Nikola Rausavljević[1*]
Miodrag Spasić[1]
Bojan Jošt[2]

MECHANICS MODEL OF THE RELATIONSHIP BETWEEN THE BODY MASS OF SKI JUMPERS AND LENGTH OF THE SKI JUMP

MEHANSKI MODEL POVEZANOSTI MED TELESNO TEŽO SMUČARJEV SKAKALCEV IN DOLŽINO SKOKA

ABSTRACT

The main purpose of this study was to simulate the influence of a ski jumper's mass on the ski jump length and flying time regardless of whether the values of other parameters used in the computer simulation procedure are constant. The simulation was made for a jumping hill HS 120m with a maximum inclination of 35 degrees. Initial velocities at take off were $v_x = 27\ ms^{-1}$ and the vertical take-off velocity was $v_y = 2.5\ ms^{-1}$. The simulated ski jumper's frontal area was 0.15 m^2 and their longitudinal area was 1.2 m^2. The air density factor was 1.0 kg/m^3 and the inclination of the ski jumper's upper body in relation to the direction of the in-flight movement was 35 degrees and did not change during the flight. The ski jumper's mass varied between 60 kg and 70 kg. The simulation started by inputting the minimal initial jumper's mass value. Apart from the jumper's body mass, all input parameters were held constant and had the purpose of calculating the position of the ski jumper's centre of mass every 0.001 second. The results show that for each extra kilogram of a jumper's total body mass the length of the ski jump is reduced by about 25 cm. The flying time was longer for lighter jumpers. The time difference between a jumper's body mass of 60 kg and 70 kg was 0.19 sec. The simulation results show significant differences in the criterion variable length of the jump. Increasing the same jumper's body mass by 2 kg could mean better or worse results in ski jumping. The International Ski Federation must take some steps to better resolve this unfair problem in the future. Two ski jumpers with a different body mass currently differ in their jump length even though they use the same equipment and perform all phases of the ski jump technique identically.

Key words: morphology, Nordic sports, computer simulation

[1] ***Faculty of Kinesiology, University of Split, Croatia***
[2] ***Faculty of Sport, University of Ljubljana, Slovenia***

*Corresponding author
Faculty of Kinesiology, University of Split
Nikole Tesle 12, 21000 Split, Croatia
Tel.: + 385(0)21385009
Fax.: + 385(0)21385431
E-mail: raus@kifst.hr

IZVLEČEK

Osnovni namen študije je bil simulirati vpliva telesne teže smučarjev skakalcev na dolžino skoka in čas leta. Pri tem se je predpostavilo, da so bili vsi ostali ključni parametri, ki vplivajo na dolžino skoka, konstantni. Simulacija dolžine skoka je bila narejena na osnovi profila skakalnice HS120m z naklonom doskočišča 35 kotnih stopinj. Osnovna začetna hitrost vzleta v horiziontalni smeri je bila 27 m/s in v vertikalni smeri 2.5m/s. Velikost frontalne površine telesa skakalca je znašala 0.15m^2 in vzdolžna površina telesa 1.2m^2. Koeficient gostote zračnega upora je bil 1 kg/m^3. Kot med telesom skakalca in naklonom tangente letenja je bil ves čas leta 35 kotnih stopinj in se med letom ni spreminjal. Telesna teža skakalca se je spreminjala od 60kg do 70kg. Simulacija se je začela z najnižjo vrednostjo teže skakalca. Za razliko od telesne teže so bili vsi ostali parametri konstantni in so služili za izračun pozicije skupnega težišča telesa za časovne odseke 0.001 sekunde. Rezultati so pokazali, da vsak kilogram povečane telesne teže pomeni zmanjšanje dolžine skoka za 0.25m. Čas leta se je podaljševal glede na manjšo telesno težo. Razlika v času leta med telesno težo 60kg in 70kg je znašala 0.19 sekunde. Simulacija je pokazala značilne razlike v dolžini skoka. Naraščujoča telesna teža za 2kg pri istem skakalcu lahko pomeni boljši oziroma slabši rezultat skakalca. Mednarodna smučarska zveza bi morala narediti korake v smeri, da bi v bodoče zmanjšala ta nepošten problem v smučarskih skokih. Dva skakalca z različno telesno težo se sedaj razlikujeta v uspešnosti pa čeprav uporabljata isto opremo in enako uspešno izvajata vse faze tehnike smučarskega skoka.

Ključne besede: morfologija, nordijsko smučanje, računalniška simulacija

INTRODUCTION

Ski jumping is a very interesting and popular winter sport discipline. The result in this sport depends on the length of the jump and style points. Ski jumpers' techniques are realised on different jumping hills. On the bigger Olympic jumping hill (HS 125m) the initial take off and flying velocity can exceed 90 km/h. The first analytical model of ski jumping mechanics during the flight phase was developed by Straumann in 1927. Since then, various authors have taken many different approaches to study the biomechanical characteristics of ski jumps (Denoth, Luethi, & Gasser, 1987). The main purpose of the flight phase in the ski jumping technique is to achieve an optimal flight velocity, where the horizontal flight velocity needs to be maximised and the vertical flight velocity must be minimised (Vaverka, 1987). The flying velocity depends on the aerodynamic lift force, aerodynamic drag force and gravity force (see Figure 1).

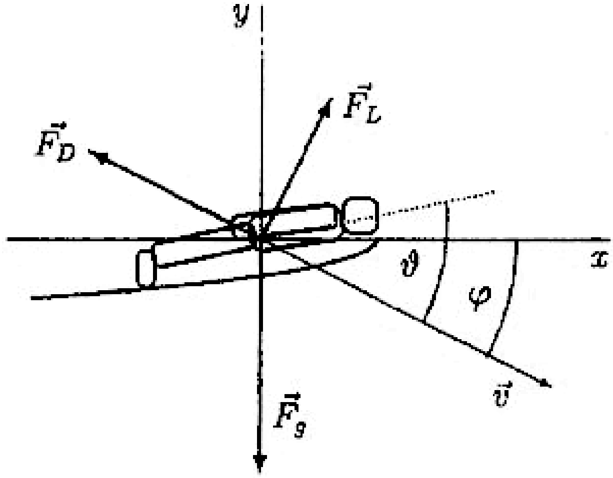

Figure 1: Diagram of forces influencing the jumper in flight ($\mathbf{F}_L$ - Aerodynamic lift force; $\mathbf{F}_D$ - Aerodynamic drag force; $\mathbf{F}_g$ - gravity force).

During the flight all three forces act upon the athlete and his equipment and determine the flight path of the ski jumper's centre of gravity with a given set of initial conditions and parameters. The interaction of the three forces first depends on the flying velocity (**v**) and the angle of flying (φ).

The vertical gravity force acts negatively on the flying angle. The aerodynamic forces depend on the velocity of motion corrected by the value of external wind, density of air, the jumper's body and ski surface and the aerodynamic coefficient of body and ski (Müller, 2009). The aerodynamic forces have increased markedly over the past three decades due to changes in equipment and flight styles (Ito, Seo, & Asai, 2009; Jin, Shimizu, Watanuki, Kubota, & Kobayashi, 1995). Associated with this situation, the low mass of jumpers has become an important performance factor in ski jumping.

Reducing the parameter jumper's mass by 1 kg in the simulation protocol led to the jump length on an HS120 m jumping hill increasing by approximately 0.79 m to 1.0 m (Schmölzer & Müller, 2005; Müller, 2009). On the biggest flying jumping hill (K185m) 1 kg less of a jumper's mass can on average produce a difference in jump distance of 1.37 m (Müller, Platzer, & Schmölzer, 1996).

For this reason, in the past jumpers started to drastically reduce their body mass, causing a series of health problems and anorexia in some ski jumpers (Müller, Gröschl, Müller, & Sudi, 2006; Schmölzer & Müller, 2002). In order to halt the trend of minimising ski jumpers' body mass, in the 2004/2005 season the International Ski Federation decided to limit the length of skies by relating their admissible length and the height of a jumper, as well as his body mass index (BMI). The maximum ski length is now 145% of a competitor's total body height. The BMI value has to be a minimum of 21 for males. For athletes with less than the minimum BMI a grading table of 0.125 BMI per 0.5% of ski length is applied. This ensures that every further reduction of the BMI below the minimal value directly reduces the maximum length of the skies a ski jumper is allowed to use. The reduced maximum ski length results in a reduced surface area of the underside of the skies, which is particularly important during the flight phase. The FIS' corrections in the area of jumpers' BMI have already led to a reduction of the correlation between body mass and the length of jumps (Jošt, 2010). Since the new FIS rules regulating the ski length relative to the BMI came into effect, a 1 kg difference in a jumper's mass has on average produced a jump length difference of approximately 0.64 m (Oggiano & Saetran, 2009).

The main purpose of this research is to find out how increasing a ski jumper's body mass determined the jump length and flying time on a simulated profile of a traditional Olympic jumping hill HS 120m. Namely, two ski jumpers with different body masses can achieve different jump lengths even though they use the same equipment and perform all phases of the ski jump identically. A question arises of whether this is fair. Already a long time ago combat sports recognised the problem of such differences among their athletes as an issue of a physical nature and participants in those sports are therefore divided into several body mass categories. The fact is that in some cases "physics works for the athlete" and one can question what success an athlete has really achieved in relation to his condition and abilities, and what is his success compared to other competitors. The use of simulation techniques for experimental purposes allows researchers to carry out exotic experiments or demonstrations without using rare materials or expensive equipment (Afrić, 1999; Spathopoulos, 2010). Simulating an activity greatly simplifies the approach to the problem by avoiding complicated and expensive field (situation) measurements. Physical models are less expensive and less demanding than field and laboratory experiments, but it is only when they are used together to complement each other that they provide the whole picture about a specific research topic.

METHOD

The computer simulation was made in order to calculate the position of the ski jumper's centre of gravity during every moment of the flight based on input parameters.

In order to demonstrate in this study that the ski jump length depends exclusively on the jumper's mass, all other variables influencing the jump were held constant for all values of the mass. The following constant parameters were used in the simulation procedure:

- The components of the initial velocity (velocities at take-off: $\mathbf{v}_{x0} = 27\ ms^{-1}$ and $\mathbf{v}_{y0} = 2.5\ ms^{-1}$) are taken from Virmavirta, Kivekas and Komi (2001).
- The value 1 is taken as the value of the aerodynamics coefficients ($\mathbf{C}_D$ and $\mathbf{C}_L$).
- As stated by Dželalija, Rausavljević and Jošt (2003), the ski jumper's frontal area $A_1 = 0.15\ m^2$ and longitudinal area $A_2 = 1.2\ m^2$.

- The take-off ramp profile – the profile of a typical HS 120 m ski jumping slope with a maximum inclination of $\alpha = 35$ degrees.
- The inclination of the ski jumper's upper body in relation to the in-flight direction of movement equals 35 degrees and does not change during the flight.

The ski jumper's mass in the simulation procedure varied between 60 kg and 70 kg. The simulation started by inputting the initial jumper's mass value of 60 kg.

The ski jumper's centre of gravity (CG) during the flight describes a curve in space. For reasons of simplicity, the trajectory is approximated by a curve within a vertical plane. Further, the athlete and the skis are assumed to be a system of rigid bodies. The origin of the x – and y – axes in this plane is located at the end of the jumping platform. When all forces influencing the jumper are known, the resultant force influencing the jumper at any moment of the flight can be calculated, as well as the horizontal and vertical components of the resultant force and with regard to the coordinate axes x and y.

Formulas used for calculating the horizontal component $\mathbf{F}_x$ and vertical component $\mathbf{F}_y$ were:

$$\mathbf{F}_x = ½ \cdot C_L \cdot \varrho \cdot v^2 \cdot A_2 \cdot \sin^2(\vartheta) \cdot \cos(\vartheta) \cdot \sin(\varphi) - ½ \cdot C_D \cdot \varrho \cdot v^2 \cdot [A_1 + A_2 \cdot \sin^2(\vartheta) \cdot \sin(\vartheta)] \cdot \cos(\varphi)$$

and

$$\mathbf{F}_y = - m \cdot g + ½ \cdot C_L \cdot \varrho \cdot v^2 \cdot A_2 \cdot \sin^2(\vartheta) \cdot \cos(\vartheta) \cdot \cos(\varphi) + ½ \cdot C_D \cdot \varrho \cdot v^2 \cdot [A_1 + A_2 \cdot \sin^2(\vartheta) \cdot \sin(\vartheta)] \cdot \sin(\varphi)$$

where the symbols mean: φ – angle between the jumper's direction of movement and coordinate axis x, ϑ – angle between the jumper's upper body and direction of movement, m – the jumper's mass, and g – acceleration of gravity (9.8 m/s²), A_1 – the jumper's frontal area, A_2 – the jumper's longitudinal area, C_D – aerodynamics coefficient for $\mathbf{F}_D$ force, C_L – aerodynamic coefficient for $\mathbf{F}_L$ force.

To calculate the jumper's velocity, it is necessary to know his acceleration at any given moment. The acceleration components were calculated by using Newton's Second Law of Motion $a_x = F_x / m$ and $a_y = F_y / m$. The velocity was calculated using the formula ${}_\Delta v = a \cdot {}_\Delta t$ or from the point of the jumper's velocity separated into the horizontal component ${}_\Delta v_x = a_x \cdot {}_\Delta t$ and vertical component ${}_\Delta v_y = a_y \cdot {}_\Delta t$.

The purpose of the computer simulation undertaken in this study is to calculate the jumper's position (x,y) at any moment during the jump. The term "at any moment" means an arbitrarily chosen range of an interval of time (${}_\Delta t$) we believe offers sufficient resolution to describe the desired activity. It is possible to demonstrate the ski jumper's position by means of two position components (coordinates): the position on the x-axis and the position on the y-axis using the formulas $x = x_0 + v_x \cdot {}_\Delta t$ and $y = y_0 + v_y \cdot {}_\Delta t$.

Apart from the jumper's mass, all input parameters are held constant and have the purpose of calculating the ski jumper's position (of their centre of mass) every 0.001 second. The fixed time step integration (0.001 s) was sufficient to obtain a jump length calculation error of less than 0.1 m. The simulation ends when the jumper's position of their centre of mass "touches" the landing surface area on the simulation jumping hill HS 120m, i.e. when the y coordinates of the position equal zero. It is then that the jumper's maximum range (jump length) and flight time are displayed on the screen.

The computer simulation of the physical model elaborated in this study was written in the FORTRAN computer programming language (Compaq Visual FORTRAN 6.5 computer program).

RESULTS

The results of calculating the jump length and flight time using the applied computer simulation based on 10 different values of the jumper's body mass are given in Table 1.

Table 1: Results of calculating jump lengths and flight times based on 10 different jumper body masses

Jumper's body mass [kg]	Jump length [m]	Flight time [s]
70	132.1	4.63
69	132.4	4.65
68	132.6	4.67
67	132.9	4.68
66	133.2	4.70
65	133.4	4.72
64	133.2	4.74
63	133.9	4.76
62	134.2	4.78
61	134.5	4.80
60	134.8	4.82

The simulated relationship between the variables Length of the jump and Jumper's body mass is graphically presented in Figure 2.

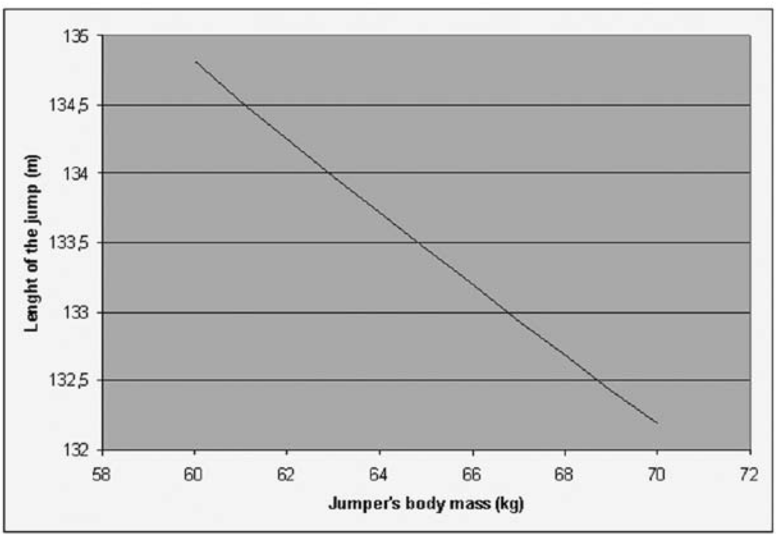

Figure 2: Jump length according to the jumper's body mass

The jump length for a heavier jumper (70 kg) was minimal at 132.1 m and a flying time of 4.63 sec. In contrast, a lighter jumper (60 kg) had a maximal jump length of 134.8 and a maximal flying time of 4.82 sec.

DISCUSSION

The simulation of jump lengths according to a jumper's varying body mass revealed a linear relationship (see Figure 2). It is important to reiterate that in this simulation all the parameters apart from the jumper's body mass were held constant. The simulation showed that for each extra kilogram of total ski jumper body mass the length of the jumps was reduced by about 5 cm. The flying time was longer for the lighter jumpers. The influence of a jumper's body mass in this simulation experiment was not as significant as has been reported in other studies with other initial simulation conditions (Müller, 2009; Schmölzer & Müller, 2002). But low body mass is still one of the determinants of a ski jump performance and must be viewed in the context of other performance factors. It has been found that while the current FIS rules do reduce the addressed problem experiments show that it is still better to lose body mass and consequently shorten the skis than gain body mass in order to retain the full ski length (Oggiano & Saetran, 2009).

The influence of the ski jumper's body mass on the jump length depends on several factors. One of these is the air pressure (p) which decreases exponentially with increasing altitude and higher air temperature. In this study was used a relative low air density factor of 1.0 kg/m^3. Jumping hills can normally be found at different altitudes. The biggest flying jumping hill in Vikersund (HS 215m) is located just above sea level and there the air density factor is greater than 1.2 kg/m and consequently the aerodynamic forces are higher. The low air density value reduces aerodynamic forces and strongly changes the movement technique ski jumpers use; they cannot lean forward as extremely as they do at lower altitudes (Müller, 2008). In these conditions a lighter jumper may be better at solving the transition from the take off to the optimal flight position.

Jumpers can influence another aspect in the flight phase, namely the area that their body and equipment close in (Jošt, Kugovnik, Strojnik, & Colja, 1997; Jošt, Vaverka, Kugovnik, & Čoh, 1998; Seo, Murakami, & Yoshida, 2004; Seo, Watanabe, & Murakami, 2004). A lighter athlete can lean forward in a more pronounced way than a heavier one, resulting in a further increase in jump length due to the advantageous lift and drag areas associated with this improved flight position (Mahnke, & Hochmuth, 1990; Müller, Gröschl, Müller, & Sudi, 2006). Since the entire jump in itself represents a "live process", the jumper's feeling to react and adapt in due time to any new situation is very important. In this study the same flying technique was used for all of the flying time in the same initial mechanical conditions. This fact may have produced not so significant differences in the simulated jumping lengths in this study. In flight a jumper interacts with different factors, sometimes even different weather conditions. For example, knowing how to resist a squall or to even turn it to his own benefit through various manoeuvres is a great skill. Unfortunately, such situations still result in a reduction of style points and, instead of awarding a jumper who knows how to deal with difficult and unpredictable situations, the current scoring system somehow further punishes him, as noted by Müller (2009).

On the basis of the results, the following conclusions can be drawn:

- The computer simulation based on physical modelling used in this study showed that increasing a jumper's body mass negatively influences the jump length on a K 120m jumping hill. A lighter athlete has the advantage of flying further and their flight time is longer. Since in ski jumps and ski flights the jump length is measured with a precision of 0.5 m, one can conclude that even a 2 kilogram difference in a jumper's body mass can influence ski jumpers' final results.

- These results were obtained in a simulation protocol where just the jumper's body mass was altered. Some possible injustices arising from not considering the problem in various sports were pointed out, i.e. the fact that certain athletes achieve better or worse results than others not due to their own merit or fault but because they are affected by the same laws of physics that benefit some but not others. In the future it is hoped that a ski jumper's body mass will no longer be an important performance factor in situations where the ski jumping technique is the same.
- The International Ski Federation recognised these problems in 2004 by introducing the first ski length regulations according to the minimal BMI value of ski jumpers. Yet the results of experiments show that the trend of losing weight to achieve a better performance has not been stopped. The body mass reduction problem in ski jumping continues due to several factors. The optimal weight for young people is a BMI of between 18.6 and 25.0. The question is: "Why do potential jumpers with a BMI in excess of 23 have no chance of success in ski jumping?" The next simulation study should reflect the new regulations concerning body weight (BMI), ski length, thickness of the athlete's ski suit, different jumping hill sizes etc. Introducing more variables would produce a more realistic situation when using simulation methods. A computer simulation based on more variables could identify the crucial determinants of a top performance and answer many questions concerning training methods, health and safety, the role of body mass, fairness, optimised hill design and changes to the regulations.

REFERENCES

Afrić, V. (1999). Simulacijski modeli. *Polemos, 2,* 95–111.

Denoth, J., Luethi, S. M., & Gasser, H. H. (1987). Methodological problems in optimization of the flight phase in ski jumping. *International Journal of Sport Biomechanics, 3,* 404–418.

Dželalija, M., Rausavljević, N., & Jošt, B. (2003). Relationship between jump length and the position angle in ski jumping. *Kinesiologia Slovenica, 9*(1), 81–90.

Ito, S., Seo, K., & Asai, T. (2009). An experimental study on ski jumping styles. In M. Estivalet, & P. Brisson (Eds.), *The Engineering of Sport, 7*(2), 9–17. Paris: Springer Verlag.

Jin, H., Shimizu, S., Watanuki, T., Kubota, H., & Kobayashi, K. (1995). Desirable gliding styles and techniques in ski jumping. *Journal of Applied Biomechanics, 11,* 460–474.

Jošt, B., Kugovnik, O., Strojnik, V., & Colja, I. (1997). Analysis of kinematic variables and their relation to the performance of ski jumpers at the world championship in ski flight at Planica in 1994. *Kinesiology, 29*(1), 35–44.

Jošt, B., Vaverka, F., Kugovnik, O., & Čoh, M. (1998). Differences in selected kinematics flight parameters of the most and the least successful ski jumpers of the 1996 World Cup competition in Innsbruck. *Biology of Sport, 15*(4), 245–251.

Jošt, B. (2010). Differences between better and worse ski jumpers regarding selected ski flying characteristics at the ski flying world championships 2010 in Planica. *Kinesiologia Slovenica, 16*(3), 33–45.

Mahnke, R., & Hochmuth, G. (1990). Recent findings concerning aerodynamic effects in ski jumping. In *Proceedings of the 8th International Symposium of the Society of Biomechanics in Sport* (pp. 99–105). Prague: Faculty of Physical Education and Sport.

Müller, W. (2009). Determinants of ski-jump performance and implications for health, safety and fairness. *Sports Medicine, 39*(2), 85–106.

Müller, W. (2008). Computer simulation of ski jumping based on wind tunnel data. In V.H Horstrud (Ed.) *Sport Aerodynamics (Vol. 506),* 161–182.

Müller, W. (2009). Determinants of ski-jump performance and implications for health, safety and fairness. *Sports Medicine, 39,* 85–106.

Müller, W., Gröschl, W., Müller, R., & Sudi, K. (2006). Underweight in ski jumping: The solution of the problem. *International Journal of Sports Medicine, 27,* 926–934.

Müller, W., Platzer, D., & Schmölzer, B. (1996). Dynamics of human flight on skis: Improvements on safety and fairness in ski jumping. *Journal of Biomechanics, 29,* 1061–1068.

Oggiano, L., & Saetran, L. (2009). Effects of body weight on ski jumping performances under the new FIS rules (P3). In V. M. Estivalet and P. Brisson (Eds.). *The Engineering of Sport 7 (Vol.1),* 1–9. Paris: Springer Verlag.

Seo, K., Murakami, M., & Yoshida, K. (2004). Optimal flight technique for V-style ski jumping. *Sports Engineering, 7,* 97–104.

Seo, K., Watanabe, I., & Murakami, M. (2004). Aerodynamic force data for a V-style ski jumping flight. *Sports Engineering, 7,* 31–39.

Schmölzer, B., & Müller, W. (2002). The importance of being light: Aerodynamic forces and weight in ski jumping. *Journal of Biomechanics, 35*(8), 1059–1069.

Schmölzer, B., & Müller, W. (2005). Individual flight styles in ski jumping: Results obtained during Olympic Games competitions. *Journal of Biomechanics, 38,* 1055–1065.

Spathopoulos, M. V. (2010). A simple model for ski jump flight mechanics used as a tool for teaching aircraft gliding flight. *E-Journal of Science & Technology (e-JST), 2,* 33–39.

Straumann, R. (1927). *From ski-jumping and its mechanics: Yearbook of the Swiss Ski Union.* Bern: Selbstverlag des SSV.

Vaverka, F. (1987). *Biomechanics of ski-jumping.* Olomouc: UP.

Virmavirta, M., Kivekas, P., & Komi, V. (2001). Take-off aerodynamics in ski jumping. *Journal of Biomechanics, 34,* 465–470.