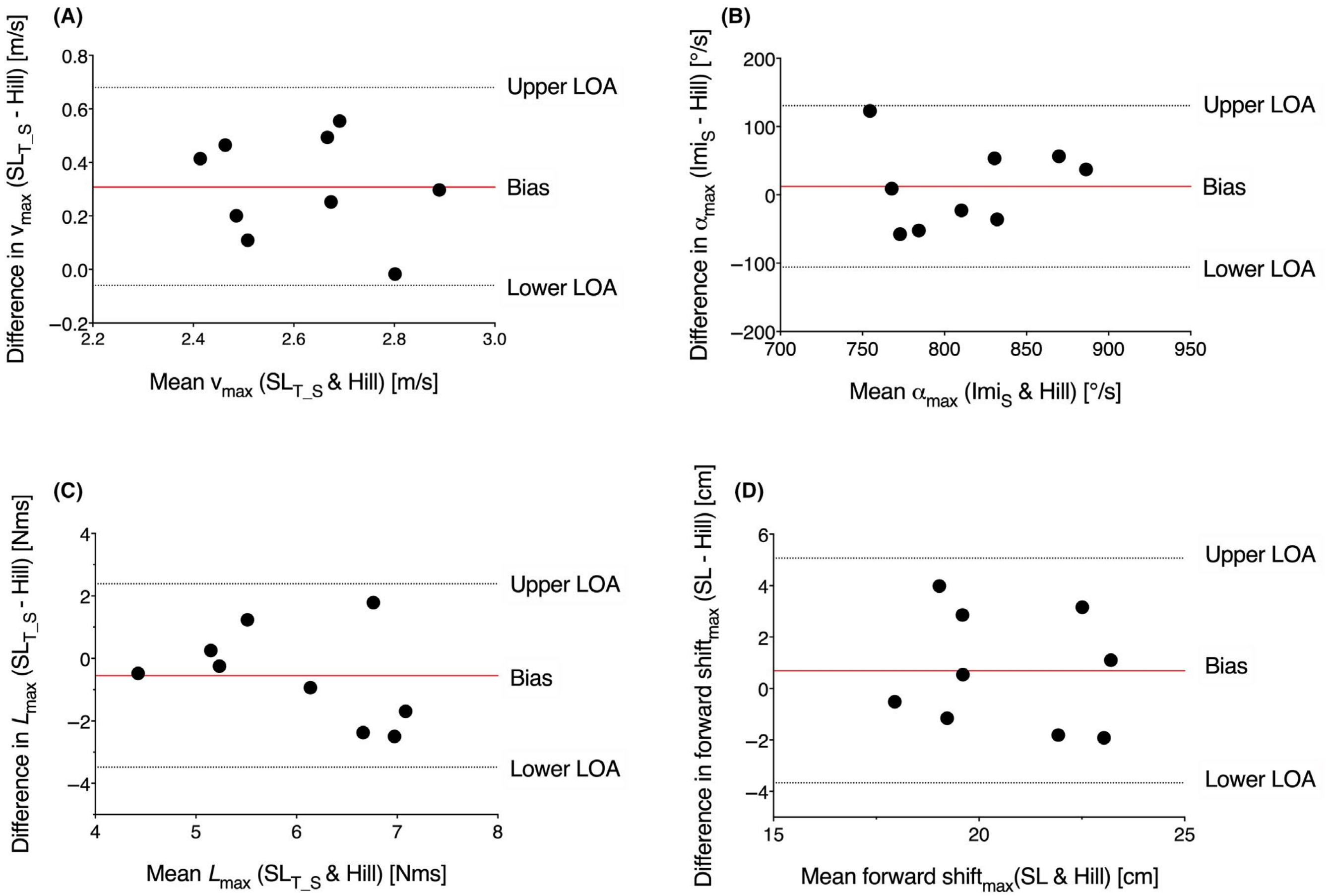


FIGURE 3 Bland-Altman plot for the imitation jump with the best agreement for (A) maximal vertical take-off velocity, (B) maximal knee extension velocity, (C) maximal angular momentum, and (D) maximal forward *shift* over the different imitation conditions

hill jump. These statistical limits are calculated by using the bias, estimated by the mean difference between the measurements, and the standard deviation of the difference between two measurements (SD of the bias). These limits of agreement (LOA; compliance interval) are the bias $\pm$ 1.96 $\times$ SD. Therefore, we can expect that 95% of the differences in the biomechanical parameter between the imitation jump and the hill jump will fall within the upper LOA (Bias + 1.96 $\times$ SD) and the lower LOA (Bias $-$ 1.96 $\times$ SD). Thus, the range within which 95% of the difference between the imitation jump and the hill jump regarding one parameter are included can be simply quantified. To illustrate this analysis the difference of the two paired measurements (imitation jump — hill jump) is plotted against the mean of the two measures.[20] As to our knowledge, no study provided information about the reliability of the methodology used in the presented study, we additionally assessed the intra- and inter-rater reliability (see supplementary data). Statistical analysis was performed using Prism 8 (GraphPad Software). All data are reported as mean $\pm$ SD. The level of significance was set at $P \leq 0.05$.

3 | RESULTS

For a clearer overview, the results are separated for each biomechanical parameter. Each results section follows the same structure and provides information about the effect of a imitation modality on the respective parameter, information about differences between the imitation jumps and hill jumps as well as about the agreement of imitation jumps with the hill regarding every parameter.

The imitation modality showed a statistical main effect on the $v_{\max}$ ($F_{2.71,\ 17.19} = 36.10$, $P < 0.001$). The comparison of the different imitation jumps with the hill jumps showed that for all imitation jumps, $v_{\max}$ was significantly higher than during the actual ski jump (Figure 2A). SL_{T_S} indicates best agreement for v_{max} with the ski jump (Figure 3A). In this condition, athletes show a 0.31 m/s faster v_{max} than on the ski jump. The LOA reveal, that 95% of the differences in v_{max} are between 0.07 m/s slower and 0.68 m/s faster in SL_{T_S} compared to the ski jump (Table 2).

The imitation modality also has a statistical main effect on the $\alpha_{\max}$ ($F_{2.38,\ 15.06} = 5.945$, $P = 0.01$). Further, there is a significant difference in the $\alpha_{\max}$ between the hill and Imi

TABLE 2 Bias and limit of agreement (LOA) between imitation jumps and hill jumps

		Imi	Imi_S	SL	SL_T	SL_S	SL_{T_S}
v_{max} [m/s]	Bias	1.15	0.60	0.78	0.71	0.44	0.31
	SD of bias	0.22	0.27	0.20	0.19	0.15	0.19
	Lower LOA	0.71	0.08	0.39	0.34	0.14	−0.07
	Upper LOA	1.59	1.13	1.18	1.08	0.74	0.68
α_{max} [°/s]	Bias	−108.5	12.3	−97.3	−69.4	−36.2	−34.8
	SD of bias	33.3	60.3	44.5	46.5	78.2	70.5
	Lower LOA	−173.8	−105.9	−184.6	−160.5	−189.5	173.0
	Upper LOA	−43.3	130.6	−10.0	21.7	117.0	103.3
L_{max} [Nms]	Bias	−2.44	−3.44	−2.04	0.89	−3.92	−0.55
	SD of bias	1.17	1.52	1.71	1.61	2.54	1.50
	Lower LOA	−4.72	−6.42	−5.40	−2.26	−8.89	−3.49
	Upper LOA	−0.15	−0.45	1.32	4.05	1.05	2.39
Forward shift$_{max}$ [cm]	Bias	−2.53	1.59	0.69	5.56	1.48	8.20
	SD of bias	2.36	2.59	2.23	3.66	3.38	2.68
	Lower LOA	−7.15	−3.49	−3.67	−1.62	−5.15	2.95
	Upper LOA	2.10	6.67	5.07	12.74	8.10	13.44

($P = 0.046$) as well as hill and SL ($P = 0.013$) with a smaller α_{max} in the imitation jumps (Figure 2B). All other imitation jumps did not show significant differences to the hill jump. Best agreement for $\alpha_{max}$is achieved with Imi_S (Figure 3B). The bias is 12°/s with LOA between −105°/s slower and 131°/s faster in Imi_S (Table 2).

Likewise, for L_{max} there was a statistical main effect of the imitation modality ($F_{2.89, 18.35} = 18.26$, $P < 0.001$). Significant differences in the generated angular momentum were measured between the hill and Imi ($P = 0.017$), hill and Imi_S ($P < 0.001$) as well as hill and SL_S ($P = 0.01$) (Figure 2C). In these simulated jumps, the athletes cannot create a L_{max} as large as on the hill. With SL_{T_S}, athletes generated 0.55 Nms less angular momentum than on the ski jump which represents the best agreement for L_{max} with respect to the hill (Figure 3C). The LOA of L_{max} in this imitation jump range from −3.5 Nms smaller to 2.4 Nms greater compared to the ski jump (Table 2).

Additionally, the imitation modality shows a statistical main effect on the *forward shift*$_{max}$ ($F_{3.24, 21.07} = 26.28$, $P < 0.001$). On the hill, *forward shift*$_{max}$ differs to SL_T ($P = 0.043$) and SL_{T_S} ($P < 0.001$) (Figure 2D). These two imitation jumps are characterized by a greater *forward shift*$_{max}$ compared to the hill. For *forward shift*$_{max}$, the smallest bias is 0.69 cm in the imitation modality SL with LOA between 3.7 cm less to 5.1 cm more *forward shift*$_{max}$, respectively (Figure 3D; Table 2).

4 | DISCUSSION

The aim of this study was to compare different imitation modalities with hill jumps regarding verifiably performance-relevant

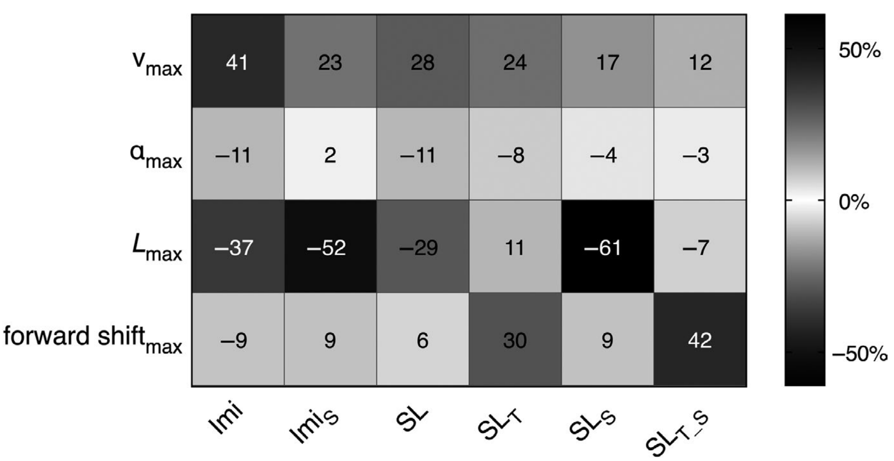


FIGURE 4 Heat map depicting the percentual differences between each imitation modality and the hill jump regarding the mean for v_{max}, α_{max}, $L_{max,}$ and *forward shift*$_{max}$. For example, in Imi the mean v_{max} is 41% greater, mean *tilt forward* 9% smaller, mean α_{max}11% smaller and mean L_{max} *37% smaller than the mean for the respective parameter on the ski jump*

biomechanical parameters using three-dimensional motion analysis with a very high temporal resolution. From the literature we were able to extract four biomechanical parameters that are verifiably performance-relevant during the take-off and therefore should be investigated in this study. These parameters are the maximal vertical take-off velocity of the center of mass, the maximal knee extension velocity, the maximal forward shift of the center of mass and the maximal angular momentum. The results show that except for the vertical take-off velocity, for every other parameter, we were able to identify a certain type of imitation jump that is not statistically different to the hill jump. Furthermore, the present results demonstrate that in three out of four parameters, the best agreement between imitation and hill jumps was observed when the imitation was performed with ski jumping boots instead of barefoot. Figure 4 summarizes the differences of the examined parameters between the hill and imitation jumps. With an increased complexity of the imitation jump (Table 1), the v_{max} continuously decreases, whereby the values in the imitation always remain above those at the hill. This in line with the findings of Vaverka et al[13] showing that, on average, only 72% of the v_{max} in the imitation can be transferred to the ski jump. The present take-off velocities measured in the laboratory also fall into this range. The difference in v_{max} between imitation jumps and hill jumps might be explained by the aerodynamic lift. Virmavirta et al[14] examined the effect of aerodynamic forces in wind tunnel experiments and found a significant decrease in take-off time under wind conditions. However, the vertical net forces did not change with increasing wind speed. This resulted in a loss of vertical impulse due to the shorter force production time with the same take-off force. Therefore, a lower v_{max} can be expected in wind conditions. The decrease in the v_{max} becomes particularly apparent when the jumps are executed with ski jumping boots (Figure 2A). Considering that even in elite ski jumpers, the ankle joint contributes to the generation of power,[12] the decrease in v_{max} can probably be explained by a limited possibility of the plantar flexor muscles to generate power due to the stiffness of the boots.[19] However, wearing ski jumping boots results in a better agreement for v_{max} in all imitation jumps compared to the hill jumps. Hence, SL_{T_S} shows the closest similarities to the hill jumps regarding the v_{max}. This is in line with a previous study by Lorenzetti et al[17] that also found a strong correlation of the v_{max} during the SL_{T_S} and the hill jumps ($r = 0.78$). According to Pauli et al,[16] the comparable take-off velocities between imitation jumps and hill jumps indicate a similar take-off situation during training compared to hill jumps, although drag and lift are fundamentally different. This suggests that when the aim of the imitation jump is to maximize the v_{max}, ski jumping boots should be definitely worn during training. The finding that hill-type ski jumps can be better simulated during imitation jumps with higher complexity becomes also evident in the $\alpha_{\max}$. In complex imitation jumps this parameter is not different to hill jumps (Figure 2B). Moreover, the results also show that the imitation jumps which are executed with ski jumping boots are not different to real ski jumps. This supports the suggestion by Virmavirta and Komi[19] that ski jumping boots should be more frequently integrated into training routines. When analyzing the v_{max} throughout the different imitation jumps this parameter appears high in less complex imitation jumps (Figure 2A). The $\alpha_{\max}$, however, is low in the complex imitation jumps (Figure 2B). This seems unexpected, since the change in vertical impulse and thus the v_{max} is proportional to the vertically applied forces induced primarily by the knee extensors.[1] However, this appears to be only valid for the imitation jumps performed without shoes. Therefore, we assume that the high vertical velocity in these imitation jumps is strongly influenced by the contribution of the plantar flexors which is limited when jumping with boots. This illustrates that increased complexity, that is, the integration of ski jumping boots, lead to parameter specifications that have better agreement with jumps on the hill (Table 2). The parameters *forward shift*$_{max}$ and L_{max} are also closely related. In *forward shift*$_{max}$, the imitation jumps with trainer support differ significantly from the real ski jumps by the much greater *forward shift*$_{max}$. During the inrun or the take-off, such a large *forward shift*$_{max}$ would likely result in a loss of balance.[11] Yet, the athletes have to transfer their CoM anterior,[8] in order to enter the flight phase in an optimal aerodynamic position.[3] This results in reduced drag and increased lift forces.[10] This transfer of the COM is further decisive to control the rotational component of the resulting ground reaction force and therefore determines changes in athlete's angular momentum during the take-off. For L_{max}, however, the imitation jumps with trainer support show no difference and the best agreement to the hill jump. This suggests that athletes can only produce an angular momentum similar to that on the ski jump because they are performing a CoM-shift that is much greater than the actual one at the hill. A further reason for the strong *forward shift*$_{max}$ in imitation jumps can be explained by the temporal course of the knee and hip extension. In imitation jumps, the athlete lifts off when the knees and hip are almost fully extended, whereas on the ski jump, the knees and hip are more inflected at the time of the take-off.[2] The extension continues into the early flight phase leaving the athlete with much less time to move the CoM forward. It appears that there is no single imitation form in which all four examined parameters show no differences to the ski jump and can therefore be simulated and trained as on the ski jump. Nevertheless, the results reveal that, except for the $v_{\max}$, every other parameter can be trained in an imitation modality that is not statistically different to the hill. The individual deficiencies of the athletes can thus be addressed and specifically trained using the appropriate imitation form. However, the results of the Bland-Altman analysis show that the agreement for v_{max}, $\alpha_{\max}$, and L_{max} is unsatisfying due to wide LOA. This is in accordance with the findings of Lorenzetti et al[17] showing that the kinematics of imitation jumps hardly resemble those at the hill, whereas most kinetic parameters do.

It can be concluded that the take-off biomechanics cannot be adequately imitated by a single imitation form. Thus, it is suggested that actual hill jumps should be included in the training as frequently as possible. Nevertheless, the approach used in this study clearly shows that the imitation modality on a rolling platform and with trainer support performed with ski jumping boots has the best agreement for v_{max} and L_{max} when compared to real hill jumps. As these parameters are known to be decisive for a successful jump, training in this most complex modality appears to be important.

Although the current study provides unique information on imitation jumps in ski jumping training, there exist several methodological limitations which need to be considered. First, the study only included nine subjects. The small sample size is caused by the very limited number of top athletes but is similar to studies from other laboratories where five to ten subjects were tested.[12,16,17,21] Secondly, for the silhouette-based tracking it is essential to have a high contrast between the athlete and the background. Due to changing light conditions on the hill the background subtraction can be difficult. Additionally, the athletes ski jumping suits are often dark colored and therefore show little contrast to the background which impairs the segmentation. However, a testing for intra- and inter-rater reliability showed excellent ICCs for all biomechanical parameters (see supplementary data).

5 | PERSPECTIVE

A number of studies have shown the importance of the take-off biomechanics in ski jumping.[2,4-7,10,11] To improve their take-offs, ski jumpers perform different imitation jumps during training. However, studies of Ettema et al[12] and Virmavirta and Komi[15] suggest that there are considerable differences between the take-off during hill jumps and the imitation jumps. The present results indicate that specific modulations of imitation jumps lead to modifications in performance-relevant biomechanical parameters in ski jumping. Increased complexity of the imitation modality results in better agreement with hill jumps for the maximal vertical take-off velocity and the maximal knee extension velocity — especially by the integration of ski jumping boots. The maximal forward directed angular momentum and the maximal forward shift of the CoM primarily depend on the availability of trainer support. This shows that not only the usually performed imitation jumps with indoor shoes, without trainer support and without rolling device should be used in training, but also more complex imitation forms such as with ski jumping boots and trainer support should be an essential component in daily ski jumping training. If a ski jumper is found to have specific deficits on the ski jump, for example, insufficient anterior shift of the CoM, the results of the present study can help coaches to choose the appropriate imitation form. For example, with the help of the imitation form SL it is possible to adequately simulate the take-off on the ski jump with regard to the anterior shift of the CoM.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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