Acta of Bioengineering and Biomechanics
Vol. 12, No. 4, 2010

Original paper

Dependence of ski jump length on the skier's body pose at the beginning of take-off

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A kinematical model of the ski jumper's body pose at the beginning of take-off was proposed. A method of measuring skier's body coordinates based on the results of video recordings and office information technologies was created. Kinematical parameters of the skier's body pose at the beginning of take-off were determined using sport competition results of 33 ski jumpers. Five parameters of the pose which show statistically significant correlation ($p < 0.03$) with the jump length were determined. A part of variation of the model parameters in the total variation of the jump length is almost equal to 53%, and relative correlation is strong and significant ($p < 0.005$). Recommendations regarding optimization of the body pose at the beginning of take-off were formulated.

Key words: *ski jumps, body pose, take-off, kinematical parameters*

1. Introduction

A special role in the system of sportsmen training is played by technical training, i.e. a process directed to mastering sports exercise technique. The necessity of making the criteria of estimating the level of sportsmen's technical skills objective is the most important issue in the theory and practice of modern sport. Without objective estimation it is impossible to intensify the process of forming and improving the motion actions in the sport performance. Effective control of the technical preparation has to be grounded, in particular, on objective kinematical parameters of the exercise, obtained as a result of biomechanical analysis of the motion actions technique [12].

Ski jumping is a complex coordinative and a high-level technical sport, therefore, it is necessary to provide a proper level of the technical preparedness of a flying skier, so that he could achieve a high sporting result. Modernization of the take-off ramps and skier's accessories substantially affects the technique of a ski jump. In particular, this has an influence on a skier's body pose at the end of the in-run position and at the beginning of take-off [3], [5]. Because an objective part of the sport result in ski jumping is the length of jump, its correlation with the body pose parameters should be studied.

The main objective of coaches in the ski jumping is adjustment of athlete's movements. It is impossible to solve this problem without available quality information about the ski jump. Kinematical analysis is regarded to be the basic one for obtaining such information [6], [10]. From the technical point of view, the most difficult phase in ski jumping is the transition from parallel position of the skis to a V-type one. A significant condition for successful completion of this movement is the appropriate take-off technique. The necessary parameters for analysis of the take-off techniques completion in ski jumping are defined as joint angles and angles of attack [4].

In several studies of highly qualified and elite athletes' competitive performance a number of pa-

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Received: July 16th, 2010
Accepted for publication: December 21st, 2010

rameters of sports exercises (kinematics, force and energy) that have statistically significant correlation with jump length have been found. First of all, the jump length shows a high correlation with the in-run velocity, which is officially recorded as the average speed of the last eight metres in the curved segment of the in-run. It is also true for the speed of skier when taking off the edge of the ramp [8].

Statistically significant correlation with the jump length has been recorded for the parameters of skier's body pose at the end of the early phase of flight (17 metres from the take-off table), namely for the angle between the skis, ski plane angle incline to the horizon, the angle between the lower extremities, and trunk angle incline to the horizon. The hypothesis that the key to achieving "correct" pose in flight is "correctness" of take-off completion is being proved [1].

It is believed that, in terms of practical suitability and clarity for coaches, models of take-off in ski jumping are to be built on joint angles that are more visual and simple parameters than energy characteristics [9]. According to research done during competitions (Intersport Tournee Innsbruck, 1992–1998) of the highly qualified athletes' body poses during the in-run at a distance of 18 metres from the take-off table, statistically significant variation of the trunk incline and overall position of jumper's centre of mass (COM) movement direction has been found. There has not been found a dependence between jump length and the parameters of skier's body pose. Instead, individual models of body pose have been identified [4]. With the help of methods of simulation modelling the dynamics of skier's body on the rounded mountain in-run area has been investigated and objective necessity of change in body pose, particularly as a result of changes in joint angle values in the lower extremities, has been shown [2].

Based on the analysis of video filming and results of the first round of competition (Westby Continental Cup, Wisconsin, 12.02.2000) of highly qualified ski jumpers a statistically significant ($p = 0.05$) correlation between the flexion in the knee joint just before the take-off beginning and the jump length has been found [7]. However, no research results regarding the jump length dependence on the jumper's take-off body pose were found to be published.

The aim was to study a correlation between the jump length in ski jumping and the parameters of skier's body pose at the beginning of take-off and to develop an appropriate model of the pose.

2. Methods

Participants. A group of young ski jumpers of Junior B category (aged 16–18 years) were filmed during the national level competition (LOTOS Cup 2010, HS-77 m) in Szczyrk, Poland, on January 30, 2010 (table 1). Two of the ski jumpers were on a 1st sport class level, six – 2nd, eight – 3rd, and sixteen – Junior sport class level. Complete results of 33 athletes achieved during competitions, according to jump length in the first round and the results of body pose parameters processed on the basis of video analysis are given in the Appendix (table A1).

Table 1. Parameters of skiers ($N = 33$), jump length (L), points at the first round (O_1) and total (O_Σ)

Statistics	Age (years)	L_1 (m)	O_1 (points)	O_Σ (points)
M	16.8	63.4	94.1	188.5
SD	0.8	8.2	24.1	47.9

Body pose parameters. Based on the fundamental features of ski jumping technique, we can assume skier's body position as symmetrical relative to its sagittal plane. Therefore, we can model the skier's body with a plane mechanical chain consisting of eight solid links: feet, legs, thighs, trunk, head, arms, forearms, and hands. The links of body form between its joints which could be modelled with kinematical pairs of a fifth class are: p – ankle; s – knee; f – hip; b – shoulder and neck; a – elbow; m – wrist joints (figure 1). Because the take-off motion occurs on the take-off table, it is reasonable to measure the joint angles relative to the table plane.

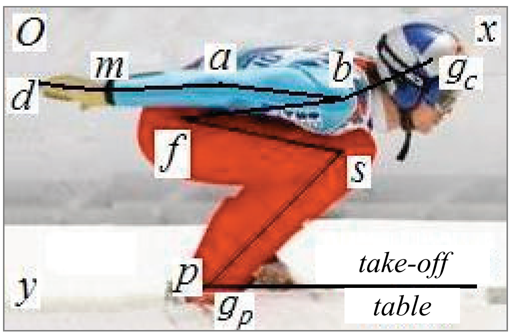

Fig. 1. An image of a ski jumper on the take-off table and a scheme model of his body with the rectangular co-ordinate system *xOy*

We can describe the pose of a skier's body relative to skis considering feet as a provisionally immobile link. Then the amount of degrees of freedom of the body could be defined using the formula for a plane kinematical chain:

$$W = 3n - 2P_5 - P_4 = 7, \quad (1)$$

where $n = 7$ is the number of mobile links (legs, thighs, trunk, head, arms, forearms, and hands); $P_5 = 7$ is the number of kinematical pairs of the fifth class (ankle, knee, hip, shoulder, neck, elbow, and wrist joints); $P_4 = 0$ is the number of kinematical pairs of the fourth class.

Therefore, for determination of skier's body pose, we need seven parameters. Because the amount of kinematical pairs of the fifth class is seven, we can take for these parameters seven joint angles (α, β, γ, θ, ψ, φ, τ) which are shown on the kinematical scheme of the skier's body (figure 2). Except for these seven, we took additionally three parameters which were accepted to characterize the pose of a jumper. They are angles of a slope to direction of skier's motion (on the take-off table) of straight lines which pass through the axes of ankle and shoulder joints (angle ω), through the axes of ankle and hip joints (angle ν), through the axis of ankle joint and COM (point C) of the body (angle ζ), and also through the axes of the hip and shoulder joints (angle κ).

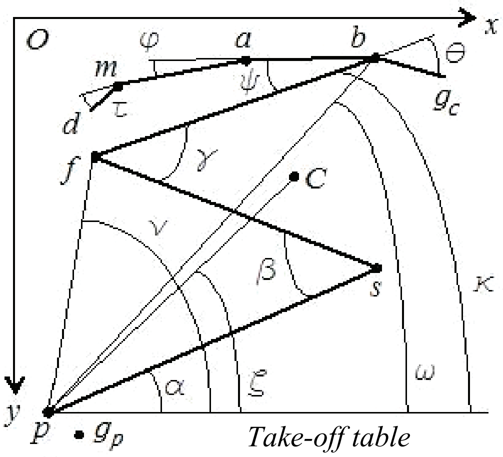

Fig. 2. Kinematic scheme of the skier's body

Processing of kinematics data. To calculate the angles, we used coordinates of joints' axes (points p, s, f, b, a, and m), which are defined above and coordinates of the distal point of middle fingers of hands (point d), COM of the head (point g_c), and COM of the body. Coordinates of the body COM were calculated using formulas:

$$x_C = \sum \mu_i x_i; \quad y_C = \sum \mu_i y_i \,, \quad (2)$$

where μ_i is the relative mass of body links (Appendix, table A2); x_i, y_i are coordinates of COM of the body link; $i = 1, 2, ..., 8$ are the numbers of body links.

We calculated the coordinates of COM of six body links (leg, thigh, trunk, arm, forearm, and hand) using coordinates of joints which were created with corresponding link:

$$x_i = x_{\text{prox}.i} + \lambda_i (x_{\text{dist}.i} - x_{\text{prox}.i}) \,; \qquad y_i = y_{\text{prox}.i} + \lambda_i (y_{\text{dist}.i} - y_{\text{prox}.i}) \,, \quad (3)$$

where $x_{\text{prox}.i}$, $y_{\text{prox}.i}$ are coordinates of the axis of a proximal joint of the corresponding link; $x_{\text{dist}.i}$, $y_{\text{dist}.i}$ are corresponding coordinates of the axis of a distal joint; λ_i is the relative distance of COM from a proximal joint (see table A2).

Coordinates of COM of the head and foot were defined on the helmet (point g_c) and the boot (point g_p) of the skier (see figures 1 and 2). Because capturing was done in competition conditions, no physical marks were used. Joint points were marked manually on a frame. Their locations were calculated according to the model of body mass distribution (see table A2). Values of the angles were calculated.

We calculated seven joint angles and four other angles as parameters of skier's body pose using trigonometric formulas (see figure 2):

ankle angle $$\alpha = \arctan \frac{y_p - y_s}{x_s - x_p} \,, \quad (4)$$

knee angle $$\beta = \alpha + \arctan \frac{y_s - y_f}{x_s - x_f} \,, \quad (5)$$

hip angle $$\gamma = \beta - \alpha + \arctan \frac{y_f - y_b}{x_b - x_f} \,. \quad (6)$$

The angle of attack of the trunk was calculated as an angle of incline of a straight line between the shoulder and hip joints to the direction of skier's motion along the take-off table:

$$\kappa = \gamma + \alpha - \beta \,, \quad (7)$$

angle of neck joint $$\theta = \kappa + \arctan \frac{y_{gc} - y_b}{x_{gc} - x_b} \,, \quad (8)$$

angle of shoulder joint $$\psi = \kappa + \arctan \frac{y_b - y_a}{x_b - x_a} \,, \quad (9)$$

angle of elbow joint $$\varphi = \arctan \frac{y_m - y_a}{x_a - x_m} + \psi - \kappa \,, \quad (10)$$

angle of wrist joint $\tau = \psi - \varphi - \kappa + \arctan\frac{y_d - y_m}{x_m - x_d}$. (11)

The angle of attack of the body was calculated as an angle of incline of a straight line between COM of body and an ankle joint to the direction of skier's motion:

$$\zeta = \arctan\frac{y_p - y_C}{x_C - x_p}. \quad (12)$$

The angle of attack of a straight line between ankle and hip joints to the direction of skier's motion was calculated using the formula:

$$\nu = \arctan\frac{y_p - y_f}{x_f - x_p}. \quad (13)$$

The angle of attack of a straight line between ankle and shoulder joints to the direction of skier's motion was calculated using the formula:

$$\omega = \arctan\frac{y_p - y_b}{x_b - x_p}. \quad (14)$$

Kinematic data collection. CANON S3 IS with frequency of 60 fps was used for the capturing. The camcorder was placed at a distance of 10.3 m opposite the border between the in-run curve and the take-off table where take-off motion starts. An optical axis of the camcorder was directed rectangular to a sagittal plane of the in-run hill 1 m over a track. As a result of video analysis values of the joint angles were calculated. The error of determination of the angles depends on the discriminative ability of an image of skier on the working table of graphics editor program. The image of a skier (in Paint graphics editor incorporated in Windows XP program) occupies a rectangular 1000 × 600 pixel area on the desk top. A distance between the axes of joints is approximately l = 300 pixels. The step of the image regarding the angles of joints was calculated with the formula:

$$2\,\Delta = \arctan\frac{1}{l} = 0.0033 \text{ radian} = 0.19°. \quad (15)$$

Thus, from expression (15), we got the error of calculation of joint angles $\Delta < 0.1$. It is the error of "technical" calculation, but not the error caused by analyser during digitization.

Statistical analysis. The Kolmogorov–Smirnov one sample test in Lilliefors adaptation was used to estimate a normality of distribution of the jump length and skier's body pose parameters [11]. The form of correlation was tested using Γ criteria of linearity and Student t-criteria:

$$\Gamma = \eta^2 - r^2, \quad (16)$$

where η is a coefficient of non-linear correlation, which is equal to a geometric mean of the pair of non-linear ratios; r is the Pearson linear correlation coefficient.

Standard deviation of the criteria was calculated using the formula:

$$m_\Gamma = 2\sqrt{\frac{\Gamma[1 + (1-\eta^2)^2 - (1-r^2)^2]}{N}}, \quad (17)$$

where N = 33 is a number of skiers.

Test value of t-Student coefficient was calculated as the well-known ratio:

$$t_\Gamma = \frac{\Gamma}{m_\Gamma}. \quad (18)$$

Excel and Statistica computer packages were used in statistical processing. The investigation of statistical correlation between jump length and parameters of skier's body pose was carried out using the function "Correlation" from the analysis package of Excel. The probability of the correlation was estimated using t-Student criteria according to the formula:

$$t = \frac{|r|\sqrt{N-2}}{\sqrt{1-r^2}}. \quad (19)$$

The Pearson coefficient of correlation was applied to estimate the dependence of a ski jump length on the skier's body pose parameters. A common influence of the factor of skier's body pose on the variation of the jump length was determined with a multiple correlation coefficient. A total contribution of the skier's pose factor at the beginning of take-off in the jump length variation was determined with the determination coefficient, calculated as the squared multiple correlation coefficient between the jump length and parameters of skier's pose. The method of partial correlation was applied in the process of forming the clusters of skier's body pose parameters. Calculations were done using the function «Statistics → Multiple Linear Regression» from Statistica package.

3. Results

Statistical parameters of the jump length in ski jumping and angles that define the skier's body pose before the beginning of take-off are given in table 2, where: M – arithmetical mean; SD – standard deviation; r – Pearson linear correlation coefficient of the

Table 2. Parameters of skier's body pose just before the beginning of take-off

Stat	$\alpha°$	$\beta°$	$\gamma°$	$\psi°$	$\varphi°$	$\theta°$	$\kappa°$	$\zeta°$	$\omega°$	$\nu°$	$\tau°$
M	52.8	74.1	34.5	9.6	8.3	–3.7	13.5	74.4	60.7	100.6	4.4
SD	4.3	7.6	4.3	4.4	4.7	8.3	5.6	3.5	3.5	3.2	5.8
r	–0.614	–0.596	–0.437	0.126	–0.050	0.103	0.038	–0.556	–0.402	–0.250	–0.063
p	**0.000**	**0.000**	**0.011**	0.486	0.782	0.568	0.834	**0.001**	**0.020**	0.161	0.727
η	0.625	0.608	0.462	0.159	0.117	0.161	0.205	0.563	0.402	0.288	0.162
Γ	0.015	0.015	0.023	0.010	0.011	0.015	0.041	0.008	0.000	0.021	0.022
m_Γ	0.042	0.042	0.051	0.034	0.036	0.042	0.067	0.031	0.001	0.049	0.051
t_Γ	0.350	0.351	0.440	0.284	0.307	0.361	0.605	0.257	0.110	0.420	0.439
p_Γ	0.729	0.728	0.663	0.778	0.761	0.721	0.550	0.799	0.992	0.677	0.664
D*	0.140	0.152	0.089	0.100	0.110	0.112	0.079	0.104	0.117	0.131	0.140

* $D_{0.05} = 0.159$.

jump length and parameters of body pose; p –level of confidence of the significant correlation ($p < 0.05$ is printed in bold numbers in the table); η – non-linear correlation ratio; Γ – criteria of correlation linearity; p_Γ – level of confidence regarding the linear form of correlation; D – Kolmogorov–Smirnov criteria of the normal distribution. Because the calculated values of Kolmogorov–Smirnov criteria (D = 0.079÷0.152; $D_L = 0.123$) do not exceed a critical value of the criteria ($D_{0.05} = 0.159$) a hypothesis of a linear distribution was accepted.

Results of intermediate calculations with formulas (16)÷(18) are given in table 2. The level of confidence for t_Γ has been determined with a number of degrees of freedom ($N - 2 = 31$), at which a null hypothesis of linearity of correlation form between the jump length and parameters of skier's body pose at the beginning of take-off may be rejected. Because the appropriate values of the level of confidence are within 0.110÷0.605, one can accept the hypothesis of linearity of correlation forms of sports results and parameters of body pose.

Since seven joint angles (α, β, γ, θ, ψ, φ, τ) definitely determine the pose of the body model with seven degrees of freedom (1), they were accepted as model parameters. A significant correlation between the jump length and parameters of skier's pose at the beginning of take-off has been found. Its level may be characterized as intermediate between medium and strong: multiple correlation coefficient equals 0.727 ($p < 0.005$) and the determination coefficient equals 0.529. This means that almost 53% of the jump length variation depends on the parameters of skier's body pose, and the remaining 47% are caused by other factors.

For the five parameters of the body pose (α, β, γ, θ, ζ, ω) a significant correlation with the jump length has been shown (p = 0.000÷0.020). It should be noted that the direction of correlation for all the five parameters is negative (see the sign of r values in table 2), which shows an increase of the jump length with a decrease in the body pose parameters.

According to the module value of pair linear correlation coefficient ($|r|$ = 0.402÷0.614), we can recognize a medium-strong correlation of the jump length with five parameters of a skier's body pose, namely, the angles at ankle ($p < 0.001$), knee ($p < 0.001$), and hip ($p < 0.012$) joints, and with the angle of inclination to the direction of skier's movement straight line segment that passes through the COM and the ankle joint axis ($p < 0.001$) and also with angle of inclination to the direction of skier's movement straight line segment that passes through the axis of the ankle and shoulder joints ($p < 0.03$).

To create a model of skier's body pose, we found out its most informative parameters. With this purpose, the correlation table for the five above-mentioned parameters was built (α, β, γ, ζ, ω). The pair correlation coefficients and relevant levels of confidence are shown in table 3. Since between the nine pairs of parameters, out of the total number of ten pairs, statistically significant correlation (p = 0.000÷0.039) was found, while in the 10th pair ($\beta \leftrightarrow \gamma$) the level of confidence may also be considered as acceptable ($p < 0.1$), the number of model parameters was reduced to those parameters which have a clear correlation.

Table 3. Correlation coefficient (left and bottom) and level of confidence (right and top) of skier's body pose parameters

Angles	α	β	γ	ζ	ω
α	–	0.000	0.039	0.000	0.000
β	0.615	–	0.010	0.014	0.086
γ	0.361	0.440	–	0.025	0.003
ζ	0.781	0.425	0.390	–	0.000
ω	0.659	0.303	0.500	0.865	–

To form clusters of parameters, we apply partial correlation between the jump length and the above-mentioned five parameters. The three parameters with a high level of correlation have attracted our attention: α, ζ, ω (r = 0.659; 0.781; 0.865). Obviously, it does not make sense to use more than one of these three parameters in particular model. In the light of this, we have found two pairs of parameters, with the partial correlation of each pair with the jump length being significant ($p < 0.05$). Results of correlation analysis are presented in table. 4. The first pair of parameters are angles in ankle and knee joints, and the second one are the angle in the knee joint and the angle of incline to the direction of skier's movement straight line segment that passes through the general COM and the ankle joint axis.

Table 4. Parameters of skier's body pose models

Models	Angles	r_{part}	t	p	R
1	α	–0.390	2.322	0.027	0.673
	β	–0.351	2.054	0.049	
2	β	–0.478	2.979	0.006	0.683
	ζ	–0.417	2.510	0.018	

4. Discussion

Comparing the two pairs of model parameters, a somewhat higher level of confidence in the second one ($p < 0.02$) could be noted. Both of the partial correlation coefficients in the second pair by the module value ($|r_{part}|$ = 0.478, 0.417) are greater than the module value ($|r_{part}|$ = 0.390, 0.351) of partial correlation coefficients of the first pair (see table 4).

Thus, to build accurate models of body pose, the second pair of parameters should be used. However, from a practical point of view, using the parameter ζ makes the preparatory calculation procedure more complicated, since this is the angle of incline to the direction of skier's movement straight line segment that passes through the COM and the ankle joint axis. Calculation of the COM coordinates needs taking into account all segments of the body. On the other hand, for building the model based on the first pair of parameters, it is enough to determine the coordinates of only the three points, i.e. ankle, knee and hip joint axes. In practical terms, the difference in the accuracy of building models based on the first and second pairs of parameters is not significant. The variation of the jump length caused by the variation of the second pair of parameters (β and ζ) equals 43.1% ($R^2 \times 100\%$). Approximately the same variation (42.3%) was shown by the first pair of parameters (α and β).

The results obtained showed practical usefulness of applying skier's body pose angular parameters to explore techniques of ski jumping, as evidenced by successful application of this approach in the well-known research works [2], [4], [5], [8]. The method of working out the results of video data of skier's body at the beginning of taking off the table can be made to order for application in sporting practice because it allows us to determine the angular parameters of body pose with an acceptable error and is accessible for the wide society of sportsmen and coaches thanks to application of the well-known information technologies of Paint and Excel.

As the direction of correlation between the jump length and the parameters of the skier's body pose (α, β, γ, ζ, ω) at the beginning of take-off is negative, it is possible to speak about increasing the jump length while decreasing the values of the body pose parameters. That is, with the links of jumper's body being lower grouped by, the probability of achieving better sporting result is higher. This can find explanation at least from two points of view. At first, a compact pose from the aerodynamic point of view is related to less air drag during the in-run. The result of the less dissipation is a greater length of jump because potential energy of a sportsman body transfers to a greater kinetic energy that causes a greater speed on the take-off table. Secondly, a compact body pose potentially enables a jumper to take off higher from the table.

On the curved area of the in-run hill, the weight of skier's body consists of the sum of two forces [2]. One of them is a normal (to the hill surface) component of gravitation force, which equals a product of body mass and gravity acceleration and cosine of incline angle of the hill slope. The second one is a centrifugal force which equals a product of body mass and centrifugal acceleration. At the instant of running on the take-off table, a centrifugal acceleration disappears, which in terms of dynamics means instantaneous reduction of the skier's body weight.

Our conclusion about the advantage of the lower body pose at the beginning of taking off summarizes a conclusion [7] concerning a significant correlation (r = 0.05) between the knee-joint un-flexion just before the beginning of pushing away and length of jump. Our conclusion is more common, as it concerns the body pose as a whole because the knee-joint un-flexion is a result of low body pose.

Recommendations regarding optimization of the skier's body pose just before the beginning of taking off are grounded on significant correlation exposed during the research between the length of jump and the parameters of skier's body pose. The criterion of optimization is, clearly, the length of the jump. As parameters of optimization the joint angles are considered, which determine the body pose. In the first approaching it is possible to recommend the jumpers to adopt more compact pose of the body before the beginning of taking off as much as possible. This allows, in particular, to carry out resilient accumulation in lower extremities of the body of potential energy on the rounded area of the hill. The more compact the body pose, the bigger the amount of potential energy accumulating in the muscles and later transferring into the push away movement.

Quadratic parabola regression models were applied to estimate a lower border of the joint angles values:

$$L(\alpha) = a_0 + a_1\alpha + a_2\alpha^2,$$
$$L(\beta) = b_0 + b_1\beta + b_2\beta^2, \quad (20)$$
$$L(\zeta) = c_0 + c_1\zeta + c_2\zeta^2,$$

where a_0 = –23.759; a_1 = 4.3554; a_2 = –0.0509; b_0 = 18.12; b_1 = 1.7975; b_2 = –0.0158; c_0 = –48.884; c_1 = 4.3388; c_3 = –0.0379.

The necessary conditions of extreme values of functions (20) are:

$$\frac{dL(\alpha)}{d\alpha} = 0, \quad \frac{dL(\beta)}{d\beta} = 0, \quad \frac{dL(\zeta)}{d\zeta} = 0.$$

Inserting (20) in the last equations, we got:

$$\alpha_{\text{extr}} = \frac{-a_1}{2a_2} = 42.8°,$$
$$\beta_{\text{extr}} = \frac{-b_1}{2b_2} = 56.9°, \quad (21)$$
$$\zeta_{\text{extr}} = \frac{-c_1}{2c_2} = 57.2°.$$

Because $\frac{d^2L(\alpha)}{d\alpha^2} \equiv 2a_2 < 0$; $\frac{d^2L(\beta)}{d\beta^2} \equiv 2b_2 < 0$; $\frac{d^2L(\zeta)}{d\zeta^2} \equiv 2c_2 < 0$ the functions (20) get maximum when the angles equal those of (21). Therefore, we can consider these values as a bottom border in the models (figure 3). They are smaller than the minimum values of corresponding angles in the group under investigation:

$$\alpha_{\min} = 46.1° \ (–7.2\%); \ \beta_{\min} = 61.7° \ (–7.8\%);$$
$$\zeta_{\min} = 66.0° \ (–13.3\%).$$

Directions of future research should be focused on the consideration of two problems, which would extend and deepen the understanding of importance of the technique of executing taking-off movement in order to achieve greater length of a jump. The first of them is stability of a skier's body pose at the beginning of pushing away. The results presented in this article are grounded on one attempt of competitions of a group of sportsmen. Interesting and useful both in the theoretical and practical sense would be to explore individual

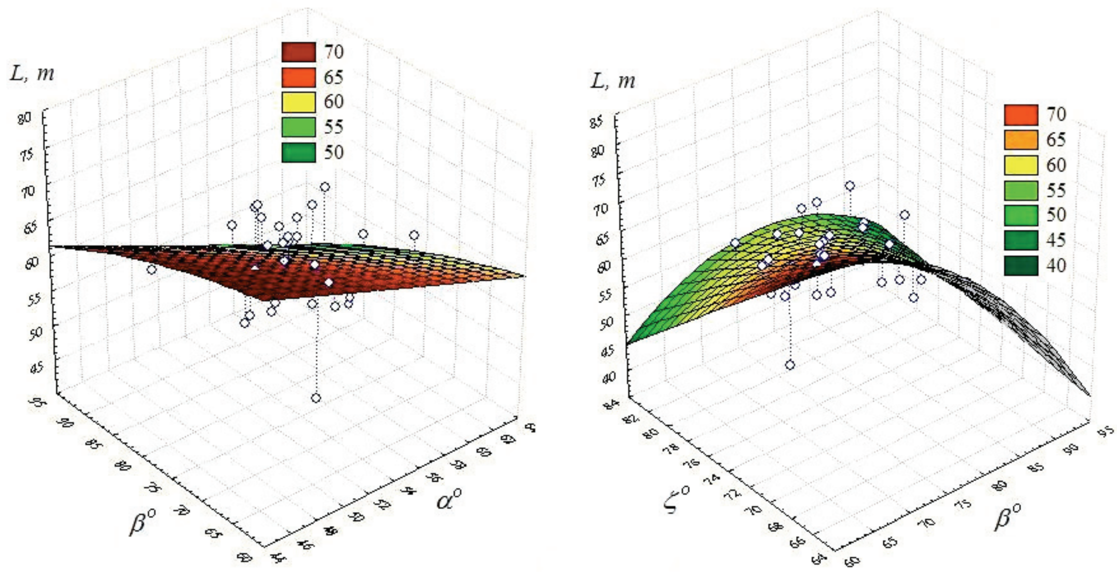

Fig. 3. Quadratic regression surfaces of two skier's body pose models

variation of parameters of the body pose, foremost, in two test jumps of competitions, and also during a series of training jumps and control competitions.

The second problem is a quantitative analysis of the process of pushing away on the take-off table. White the analysis of skier's body pose is a problem of statics (or pseudo-statics, as movements of body links and changes of a pose in this analysis are eliminated), for the analysis of pushing away one needs to formulate and solve the problem of dynamics, namely to explore conformities of changing the body pose parameters in time and to expose their influence, if there is any, on the length of a jump.

5. Concluding remarks

1. The eight-link kinematic model of skier's body showed its usability in analysing the dependence of ski jump length on the skier's body pose at the beginning of taking-off. As a result of multiple correlation analysis, it has been established that a part of variation of the model parameters in the total variation of jump length is almost equal to 53%, and relative correlation is strong and significant ($R = 0.727$; $p < 0.005$).

2. The developed method of working out the results of video capturing of the skier at the beginning of the take-off can be recommended for application in the sporting practice, as it allows the angular parameters of body pose to be determined with an absolute error near 0.1°, and is accessible for the wide society of sportsmen and coaches thanks to the use of the well-known office information technologies Paint and Excel.

3. Significant correlations between the jump length and five parameters of skier's body pose were determined, namely with angles in the ankle ($r = -0.614$; $p < 0.001$), knee ($r = -0.596$; $p < 0.001$), and hip joints ($r = -0.437$; $p < 0.012$), with the angle of slope to direction of motion of skier of segment of straight line which passes through the COM of body and axis of ankle joint ($r = -0.556$; $p < 0.001$), and also with the angle of slope to direction of motion of skier of segment of straight line which passes through the axes of the ankle and shoulder joints ($r = -0.402$; $p < 0.03$).

4. As the direction of correlation for all the five parameters of the body pose with jump length is negative, it is possible to accept a conclusion that as more compact body links are grouped by, the probability of achieving a better sporting result is higher.

5. For construction of the most exact two-parameter model of the skier's body pose at the beginning of the take-off one needs to use a knee-joint angle and angle of slope to direction of motion of skier of segment of straight line which passes through the body COM and the ankle joint ($R^2 = 43.1\%$). From the practical point of view it is simpler to use in solving the problem the model based on the ankle and knee joint angles ($R^2 = 42.3\%$).

Acknowledgements

1. The research was partly supported by the Polish Ministry of Science and Higher Education, Research Grant No 2814/58/P.

2. The authors thank anonymous Referee for valuable remarks.

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Appendix

Table A1. Jump length and body pose angles

No.	L, m	α°	β°	γ°	ψ°	φ°	θ°	κ°	ζ°	ω°	ν°	τ°
1	44.5	61.2	88.9	43.1	9.4	11.1	–13	15.4	79.4	65,5	101.4	1.4
2	46.5	60.2	91.2	34.0	3.8	6.1	–9.6	3.0	77.2	59,9	101.2	2.5
3	48.0	52.2	68.8	35.7	8.1	3.6	–3.8	19.1	74.3	61,3	101.0	1.9
4	51.5	58.5	76.7	42.0	16.4	5.2	6.2	23.8	80.5	67,6	104.3	8.7
5	52.0	57.4	76.7	31.7	13.8	14.5	–20.7	12.4	77.3	61,3	103.8	8.5
6	53.5	53.7	83.3	43.6	8.9	12.5	–9.5	14.0	72.8	59,1	96.9	10.4
7	58.0	49.3	74.2	32.0	5.1	3.9	–8.2	7.1	74.2	59,4	100.7	5.2
8	58.0	62.8	89.4	35.5	4.4	3.3	–9.2	8.8	82.9	67,4	105.7	–0.8
9	59.0	53.1	71.5	32.8	8.8	12.1	0.8	14.4	75.6	62,4	101.2	4.4
10	60.0	50.3	72.0	39.7	7.9	7.0	2.7	18.0	76.6	63,2	104.6	0.3
11	61.0	56.4	87.7	38.1	1.5	6.6	–9.3	6.8	76.5	62,2	99.4	2.5
12	62.5	56.8	81.6	34.1	11.8	7.9	–3.7	9.2	73.9	58,6	97.9	0.9
13	63.0	53.3	65.9	27.5	7.6	8.8	–2.2	14.9	73.9	58,7	102.1	9.4
14	63.5	46.1	82.3	33.4	9.0	12.9	–5.3	–2.8	67.2	54,2	89.5	9.8
15	64.0	52.8	70.2	33.3	13.4	20.9	–2.8	15.9	74.9	60,7	103.2	8.0
16	64.5	57.7	72.5	36.5	13.7	8.2	14.0	21.6	78.1	64,5	105.1	6.1
17	64.5	47.0	68.4	32.7	7.7	6.8	–10.6	11.2	73.5	59,4	101.6	8.7
18	64.5	54.4	76.6	37.9	11.4	13.8	–4.6	15.7	75.9	63,2	99.5	22.7
19	67.5	48.8	71.3	28.2	15.9	15.4	–2.6	11.6	73.1	58,5	101.0	–3.4
20	67.5	47.5	65.5	37.5	17.9	3.1	–0.3	19.5	74.4	63,2	100.5	–9.1
21	67.5	52.1	73.2	40.6	8.8	6.3	7.2	16.0	74.2	60,4	101.2	1.5
22	67.0	58.5	66.4	30.9	3.1	1.1	8.9	23.0	77.5	65,4	105.8	2.2
23	69.0	50.0	77.7	35.0	6.1	9.0	–14.4	13.0	73.5	60,4	97.2	–0.8
24	70.0	51.3	75.7	29.8	7.7	8.5	–3.7	9.7	76.5	62,9	101.2	0.9
25	70.0	49.3	68.1	31.2	5.9	–0.1	–15.4	10.2	71.2	56,2	101.1	7.1
26	70.5	49.6	61.7	28.3	11.8	8.6	–10.6	16.6	69.6	52,8	99.1	–2.8
27	71.5	49.6	64.0	37.1	2.2	16.6	–12.5	13.9	72.7	58,6	99.9	12.0
28	71.5	49.0	69.7	28.3	17.3	5.3	5.9	16.3	72.1	59,5	98.0	2.3
29	72.0	50.2	69.1	34.4	16.0	5.2	8.1	15.5	73.5	59,6	101.8	0.1
30	72.0	50.4	71.2	33.4	11.1	9.5	0.3	12.6	66.0	58,8	101.2	12.4
31	72.0	53.4	72.3	37.8	12.6	9.7	8.8	18.9	75.6	64,5	98.7	3.4
32	72.5	49.3	68.1	30.3	10.9	8.8	–9.7	11.5	70.5	57,6	94.8	5.4
33	74.5	49.7	73.0	32.3	5.6	2.2	–14.5	8.9	70.4	55,0	98.7	2.3

Table A2. Body mass distribution in young sportsmen [12]

i	Body links	Relative mass (μ_i)	COM relative distance (λ_i)
1	Head and neck	0.069	0.494
2	Trunk	0.435	0.430
3	Upper arms	2 × 0.027	0.436
4	Forearms	2 × 0.016	0.427
5	Hands	2 × 0.006	0.369
6	Thighs	2 × 0.142	0.437
7	Legs	2 × 0.043	0.434
8	Feet	2 × 0.014	0.441