MODELLING AND SIMULATION OF TWO COMPETITION SLALOM TECHNIQUES

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Original scientific paper
UDC 796.92:004.358

Abstract:

The new geometry of skis highly affects skiing and consequently the slalom technique. A new improved slalom technique with a single movement has been recently presented. This study deals with the biomechanical modelling and computer simulation of the new technique and the old technique with double movement. The simulation is set to enable a comparison of forces and force distributions. It was found that the behaviour of the force is of vital importance because of the skier's movement. Due to the movement, the force causes an increase and decrease in the total ground reaction force. The consequence of the different movements is a higher presence of the highest and strongest ground reaction forces acting in skiing when the double movement technique is applied. Furthermore, a much better steering of the skis can be achieved as a consequence of better contact with the snow, especially during the transfer of weight using the single movement technique. In addition to that, much lower knee momentums act around the gate in the single movement technique as a result of a more stretched body position. The final conclusion relating to the forces point of view achieved with computer simulation is that the new technique with a single movement is much more appropriate for the new skis. The conclusion is consistent with the measurement of forces and times presented in previous articles.

Key words: *alpine skiing, slalom, competition technique, computer simulation, biomechanical modelling*

MODELLIERUNG UND COMPUTERSIMULATION ZWEIER SLALOMTECHNIKEN BEIM WETTBEWERB

Zusammenfassung:

Die neue Beschaffenheit von Skiern hat einen starken Einfluss auf das Skifahren und als Folge dessen auf die Slalomtechnik. Eine neue verbesserte Slalomtechnik mit einer Bewegung wurde neulich vorgestellt. Dieses Projekt befasst sich mit der biomechanischen Modellierung und Computersimulation der neuen und der alten Technik mit doppelter Bewegung. Die Simulation sollte einen Kräftevergleich vemitteln, sowie einen Einblick in die Distribution der Kräfte gewähren.

Es wurde festgestellt, dass, was die Bewegung des Skifahrers betrifft, das Benehmen der Kraft von größter Wichtigkeit ist. Abhängig von der Bewegung verursacht die Kraft entweder eine Zu- oder Abnahme der gesamten Bodenreaktionskraft. Die Folge verschiedener Bewegungen ist eine höhere Anwesenheit der höchsten und stärksten Bodenreaktionskräfte, wenn die Doppelbewegungstechnik angewendet wird. Außerdem kann man eine weit bessere Skierführung erreichen, als Folge besseren Schneekontakts, besonders während der Gewichtsverlagerung bei der Einzelbewegungstechnik. Zudem macht der Skifahrer weit kürzere Schwünge um das Tor in der Einzelbewegungstechnik, als Folge einer ausgestreckteren Körperposition. Ensprechend der Computersimulation lässt sich folgern, im Bezug auf die mittels Computersimulation erhaltenen Kräfte, dass die neue Einzelbewegungstechnik für die neuen Skier angemessener ist. Das ist auch im Einklang mit den Messungen von Kräften und Zeit, die in vorhergehenden Artikeln beschrieben wurden.

Schlüsselwörter: *Ski alpin, Slalom, Wettbewerbstechnik, Computersimulation, biomechanische Modellierung*

Introduction

The new geometry of skis, i.e. carving skis, highly affects skiing (Casolo & Lorenzi, 2001; Kugovnik, Nemec, & Supej, 2000; Supej, Nemec, & Šmitek, 2001; Supej, Kugovnik, & Nemec, 2004, etc.). Consequently, a new improved slalom technique with a single movement has been presented and tested in natural conditions (Supej, Kugovnik, & Nemec, 2002; Kugovnik, Supej, & Nemec, 2004). Several differences and advantages relating to the "old" technique of double movement have been proven, e.g. better snow contact, lower maximal ground reaction forces, better racing times, etc. (Supej, Kugovnik, & Nemec, 2002; Kugovnik, Supej, & Nemec, 2004). The new technique, i.e. the single movement technique is the result of biomechanical modelling. By means of simulation the differences and advantages of the improved technique will be presented in laboratory conditions where all the disturbing factors of the changing conditions in nature can be eliminated. Since the fundamental measurements have been based on the force level (Supej, Kugovnik, & Nemec, 2002), the simulation has been set to enable a comparison of forces.

Methods

Computer simulation based on the biomechanical model has been programmed in the software package *Matlab* that enables a simpler calculation than the classical software languages. A simulation basis contained four slalom turns with a vertical distance among the gates amounting to 13 metres and a shift of 2.5 metres. The skiing trajectory was generated by a sinusoid curve so that the gates were at the maximum or minimum of the curve. It was assumed the skier performed carved turns. Sampling of the trajectory was performed at 600 Hz. Due to a simple comparison and without any loss of the relevance of dynamic parameters, the simulated skier's speed was equal to 13 m/s at all times. The simulated slope had a permanent inclination of 20°.

A skier's model was a rigid body with its mass concentrated in the centre of gravity. Subsequently, movement in the main axis of the body imitating the movement, i.e. stretching and bending, was added. Radial force was calculated at each point on the trajectory. The vector sum of a radial force and static component of the weight force gave the first approximation of the ground reaction force hypothetically corresponding to the ground reaction force of the skier, without any of the skier's movements in terms of stretching and bending or, in other words, it gave the single-pointed body approximation. The static component of the weight force was defined by an adequate balance of the skier, which means that the ground reaction force acted centrically on the centre of gravity in the body. The skier's centre of gravity moved only in one plane, taut over the normal and bi-normal vector of the movement trajectory, which is an optimal longitudinal balanced position of the skier, if the friction between the skis and the snow and the air resistance are neglected.

Since two slalom techniques were to be compared, one with a single and the other one with a double movement, the movement of the skier had to be simulated from the aspect of stretching and bending. Both models were presented in Figure 1. In both cases the skier's movement had been modelled in the main vertical axis of the body and always turned in the direction of the skier's inclination, as a consequence of maintaining an adequate balanced position. In the case of the single movement technique, the amplitude of the movement amounted to 20 cm; 40% of the turn's duration the skier stretched and he/she bent 60% of the time. Simulation of the movement consisted of two sinusoid curves that were joined at the top. Since the force would be abnormal due to the movement at the point of connection, the joined curve was flattened by a digital Butterworth filter of the 3rd order and frequency of 6 Hz. The double movement technique had been modelled by a sinusoid curve of the double turn frequency (the double movement) and lower amplitude 15 cm (see Fig. 1), because of the higher movement frequency. The amplitudes were different and estimated on the basis of kinematic measurements in slalom (Supej, Kugovnik, Nemec, & Šmitek, 2001; Supej, Kugovnik, & Nemec, 2004). Since the nature of movement in the second technique is of such a character that the skier is at the lowest position behind the gate, his/her movement was shifted by an eighth of the turn frequency.

The force caused by the movement of the first or the second technique was obtained by the calculation of the second differential of the modelled movement and by the multiplication of the skier's weight.

Besides the forces modelled, disturbances that in natural environment occur due to bumps on the slopes, the measuring method or other reasons usually appear during skiing. These disturbances were modelled in a simulation by

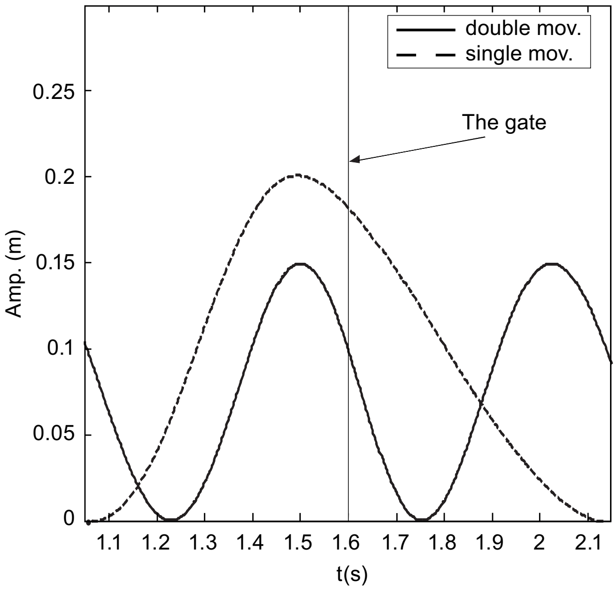

Figure 1. Modelling of the skier's movement in the single and double movement techniques.

50 Hz of coincidental noise of the amplitude ± 150 N. When the ground reaction force had been finally assembled, it had to be checked if it was lower than 0 in any of the points of the ground reaction force, which may happen due to the noise added. In this case the force was set at 0. The same effect can be observed in real measurements. The distribution of forces presented in the form of histograms with columns at a width of 300 N was calculated for a better comparison of techniques.

Results

A simulation of the model calculated the forces for the single movement technique, presented in Figure 2, and the forces for the double movement technique, presented in Figure 3. In both cases the following is presented: force occurring due to movement, radial force, mutual ground reaction force and contribution of gravity to the total force calculated in the approximation as a difference between the absolute value of the vector sum of radial force and static component of the weight force and absolute value of the radial force.

Figures 2 and 3 show the course of a force in the turn. Figures 4–6 present the distributions of forces in histograms where the relative presence of forces of an individual size class (histogram columns) can be monitored. The first diagram corresponds to the distribution of forces for the single-pointed body model ("skiing without movement"); the second and the third ones correspond to the single and double movement technique.

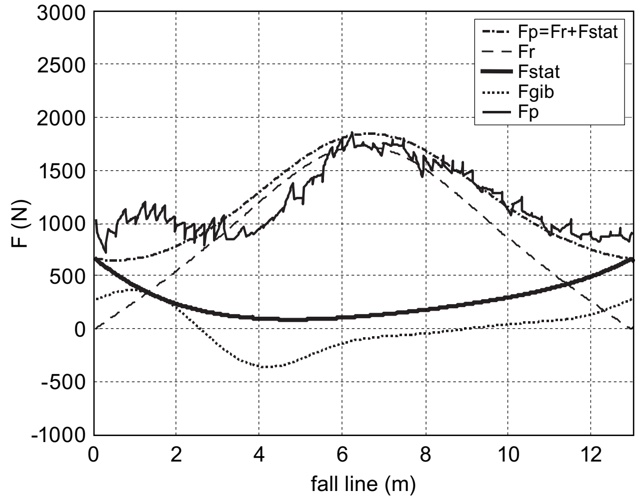

Figure 2. Forces in a turn that occur in the single movement technique: Fp – ground reaction force for a single-pointed body model ("skiing without movement"), Fr – radial force, Fstat – contribution of gravity to the force Fp, Fgib – force occurring due to the skier's movement and Fp – total ground reaction force.

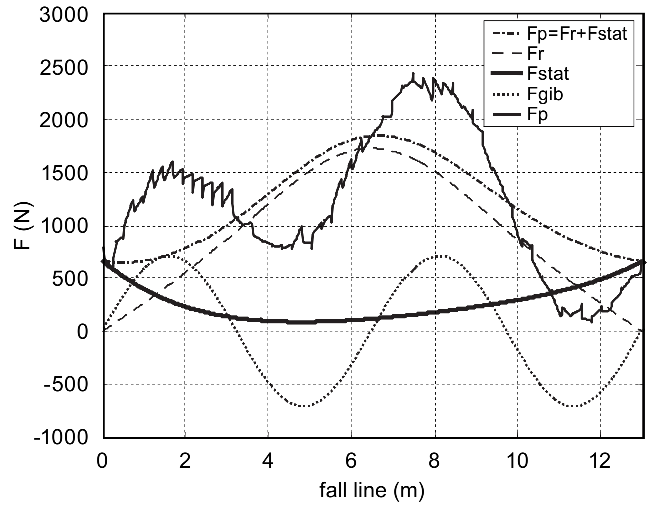

Figure 3. Forces in a turn that occur in the technique of double movement: Fp – ground reaction force for a single-pointed body ("skiing without movement"), Fr – radial force, Fstat – contribution of gravity to the force Fp, Fgib – force occurring due to the skier's movement and Fp – total ground reaction force.

Discussion and conclusions

The model of the double movement technique complies with the measurements of kinematics of the best racers in the world championships, which means that the simulated movement in Figure 1 complies with the description and analysis of actual competition techniques. The model of the single movement technique is a consequence of biomechanical

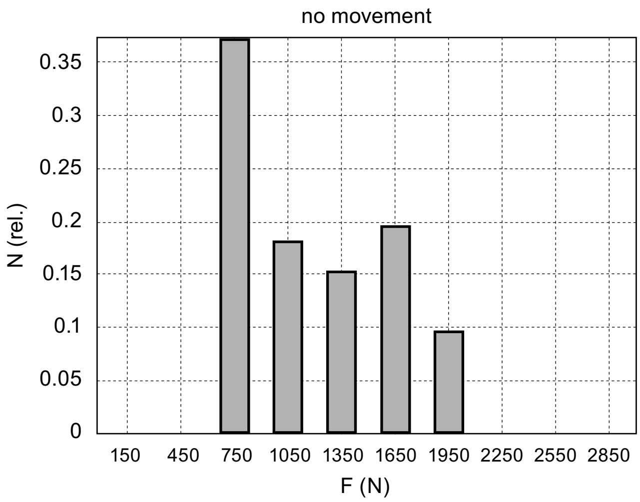

Figure 4. Histogram of forces for the single-pointed body model ("skiing without movement").

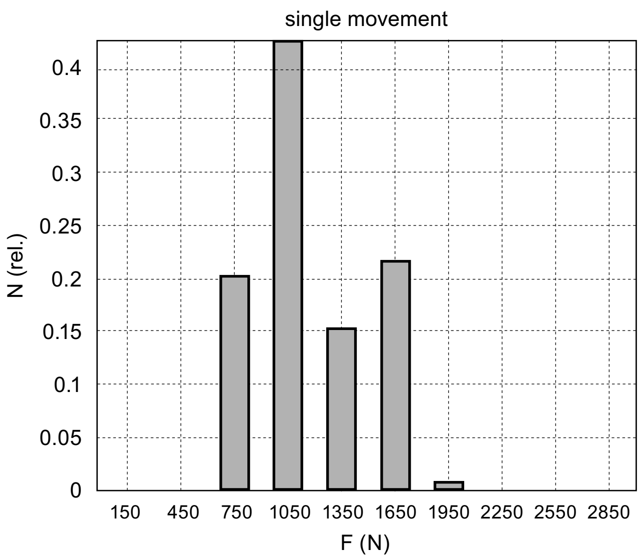

Figure 5. Histogram of forces for the single movement technique.

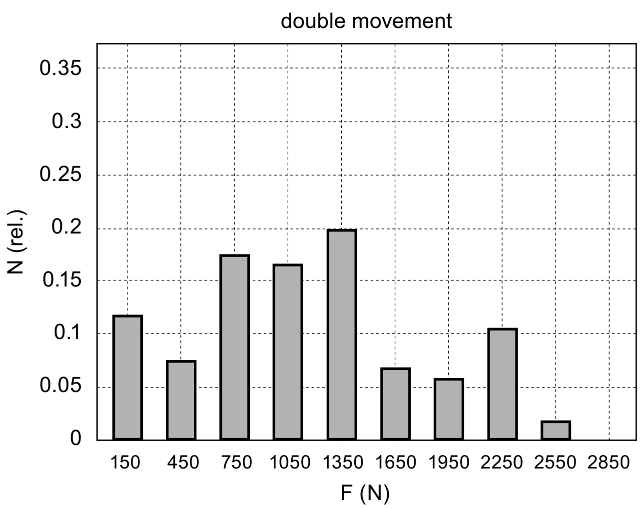

Figure 6. Histogram of forces for the double movement technique.

modelling and practical tests of the technique under competition conditions performed by selected racers.

In the single movement technique the skier is at the lowest position during the transfer of weight and then he/she stretches. He/she is most stretched already in front of the gate, which is also visible in the Figure 1. Further, he/she slowly bends and his/her centre of gravity gets close to the skis.

In the double movement technique the skier is not maximally bent during the transfer of weight. It happens later when he/she strongly places the skies on their edges. Then he/she continues moving downwards and reaches the lowest position (the centre of gravity is closest to the skis) soon after the gate. This is followed by a push and stretching; moving of the centre of gravity close to the skis begins when the weight is to be transferred again. A shortcoming of the model is that a sinusoid or compound sinusoid movement has been simulated in both cases. In real competition circumstances the movement may deviate from the simulated movement, but not to the extent which may drastically influence the distinction between the techniques, since the basic idea of movement is the same. The modelled trajectory of the skier is rather similar to the real one. In this case the leaning radii decreased down to less than 7 metres in the part of the turn where they were smallest. During the weight transfer they reached infinity, which was also evidenced in a good approximation on the snow. The only shortcoming of the model of a sinusoid turn is that skiers in the real world do not change their radius at each point, but they usually maintain the same radius of the turn in the vicinity of the gates. The approximation to reality is the even speed of the skier in the turn that typically and cyclically oscillates in real conditions in a range from 0.5 to 1 m/s. The changing speed does not cause any significant differences in the distribution of forces and besides that it complicates the problem without any need; therefore skiing has always been simulated at an even speed. Simulations with different even speeds (from 10 m/s up to 14 m/s) and different slope inclinations (0°, 10° and 20°) were performed, but all the results were similar and therefore not presented here. The present differences are the consequence of higher radial forces, shorter stretching and bending cycles and different inclinations of the skier.

Since we have been well aware of all the limitations, we can have a look at the results of forces. Figures 3 and 4 present forces for the first and the second technique. The base is the same for both diagrams. In real terms all forces are equal, except the one that is a consequence of either a single or double movement. It can be established that the radial force determines the main form of the ground reaction force. The gravity contribution is relatively small in the top part of the turn or above the gate and it is larger on the bottom side of the turn or under the gate. Of course, the largest contribution can be observed in the vicinity of the weight transfer point. Behaviour of the force occurring due to the skier's movement is of a vital importance. Because of the movement the force causes an increase and decrease of the total ground reaction force. In the case of the double movement technique the force causes the skier to have an interval of very low minimal force at the time of weight transfer because of the movement. On the other hand, the maximum forces are under the pole, where all forces are summed up. The result is a typical curve with a double peak. The single movement technique shows a completely different picture, since the ground reaction force decreases at the time of maximum forces and increases in the area of minimal forces due to the skier's movement.

The results of the distributions of forces for both techniques and in terms of reference for theoretical "skiing without movement" (single-pointed body model) are presented in the histograms of Figures 4–6. It can be established in the single-pointed skier's model ("skiing without movement") that the distribution of the ground reaction force is limited at the bottom edge, to the slightly less than the force of the skier's weight (600 N), and at the top edge, to values approximately a three--time force of the skier's weight (2100 N) (see Fig. 4). The distribution reaches its peak in the vicinity of the value force of the skier's weight. The double movement technique significantly expands the distribution (see Fig. 5). Firstly, there is a great concentration of forces in the vicinity of zero, which means that the skier can hardly manoeuvre the skis. The main peak is much lower and wider due to the broad distribution. It ranges from 600 N to 1500 N. Another disadvantage of this technique is also a rather high presence of the highest and strongest forces. The distribution reaches up to 2700 N, which corresponds almost to a four-time force of the skier's weight and the presence of forces in the interval ranging from 2100 N to 2400 N amounts even to 11%. In practice, the highest forces mean more braking and more difficult conditions for the skier who should be able to tolerate them.

The picture of the single movement technique is completely different since the peak of the distribution is similarly shifted by a column higher, to approximately 1.5 of the force of the skier's weight, but it is substantially narrower (see Fig. 6). The distribution is not expanded, but even shrunk and it approximately ends 300 N lower than in the single-pointed body model ("skiing without movement") or approximately 600 N lower than in the double movement technique. By means of the technique the skier decreases the highest forces and their presence. In the case of the single movement technique the area of forces does not exist in the vicinity of 0 N, which means that the skier has a good contact with the base all the time.

Another fact arising from the model is rather important. In the double movement technique the skier is bent in the interval of high forces which increases the muscle power due to the lever principle in joints (see Fig. 2 and 4). The situation is exactly the opposite in the single movement technique since the skier is quite stretched in the area of high forces (see Fig. 2 and 3).

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Submitted: December 16, 2003
Accepted: December 7, 2004

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MODELIRANJE I SIMULACIJA DVIJE NATJECATELJSKE SLALOMSKE TEHNIKE

Sažetak

Uvod

Nova, poboljšana slalomska tehnika s jednim pokretom tek je nedavno predstavljena javnosti. U radu će biti prikazane razlike i prednosti poboljšane tehnike uz pomoć simulacije u laboratorijskim uvjetima, gdje su svi remeteći faktori i promjenjivi uvjeti prirodne okoline uklonjeni.

Temelj računalnog modela slalomske tehnike jesu četiri zavoja. Trajektorija skijanja generira se pomoću sinusoidnog zavoja i pretpostavlja da skijaš izvodi karving zavoj. Simulirana skijaševa brzina sve vrijeme iznosi 13 m/s, a nagib padine je konstantan i iznosi 20°. Model skijaša je kruto tijelo s masom skupljenom u centar težišta tijela. Zatim je dodan pokret koji, po glavnoj osi tijela, oponaša pokrete opružanja i sagibanja. Skijaševo težište tijela pokreće se samo po površini, protegnuto preko normalnih i binormalnih vektora trajektorija gibanja, što je optimalan ravnotež-ni položaj skijaša.

Metoda

Uspoređuju se dvije slalomske tehnike. U oba se slučaja skijaševi pokreti modeliraju po glavnoj vertikalnoj osi tijela i uvijek se okreću u smjeru skijaševa nagiba, što za posljedicu ima održavanje tijela u ravnoteži. U slučaju tehnike jednog pokreta, amplituda pokreta obuhvaća 20 cm, a tijekom zavoja skijaš se uspravlja 40% vremena, a sagiba 60% od ukupnog vremena. Simulacija pokreta sadrži dva sinusoidna zavoja koja su spojena pri vrhu. Tehnika dvostrukog pokreta modelirana je sinusoidnom krivuljom dvostrukog zavoja frekvencije i amplitude 15 cm (slika 1).

Za vrijeme tehnike jednog pokreta skijaš je u najnižoj poziciji za vrijeme prijenosa težine nakon čega se uspravlja. Najuspravniji je ispred vrata, a potom se sagiba. Za vrijeme izvođenja tehnike dvostrukog pokreta skijaš nije maksimalno pognut za vrijeme prijenosa težine, već tek nakon toga, kada već čvrsto premjesti skiju na rubnik. U tom se trenutku počinje kretati prema dolje i zauzima najniži položaj ubrzo nakon vrata. Potom slijedi odguravanje i uspravljanje, pokretanje težišta tijela bliže skiji počinje kada skijaš ponov-no priprema prijenos težine.

Rezultati

Dijagrami na slici 3 i 4 prikazuju silu generiranu za vrijeme simulirane izvedbe prve i druge tehnike. Može se utvrditi da zakretna sila determinira glavni oblik sile reakcije podloge. Najveće je djelovanje gravitacije u blizini prijenosa težine, a mnogo manje u blizini vrata. Ponašanje sile zbog skijaševa kretanja je iznimno važno. U slučaju tehnike dvostrukog pokreta sila uzrokuje da skijaš ima područje vrlo niske minimalne sile u vrijeme prijenosa težine. Suprotno tome maksimum sile jest ispod štapa, kada se svi doprinosi sila zbrajaju. Rezultat je tipičan zavoj s dvostrukim vrhom. Tehnika jednog pokreta pokazuje potpuno različitu sliku, reakcija podloge se smanjuje u vrijeme djelovanja maksimalne sile i povećava u području vrlo niskih minimalnih sila.

Rasprava i zaključak

Može se utvrditi da je u modeliranju skijaša kao krutog tijela u jednoj točki ('skijanje bez kretanja') raspodjela sila reakcija podloge ograničena na donji rub, nešto manje nego Fg na gornjem rubu, do približno 3*Fg (vidi sliku 4). Distribucija doseže vrh u blizini sile skijaševe težine. Tehnika dvostrukog pokreta značajno proširuje distribuciju sila (slika 5). Prvo, postoji veća koncentracija sila u blizini nule, što znači da skijaš teško može manevrirati skijama. Glavni vrh je mnogo niži i širi zbog širine raspodjele. Drugi nedostatak ove tehnike je također veća prisutnost najviše i najjače sile (do 2700 N). U praksi, najviša sila znači više kočenja i teže uvjete skijanja.

Slika tehnike jednog pokreta potpuno je različita, vrh distribucije je slično pomaknut višom kolonom, do otprilike 1.5*Fg, ali je bitno uži (vidi sliku 6). Raspodjela nije rastegnuta, naprotiv čak se sužava i završava otprilike 300 N niže od skijaševa modela u jednoj točki, ili otprilike 600 N niže nego u tehnici dvostrukog pokreta. Pomoću ove tehnike skijaš umanjuje najvišu silu i njezinu prisutnost. U slučaju tehnike jednog pokreta područje sila nije vidljivo u blizini 0 N, što znači da skijaš cijelo vrijeme ima dobar kontakt s podlogom. Važna je još jedna činjenica koja proizlazi iz ovog modela. U tehnici dvostrukog pokreta skijaš je pognut u području visokih sila, što povećava snagu mišića zbog poluga u zglobovima (vidi slike 2 i 4). Situacija je upravo suprotna u tehnici jednog pokreta; skijaš je prilično opružen u području djelovanja većih sila, koje su u ovom slučaju prilično niske (slike 2 i 3).

Konačni zaključak sa stajališta djelovanja sila, utvrđen računalnom simulacijom, jest da je nova tehnika jednog pokreta znatno prikladnija za novo skijanje kada skijaš izvodi karving zavoj. Zaključak je sukladan mjerenju sila i vremena predstavljenima u prethodnom članku.