Biomechanical analysis of cross-country skiing techniques

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ABSTRACT

SMITH, G. A. Biomechanical analysis of cross-country skiing techniques. *Med. Sci. Sports Exerc.*, Vol. 24, No. 9, pp. 1015–1022, 1992. The development of new techniques for cross-country skiing based on skating movements has stimulated biomechanical research aimed at understanding the various movement patterns, the forces driving the motions, and the mechanical factors affecting performance. Research methods have evolved from two-dimensional kinematic descriptions of classic ski techniques to three-dimensional analyses involving measurement of the forces and energy relations of skating. While numerous skiing projects have been completed, most have focused on either the diagonal stride or the V1 skating technique on uphill terrain. Current understanding of skiing mechanics is not sufficiently complete to adequately assess and optimize an individual skier's technique.

CROSS-COUNTRY SKIING, SKATING, KINEMATICS, KINETICS, FORCE

Biomechanical studies of locomotion have contributed to the general understanding of the kinematic and kinetic characteristics typical of various movement patterns. In cross-country skiing, biomechanics researchers have been particularly challenged during the past decade as ski techniques have changed in a revolutionary manner rarely seen in sport. The development of skating techniques has been a stimulus to the sport and to research as well, and understanding the new techniques has motivated much of the exploration and discussion of the past several years. Skiers experiment with both skating and classic techniques with the evolving techniques staying well ahead of the ongoing research projects.

Understanding a complex movement pattern like cross-country skiing involves several levels of assessment. Initially, it is helpful to describe how the body moves through space to describe the kinematics of the pattern. This may involve whole body characteristics such as cycle velocities or rates as well as more isolated measures such as knee or elbow angles. Kinematic description is of interest for comparing individuals or techniques, but kinetic evaluation of movement in terms of force and energy is a more basic approach to understanding the causes behind an observed pattern.

Measurement techniques. Kinematic assessment of movement has usually involved some means of recording the movement for later analysis. High-speed film and, more recently, video have proven to be appropriate media for data capture. Single-camera, two-dimensional analyses have been used in cross-country skiing for measurement of relatively planar techniques like diagonal stride or double poling. The skating techniques are nonplanar movements, however, and have required three-dimensional methods for both kinematic and kinetic assessment. Three-dimensional computation has generally involved the Direct Linear Transformation (1). This approach uses two or more cameras to record the motion along with a three-dimensional calibration of the field. While the availability of high-speed microcomputers has made such data collection a routine matter, such techniques are tedious to perform, particularly under difficult environmental conditions, and involve time-consuming digitizing of two or more camera views. The results of such three-dimensional coordinate determinations, however, have proven to be relatively accurate (10).

To understand the causes of the kinematics observed in cross-country skiing, both force and energy analyses have been carried out. Force measurement in skiing is complicated by the ski equipment and the snow surface. Komi (11) described two approaches to such measurements: an array of force plates placed beneath a snow surface, and alternatively a portable force plate attached to the ski. In general, researchers have chosen the latter approach. Various portable force collection systems have been devised (6,11,19,24,30). In each case, the ski's orientation must be known for the ski as a function of time. For classic techniques such as the diagonal stride, the skis are constrained to tracks in the forward direction so it is a relatively simple matter to obtain force components from a force plate moving with the ski. In skating techniques, the skis change their orientation throughout a cycle, making it considerably more difficult to obtain force components. Resultant forces on the ski must be oriented in space based on three-dimensional tracking of ski angles (see Fig. 1), which may be accomplished by simultaneous determination

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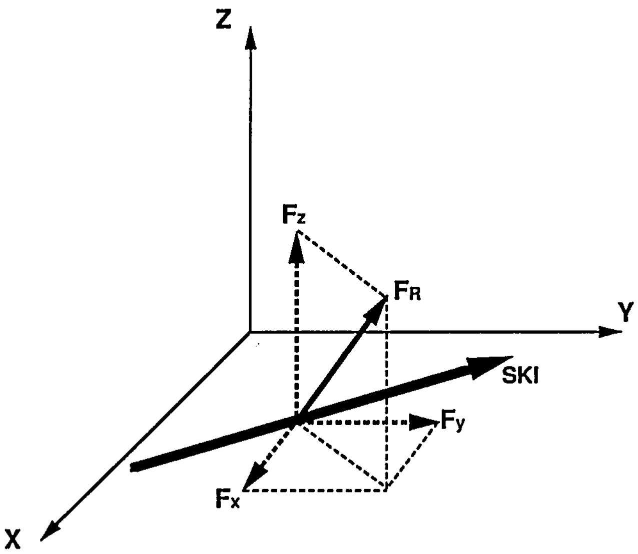

Figure 1—In skating, the ski is at an angle to the forward direction and is edged during the skating stroke. Force components in the lateral (X), forward (Y), and vertical (Z) directions can be determined if the resultant force direction is known.

of force and three-dimensional position. Unfortunately, the complexity of such data collections has made skating force measurement too difficult for routine use with ski teams or clubs.

Energy analysis methods have been applied to locomotion patterns for determination of mechanical power, energy exchange, efficiency, and metabolic cost (20,21,31,33). In cross-country skiing, energy methods have been used to determine mechanical power requirements for diagonal stride (16–18) and for skating techniques on several slopes (27). The methods start with kinematic measures of body segment positions and proceed to segmental energy levels, mechanical work, and mechanical task cost. The usefulness of such determinations is in characterizing technique with quantities that have some relationship to metabolic cost. While there is some disagreement about mechanical to metabolic energy relations, the potential of such assessments is substantial in endurance events such as cross-country skiing where economy of motion is an important factor affecting performance. Mechanical energy changes have the potential to be used to determine the relative effectiveness of a skier's technique or to compare techniques; and, in addition, estimations of metabolic cost can be made from the energy calculations without the invasive and disruptive problems of direct metabolic measurement.

The following discussion has been organized by kinematic and kinetic analyses of the classic and skating techniques.

KINEMATICS

Researchers from the Swiss Federal Institute of Technology (Zurich) carried out several of the earliest studies of cross-country skiing mechanics utilizing high-speed film of world-class skiers during races. For example, Waser (unpublished data, 1976) analyzed the First International 15-km race in Davos, Switzerland (December 1974), and other researchers analyzed the men's 15-km race at the 26th International Ski Competition in Le Brassus, Switzerland (January 1977), resulting in a comprehensive analysis of diagonal stride as well as the kick double pole technique (2,8,29). A consistent finding from the diagonal stride studies was the relationship of stride length with performance: the best skiers exhibited longer stride lengths on all terrain while for the kick double pole technique it was stride rate that was positively related to performance. Faster skiers were double poling at higher tempo than slower skiers.

Shortly thereafter, Dillman and colleagues at the University of Illinois began a series of studies based on films from the Gitchi Gammi Games (Telemark, Wisconsin, December 1977) and from the Lake Placid Pre-Olympic Games (1979) in which he corroborated the relationship of stride length and performance observed previously (4). Of the various kinematic and temporal variables that were analyzed on flat and uphill terrain, stride length was emphasized as perhaps the most significant factor distinguishing the best of the elite skiers (9,15)

In studies of elite female skiers (North American Championships, 1979), stride length was subdivided into component phases (14). Glide phase distances were found to be a particularly important component of the total stride length, and stride length was found to be strongly related to velocity and to race performance. Komi and colleagues (13) extended their kinematic analysis of male racers (World Championships in Lahti, Finland, 1978) to include center of mass (CM) velocity variations throughout a diagonal stride as well as hip joint and knee joint angular responses. The five elite skiers exhibited quite individual patterns of velocity variation in a complete stride. While angular patterns were similar among skiers, individual characteristics were noticeable.

Skating began to appear in cross-country skiing throughout the early 1980s. The first kinematic analysis was of the marathon skate (23), which was systematically compared with the kick double pole technique as a means of estimating the relative effectiveness and the method of velocity control in each case. The proportions of the stride phases were found to remain relatively stable across a range of velocities, but for a given intensity the marathon skate was found to be significantly faster than the kick double pole.

Initial kinematic analysis of the V1 skating technique began with the 30-km World Cup race at Biwabik, Minnesota (December 1985). On steep uphill terrain (5), 10 elite male racers were characterized in terms of cycle velocity, length, and rate. Like the findings for diagonal stride, racers using the V1 skate exhibited quite similar tempo, but the faster skiers had longer cycle lengths.

In the first of several ski studies from the Pennsylvania State University Biomechanics Laboratory, films from the Oslo World Cup 4 × 10 km relay race (March 1986) were evaluated in which the V1 technique of 10 elite male skiers was analyzed in kinematic terms (25). Several of the primary characteristics included the following mean values: cycle velocity of 3.23 $m \cdot s^{-1}$, cycle length of 3.84 m, cycle rate of 0.84 Hz, strong and weak ski angles of 25.3 and 22.7 degrees, and CM velocity vector angle of 8.5 degrees. Cycle length, weak ski angle, and CM velocity vector angle were significantly related to velocity: the fastest skiers tended to skate with smaller weak side ski angles and smaller CM deviation from the forward direction but with larger cycle lengths. Cycle thrust phases tended to be shorter for faster skiers.

At the Calgary Winter Olympics (1988), several cross-country ski projects were conducted. The men's 50-km and women's 20-km races were each filmed from two sites involving a steep uphill (approximately 11 degrees) and a moderate uphill (about 7 degrees). Kinematic analysis of the steeper uphill site, completed for 20 male and 22 female Olympic skiers determined smaller cycle velocities and lengths than for more moderate terrain (28). Both ski angles and CM lateral motion tended to be somewhat greater due to the steeper hill. On the steep uphill, cycle velocity was not significantly correlated with cycle length or cycle rate which was contrary to other findings relating cycle velocity and length. No consistent pattern was demonstrated by the more than 40 skiers analyzed in the Olympic races. Cycle length and rate both contributed to determining faster from slower skiers. Significant negative correlations were found between cycle length and rate. CM lateral motion and cycle length were positively related while cycle rate was negatively related to CM lateral motion. Ski edging angle estimations through the skating phases of the V1 skate demonstrated no clear pattern of edging between strong and weak sides; however, most skiers exhibited a relatively flat gliding ski on one side while the other side was more sharply edged. Figure 2 illustrates the mean phase pattern for the steep uphill terrain. A temporal comparison of the skating phases suggested that on the low angle hill, the poling phases tended to be shorter while the skating phases were of longer duration than on the steeper terrain; combined with longer recovery phases, cycle rates were lower on the moderate hill than on the steep hill. In a follow up analysis of the Olympic skiers (3), comparison focused on technique changes from moderate to steep uphill terrain. On the steeper hill, skiers skated with more strongly edged skis, greater stance width, and longer forward steps but with shorter cycle lengths and less lateral movement.

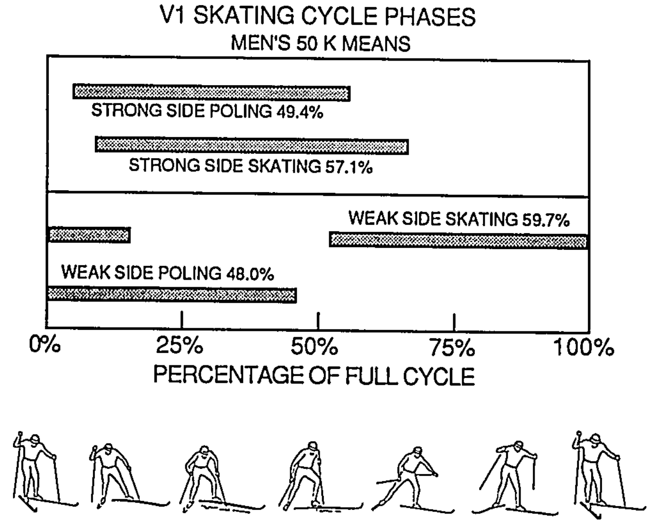

Figure 2—Mean skating cycle phases on a steep uphill during the men's 50-km race of the Calgary Winter Olympics. From "Analysis of V1 Skating Technique of Olympic Cross-Country Skiers" by G. A. Smith, R. C. Nelson, A. Feldman, and J. L. Rankinen, 1989, *International Journal of Sport Biomechanics*, (Vol. 5, No. 2), pp. 188. Copyright 1989 by Human Kinetics Publishers, Inc. Reprinted by permission.

Control of velocity. One aspect of characterizing locomotion kinematics involves the mechanisms used in the control of velocity. In cross-country skiing, cycle velocity of classic techniques has been found to be typically controlled through adjustment of cycle rates (7,23). In the marathon skate, skiers also tend to skate with relatively constant cycle lengths across a range of speeds (23); increases of speed are produced by higher tempo skating. Figure 3 illustrates the cycle rate and cycle length relationships to velocity for kick double pole and for the marathon skate.

In V1 skating, faster skiers consistently skated with longer cycle lengths than slower skiers but with quite similar cycle rates (26). However, across a range of intensities, both slower and faster skiers were found to increase their velocities by increasing the tempo of skating rather than cycle length. The implications were that cycle length is very important for performance since the faster skiers had the longest cycle lengths, but is not generally the mechanism used to go faster: both slower and faster skiers increase their relative speeds by increasing cycle rates. At any given moment in a race, the tempo governs velocity and should be the skier's focus. It is in training that emphasis should be given to cycle length. There, the racer should strive to increase the natural skating cycle length through improved glide and increased propulsive force.

KINETICS

Studies of skiing kinetics have taken two directions: the determination of skier mechanical energy characteristics and the measurement of forces applied to skis and poles. A series of papers dealing with mechanical

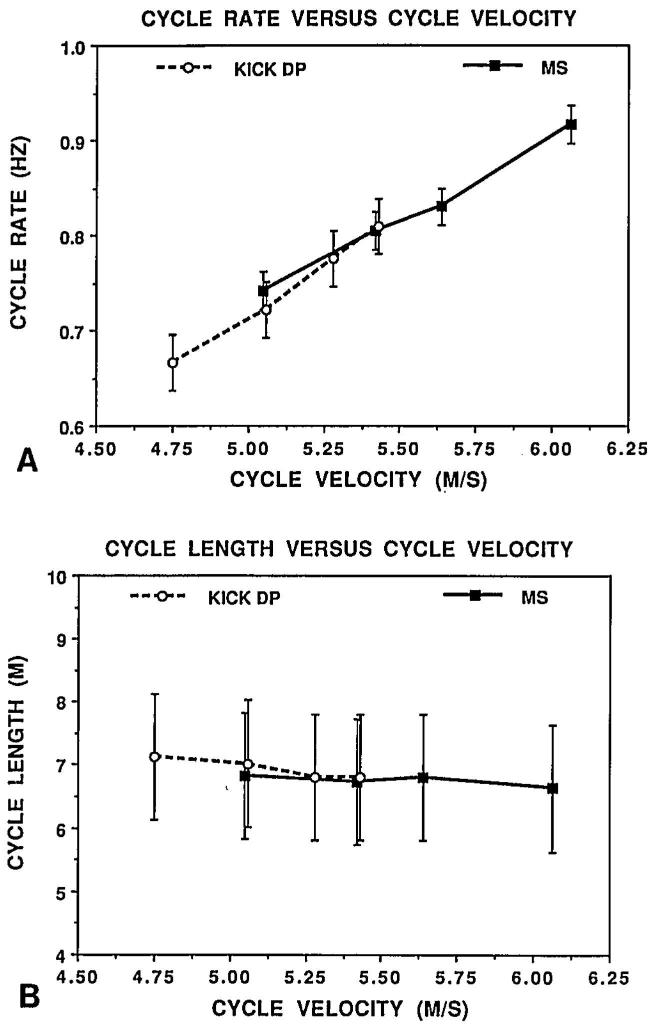

Figure 3—For both the kick double pole and the marathon skate techniques, A) cycle rate increased with velocity while B) cycle length remained relatively constant (23).

energy levels in skiing based on high-speed films from World Championship and Olympic races determined body segment energy utilization patterns exhibited by elite skiers on flat terrain, which were compared with those patterns exhibited by "recreational" cross-country skiers on flat terrain (16). A second study (17) focussed on elite skiers on both flat and uphill sites in a World Championship race (Lahti, Finland, 1978) while two studies have analyzed skiers from Calgary's Olympic races (18,27). Each of these investigations employed relatively similar methods: digitized records from the high-speed films were analyzed in terms of body segmental energy levels using methods detailed by Winter and colleagues (20,21,33).

Elite skiers were found to use larger within-segment potential and kinetic energy exchanges during swing and pushing phases of the diagonal stride compared with recreational skiers (16). Further, the elite skiers consistently obtained longer glide per stride and greater stride length, probably due to higher leg swing and greater use of gravitation force as a supplement to muscle force in the leg swing.

In a comparison of mechanical energetics on two slopes (17), calculation of mechanical work rate (work output divided by period of time), mechanical energy transfers, and mechanical task cost (MTC, work to move 1 kg 1 m) were made from digitized data. Norman and Komi (17) described the MTC as the "best overall relative indicator of mechanical effort, and thus technique efficiency of individual skiers. . . ." Based on the MTC, uphill terrain involved 2.2 times the energy cost of flatter terrain (1.8 vs 4.0 $J \cdot kg^{-1} \cdot m^{-1}$).

Similar MTC methods were combined with muscle efficiency estimates to determine oxygen uptake for selected male skiers in the Calgary Olympic 30-km classic race on an 11-degree uphill (18). An assumption of complete energy exchanges between body segments resulted in conservative estimates of oxygen cost. Mechanical power outputs and estimated oxygen uptakes were found to be substantially greater for the faster skiers compared with the slower skiers of the sample. Skiers in the Calgary 50-km race (skating) were analyzed on the same slope as well as a lower-angle slope (27). Skiing velocities were quite similar for both the diagonal stride and skating observations. However, diagonal stride involved substantially greater mechanical power output, greater mechanical task cost, and greater estimated metabolic costs. Figure 4 illustrates these comparisons of diagonal stride and skating energetics.

Ski forces. An important element in understanding ski locomotion patterns is the direct measurement of forces applied to skis and to poles. Two instrumentation approaches have been used: a force plate array set under the snow surface and portable force plates mounted on each ski (11). In the first approach, adapting standard laboratory force plates to a winter outdoor environment requires careful mounting of force plates to isolate them from snow and ice as well as from adjacent plates. Once a set of force plates is in place beneath a ski track, repeated trials of many skiers can be easily measured. With an appropriate array of plates, independent measures of each ski and pole resultant and component force can be obtained for classic techniques (diagonal stride, double pole) where the skis are constrained to set ski tracks (see Fig. 5). However, no separate measures are possible for skating, as the skis are free to be placed anywhere. Other force measurement approaches most be used for studying the skating techniques.

In his review paper of force measurement techniques in cross-country skiing, Komi (11) also described a small, portable force plate system to be attached to a ski between the binding and the upper surface of the ski, allowing for measuring forces from numerous consecutive strides, but also requiring some means of either recording or transmitting data via telemetry. Ekstrom (6) was perhaps the first to instrument and measure

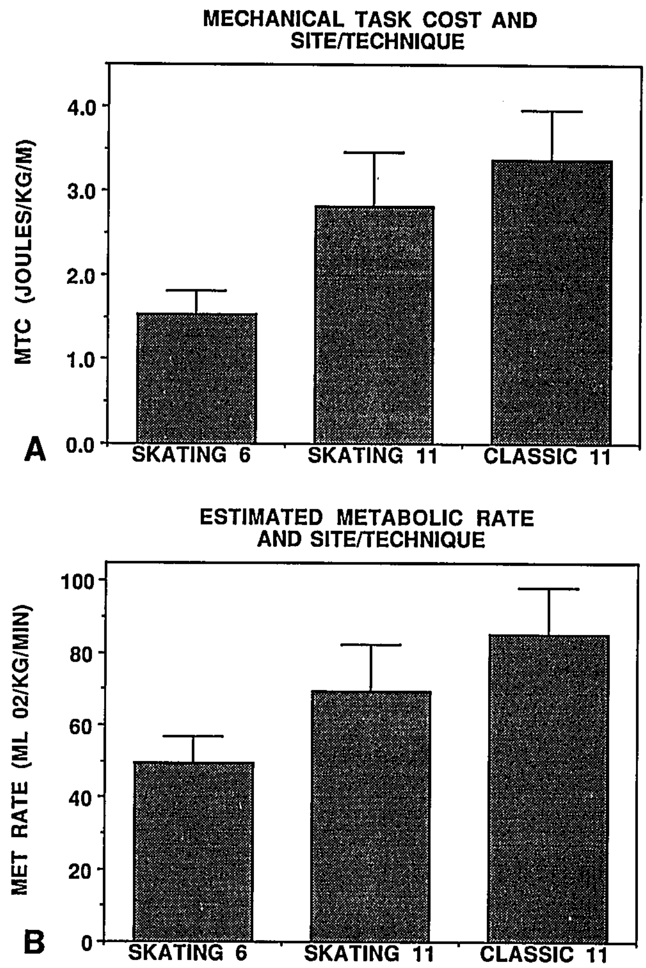

Figure 4—Energy analysis from the men's 30- and 50-km races of the Calgary Winter Olympics was used to determine mechanical task cost and to estimate metabolic rates. (Mechanical Task Cost is the mechanical work per kilogram body mass per meter traveled.) Skating 6 and Skating 11 were 6- and 11-degree uphills while Classic 11 was on the same 11 degree slope (18,27). Skating involved a lower cost of transport and lower metabolic costs than did diagonal stride on the same slope.

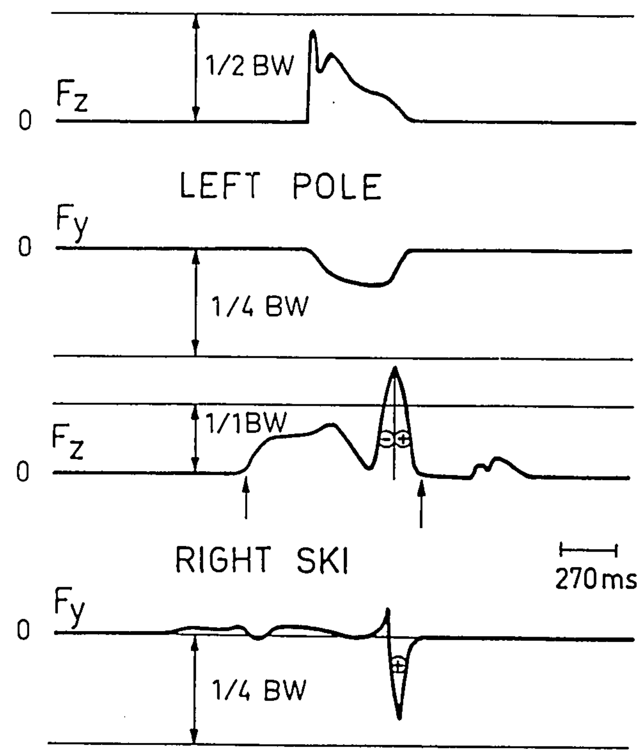

Figure 5—Typical reaction forces from skis and poles in the diagonal stride technique using an array of force plates for measurement. The Fz forces are vertical reaction forces while the Fy forces are oriented anterior-posterior in the direction of the ski tracks. From "Force Measurements During Cross-Country Skiing" by P. V. Komi, 1987, *International Journal of Sport Biomechanics*, (Vol. 4, No. 3), pp. 373. Copyright 1987 by Human Kinetics Publishers, Inc. Reprinted by permission.

forces involved in cross-country skiing. He used a portable telemetry-force plate system built around five load cells with three cells placed beneath the plate for measuring normal forces and two cells bracketed vertically to respond to anterior-posterior force components. Unfortunately, other than representative force tracings for typical diagonal strides, little of the force analysis has been published.

Pierce and colleagues (19) measured resultant forces for a variety of ski techniques: diagonal stride, double pole, kick double pole, and a skating stride (type unspecified). While poling force maxima were relatively small fractions of body weight (10–17%), ski force maxima were as great as 164% of body weight. Force components were not resolved in these studies, making more complete comparison impossible.

The force plate array system described by Komi (11) and Komi and Norman (12) was used in several studies of diagonal stride where electromyographic measurement was combined with high-speed filming and force measurement. The force-time curves included in the papers were resolved into normal and propulsive forces throughout the stride. Several conditions were tested though none was illustrated systematically (uphill slopes of 2.5 and 11 degrees and three velocities). In addition, these reviews included a vector analysis of the direction of kick force under three waxing conditions and a comparison of poling forces on three slopes (2.5, 5.5, and 11 degrees) with three waxes. Unfortunately, most of this graphic information was not elaborated upon in text.

These initial force measurements were aimed primarily at understanding diagonal stride kinetics, and although examples of typical skating forces were included in several cases (11,19) no systematic analysis was performed. Street (30) developed instrumented roller skis and poles for measurement of skating forces in dry-land training. While roller skiing has been shown to differ in some respects from on-snow skiing, the analysis of roller skiing forces provided at least an initial estimation of what might be found on snow. Four collegiate-level skiers were involved in the study that systematically varied skating velocity while observing the applied forces on a moderate uphill (7 degrees). Three-dimensional methods used in conjunction with the force measurement to determine directions of the applied forces showed poling forces to be a large proportion of the total force involved in V1 skating (40–50% of body weight) and were considerably larger than previously reported for diagonal stride. Resolution of the skating and poling forces into vertical, mediolateral, and propulsive components showed the contributions of each to be quite different: most of the vertical and lateral forces were provided by roller ski forces while propulsive forces were rather evenly distributed between roller skis and poles. Velocity increases in roller skiing were found to derive from increased poling forces more than from increased skating forces. Forces in skating were considerably different from those in diagonal stride: poling forces were 2–4 times larger than in diagonal stride and the duration of the skating thrust was about 70% longer than in diagonal.

On snow skating forces were recently studied for the V1 skating technique (24). A custom force plate was developed using small load cells at each corner. Placement of the plate between the ski and binding allowed for measurement of forces normal to the ski surface and measurement of the instantaneous center of pressure of the force (22). Analog forces were converted to digital data and stored in a small portable computer (1.3 kg) carried by the skier in a waist pack. In conjunction with three-dimensional video analysis of the V1 skating patterns, force components of ski and pole reaction forces were determined for a range of skiing speeds on two uphill slopes: typical reaction forces are illustrated in Figure 6. From these resultant forces, components in the lateral (X), forward (Y), and vertical (Z) directions were determined (Fig. 7): peak skating forces ranged from 1.2 to 1.6 times body weight (BW) while peak poling forces were between 0.5 and 0.6 BW. Average propulsive force increased with velocity and

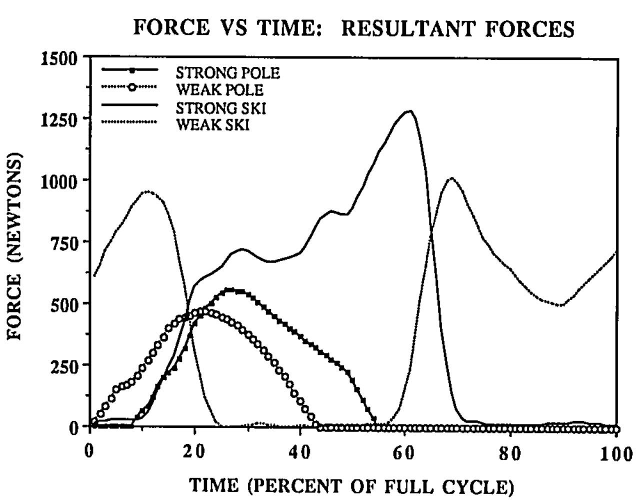

Figure 6—The resultant forces from skis and poles during the V1 skating cycle were measured using portable force plates attached to the skis and using instrumented poles (24).

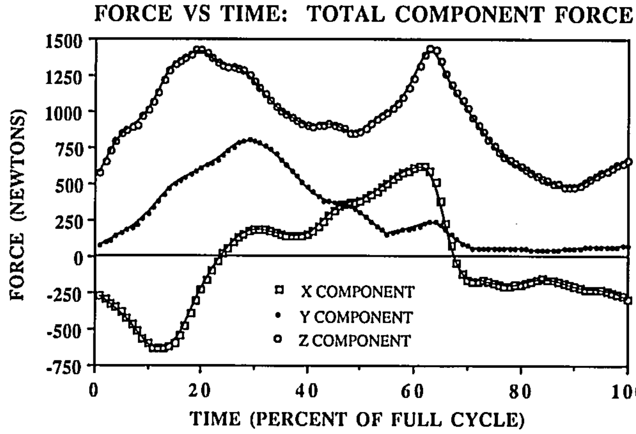

Figure 7—The total component forces were summed from the X, Y, and Z forces of each ski and pole. The propulsive force (Y) was largest during the synchronized poling and skating during the first half of the cycle (24).

with slope. Poling provided most of the propulsive force (about 66%) while contributing less than 20% to the lateral and normal forces. Skating forces were greatest in the vertical and lateral directions and served primarily to induce lateral motion and support the body against gravity while contributing little to propelling the skier uphill. Though the skiers involved in this study were "citizen" racers successful at regional level races, similar relationships of force components would be expected for elite skiers because of the limitations on generating forward-directed force from an edged ski.

Center of pressure of the skating force was also determined throughout the V1 skating cycle (22), with center of pressure patterns individually consistent across velocities but exhibiting some characteristic differences among skiers. The typical pattern involved an initial center of pressure approximately centered on the ski in the mediolateral direction and near midfoot (see Fig. 8). As the skating phase progressed, the center of pressure migrated medially and anteriorly in sequence with ski edging and plantar flexion of the foot near the end of the skating stroke. Some side-to-side asymmetry of the center of pressure pattern was also observed. The strong side skate that is accompanied by poling in the V1 technique involved center of pressure position forward by about 10–15% of foot length compared with that observed for the weak side.

While the V1 skate is the predominate technique used on uphills, several other skating techniques are used under fast skiing conditions on flat terrain. For example, the marathon skate, the V2 skate, and the V2-alternate (also called the "open field" and the "Gunde" skate) are all used by cross-country racers on flat and moderate rolling terrain. These techniques differ from the V1 skate in the timing of the poling and in the ski angles. On very steep uphills, skiers often use a "low gear" skating technique that involves a single poling thrust with the contralateral skate. This diagonal skate is used by elite skiers only on very steep uphills

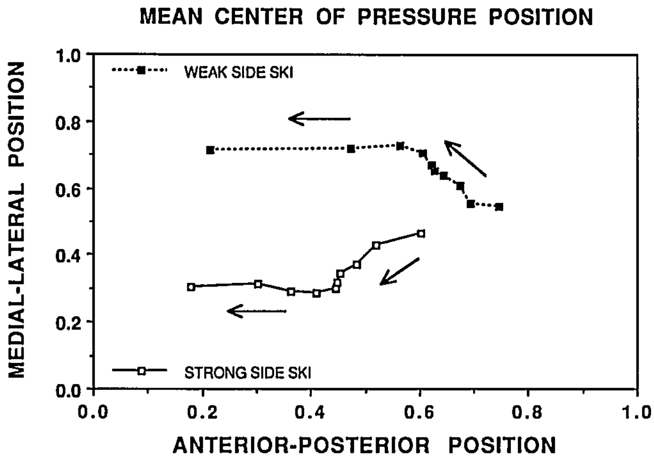

Figure 8—Center of pressure during a V1 skating cycle was determined using a portable force plate on each ski. Axis scaling on the graph is as a fraction of the force plate length or width. The front of the plate is zero (A-P direction) while on the vertical axis zero is the medial edge of the strong side and the lateral edge of the weak side ski. For both the strong and weak side skis, the center of pressure was initially centered on the ski near the skier's heel. As skating progressed, the center of pressure migrated anteriorly and medially in each case (22). The *arrows* indicate the time progression of the center of pressure during the skating phase.

where the V1 skate may be difficult to sustain. None of these techniques has been systematically studied to date; however, typical reaction force patterns for several of these techniques (Fig. 9) were measured using the force plate system described above (24). The marathon skate pattern can be recognized as a variant of the V1 pattern where double poling is nearly synchronous with one skating stroke. In the V2 skate, the double poling occurs near the middle of each skating stroke (two double poles per cycle). In the diagonal skate, a single poling thrust is synchronized with each skating stroke spreading out the poling forces across the whole cycle. Kinetic analyses of these various skating patterns have not been performed.

SUMMARY

Skating has contributed to a renewed interest in understanding the mechanisms of ski technique and ski equipment that contribute to performance. Much of the recent biomechanical research in skiing has been directed at the mechanics of the V1 skating technique on uphill terrain. Relatively little is known about the kinematics or kinetics of any skating technique on flat terrain. Skiers have developed alternative skating patterns like the "open field" skate; however, the effectiveness of such techniques has not been studied. The classic techniques of skiing have been analyzed for some time with the research focused mainly on the diagonal stride on uphills. Double pole and kick double pole techniques are less well understood. The effects of varying snow and/or wax conditions on technique have not been explored despite the daily struggle every skier

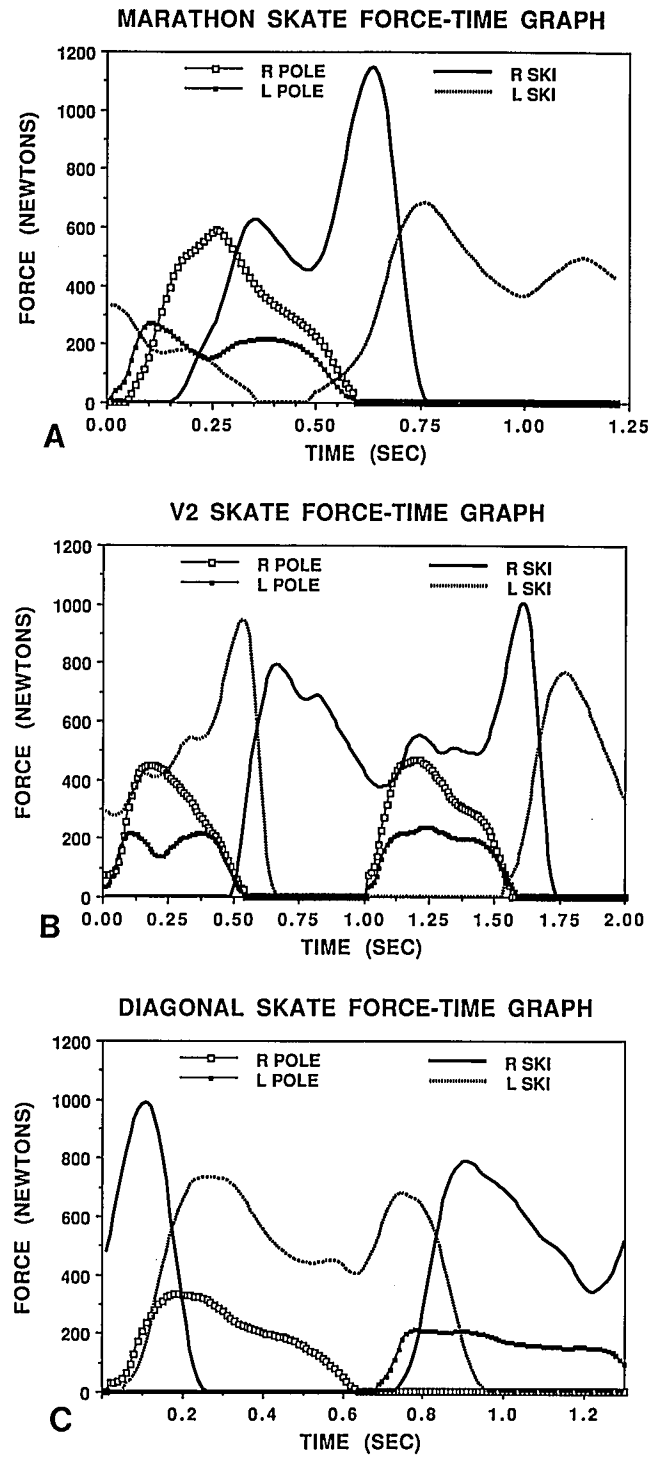

Figure 9—The resultant forces from skis and poles during A) the marathon skate, B) the V2 skate, and C) the diagonal skate were measured using portable force plates attached to the skis and using instrumented poles. The three graphs were all of the same skier on a moderate uphill. The right and left poling forces were asymmetrical for this skier for every technique. This is not a typical pattern for all skiers but illustrates common imbalances that can exist and that force measurement can detect.

faces with those conditions. In the realm of ski equipment, relatively little is known about a skier's interaction with skis and poles. Ski and pole lengths have changed substantially with the development of skating techniques, yet relatively little is known about the effect of ski and pole dimensions. The influences of such changes on technique and performance have yet to be determined.

Application of ski technique research to individual skiers is still a somewhat ambiguous undertaking. While the movement patterns of elite skiers might be assumed to be the optimum manner of performing, molding any given individual into the pattern of another ignores the idiosyncrasies of the individual. More complete understanding of the kinematic and kinetic relationships to individual characteristics will be necessary before technique optimization for individual skiers becomes possible.

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