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Biomechanical aspects of new techniques in alpine skiing and ski-jumping

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There have been considerable changes in equipment design and movement patterns in the past few years both in alpine skiing and ski-jumping. These developments have been matched by methods of analysing movements in field conditions. They have yielded new insights into the skills of these specific winter sports. Analytical techniques have included electromyography, kinetic and kinematic methods and computer simulations. Our aim here is to review biomechanical research in alpine skiing and ski-jumping. We present in detail the techniques currently used in alpine skiing (carving technique) and ski-jumping (V-technique), primarily using data from the authors' own research. Finally, we present a summary of the most important results in biomechanical research both in alpine skiing and ski-jumping. This includes an analysis of specific conditions in alpine skiing (type of turn, terrain, snow, speed, etc.) and the effects of equipment, materials and individual-specific abilities on performance, safety and joint loading in ski-jumping.

Keywords: electromyography, equipment, hills, simulation, turns.

Introduction

Over the past few years, dramatic changes have taken place in alpine skiing and ski-jumping. In alpine skiing, the skis have become much shorter, their side-cut has increased in size and binding plates are now fixed between the ski and the binding. The stiffness of the ski has changed also. This evolution has, of course, changed the movement patterns of ski turns to a great extent, but it may also have affected the risk of sustaining an injury. In ski-jumping, the introduction of the V-technique (V-position of the skis during the flight phase) has affected almost all the characteristics relevant to performance of a jump. This was followed by new regulations concerning ski equipment to improve the ski-jumper's safety.

Performance diagnostics are especially significant in modern sport. The financial cost of biomechanical movement analyses is high, because of the measurement accuracy required on the one hand, and the need to limit the impact of measurement sensors on the course of motion on the other. This means that the athlete should not be seriously affected by the measurement system. In the past, it was not always possible to achieve these partly contradictory aims simultaneously during data acquisition and often compromises had to be made to arrive at the best possible solution. Within the last few years, changes in measurement methods have, especially in biomechanical field studies, made it possible to gain new insights into the various performance techniques.

This review presents examples of biomechanical field studies using the new measurement methods. In particular, we focus on the new carving technique in alpine skiing and the new V-technique in ski-jumping.

Biomechanics of the new carving technique in alpine skiing

Introduction to the biomechanics of alpine skiing

The literature on the biomechanics of alpine skiing can be characterized essentially by three phases of development. Contributions to the first phase were qualitative studies of the forces and resulting motion sequences during skiing. The early studies were those of Reuel (1930), Brandenberger (1934) and Schuppe (1941). In the 1960s, a series of contributions followed in the Viennese specialty journal *Leibesübung-Leibeserziehung* ('Physical exercises–physical education') (Gabler, 1959; Schöck, 1963, 1965, 1966; Fetz, 1964; Nieke, 1964; Hatze, 1966, 1967; Groll, 1969), which Groll summarized for the most part in his book *Zur Bewegungslehre des*

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Skilaufs ('Concerning the theory of motion in skiing'). Since the 1970s and 1980s, contributions of this type have appeared and been widely distributed internationally (Brehm, 1982; Göhner, 1982). The monographs of Brandenberger (1974), Howe (1983) and Lind and Sanders (1997) are especially significant.

The second phase is characterized by specific quantitative descriptions of motion processes in alpine skiing using biomechanical methods. The first comprehensive description was that of Möser (1957). He developed a dynamograph in the form of a ski-mounted mechanical lever gear. Using this device, the ground reaction forces acting on the ski during the run could be registered on paper strips.

Since the 1970s, several studies have been published in which various methods for analysing skiing techniques were described. Most worthy of note are the contributions of Fukuoka (1971), Nigg *et al.* (1977), Kassat (1985), Müller (1986, 1991, 1994) and Raschner *et al.* (2001), who were concerned with the sport skiing techniques of ski instruction. Most recently, biomechanical descriptions of the run techniques of international elite ski racers have been published in the disciplines of slalom and giant slalom. Especially important are the studies of Müller *et al.* (1991), Raschner (1997) and Raschner *et al.* (1999), in which the three-dimensional kinematic and kinetic characteristics of slalom and giant slalom techniques are outlined.

In the third phase of development, which began in the 1980s, key variables have been measured using biomechanical methods. On the one hand, these inform the quality of the technique of motion and, on the other, they provide information about factors that may cause typical skiing injuries. Fetz (1977, 1991) considered the key variables for finishing techniques and developed the *Vorlagetechnik*, which is still practised today in the slalom and giant slalom when skiers are passing the finishing line of the race. Many studies were concerned with the optimization of the course run line. Nachbauer and Rauch (1991) assessed the influence of the run line on race time in the slalom and giant slalom. Nachbauer and Kaps (1991) discussed the aerodynamic aspects of the standing position of the skier and their influence on running time in ski racing. Due to current developments in ski construction, studies of the relationship between ski geometry and run line are especially significant (Casolo *et al.*, 1997; Mössner *et al.*, 1997; Margane *et al.*, 1998; Niessen, 1999; Niessen and Müller, 1999). The studies of Scharfenberg (1992) and Mester (1997) focused on motion regulation during skiing.

The loading of the musculoskeletal system during skiing and the possible consequent causes of injury have been examined by several working groups. Among the most important publications are those by Nachbauer and Kaps (1995), Niessen and Müller (1999), Nigg (1997), Quinn and Mote (1992), Read and Herzog (1992) and Senner *et al.* (2000).

Of particular significance for the biomechanics of skiing is the international 'Science and Skiing' movement, established in 1996. The communications to congresses convened in 1996 and 2000 have been published as proceedings (Müller *et al.*, 1997, 2001).

A description of the new carving technique

With the introduction of carving skis, alpine skiing has experienced a tremendous boom. Carving skis are essentially more strongly waisted and markedly shorter than conventional skis. Additionally, a binding plate is mounted between the ski and binding whereby the standing height of the skier is increased by 1–2 cm.

In carving, the 'curved turn' is important. Using this technique, steering takes place along the ski edges without any lateral skid component. The navigable curve radius during carved turns is a function of the following variables: ski waist, on-edge angle and ski flexion (Fig. 1). The more strongly waisted the ski and the greater the on-edge angle, the more strongly the ski must flex to maintain contact with the slope along the total length of the edge. The curve cut into the snow under full contact with the slope is designated the turn radius. Figure 2 shows the ideal cut curve radius as a function of the on-edge angle with variously waisted skis (Niessen and Müller, 1999).

In the ski methodology literature, it is often stated that the run technique, in comparison with traditional parallel turns, has been strongly modified. In a recent study, Schiefermüller *et al.* (in press) used a combination of kinematic, kinetic and electromyographic methods. To allow a comparison with the conventional technique of the parallel turn, the same participants performed parallel and carved turns with conventional and carving skis, respectively, under otherwise identical boundary conditions. On a well-prepared, moderately steep slope (15°), the test skiers had the task of making six runs each with eight turns per run with differently waisted skis (carving: $r = 14$ m; parallel technique: $r = 32$ m). The runs were filmed with three video cameras and the data evaluated three-dimensionally using the SIMI software package (Munich, Germany). The ground reaction forces and the pressure distribution in the ski boot were measured by two pressure measurement sole inserts (Novel, Munich, Germany). Simultaneously, it was possible using electromyography to observe the activities of the gluteus maximus, vastus medialis, vastus lateralis, rectus femoris, biceps femoris, tibialis anterior and peroneus longus muscles (Biovision system, Frankfurt, Germany).

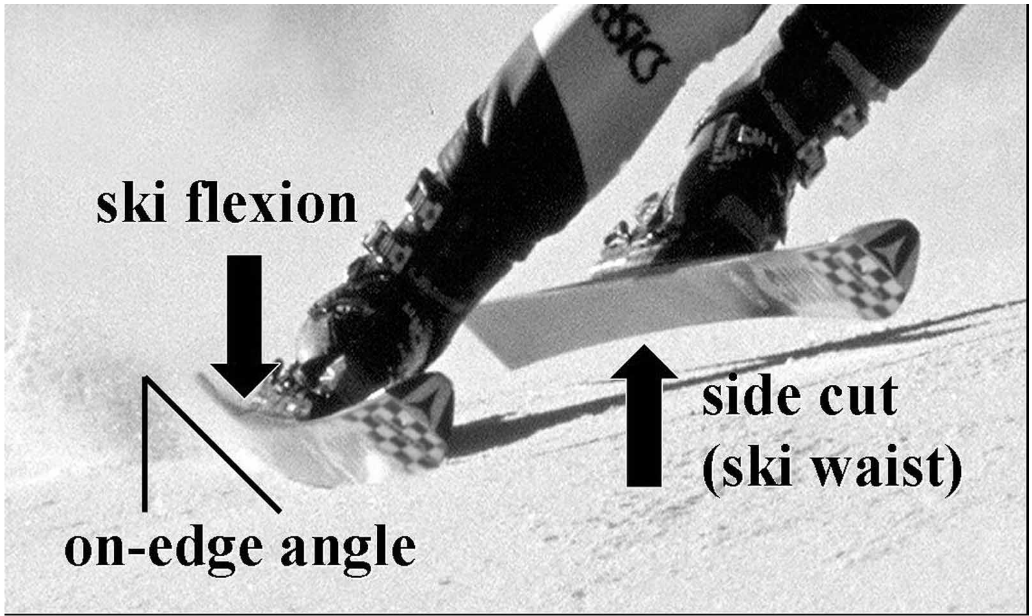

Fig. 1. Side cut (ski waist), on-edge angle and ski flexion of carving skis.

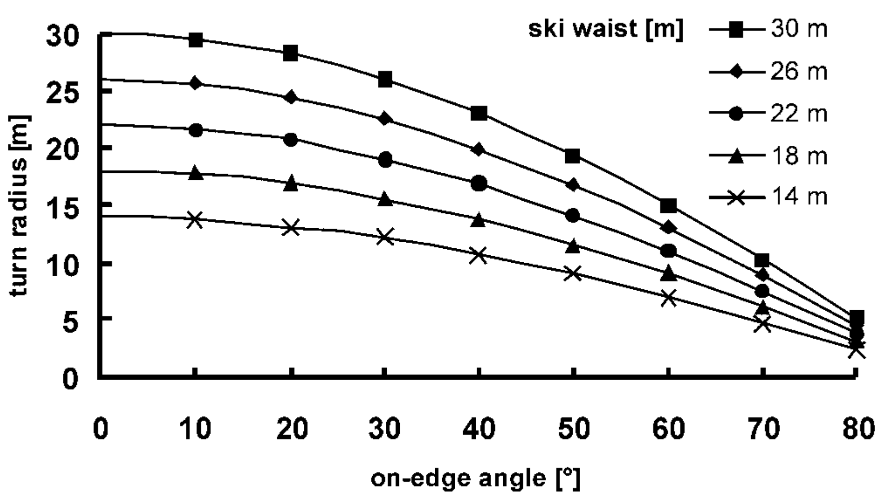

Fig. 2. Turn radius as a function of on-edge angle for variously waisted skis.

During the steering phase, the greatest load is on the outer ski. The load is increased continuously while steering into the fall line and reaches a maximum of about 180% during steering out of the fall line. During both steering phases, the force–time courses are very uneven. This can be attributed to the repeated lateral skid phases, as continuous steering along the slightly waisted edges is very difficult. The initiation phases are characterized by a load change from the outer to the inner ski and a relatively intensive increase in load on the inner ski. With the introduction of the up-unweighting phase, the skis' edges are shifted and turned towards the direction of the new turn (Fig. 3).

During the steering phase, the knee angle of the outer leg is greater throughout than that of the inner leg. With relatively small fluctuations, it remains relatively constant at 120–130° (Fig. 4). The knee angle of the inner leg at the onset of the first steering phase is about 120°. However, it is reduced in the course of the turning phase and reaches its minimum of about 95° at the beginning of the initiation phase (the skier changes the ski–snow contact from the uphill edge to the downhill edge of the skis and initiates the turning of the skis into

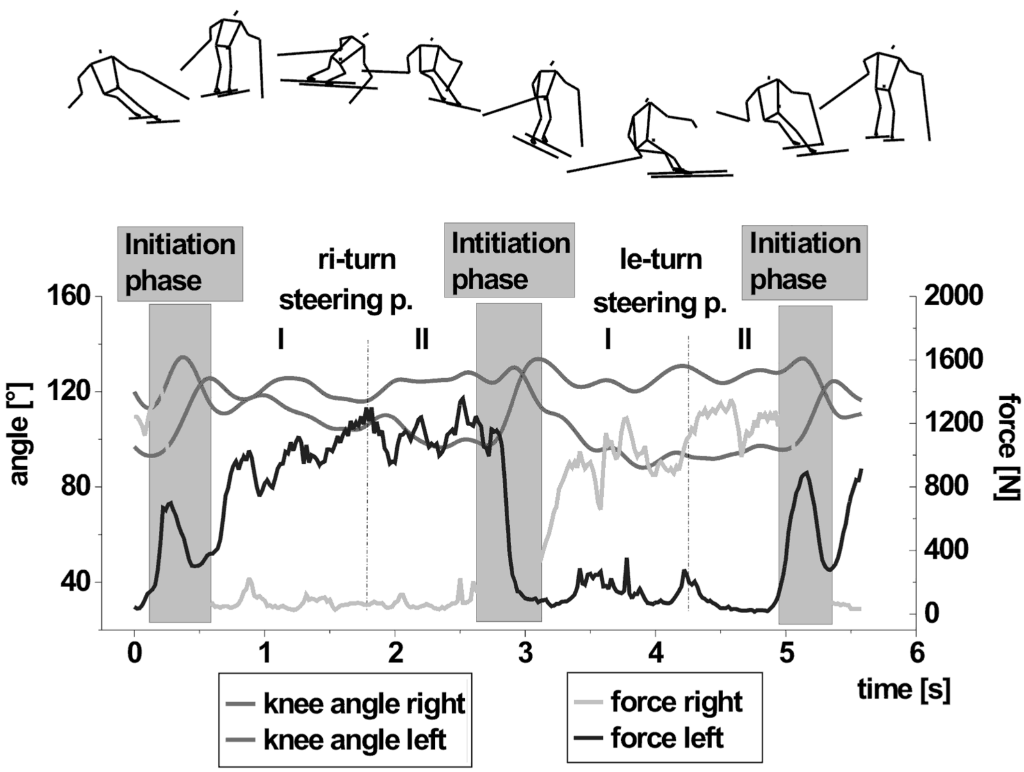

Fig. 3. Ground reaction forces and knee angles during two turns with the traditional parallel technique (mean values of six runs). Reproduced with permission from Schiefermüller *et al.* (in press).

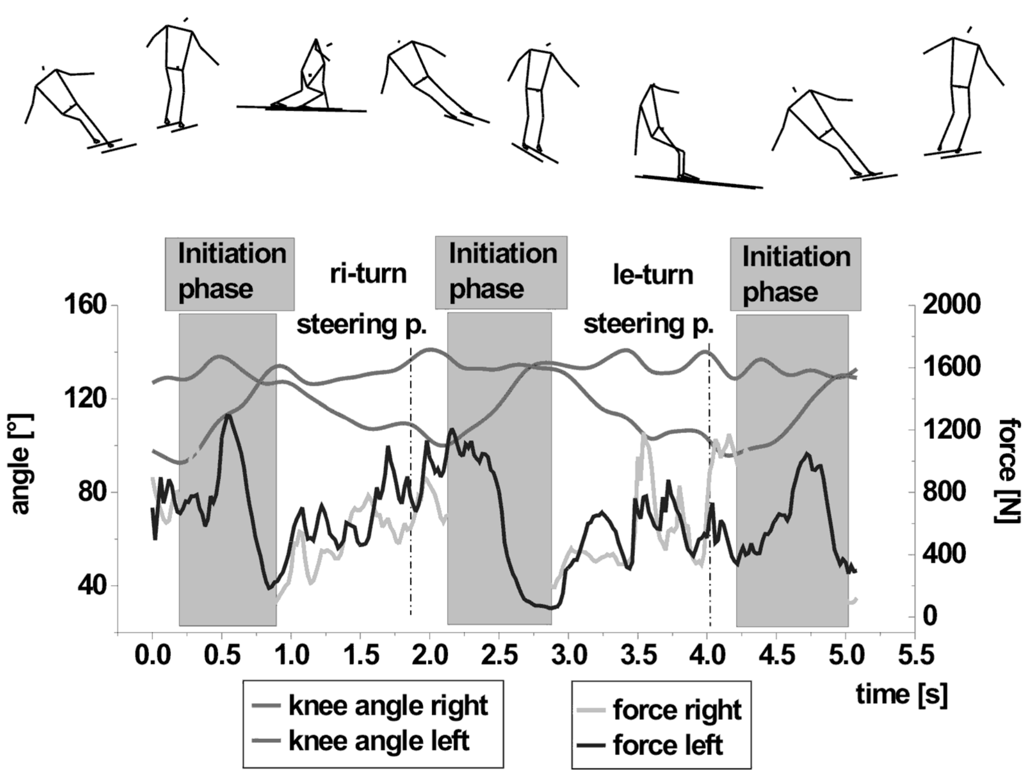

Fig. 4. Ground reaction forces and knee angles during two turns with the carving technique (mean values of six runs). Reproduced with permission from Schiefermüller *et al.* (in press).

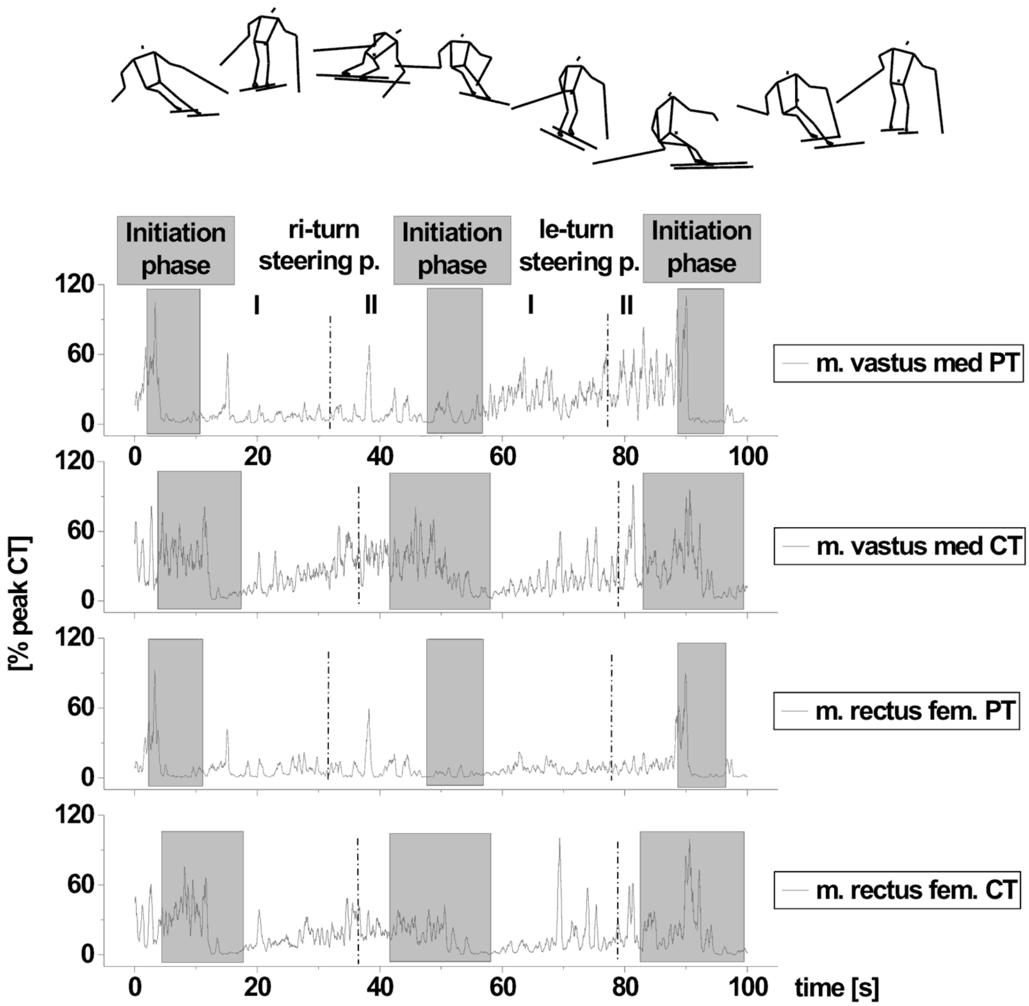

Fig. 5. Comparison of EMG of the vastus medialis and rectus femoris during two turns with the parallel (PT) and the carving (CT) technique. Reproduced with permission from Schiefermüller *et al.* (in press).

the new direction). The steep increase in knee angle in the first part of the initiation phase reflects the up-unweighting movement and the large contribution of the inner leg to the total unloading.

The carving turn can be distinguished from the conventional parallel turn by the strongly pronounced co-loading of the inner leg in all turn phases. Another distinguishing characteristic is the relatively short second steering phase and the comparatively long turn phase of initiation.

The initial steering phase is characterized by a continuous increase in load on both legs, with the load distribution being approximately equal. In the second turning phase, the outer ski is again more strongly loaded, whereby the following initiation phase is introduced very quickly. The turn initiation phase is very similar in structure to that of the traditional parallel turn. The up-unloading is first introduced by the outer and then by the inner leg, whereby the increase in force does not occur as quickly as in the traditional parallel turn. The temporal percentage of the initiation phase relative to the total turn is essentially greater with the carving technique.

In the steering phases, the knee angle of the outer leg is relatively constant at 125–135°, whereas that of the inner leg is continuously reduced and, at the beginning of the initiation phase, is only about 95°. During the initiation phase, there is a strongly pronounced extension of the inner leg by about 40°. This extension motion, which leads to a very pronounced unloading of the skis, is completed relatively slowly within 0.75 s.

By a direct comparison of the activity of the quadriceps femoris in both techniques, the essential difference between the traditional parallel turn and the carving turn becomes clear (Fig. 5). During the carving turn the inner leg is strongly co-loaded, whereas in the traditional parallel turn the activity of the inner leg takes on a significantly subordinate role.

In summary, the following were identified in the comparison of the traditional parallel and the new carving turn:

- In the traditional parallel turn during the steering phases, the predominant load is on the outer ski, whereas intensive co-loading of the inner leg is found in all turning phases with the carving technique.
- The carving technique has a relatively short second steering phase (steering the skis out of the fall line) and a comparatively long initiation phase.
- The turn initiation phase of the carving technique is in structure very similar to that of the traditional parallel turn. Up-unweighting in combination with a changing edge is seen with both techniques.
- Turns with carving skis demand better sagittal balance as well as an improved edge steering ability to remain centrally positioned over the ski.
- The more waisted and more flexible skis, together with the greater on-edge angles during the steering phase, make the much smaller turning radii with the new carving technique possible.

Biomechanics of ski-jumping

Introduction to the biomechanics of ski-jumping

Biomechanical research in ski-jumping has a fairly long tradition, going back to the 1920s. Straumann (1926, 1927) was the first to use biomechanical methods in ski-jumping for research purposes. He attempted to determine the most aerodynamically advantageous body position during flight using flight path calculations and wind tunnel measurements. Many different and very specific methods have been developed to study locomotion in ski-jumping from the biomechanical point of view. The main research areas include: (1) field studies of hill jumps; (2) laboratory investigations of simulation jumps (take-offs in dry-land exercises); and (3) computer simulations of the flight phase (Schwameder and Müller, 2001b). Most field studies of hill jumps have used standardized research and training conditions; few studies have been conducted under competitive conditions (Komi *et al*., 1974; Virmavirta and Komi, 1989, 1993a,b; Arndt *et al*., 1995; Yamanobe and Watanabe, 1999). Simulation jumps are commonly used for the technique training of ski-jumpers. From the scientific point of view, simulation jumps are of interest because of: (1) performance diagnostics and their connection to hill jumps; (2) the comparison that can be made between hill and simulation jumps; and (3) specific aspects, such as joint power distribution (Sasaki *et al*., 1997), position before take-off (Schwameder *et al*., 1997), the effect of jumping boots on muscle activation and performance (Schwameder *et al*., 1997; Virmavirta, 2000) and the effect of headwind on dynamic parameters (Virmavirta, 2000). The main purposes of computer simulations of the flight phase are to optimize the flight position of the ski-jumper/ski system and to provide basic information for the construction of hills for jumping. Many scientific articles have been published on these aspects (Tani and Iuchi, 1971; Remizov, 1984; Hubbard *et al*., 1989; Müller *et al*., 1996; Müller, 1997). In most of these studies, results from wind tunnel measurements and/or analytical calculations served as input data for the simulations.

The main biomechanical methods used in these studies are (1) kinematics, (2) kinetics, (3) electromyography (EMG) and (4) computer simulation. Our aim here is to provide a review of the most important biomechanical studies of ski-jumping, differentiated according to the methods used.

Kinematic methods and results

Hill jumps

The two main aims of kinematic field studies of hill jumps are the description of motion characteristics during ski-jumping and the determination of kinematic parameters related to performance. Results have been provided both for the jump as a whole and for the in-run, take-off, flight and landing separately. While early studies concentrated on two-dimensional methods (e.g Hochmuth, 1964; Komi *et al*., 1974; Baumann, 1979), describing the motion in the sagittal plane, more recent studies have also provided three-dimensional data (Arndt *et al*., 1995; Schwameder and Müller, 1995).

From a kinematic perspective, the take-off has received most attention. As optimal conditions for flight are created during the take-off, this phase is deemed crucial by many investigators (Komi *et al*., 1974; Baumann, 1979; Arndt *et al*., 1995; Schwameder and Müller, 1995). In this phase, the ski-jumper has to perform the transition from an aerodynamically convenient squat position to optimal flight position within about 300 ms and at a speed of about 25 $m \cdot s^{-1}$. It has been comprehensively discussed whether ballistic variables (those referring exclusively to the state of motion of the centre of gravity, such as magnitude and direction of release velocity, flight path, etc.) can be used to explain the quality of the jump and jump distance. Although several authors indicate such a connection (Komi *et al*., 1974; Schwameder and Müller, 1995), others have suggested that the ballistic parameters play a minor role compared with the aerodynamic characteristics that describe the relative positions of body segments and skis (Baumann, 1979; Arndt *et al.*, 1995). Many studies of the correlation between release velocity and jump length can be found in the literature. Because of the varying conditions, the results of these studies are not comparable and, therefore, inferences are inconsistent. The range of the correlation coefficients is surprisingly high [0.75–0.80 (Hochmuth, 1958/59), low (Komi *et al.*, 1974), 0.34 (Baumann, 1979), 0.40–0.67 (Vaverka, 1987), 0.68 (Virmavirta and Komi, 1993a), not significant (Arndt *et al.*, 1995) and 0.35 (Schwameder and Müller, 1995)]. The reasons for these inconsistent results are manifold. In summary, correlations between the approach and release velocity to jump distance tend to decrease with (1) increase in the standard of performer, (2) increase in sample homogeneity and (3) size of the jump hill. Based on kinematic studies, the magnitude of the approach and release velocities observed during competition for reaching greater jump distances are of subordinate importance. For longer jump distances, the take-off and flight quality are more important than a high approach and release velocity.

The vertical release velocity or, rather, the component of release velocity perpendicular to the take-off table, is another kinematic parameter that has been studied in relation to jump distance. Some of the correlations reported in the literature include 0.85–0.90 (Hochmuth, 1959), 0.39 (Komi *et al.*, 1974), 0.61 (Schwameder and Müller, 1995) and 0.30 (Arndt *et al.*, 1995). These results show that the correlation depends on the standard of performance and the homogeneity of the athletes analysed, the conditions of the study (training *vs* competition), the size of the hill and the technique (parallel *vs* V-technique).

In addition to these ballistic parameters, aerodynamic variables such as body angles, body positions and changes of body positions during take-off have been studied increasingly with respect to their effect on jump distance. Gisler *et al.* (1977) and Virmavirta and Komi (1993a) reported a strong relationship between upper body position and jump distance. Three parameters indicating changes in body position during take-off are important for a long jump distance: (1) the generation of angular momentum during take-off (Gisler *et al.*, 1977; Virmavirta and Komi, 1994; Arndt *et al.*, 1995; Schwameder and Müller, 1995); (2) high leg-extension velocity (Baumann, 1979; Virmavirta and Komi, 1993a; Arndt *et al.*, 1995; Schwameder and Müller, 1995); and (3) the direction of the take-off movement (Virmavirta and Komi, 2000a; Schwameder and Müller, 2001a). In addition, the correct timing during take-off is important for length of distance jumped (Baumann, 1979; Campbell, 1980; Segesser *et al.*, 1981; Klauck, 1989).

After the take-off, the early flight (about 25 m after take-off) may be the most sensitive and significant phase. Kinematic studies of this phase have been published by Baumann (1979) for the parallel technique using a two-dimensional kinematic approach, as well as by Schwameder and Müller (1995) and Arndt *et al.* (1995) for the V-technique using three-dimensional kinematic analyses. Although Baumann restricted his study to a description of the position angles, Schwameder and Müller (1995) and Arndt *et al.* (1995) ascertained performance-determining variables using multi-variable approaches. Schwameder and Müller (1995) found that jump distance correlated most strongly ($r = 0.89$) with a combination of high vertical velocity, high knee-angle velocity, high torque during the take-off and a small body–ski angle after 20 m of flight. An investigation under competitive conditions (Arndt *et al.*, 1995) has shown that a combination of a large forward lean of the upper body, the lower body and the skis after 17 m of flight, together with a large ski and leg opening angle after 17 m of flight, correlate most highly with jump distance ($r = 0.92$).

Simulation jumps

Simulation ski-jumps have not been analysed very intensively using kinematic methods. The main interest has been the kinematic comparison between hill and simulation jumps. Using a two-dimensional kinematic approach, Sasaki and Tsunoda (1988) reported a release direction perpendicular to the take-off table for hill jumps, whereas for simulation jumps a strongly forward-oriented movement was performed. This movement pattern results from the lack of wind resistance and high friction during simulation jumps. In another study, Sasaki *et al.* (1990) tried to clarify the technique-specific problems of the take-off in dry-land training. They observed differences between hill and simulation jumps with respect to kinematics. Additionally, differences were noted in the spatial–temporal structure of movement for jumpers of varying standard.

Kinetic methods and results

Hill jumps

Force measurements in hill jumps are difficult technically, so the number of kinetic studies in ski-jumping is limited. The most frequent method used is to measure ground reaction forces using force plates installed in the take-off table (Segesser *et al.*, 1981; Vaverka, 1987; Vaverka *et al.*, 1993; Virmavirta and Komi, 1989, 1991, 1993a,b). The advantage of this method is that the jumpers are not affected in any way by the measuring system and that it can also be used during competition.

On the other hand, only a limited sequence (take-off phase) and the resulting ground reaction forces can be measured.

Virmavirta and Komi (1993b) reported that their measurement method is able to register differences in the forces of different jumpers and, therefore, individual-specific jumping techniques. They used this method to compare the ground reaction forces of elite and juvenile jumpers during competition. The peak ground reaction forces for the juvenile jumpers were significantly smaller and occurred significantly later than those of the elite performers (Virmavirta and Komi, 1993b). Using the same method, Virmavirta and Komi (1994) compared the maximal ground reaction force of the contemporary top world ski jumper (also the winner of this competition) with those of the eight ski jumpers who finished second to ninth under competitive conditions. The winner proved to have a significantly lower peak force in the early take-off phase and a significantly higher peak force in the late take-off than the jumpers placed second to ninth. The increasing force development towards the end of the take-off phase may well characterize the main advantage of the winning jumper's profile.

Tveit and Pedersen (1981) were the first to introduce a device to measure forces between the boot and the ski; this device was only usable, however, under training conditions. Force data were collected separately using load cells mounted in the toe and heel of the right foot. The authors used this method primarily to indicate differences in force production during hill, simulation and roller-skate take-offs.

Schwameder and Müller (1995) used a pair of insoles (Pedar, Novel), each with 85 capacitive sensors, to measure the pressure distribution under the foot in hill jumps. These data served to calculate the ground reaction forces for the entire foot or selected and defined regions (left–right, forefoot–heel, etc.). The advantages of this method are the registration of ground reaction forces for the entire sequence from in-run to landing and the differentiation in separated insole areas. The limitations of this study were the low sampling rate of 40 Hz and the fact that the device cannot be used during competition

Schwameder and Müller (1995) presented a detailed description of total and partial forces over the entire sequence from in-run to landing of 22 hill jumps (four elite and four juvenile jumpers). An example of the ground reaction forces according to forefoot and heel are presented in Fig. 6. During the straight part of the in-run, the distribution of force at the forefoot and the heel is balanced; in the in-run curve (mid-way between the straight in-run and take-off table) and during take-off, a pronounced increase in force at the forefoot is observed (Fig. 6). The landing peak reaches values around three times body weight. In the context of this study also, discrete force parameters between elite and juvenile jumpers were compared. One of the results was that the elite jumpers realized significantly higher forces during the take-off than the juvenile jumpers (Schwameder and Müller, 1995).

Force distribution monitoring with 16 pressure sensors (Paromed) was introduced by Virmavirta and Komi (2000b). This method of measurement is characterized by a substantially higher sampling rate

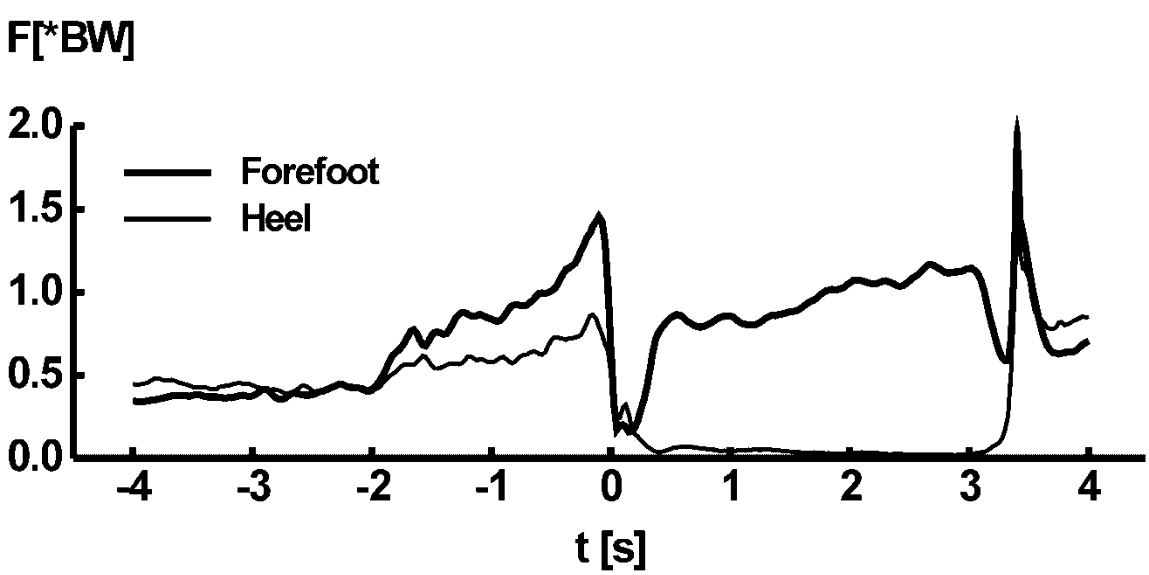

Fig. 6. Mean of the forces at the forefoot and heel over time during hill jumps ($n = 22$, $t = 0$: take-off). Reproduced with permission from Schwameder and Müller (1995).

compared with the Pedar insoles. The insoles, however, have to be adjusted individually to the jumper to guarantee reliable pressure and force measurement. Virmavirta and Komi (2000b) observed a balanced pressure distribution between heel and forefoot in the straight part of the in-run for all three jumpers. During the in-run curve and during take-off, however, a significant increase of force was noted in the toe and forefoot (Fig. 6).

Simulation jumps

The first scientific studies of simulation jumps were those of Hochmuth (1958/59). He was the first to use force plates to analyse the take-off movement of ski-jumpers. Simulation jumps on force plates have developed to become a very helpful and informative tool in the training process of ski-jumpers. They are used in performance diagnostics, to analyse the differences between hill and simulation jumps and to study special effects of techniques and equipment under dry-land conditions.

Vaverka (1987) studied the stability of time and force parameters in simulation jumps using force plates. He observed that: (1) time and force parameters were individual-specific; (2) force maxima were correlated positively with jump height; (3) intra-individually, time and force parameters were very stable ($r = 0.72$ and 0.75); (4) the stability of the parameters investigated correlated positively with the performance of the jumper; and (5) the characteristics in the late take-off phase showed greater stability than in the initial phase.

Pedotti and Rodano (1987) presented a method to quantify jump quality and biomechanical patterns. They used a two-component force plate to test three groups of jumpers of varying standard during three types of jumps. The jumps were characterized according to the resulting release velocity, the release angle and force vector diagrams. As release velocity differed significantly among the three groups, the authors assumed these parameters to be performance-related. In contrast, there was no significant difference in release angle among the three groups. The authors considered their method useful to improve jump performance and to develop helpful training equipment and support devices.

Force plate measurements were also used to study the effect of the initial position on dynamic characteristics during take-off in simulation jumps (Schwameder *et al.*, 1997). Take-off duration, release velocity and explosive force (peak force rate) from jumps out of a deep (knee angle $\kappa = 78^\circ$), neutral ($\kappa = 70^\circ$) and high initial position ($\kappa = 91^\circ$) were measured in world-class ski-jumpers. With the high position, the take-off duration decreased and the explosive force increased significantly compared with the neutral position, whereas with the deep position the relationship with the neutral position was the reverse. Regarding release velocities, however, no differences between the three positions were observed. Based on these results, the authors recommended individual-specific optimal in-run positions, adapted to anthropometric and sensorimotor pre-conditions as well as to the force capacities of the jumpers.

In the same study, Schwameder *et al.* (1997) addressed how footwear influences take-off parameters. Compared with jumping boots, training shoes increased the release velocity significantly by 4–5%, due to the limited plantar flexion in jumping boots. A comparative EMG analysis of the gastrocnemius supported this explanation. Based on these results, the authors recommended increased training specificity by using jumping boots for simulation jumps. These results were confirmed by Virmavirta (2000).

Virmavirta (1999, 2000) studied the effect of headwind on dynamic parameters in simulation jumps. World-class jumpers performed simulation jumps in a wind tunnel with headwinds of 27 and 33 $m \cdot s^{-1}$, respectively, and in no-wind conditions. Based on ground reaction force measurements of take-off duration, peak force and momentum were selected as parameters. In wind conditions, the take-off duration was significantly reduced (by up to 14%), while peak force and momentum did not change. The results were explained by the supporting lift in the wind conditions. Additionally, the explosive force and, subsequently, the dynamic structure of simulation jumps were considerably changed in the wind conditions. Wind tunnel simulation jumps are more training-specific by taking advantage of aerodynamic forces.

The first comparative analysis of hill and simulation jumps in terms of kinetics was made by Tveit and Pedersen (1981). They used skis instrumented with load cells under the ball and the heel and found higher take-off forces for simulation jumps than for hill jumps. The authors concluded that vertical acceleration during take-off has been assigned too much importance. Vaverka *et al.* (1993) compared the dynamic structure of hill and simulation jumps. They observed that, on average, hill jumps reached 72% of the release velocity of simulation jumps. On the basis of this result and based on the high correlation between release velocity under hill and laboratory conditions ($r = 0.89$), the authors considered simulation jumps to be a reliable test to determine the take-off abilities of ski-jumpers.

A differentiated and comparative analysis of the pressure distribution on the sole of the foot between hill and simulation jumps was presented by Virmavirta (2000). The results were analysed for the in-run and for three take-off segments (100 ms each). In all phases, the pressure distribution differed significantly between hill and simulation jumps and were caused by the differing boundary conditions (friction, lift, drag) of hill and simulation jumps.

Electromyographic methods and results

Hill jumps

There have been few studies on hill jumping in which electromyographic methods have been used. One of the most comprehensive and detailed studies was that of Komi and Virmavirta (1997), in which the activities of vastus lateralis, vastus medialis, gastrocnemius, tibialis anterior and gluteus maximus were recorded over the entire sequence from in-run to landing. Virmavirta (2000) studied the activity of the tibialis anterior, gastrocnemius, vastus lateralis and gluteus maximus, together with the pressure under the heel and the toe for the entire jump (Fig. 7). During the in-run, the activity of all muscles is very low. The entry into the in-run curve increases the activity of the vastus lateralis, tibialis anterior and gastrocnemius, thus stabilizing the knee and ankle joint. The jumper has to counteract the additional load caused by the centrifugal force in the in-run curve. The gluteus maximus still remains inactive. During the entire take-off, the vastus lateralis and gastrocnemius increase their activities substantially. The tibialis anterior and gastrocnemius are active, although not more than during the in-run curve, to stabilize the ankle joint. The flight phase is characterized by high activities of the vastus lateralis, tibialis anterior and gastrocnemius. During landing, the activities of all muscles are high to control the large transient landing forces and to guarantee stabilization of the body.

Virmavirta (2000) also studied the activities of the tibialis anterior, gastrocnemius, vastus lateralis and gluteus maximus in hill jumps during the in-run, the in-run curve and the take-off depending on size of the hill (35 m, 65 m, 90 m). The differences were found to be very small. In some phases and for some muscles, significant differences were observed (gastrocnemius: take-off; gluteus maximus: take-off; vastus lateralis: in-run, in-run curve). In all of these cases, the activities decreased with the size of the hill.

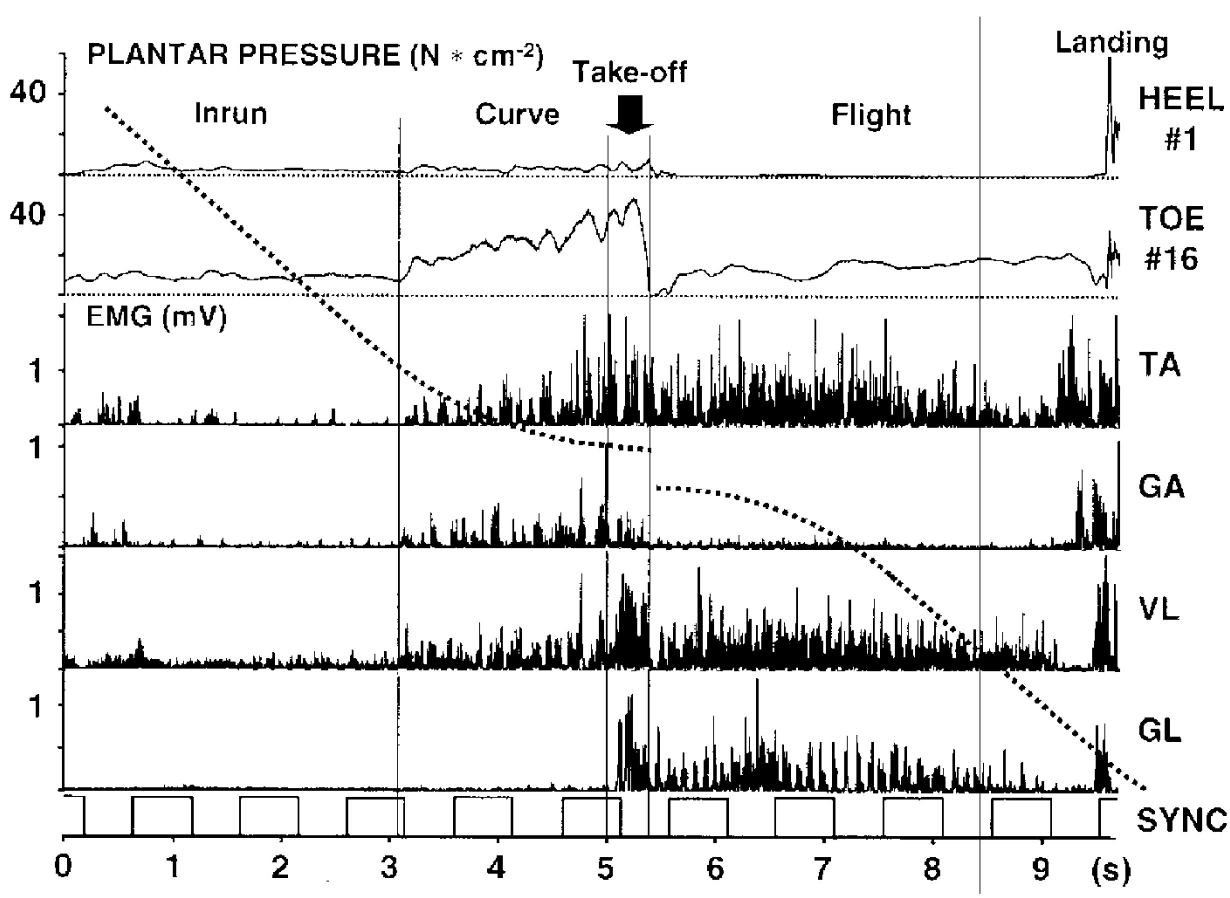

Fig. 7. EMG and heel–toe pressure for a hill jump. Reproduced with permission from Virmavirta (2000).

Simulation jumps

A differentiated and comparative analysis of muscular activity of the tibialis anterior, gastrocnemius, vastus lateralis, gluteus maximus and biceps femoris between hill and simulation jumps was presented by Virmavirta (2000). The activities of all muscles differed, in some cases substantially, between hill and simulation jumps; the most distinct differences, however, were found for the tibialis anterior and gastrocnemius. The differences were described in detail and were justified by the differing boundary conditions (friction, air resistance and lift) of hill and simulation.

Virmavirta (2000) also analysed the activity of the same muscles for simulation jumps with training shoes and with jumping boots. While the differences for the vastus lateralis, gluteus maximus and biceps femoris were small, substantial and significant differences were found for the tibialis anterior and gastrocnemius. Wearing jumping boots resulted in a restricted plantar flexion of the foot with the effect of reducing the range of motion and, subsequently, reducing the activity of the tibialis anterior and gastrocnemius. These results, in combination with the relevant force and pressure distribution data described above, support the recommendation of wearing jumping boots in simulation training to increase the training specificity.

Computer simulations of the flight phase

Most computer simulations of ski-jumping presented in the literature were aimed at determining (1) the dependence of flight position on jump distance or (2) the effect of the transition from take-off to flight on jump distance (Ward-Smith and Clements, 1982; Remizov, 1984; Denoth *et al.*, 1987; Hubbard *et al.*, 1989). Only a few reports have focused on aspects of safety and loading (Straumann, 1927; Müller *et al.*, 1995, 1996; Müller, 1997). Kinematic data from field studies (Baumann, 1979; Gasser, 1979) or results from wind tunnel measurements (Straumann, 1927; Ward-Smith and Clements, 1982; Watanabe, 1983; Müller, 1997; Yamanobe and Watanabe, 1999; Sasaki *et al.*, 2000) have served as input data for the models or for validating the models.

Because of the different kind of models used in the simulations, the results for optimal flight positions differed quite substantially. The calculations of Ward-Smith and Clements (1982) matched closely with real flight paths regarding the angle of attack and showed a negative correlation between the angle of attack and the distance jumped.

Remizov (1984) demonstated that an increased jumping distance could be achieved if the body's angle of attack was increased with respect to a convex function. Hence, the path of this function depended on individual aerodynamic parameters. On the basis of these calculations, he claimed that there is only one time-dependent combination of air forces to guarantee maximal jumping distance.

Hubbard *et al.* (1989) presented a four-segment model with time-dependent joint torques. With an increase in the number of degrees of freedom in the model, higher agreement with kinematic measurements could have been achieved. In this context, the authors emphasized that the quality of experimental aerodynamic data is important for high-quality computer simulations.

Watanabe and Watanabe (1993) measured aerodynamic forces and torques for the V-technique using a 1:1 wood model in a wind tunnel study. The positive influence of the V-technique on jumping distance was confirmed through calculations derived from wind tunnel investigations. Furthermore, the authors observed that jumping distance was increased by reductions in the body–ski angle caused by the reduced turbulences on the dorsal side of the jumper.

Müller *et al.* (1995, 1996; Muller, 1997) studied aspects of loading as well as optimization of hill profiles in ski-jumping. Their results can be summarized as follows: (1) dangerous landing impacts do not result from increased landing velocity at the end of long-distance jumps, but primarily from the mismatch of the glide paths and existing hill profiles; (2) almost all existing hill profiles have a curvature after the K-point, which causes a dramatic increase in the equivalent landing height within a few metres; (3) due to the extremely difficult and dangerous landings in the upper part of the hill, particular care should be taken for the design of the hill curvature adjacent to the ramp; (4) glide path modifications due to changes in equipment must correspond with regulations about the design of jumping hills.

Summary

Biomechanics play an important role in ski-jumping research. Both hill and simulation jumps have been measured and analysed using the methods of kinematics, dynamics, electromyography and computer simulation. Limitations on biomechanical data collection for hill jumps include the wide spatial range of motion and, subsequently, the time expenditure in field studies. Under competitive conditions, only kinematic parameters for the entire sequence from in-run to landing and kinetic parameters during take-off can be determined. All other methods can only be used under training conditions. Based on the studies presented and the methods of measurement described above, the following are important:

- The development of feedback systems to evaluate the quality of hill jumps immediately after exercise using kinematic and kinetic parameters. The jumper-related optimum should be of central and specific interest.
- A comparison of simulation jumps in different conditions with hill jumps, especially regarding kinematics, kinetics and the muscle activation pattern using EMG.
- The testing and development of materials and equipment.
- An examination of the effects of equipment and material modifications (skis, bindings, suits, etc.) on flight characteristics with the aim of increasing jumper safety and determining groups of jumpers with particular anthropometric and neuromotor requirements.
- Basic principles for hill construction to ensure the safety of jumpers, minimize the risk of injury and preserve the attractiveness of competition.
- An analysis of musculoskeletal loading in hill jumps (primarily during landing and take-off) and simulation jumps.

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