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The Factor Structure of Chosen Kinematic Characteristics of Take-Off in Ski Jumping

by
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With a sample of 29 of the best Slovenian ski jumpers, a research project was carried out with the purpose of determining the structure relation of chosen dynamic and kinematic variables during the take-off of ski jumpers. The experiment was performed in August 2008 on the jumping hill in Hinterzarten, Germany (K=95m). The subjects jumped seven times without breaks between rounds. The analysis was done on variables that determine the technique of take-off in ski jumping (in-run velocity – km/h, vertical take-off velocity – m/s, precision of take-off – cm). The criteria variable was the length of the jump (m). The variability of the long distance of the jumps was significantly strong. The reliability of all used multi-item variables was high and satisfactory in most variables (in-run velocity – 0.98, vertical take-off velocity – 0.98, precision of take-off – 0.85, length of the jump – 0.95). The factor analysis produced an independent latent structure (explanation of variance = 93.3%) of five specific factors (1. in-run velocity connected to distance jumped (39.8 % of VAR.), 2. vertical take-off velocity strongly connected to distance jumped (26.0 % of VAR.), 3. precision of take-off partly connected to distance jumped (14.9 % of VAR.), 4. precision of take-off in the 7th round (6.7 % of VAR.), 5. precision at take-off in the 4th round (5.7 % of VAR.). The present factor structure confirms the hypothetical model of three independent motor tasks to be optimally realized in the take-off of the ski jumper. Criteria variables influencing the length of jumps were mainly associated with the first two factors, which confirm the basic hypothesis that the length of the jump reflects the overall output quality of the first two factors. The accurancy factor of take-off affects the length of the jumps indirectly and latently through these two fundamental factors.

Key words: *ski jumping, factor structure, kinematics of take-off*

Introduction

Ski jumping is a sport requiring extreme technical skills. To establish an appropriate system of technical factors involved in performance of ski jumping is not an easy task, especially if interested in exploring the depth of this system. The construction and supplementation of performance kinematic factors is especially productive when carried out by modeling the optimal ski jumping technique. However, here we can very quickly encounter the dangers and traps of such modeling. The theoretical models are, and will always be, the reflections of the viewpoints of their authors, which need to be scientifically evaluated. Our efforts have resulted in the evaluation of the technical movements in ski jumping, which is based on factor analysis of chosen kinematic characteristics.

The need for biomechanical assessment of ski jumpers' movements are important in order to deal with numerous essential issues related to the practical problems of the ski jumping technique or long-term maintenance of the ski jumpers' capacity for athletic performance. The results of this study provide the basis for dealing with the following problems:

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- to determine the manifest and latent structure of chosen kinematic characteristics of ski jumpers' take-off techniques;
- to provide an appropriate ski jumping profile of specific kinematic factors from the aspect of the ski jumping take-off technique;
- to design more efficient ski jumping take-off techniques with help from the results of this investigation;
- to identify the influence that special kinematic characteristics have on the optimal ski jumping take-off technique.

The aim of the study was to identify kinematic factors that determine the achievement of top-level results in ski jumping. Performance in ski jumping depends on the optimal realization of the ski jumping technique, which is determined by mechanical factors, factors of bio-psycho-somatic status of ski jumpers and by sport-specific ski jumping equipment. The chosen kinematic factors are essential for the technique performance and, together with the unqiue equipment features, they determine the individual style of the ski jumping technique (Schmolzer & Muller, 2004). Elite athletes are able to adapt their movement technique to thin-air conditions in order to maximize jump length and to obtain the greatest possible number of style points. For that goal, the jumpers need to execute an ideal kinematic technique profile, which is the object of this study.

In this study, the take-off technique was evaluated. Take-off is probably the most crucial phase for the entire ski-jumping performance. The purpose of the take-off technique is to optimally solve three independent, specific motor tasks or independent factors (Vaverka, 1987):

1. Increase the vertical velocity of the take-off,
2. Maintain or even increase the horizontal release velocities (minimize the horizontal drag forces),
3. Optimization of the precision of take-off

The present article attempts to evaluate the mentioned factors, which are involved in take-off performance. Each factor is represented by seven manifest variables or items. In the theoretical model, a high reliability between items in each factor is expected. The greatest difficulty is with the factor of take-off precision. The reason is in the complexity of movement coordination, which is consequence of many mechanisms of the nervous system that are responsible for the integration and control of human movement patterns. Ski jumping technique is characterized by high take-off power in a very short period of time (Sasaki, Tsunoda, Uchida, Hoshino & Ono, 1997). Each mistake in the time and space dimensions has a high negative relation to the performance of ski jumpers. In addition, errors in the accuracy of the push-off significantly affect the realization of the two aforemetioned motion tasks. In fact, the negative impact on the length of the jump may be reflected only through the quality of the output of the first two motor tasks. In many studies (Virmavirta & Komi, 1989; Vaverka et al., 1997; Schwameder & Muller, 2001), the correlation coefficients between the kinematic parameters describing the take-off and the length of the jump have occurred mainly in the interval r = 0.3 - 0.6, with the percentage of the variability explained by the criterion being relatively low ($R^2 = 0.10 - 0.35$).

Based on these findings, it can be suggested that the realization of take-off is probably very individual and that subjects perform the take-off using different combinations of take-off factors (Arndt Bruggemann, Virmavirta & Komi, 1995). Using statistical methods require a large number of take-offs by a large number of individuals under the same jumping conditions. Unfortunately, collecting such data is very difficult. The minimum requirement for statistical analysis is about 25 samples. There are few research studies with larger samples. With an increased number of repeated jumps in a relatively short period of time, and in approximately the same conditions, the jumping hill provides insight into the stability and reliability of expression of the individual kinematic variables of ski jumpers. One of the key objectives of this research was to determine the degree of reliability in the survey, including overt kinematic variables.

Methods

With a sample of 29 of the best Slovenian ski jumpers, a research project was carried out with the purpose of determining the structure relation of chosen kinematic variables of the take-off in ski jumpers. The experiment was done on August 20, 2008, on a jumping hill in Hinterzarten (K=95m) from 11.00h until 13.30h. The jumpers jumped seven times without breaks, between rounds from the same starting gate and in the same starting orders. The analysis was done on independent variables that determine the technique of take-off in ski jumping (in-run velocity – km/h, vertical take-off velocity – m/s, preci-

Picture 1

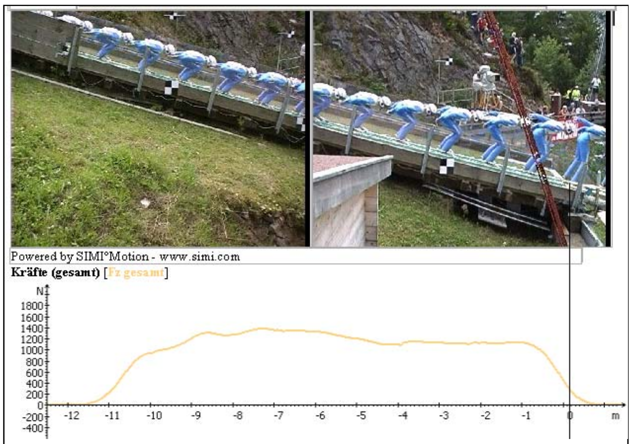
The take-off platform with seven force plates 1.5 m long, on the jumping hill in Hinterzarten, K95m

sion of take-off – cm). The dependent criteria variable was the length of the jump (m).

The in-run speed was measured according to the FIS rules . The devices for measuring in-run velocity were placed as follows: the measured distances were at 8 m, the second photocell beam located 10 m before the edge of the take-off, with a photocell beam of 0.2 m above the inrun area. The vertical take-off force was measured with a special 10.5 m long tensio-platform on the take-off table (see Picture 1). The force measuring system was constructed by SIMI Motion (www.simi.com), consisting of seven force plates (each 1.5 m long and 1 m wide) that was installed to the jumping platform (7.5 m long) and partly to the in–run curve of the 90-m jumping hill.

The force plates were designed to record vertical (Fz) reaction forces. The force signals from the seven force plates were summed so that the output represented the total force impulse during the entire length of the 10.5m platform. The force curves of all jumpers could be seen on the oscilloscope screen immediately after the jumps. The last 10 m of the take-off phase was also filmed with a NAC-video system operated at 200/FPS (See Picture 2).

The force data analysis was produced automatically by a special program with the help of Institute of Sport und Sportscience at Albert-Ludwigs University of Freiburg. The jumpers' body weights, complete with skis and jumping suits, were obtained immediately before the jumpers entered the jumping tower. The vertical velocity was calculated with a unique formula based on the impulse of vertical take-off force ($\mathbf{F}_{\mathrm{REA1}}$) in Δt (Δt - time from beginning of take-off to the end of take-off), mass of the ski jumpers together with the equipment (**m**) and angle of take-off table (cos**Q**): $\Delta \mathbf{v} = \int \mathbf{F}_{\mathrm{REA1}}(t)\, \Delta t \,.\, 1/\mathbf{m} \,.\, \cos\mathbf{Q}$. The precision of take-off was calculated on the basis of the location of maximal vertical velocity on the take-off table, relative to the take-off edge).



Picture 2

Example of the take-off force impulse curve on the jumping hill in Hinterzarten, K95m, August 2008

Statistical analysis was done by SPSS 16.0 for Windows and included means, standard deviations, maximal and minimal results for all variables in the seven jump rounds. The reliability of testing items was computed by Crombach alpha coefficient. Coefficient alpha is probably the most commonly used method of estimating reliability in standardized tests.

The factor analysis (principal components analysis) was used to determine the latent ski jumping kinematic structure. The algorithm (the oblimin rotation method with Kaiser normalization) consisted of the oblimin transformation of latent dimensions obtained by the orthoblique transformation of the characteristic vectors (rotation converged in nine iterations) of the correlation matrix of variables. The correlation analysis was done to determine the dependency between latent vectors.

Results

The results of the basic statistical data and reliability for chosen kinematic characteristics are presented in Table 1.

The graphical form of average values and standard deviations of depends and independent variables are presented in figures 1,2,3 and 4.

The results of factor analysis are presented in Figure 5 and Table 2.

The factor analysis produced independent latent structure (explanation of variance = 93.3%) of five specific factors (see Figure 5):

Table 1

Descriptive statistical characteristics of kinematic variables and coefficient of the reliability

	M	SD	MIN	MAX	CR. ALPHA
Factor of length distance (m)	**91.0**	**6.4**	**67.0**	**108.0**	**0.95**
Length distance 1 (m)	90.0	8.8	71.0	103.0	
Length distance 2 (m)	92.0	9.3	70.0	107.0	
Length distance 3 (m)	92.0	8.7	67.0	103.0	
Length distance 4 (m)	91.0	7.6	77.0	103.0	
Length distance 5 (m)	92.0	8.2	78.0	107.0	
Length distance 6 (m)	94.0	6.9	78.0	108.0	
Length distance 7 (m)	89.0	8.5	71.0	106.0	
Factor of in-run velocity (km/h)	**86.9**	**0.4**	**85.4**	**88.2**	**0.98**
In-run velocity 1 (km/h)	86.9	0.5	86.0	88.0	
In-run velocity 2 (km/h)	86.9	0.6	86.0	88.0	
In-run velocity 3 (km/h)	86.9	0.5	85.0	88.0	
In-run velocity 4 (km/h)	86.9	0.6	86.0	88.0	
In-run velocity 5 (km/h)	86.7	0.6	85.0	88.2	
In-run velocity 6 (km/h)	86.8	0.5	86.0	88.0	
In-run velocity 7 (km/h)	86.8	0.5	86.0	88.0	
Factor of vertical take-off velocity (m/s)	**2.30**	**0.10**	**1.65**	**2.71**	**0.98**
Vertical take-off velocity 1 (m/s)	2.36	0.19	2.03	2.65	
Vertical take-off velocity 2 (m/s)	2.32	0.23	1.67	2.67	
Vertical take-off velocity 3 (m/s)	2.33	0.23	1.70	2.65	
Vertical take-off velocity 4 (m/s)	2.30	0.20	1.75	2.60	
Vertical take-off velocity 5 (m/s)	2.34	0.23	1.65	2.71	
Vertical take-off velocity 6 (m/s)	2.34	0.22	1.67	2.71	
Vertical take-off velocity 7 (m/s)	2.31	0.20	1.72	2.68	
Factor of precision of take-off (cm)	**0.8**	**14.0**	**- 66**	**34**	**0.85**
Take-off precision 1 (cm)	8.3	13.3	- 12	31	
Take-off precision 2 (cm)	5.8	15.0	-24	25	
Take-off precision 3 (cm)	-4.5	20.3	-63	22	
Take-off precision 4 (cm)	7.0	17.7	-53	29	
Take-off precision 5 (cm)	-0.8	17.9	-41	34	
Take-off precision 6 (cm)	-0.8	18.9	-58	22	
Take-off precision 7 (cm)	-4.2	20.9	-66	34	

1. Factor of in-run velocity – explained 39.8 % of total variance,
2. Vertical take-off velocity – explained 26.0 % of total variance,
3. Factor of precision of take-off – explained 14.9 % of total variance,
4. Specific factor of precision of take-off in the 7th round – explained 6.7 % of total variance,
5. Specific factor of precision of take-off in the 4th round – explained 5.7 % of total variance).

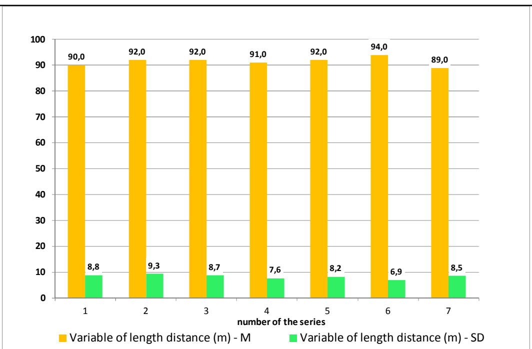


Figure 1

Graphical presentation of average values and standard deviations of the independent variable, length of the jumps

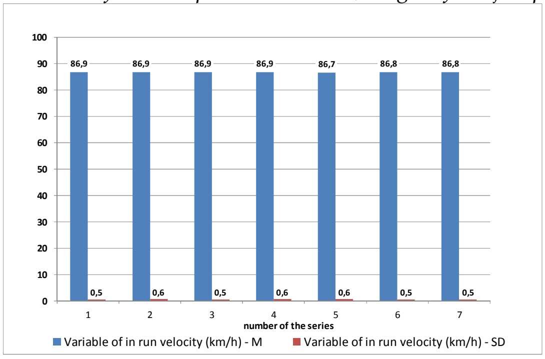


Figure 2

Graphical representation of average values and standard deviations of the independent variable, in-run velocity (km/h)

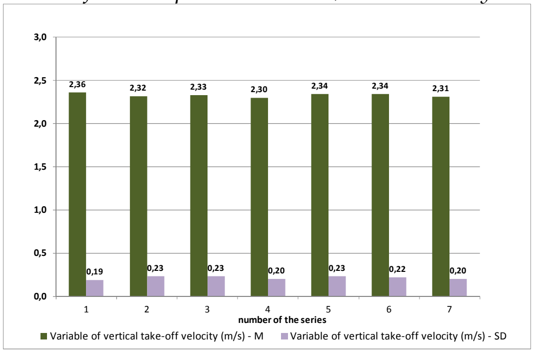


Figure 3

Graphical representation of average values and standard deviations of the independent variable, vertical take-off velocity (m/s)

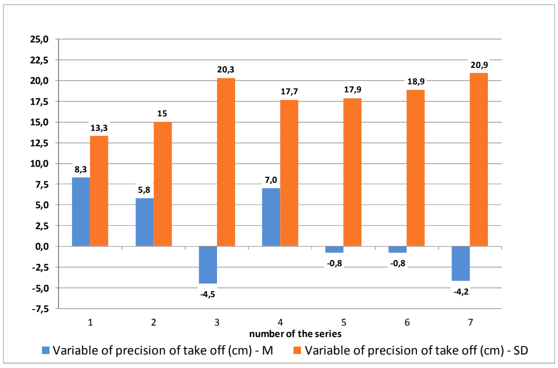


Figure 4

Graphical representation of average values and standard deviations of independent variables Precision of take-off (cm)

Table 2

Orthogonal projections of manifest variables on the oblimin factors

Name of the factors and of the initial manifest variables	Orthogonal projections of manifest variables on the oblimin factors					Cumul.
	F1	F2	F3	F4	F5	
F1: Factor of in-run velocity (r)	1.00	0.08	-0.11	-0.04	0.15	
In-run velocity 2	**0.95**	-0.04	-0.27	0.04	0.19	0.96
In-run velocity 3	**0.95**	-0.12	-0.30	0.04	0.01	0.99
In-run velocity 6	**0.94**	0.05	-0.14	-0.11	0.07	0.90
In-run velocity 5	**0.94**	0.05	-0.34	0.06	-0.08	0.97
In-run velocity 1	**0.93**	-0.17	-0.21	0.02	0.09	0.95
In-run velocity 4	**0.93**	-0.09	-0.21	0.06	0.13	0.92
In-run velocity 7	**0.92**	0.06	-0.30	0.06	0.30	0.94
F2: Vertical velocity of take-off (r)	0.08	1.00	0.07	-0.05	0.01	
Vertical take-off velocity 7	0.13	**0.98**	0.12	0.03	0.09	0.98
Vertical take-off velocity 3	0.10	**0.96**	0.02	-0.18	-0.03	0.96
Vertical take- off velocity 2	**-0.04**	**0.95**	0.12	0.09	-0.06	0.94
Vertical take-off velocity 4	0.05	**0.95**	0.12	-0.05	-0.23	0.97
Vertical take-off velocity 5	-0.00	**0.95**	0.07	-0.00	0.10	0.94
Vertical take-off velocity 6	-0.13	**0.92**	-0.02	-0.12	-0.04	0.91
Vertical take-off velocity 1	0.14	**0.90**	-0.13	-0.05	0.05	0.87
F3: Factor of Precision of take-off (r)	-0.11	0.07	1.00	-0.06	0.19	
Take-off precision 6	-0.27	-0.03	**0.91**	-0.34	0.22	0.96
Take-off precision 5	**-0.41**	-0.12	**0.86**	0.24	0.04	0.95
Take-off precision 3	0.01	-0.15	**0.87**	-0.14	**0.41**	0.89
Take-off precision 1	-0.34	0.33	**0.81**	0.22	-0.09	0.93
Take-off precision 2	**-0.67**	-0.16	**0.50**	-0.33	0.35	0.90
F4: Specific factor of precision of take-off in the 7 round (r)	-0.04	-0.05	-0.06	1.00	-0.07	
Take-off precision 7	0.38	0.16	**0.46**	**0.64**	0.29	0.93
F5: Specific factor of precision of take-off in the 4 round (r)	0.15	-0.01	0.19	-0.07	1.00	
Take-off precision 4	-0.18	-0.03	0.22	-0.08	**0.92**	0.96
Dependent factor of the ski jumping length distance						
Length distance 3	**0.88**	0.17	0.25	-0.30	0.22	0.97
Length distance 6	**0.75**	**0.40**	-0.12	-0.0	0.03	0.75
Length distance 4	**0.74**	**0.49**	0.29	-0.15	**0.47**	0.94
Length distance 2	**0.71**	0.31	0.31	**-0.45**	0.30	0.87
Length distance 7	**0.70**	0.04	-0.03	0.27	**0.67**	0.96
Length distance 5	**0.60**	**0.61**	0.19	-0.22	**0.47**	0.86
Length distance 1	**0.59**	0.14	0.13	**-0.77**	0.31	0.95
Eigen values	11.1	7.2	4.1	1.9	1.5	25.8
Variance %	39.8	26.0	14.9	6.7	5.7	93.3

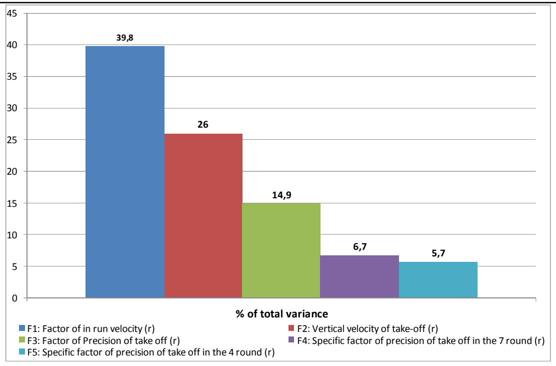


Figure 5

Graphical presentation of average values and standard deviations of the independent variable, length of the jumps

The first factor, **in-run velocity,** was the basic kinematic factor (see Table 2) defined by the highest projections of all manifest variables (the orthogonal factor projections was greater than 0.90). This factor showed the greatest correlation to the factor length of the jump, especially on the third jump (0.88). The second factor, **vertical velocity of take-off,** included the highest factor projections from the set of manifest variables of vertical velocity of take-off. This factor was also connected to the length of the ski jump, especially in the fifth round. The third factor was determined by the highest projections of the variables of take-off precision, and could therefore, be interpreted as that of **take-off precision.** The fourth factor, **specific factor of take-off precision in the 7th**

round, was defined by the initial variable take-off precision in the 7th round. This is similar to the structure of the last factor: **specific factor of precision of take-off in the 4th round.**

Discussion

The variability of the jumping distance was significantly strong (Table 1) particularly, the second series of jumps (SD = 9.3 m). The statistical significance of these variables confirmed the high degree of heterogeneity of the sample ski jumpers according to their potential quality. The average values (Figure 1) of the jumping distances in the individual series are varied near the overall average value of all the jumps (M = 91.0 m). In-run velocity was generally 86.9 km/h (Figure 2) and was similar to the in-run velocity, on the same hill, achieved by the best jumpers in the summer competitions of the 2009 Grand Prix.

Average vertical take-off velocity of all jumps was 2.30 m/s. Even within individual series, this value is not significantly different (Figure 3). In general, the average values of these kinematic variables are significantly lower (Medved, 2007) than that achieved by the best jumpers in the world on the same hill (their values ranged from 2.7 m/s to 3.2 m/s). From this perspective, the selected sample of the best Slovenian jumpers slightly deviates from the pattern (sample) of the best jumpers in the world. The detrimental precision variables in vertical take-off were bipolarly manifested (Figure 4) as either premature or late push-off. Early take-off is more common, because it leads to a higher degree of safe jumps.

The reliability of all used multi-item factors was high and satisfactory (Table 1) in most variables (in-run velocity – 0.98, vertical take-off velocity – 0.98, precision of take-off – 0.85, length of the jump – 0.95). The reliability of the same intentional object of measurement was on the border at variables of precision of take-off and very high at others factors. The reliability of variables for vertical velocity on the jumping hill was even slightly higher, as established in laboratory conditions (Jost & Strojnik, 1992). The minimum level of assurance has been expressed in the accuracy of the precision variables of take-off. Ski jumping is performed at high speeds (often more than 90 km/h); the most important phase of take-off occurs in only 0.2 seconds. These factors cause great stress on jumpers, who must train their nervous systems accordingly. Take-off precision is associated with a variety of complex neural mechanisms and processes, which are strongly influenced by largely unstable psychological factors (sometimes in the presence of an increased state of fear).

The results of the factor analysis made on the sample of 29 Slovene ski jumpers, aged 15 years and older, showed that the manifest structure of 28 kinematic variables was reduced to five independent kinematic factors (Figure 5). These findings confirm the theoretical statements of Vaverka (1987) and findings of Jost (1993). Moreover, the study by Vaverka (1987) used three similar factors as in our study: vertical velocity, in-run velocity and forward-backward position of the body.

The first factor was strongly dominated by the in-run velocity variable with high-saturation factor (from 0.88 to 0.95). These five independent variables were also most strongly associated with the criteria of jumping distance (Table 2). In particular, a strong correlation was expressed in the third series of jumps. Skijumping is a sport that makes extreme demands on the athletes. Many studies have conducted correlations between take-off and ski jumping performance. However, the in-run is also considered to be an important performance variable (Ettema, Braten, & Bobbert, 2005), because the parameters of the in-run determine the initial conditions for take-off.

The structure of the second factor defines the potential performance from the aspect of the vertical take-off velocity. The interaction of variables with the length of the jumps was relatively low. Perhaps it was the root cause in the best-defined pattern of Slovenian jumpers, who are far from the best jumpers in the world in terms of vertical take-off velocity. For high-performance jumping, only a degree of the maximal vertical take-off velocity is necessary. Its importance will increase only when the technique of take-off is perfected-from an aerodynamic point of view. Top ski jumpers must have sufficient amplitude of vertical force at take-off, which is produced by joint movement (Sasaki, Tsunoda, Uchida, Hoshino & Ono, 1997). Most of the power from the initial action until the take-off is produced by two joints: the hip and the knee (Virmavirta & Komi, 1993a). Knee joint power is important for achieving the optimal level of angular momentum in the forward direction (Virmavirta & Komi, 1994). Ski jumpers with the highest vertical take-off velocities have greater potential to reach a higher flight curve after the take-off phase (Virmavirta & Komi, 1993b). It is evident that this factor is responsible for acquiring a successful ski jumping technique (Komi & Virmavirta, 1997).

In the third variable (the more general factor of take-off precision), which explained 14.9 % of TEV, the projections of four jumping rounds were prevalent. This forward-backward body position factor has a hypotetically strong impact on the execution of ski jumping technique. Ski jumpers with a higher quality of this factor show higher potential capacities for successfully executing the jump and flight phases. This finding is of great importance in selecting talented jumpers and evaluating their training regimen. The specific coordination of movement covers the precision of take-off action of those latent motor mechanisms which control and regulate information processes. Of course, the manifestation of these coordinated abilities depends also on the mechanisms for regulating synergistic and antagonistic muscle groups (Lurija, 1976).

The most elite ski jumpers must be excellent in all independent factors, especially in first three general factors. Only in such cases could the realization of ski jumping technique be successful in the take-off phase, which is crucial for the best realization of the ensuing flight phase. Early flight is considered a crucial phase for length of the jump, since it also reflects the dynamics of take-off (Virmavirta, Isolehto, Komi, Brüggemann, Müller & Schwameder, 2005). The study (Virmavirta & Komi, 1994) of the world's most successful ski jumper, Matti Nykanen, showed that the superiority of his take-off was not due to only one or two attributes, but it was a sum of many take-off factors influencing his performance. Ski jumping is complex; each factor's exact contribution is difficult to measure (Virmavirta & Komi, 1989). For example, some jumpers can compensate for a weaker vertical take-off velocity performance with better aerodynamic flight.

The kinematic structure of the five take-off factors was hypothetically unexpected. Solutions to an increased number of the expected hypothetical factors were due to cleavage of the accuracy factor take-off on three factors, while the second and third factors are quite specific and they are expressed only in one series of jumps. The results confirm the presumption of significant variables differentiating the accuracy of take-off, which are strongly influenced by many random factors, whose background remains hidden and unclear. However, the impact of the accuracy of take-off on the jumping distance – because of the strong presence of individual series may be significantly altered from one series to another. The obtained results also raise the concern that the accuracy of take-off is difficult to effectively measure and independently determine its content. This recognition is welcome and will require accuracy in measuring variables from future authors when evaluating ski jumpers in Hinterzarten (K = 95m).

Conclusion

Individual performance measurements during ski jumping are very important for coaches. Based on our results, it is possible to assert that measurement procedures used in this study are both valid and objective. Regarding the Chrombach alpha coefficients, we can presume that all ski jumping variables showed high-levels of reliability and stability. The present factor structure confirms the hypothetical model of three independent motor tasks to be optimally realized in the take-off of the ski jumper. Criteria variables influencing the length of jumps were mainly associated with the first two factors, which confirm the basic hypothesis that the length of the jump reflects the overall output quality of the first two factors. The accuracy factor of take-off affects the length of the jumps indirectly and latently through these two fundamental factors.

The kinematic model for optimal push-off technique could be assumed with only two factors:

1. Aerodynamic aspect of take-off ;
2. Vertical take-off velocity

Both factors influence the accuracy of the push-off, which may be (within the structure of the push-off technique) shown only through these two factors. The hypothetical factor influencing the accuracy of push-off does not exist as a separate independent factor, but only as a causal variable influencing both the kinematic factors. Premature push-off, otherwise, allows the development of optimal vertical velocity, but this is achieved at the wrong place, and therefore, the jumper is in disadvantageous position when crossing the edge of the jumping platform, with regard to the aerodynamics of take-off. Every change in an individual variable has a multi-factor effect on all other variables. These effects are hypothetically independent when observing and comparing inter-variables among ski jumpers, and they are hypothetically inter-dependent and inter-influential when observing intra-variables of the same subjects. This implies that despite the recognized general tendencies, there are observed individual tendencies, and their associated effects, which must be understood and evaluated (Vaverka, Janura, Elfmark & Salinger, 1997).

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