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A kinematic investigation of the diagonal stride techniques of highly skilled cross-country ski racers.

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A KINEMATIC INVESTIGATION OF THE DIAGONAL STRIDE TECHNIQUES OF HIGHLY SKILLED CROSS-COUNTRY SKI RACERS

by

Brian Eric Titley

A Thesis
submitted to the Faculty of Graduate Studies
through the Faculty of Human Kinetics
in Partial Fulfillment of the requirements for
the Degree of Master of Human Kinetics
at The University of Windsor

Windsor, Ontario, Canada
1980

DEDICATION

with Love and Admiration,
for my Mother and Father

ABSTRACT

A KINEMATIC INVESTIGATION OF THE DIAGONAL STRIDE TECHNIQUES OF HIGHLY SKILLED CROSS-COUNTRY SKI RACERS

BY

Brian Eric Titley

The purpose of the study was to investigate the kinematic characteristics of the diagonal stride as performed by high caliber cross-country ski racers, in order to construct a descriptive profile based on these quantitative parameters.

Twelve experienced male racers were filmed at the 1979 North American Cross-Country Skiing Championships through the use of a Locam 16 mm camera operating at 97.5 frames per second. Displacement data were collected from every second frame throughout one stride for 16 reference points on the image of each racer, using a Vanguard Motion Analyzer. The data were then mathematically treated with a computerized error reduction process known as the cubic spline data smoothing procedure. Analysis of data included computerized calculations of displacement of the center of gravity, body segment configuration and phase proportions for a complete diagonal stride. Additionally, the stride length, stride rate and horizontal velocity of the center of gravity were determined for each skier and Pearson Product-Moment correlation coefficients were calculated for various pairs of performance parameters.

Results revealed a mean horizontal velocity of 4.29 m/sec (S=.47) produced by a mean stride length of 2.41 m (S=.22) and a mean stride

rate of 1.78 strides per second (S=.15). Mean time components accounted for by the various actions involved in the diagonal stride were found to be 18% for the free glide phase, 74% for the pole implantation phase; 36% for the foot stationary phase; and 27% for the leg thrust phase. The stride phase analysis indicated that 64% of the mean stride time was consumed by a sliding activity by the support ski(s) while a large proportion of the sliding was associated with pole implantation. The center of gravity analysis revealed a consistently increasing horizontal displacement. The vertical displacement results indicated a rise of the body beginning just prior to the time the thrust leg became stationary; the center of gravity returned to a low point during the pole implantation phase. The vertical velocity results for the center of gravity revealed a considerable range in magnitude for the twelve subjects, while no rapid fluctuations were discovered for the duration of the stride. Results indicating body segment configuration revealed a relatively flexed total body position at the initiation of the leg thrust phase; conversely, the body was maintained in an extremely extended position throughout the free glide phase. Concomitantly, the center of gravity was positioned behind the toe of the support leg during the free glide phase and in front during the leg thrust phase. Further analysis revealed a statistically significant relationship between horizontal velocity and each of stride length and stride rate ($P < .05$). No other significant correlations were discovered among pairs of performance parameters.

Upon completion of the study, several conclusions were warranted: (1) The diagonal stride is composed of a distinctly timed sequence of actions characterized by a relatively large period of leg support assisted by arm action and a subsequently small component of leg thrust; (2) High caliber skiers achieve average horizontal velocity through different combinations of stride length and stride rate; (3) The horizontal velocity of the center of gravity remains relatively constant, while the vertical velocity experiences a patterned fluctuation during the stride cycle; (4) Racers exhibit a forward-leaning, flexed body configuration prior to leg thrust while their bodies remain backward-leaning and extended during the free glide portion of the stride.

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CHAPTER I

INTRODUCTION

There is evidence of a rapidly increasing participation in cross-country skiing. Indeed, both racing and touring have recently experienced unprecedented growth. This popularity has been mirrored by the following observations:

> "Since the well-televised Olympics in Innsbruck the general public has become increasingly conscious of competitive cross-country skiing as a major sport." (Baldwin, 1977, p.12)

> "And its (Vasaloppet's) greatest fame came with the invasion of "Sunday-skiers", which began in the sixties and has now grown to a horde of 10,000 enthusiasts every year." (Petersson, 1974, p.12)

Despite this expanded interest in cross-country skiing as a recreational and competitive sport, there appears to be a shortage of high quality instruction. The numbers of knowledgeable coaches and trained instructors have not experienced a parallel development. This problem was succinctly described at the U.S. National Cross-Country Skiing Symposium in August, 1978:

> "Cross-country skiing is growing rapidly and there is a serious information gap existing in many parts of the country. Now skiers come into the sport daily and there are few qualified people providing quidance to not only the beginning skier, but especially the neophyte citizen's racer.. As a result, there are "experts" appearing like mushrooms overnight who have neither the experience nor the knowledge and our sport suffers as a result." (Bower, 1978, p.4)

Qualified instruction regarding technique is valuable for both recreational and competitive skiers; it is of utmost importance to the racer and it may enhance the efficiency and enjoyment of a ski tourer. This concern for the maintenance of adequate technique instruction is shared by authors of most publications regarding cross-country skiing. For example:

> "If you are skilled, you likely will prefer skis because a skilled skier can travel faster with less energy on skis than on snowshoes. Conversely, one who has little or no skill on skis will travel with greater ease and enjoyment on showshoes." (Jensen, 1977, p.5)

> "The importance of technique in cross-country ski racing is paramount. At the amateur levels the experienced skier and the one who has developed the smoothest striding technique is inevitably the winner." (Baldwin, 1977, p.12)

Their concern suggests an increased need for highly qualified instructors and coaches who may hasten the understanding and subsequent improvement of cross-country skiing technique. These professionals should be better able to achieve their objectives if they have a sound understanding of the mechanical principles involved in skilled performance. Such additional knowledge, combined with a coach's personal ability and experience, may enhance his effectiveness in achieving improved technique. Quantitative biomechanical research is an excellent source of information with which to provide an increased understanding of the mechanics of a skill. This relatively new area of study has gained considerable recognition for its benefits to teachers and coaches:

> "The more knowledge an individual has concerning the performance of a physical skill, the better he will be prepared not only to analyze but to suggest changes which result in improved performance. A knowledge of biomechanics can greatly aid the teacher in understanding and improving sport skill." (Martin, 1975, p.29)

> "Research is conducted at three levels along a continuum; practical, fundamental, and theoretical. The first of these focuses upon the analysis of sports skills to provide a better understanding of the execution of these movements so that teachers and coaches can work more effectively. (Miller and Nelson, 1973, p.3)

Thus, a practical approach to biomechanics research may be helpful in improving the technique levels of competitive and recreational cross-country skiers. It is therefore necessary that quantitative studies be undertaken.

High Speed Cinematography

One method of obtaining useful biomechanical information is the study of high caliber execution of a skill through high speed cinematography. This technique produces a permanent two dimensional record of the skilled performance without the subjects' knowledge and under actual competitive conditions. Thus, data may be collected in a realistic setting, eliminating the effects of experimentation. A basic assumption of this method of research, however, is that highly skilled performers will produce a desirable movement pattern. Subject to this assumption, the results may be utilized in numerous fashions. Firstly, the movement patterns may create a quantitative profile of highly skilled execution of the activity. Concomitantly, this profile may be considered an objective for poorly skilled performers. Secondly, an individual's performance may be compared to the performance profile of the group in order to evaluate the similarities and differences which have been quantified. These comparisons may reveal information regarding a particular performer's technique. This process identifies factors to which an enhanced or limited performance may be attributed. This claim has been reiterated in a work concerned with technique evaluation:

> "All of this serves to illustrate one of the problems with which physical educators and coaches are faced. How can they determine which features of a champion's technique contribute to the high quality of his performance--and thus are possibly worth copying--and which faults are limiting that performance? The answer to this question lies with the science of biomechanics, for it provides the basis, the only sound logical basis upon which to evaluate the techniques brought to our attention by champions." (Hay, 1973, p.4)

Although numerous manuscripts of qualitative technique analysis are readily available, relatively few quantitative investigations of cross-country skiing have been conducted. The majority have examined the diagonal stride, which is a basic movement pattern employed by skiers at all levels of expertise. The stride may be described as an exaggerated walking action for a beginner, while it appears to be composed of successive thrusting and gliding actions in the case of an experienced racer. The remaining component skills involved in cross-country skiing include an autonomous gliding technique aided by gravity and a double poling action which gains no obvious propulsion from the legs. Additionally, various combinations of pole utilization, striding, and hill climbing techniques are employed throughout a typical race. These varying techniques are required as a result of the diversity of cross-country skiing terrain. Although there can be little doubt regarding their importance to overall racing style, components other than the diagonal stride technique have not been evaluated in the present study. The selection of the diagonal stride technique was based on the fact that relatively few quantitative investigations of cross-country skiing have been undertaken. Thus, it was necessary that scientific study be conducted involving the basic component which spans the entire range of expertise in cross-country skiing. The relative importance of the diagonal stride component has been recognized in the literature:

> "This is the diagonal stride, which forms the basis for all running on cross-country skis. Many people take up the sport enthusiastically and never even learn the diagonal stride. They prefer, instead to shuffle along at their own pace. Developing a good stride is essential if you hope to ski long distances or at high speed." (Baldwin, 1977, p.69)

Kinematic Investigation

Quantitative sports skills analysis may be divided into two categories: kinematic and kinetic. The first deals with body positioning and timing of various movement aspects of the performance. Thus, kinematic investigation concentrates entirely on the temporal and spatial qualities of movement without regard for the forces producing it, while kinetic study is involved with the analysis of forces responsible for movements. The present study examined the kinematic parameters of highly skilled execution of the diagonal stride technique.

The following parameters were chosen to represent measures of a skier's movement pattern:

(1) Vertical and horizontal displacement and velocity of a skier's center of gravity; (2) Positioning of various body segments throughout the diagonal stride; (3) The component percentages of different phases of the stride. These parameters are basic measures of body movement often suggested for quantitative skill analysis:

> "Almost any sports skill can be divided into similar components which have practical significance when they are related to the performance."
> (Miller and Nelson, 1973, p.40)

Thus, measurement of body parameters may provide information useful in drawing practical comparisons among aspects of various skiers' techniques. The determination of horizontal displacement and velocity of a skier's center of gravity produced two results. Firstly, average horizontal velocity of the racer during the diagonal stride was revealed; secondly, variations in instantaneous horizontal velocities of a skier's center of gravity throughout one complete stride were produced. Vertical displacement and velocity of a skier's center of gravity illustrated the kinematics of the body as a whole in the vertical plane of movement. From this center of gravity analysis, comparisons among the skier's total body movement patterns were drawn. Measurement of body segment positioning throughout the stride illustrated a profile of the combined rotational locations of connected body segments and provided a better view of the coordination of their interactions. The components percentages of distinctive portions of the stride provided information regarding the aggregate rhythm of the various actions involved in the complete diagonal stride. Comparisons among the profiles of a number of skiers provided insight regarding patterns of movement involved in the diagonal stride; also, they aided in identifying factors integral to highly skilled performance. This evaluation was based on the objectives underlying the employment of good racing technique— to efficiently produce a high horizontal velocity and subsequently better racing results.

The accurate measurement and analysis of human performance during the execution of a complex skill was a major objective of the present study. The feasibility of this goal has been evaluated by biomechanicians:

> "The human body is a link system of variable weights, lengths, and shapes; by combining anatomical data, principles of mechanics, data-collecting equipment and the computer, more specific and accurate data can be obtained on human movement than ever before." (Plagenhoef, 1971, p.1)

To increase the reliability of measurement, a strict experimental methodology was utilized, as well as a computerized data smoothing treatment. Thus, quantitative biomechanical research techniques have been employed to provide a kinematic investigation of the diagonal stride technique of cross-country ski racers. It was the author's intention to provide a technique profile upon which practical recommendations could be based. Coupled with this intention was the desire to increase the available body of knowledge based on scientific research concerning technique analysis of cross-country skiing.

Statement of the Problem

The purpose of the study was to quantify the kinematic parameters of highly skilled performance of the diagonal stride technique in cross-country skiing. These parameters were used to construct a descriptive performance profile which was considered to be indicative of good racing technique. Additionally, an assessment was completed of the relative contribution of various aspects of technique to the production of optimal horizontal velocity during the diagonal stride movement pattern.

Definitions

Several terms related to the diagonal stride technique in cross-country skiing have been applied throughout the study. Following are detailed definitions of the major terms:

(1) The diagonal stride is the technique during which the laterally opposed arms and legs move simultaneously forward and backward in the sagittal plane. It is a cyclic activity involving alternating support and recovery periods for each leg. One stride has been defined as the movement occurring between successive take-off points of the skier's feet.

(2) Take-off refers to the instant at which the portion of the ski directly under the support foot loses contact with the track. This occurs when the ski regains its camber and becomes flexed as weight is removed from the stationary ski.

(3) Recovery has been defined as the action during which the leg is carried forward to a position in front of the body. This action prepares the leg for a subsequent support phase.

(4) Single support refers to the condition where one leg is providing the entire support for the skier. Although the tip of the recovery ski remains in the track, it is considered to provide negligible support.

(5) Double support is the condition of both legs providing a portion of the weight bearing.

(6) The free glide phase refers to the time during which no apparent propulsive method is being employed; thus, the skier glides freely on the sliding ski(s).

(7) The leg thrust phase is the period during which the support leg appears to be pushing downward and backward against a stationary ski. It begins when the legs come together and it ends at take-off.

(8) The foot stationary phase refers to the time during which one support ski is motionless in the track. This portion of the stride contains the leg thrust phase.

(9) The pole implantation phase is the period of time during which the pole tip maintains contact with the snow.

(10) The center of gravity is the point at which the mass of the entire body may be theoretically represented. It has been calculated using the relative masses and locations of the centers of mass

of the body segments. Thus, displacement of the center of gravity is a representation of movement of the total body mass as one particle.

Limitations

The limitations of the study have been divided into two categories: cinematographical and theoretical restrictions. The major limiting factors of high speed cinematography are associated with the reliability and validity of measuring actual body movement through the use of a projected image. There were many possible sources of experimental error; fortunately, these were minimized through the employment of strict experimental and measurement procedures. Despite these precautions, a degree of error was unavoidable. It resulted from a distortion of the image and from measurement of displacement data. Due to the fact that filming procedures recorded movement in one plane, lateral movements were not quantifiable and may have caused distortion. Appropriately, as a direct result of the nature of the diagonal stride technique, most movement occurred in the sagittal plane. The arms and legs moved parallel to the skiing track and there was relatively little rotation of the hips and shoulders. This movement allowed the skiers to maintain balance as they shifted their weight to alternating support legs. The lateral shift should have caused negligible distortion due to the close, consistent spacing of the right and left grooves of the track. Also, the fact that the camera was positioned a relatively long distance from the performance plane (10 meters) should have minimized distortion caused by lateral movements. Distortion of the conversion factor could have occurred with increased distance of the image from the frame center toward the periphery. This possible source of error was controlled by obtaining data from the stride completed nearest the center of the field of vision.

Measurement procedures involving a Vanguard Motion Analyzer normally determine spatial coordinates measured to the nearest .001 inch. This measurement is achieved by manually superimposing vertical and horizontal cross-hairs on a point on the projected image; usually the point represents the transverse axis of a joint. This process was, of course, subject to human error in spite of efforts to reliably identify joint centers and to analyze subjects with tightly fitting clothing. In the present study, a reliability check was performed using a correlated samples T-test with the test and retest recordings for twelve joint centers. A T-value of 1.63 was produced, indicating that the difference between the test and retest values were not significantly different from zero. Also, the reliability of the data obtained through filming and measurement procedures was increased using a computerized, mathematical data smoothing method called the cubic spline function. This method has been shown to effectively reduce error associated with the determination of displacement data (McLaughlin et al., 1977a). However, some problems were discovered with the second derivative of the function, particularly at the endpoints. Thus, acceleration estimates produced by the cubic spline may be of questionable reliability, while the displacement and velocity estimations have been shown to be reliable, error-reduced determinations. The data smoothing technique uses an a priori estimate of the total error associated with a particular filming and analysis system. In the present study, the error estimate (plus or minus 2.9 millimeters) was determined by measuring known distances located at various positions in the field of view and then calculating the average difference between their true and measured values. In a similar cinematographical analysis, the average error band was estimated to be plus or minus 3.0 millimeters (McLaughlin et al., 1977b). Therefore, measures of reliability regarding the quantitative data analysis were increased through adherence to strict experimental procedures and the use of computerized cubic spline data smoothing.

The validity of procuring real life measures from film and of applying the principles of mechanics to the data has often been questioned. This concern stems from the assumption that the volume, density and rigidity of body segments are similar to the properties of rigid segments from engineering systems. In reality, a straight line constructed between joint centers may not adequately represent a true body segment for the following reasons: The actual axes of rotation may not correspond with surface landmarks and may change during movement due to displacement of the skin. Also, the collagenous tissue fastening joints may permit some displacement of adjacent bones. Finally, both volume and density of a body segment may vary as a result of movement of body fluid and distortion of the shape of tissue mass during rapid accelerations. For these reasons, treatment of the body segments as rigid mechanical systems may not constitute an entirely valid representation. In order to quantify human movement, however, accurate estimates of the lengths, masses, and centers of mass must be procured. Several cadaver studies have provided standarized body segment descriptions and quantities with which to calculate centers of gravity and moments of inertia (Miller and Nelson, 1973). Additionally, previous research has considered the effects of error to be negligible when compared to total limb movement (McLaughlin et al., 1977b). Therefore, it was considered to be within acceptable boundaries of validity to employ the representation of the body as a series of rigid segments connected by stable joint axes for the purposes of a quantitative investigation of the diagonal stride.

The major theoretical limitations of the study were related to a number of assumptions. A basic premise of the study was that proper technique was important for the high caliber execution of the diagonal stride. Additionally, it was presumed that the selected parameters were those which appropriately quantified aspects of the skill and that differences in the ability to achieve the objectives of the diagonal stride were exposed through quantification of these parameters. The assumed performance objectives were a high horizontal velocity coupled with a better finishing time. There is support in the literature for statements that technique is important to the diagonal stride (Baldwin, 1977) and that the parameters considered in the present study are related to the performance (Dillman, 1978). Thus, the assumption is not unreasonable that the selected parameters produced a realistic profile related to the actual performances of the diagonal stride technique.

A major assumption of the study was that performance relied heavily on mechanical factors; no psychological variables nor physiological variables were considered. This assumption was considered realistic for a technique study of this nature, since the filming was completed under identical racing conditions for each subject, and the filming procedure was relatively early in the contest. These factors were considered to have been beneficial in controlling the effects of motivation and fatigue.

The diagonal stride technique was used primarily on flat and slightly inclined sections of the race; this accounts for possibly one-third of the total race time. Thus, the technique may be evaluated on the basis of comprising only a portion of complete cross-country racing technique. A time interval study, however, revealed that differences between the performances of successful and non-successful skiers were especially evident during the uphill sections of the competition (Rusko and Kantola, 1978). Therefore, the diagonal stride component was considered important to the total race, but limitations were recognized regarding its relationship with the outcome.

Finally, the particular stride which was analyzed from each skier's performance was assumed to be representative of the subject's normal diagonal stride technique. This was a reasonable assumption in view of the fact that the styles exhibited by all competitors appeared to be smoothly coordinated during the completion of several strides. The strides chosen from the study did not appear atypical; thus, they were considered valid indications of skiers' techniques.

In summary, the design for this study was a valid and reliable approach to quantitative analysis of the diagonal stride. The investigation, however, was subject to the implicit restrictions imposed by the theoretical assumptions necessary for completion of such a study.

CHAPTER II

REVIEW OF LITERATURE

The present study was concerned with the quantitative evaluation of the body movement parameters involved in the diagonal stride technique. This section is a summary of the present state of published work concerning analysis of body motion in general, forms of locomotion, and more specifically, qualitative and quantitative descriptions of performance of the diagonal stride.

Mechanical Analysis of Body Motion

The fact that biomechanical analysis of sport is rapidly growing may be substantiated by increases in the amount of literature and numbers of research laboratories and graduate programs. Expanded knowledge in the field has produced new books which stress the mechanical analysis of human motion:

> "Though biomechanics is presently primarily concerned with the description of performance, it is predicted that, with increased development of the area, biomechanicians will be formulating performance methodology based on sound biological and mechanical principles." (Martin, 1975, p.37)

Thus, the suggestion that performance profiles may be produced is not an unreasonable claim.

Most forms of human locomotion are associated with bipedalism. It is important to realize, also, that all translatory motion of the body is produced by a combination of coordinated rotations of body segments. For these reasons, the diagonal stride may be compared with walking and running.

> "Human locomotion evolves from a profusion of interrelated minutae, and it attains its greatest perfection in the smooth, even, graceful running gait of the trained athlete. Each body segment contributes to this final pattern. The synchronous motions of the trunk and upper extremities aid in the balance and rhythm of forward progression by constantly positioning the body's centre of gravity where it can be used most effectively." (Slocum and James, 1975, p.64)

All three forms of locomotion are produced by self-propulsion and are executed in a cyclic pattern, such that a predictable sequence of events occurs with alternate legs -- a period of support followed by a period of recovery. The support foot remains relatively stable while the body rotates over it to create translation. The diagonal stride is more similar to walking in this respect in that there is no non-support phase, which is present in running:

> "Walking may be described as alternate loss and recovery of balance during which a new base of support is established for each step." (Wells and Luttgens, 1976, p.164)

> "Running is a series of smoothly coordinated jumps during which the body is alternately supported on one foot, airborne, then supported on the opposite foot and again airborne." (Slocum and James, 1975, p.66)

Further detailed analysis of these activities has been based on the foot-ground relationship. Descriptions of running and walking have been characterized by foot-strike, mid-support, and take-off points during the stride; and by follow-through, forward-swing, and foot-descent phases during recovery. The diagonal stride has been described in a similar fashion by technique analysts of cross-country skiing (Dillman, 1978). The double support phase in walking has been further divided into restraining and propulsive portions, separated by the instant when the center of gravity is located directly above the base of support. The restraining portion for one leg coincides with part of the propulsive portion for the opposing leg, the result of which is double support. The diagonal stride is similar, but due to the forward sliding of the restraining ski, there should be a less significant restraining effect. Finally, the purpose of a stride in walking, running and cross-country skiing is to maintain horizontal velocity while providing support. For each, this velocity is a direct product of stride length and stride rate. All have a common objective in producing efficient body translation -- maintaining the desired horizontal velocity by using the least amount of energy. Therefore, there must be a minimization of all movements unnecessary in attaining that objective. Lateral movement should be kept to a minimum, although it may not be entirely eliminated:

> "Some side to side shift of the pelvis is the inevitable result of postural adjustment as the common centre of gravity is balanced alternately over each leg as it bears the body weight." (Slocum and James, 1975, p.68)

For all forms of locomotion, unnecessary vertical movement is considered a waste of energy. Thus, extreme vertical movements of the head, legs, and arms are considered poor technique:

> "Again, the technique (diagonal stride) resembles walking, but as if you were reaching out with two canes to help you move along faster. There is little sideways movement, no bobbing of the head and no bending at the waist. (Tokle and Luray, 1977, p.80)

> "There is little question that the less the vertical displacement of the body, the greater the efficiency of the runner, for energy is then not wasted in lifting the body with every step, but is concentrated largely on thrusting it forward into the airborne state." (Slocum and James, 1975, p.68)

Similar qualitative descriptions of the diagonal stride are available from instructors, coaches and performers (Baldwin, 1978; Lederer, 1972; Caldwell, 1971; Jensen, 1977). Most of these sources approach technique discussion from an instructional point of view; detailed descriptions of their views of good diagonal stride technique have been presented. In an unpublished review (Dillman et al., 1979), some of the findings of recent investigations were presented in a comparative analysis of highly skilled versus average skilled diagonal stride technique. However, relatively little scientific study of cross-country skiing technique has been undertaken.

The Diagonal Stride Technique

The following technique discussion includes a review of qualitative technique analysis by contemporary "experts" and the findings of recent quantitative investigations. There is general agreement that the diagonal stride is a skill basic to cross-country skiing.

It is used extensively during racing on flat terrain and moderate inclines. Its importance is substantiated by the results of a time-interval study at the Lahti World Championship Games:

> "The conclusion concerning the time-intervals is that the skiers spent as much time for "grip-sections" (uphills) as for "glide-sections" (downhills) and flats. Looking toward the future, it seems that skiers should continue uphill training. The differences in performance level between successful and non-successful skiers appeared especially on uphills." (Rusko and Kantola, 1978, p.85)

For descriptive and analytical purposes, the diagonal stride has been divided into phases by various researchers. Nigg and Waser (Dillman, 1978) used the gliding, pole planting, stillstand and leg push-off phases while Dillman (1978) used similar time divisions: He excluded the stillstand phase and labelled the others the free glide, thrust, and pole implantation phases. The parameters used for quantitative analysis of the diagonal stride may be divided into three main categories: Body position, performance, and time factors.

Body position during various phases of the stride has been considered important for proper execution of the technique;

> "Good body position is of critical importance: It can help you get up hills and can effect speed of kick. The key is that good body position enables maintenance of momentum. Rob Kiesel (U.S. coach) and Hans Equist (Swedish coach) both reinforced these comments. The Swedish and U.S. coaches look at body position before anything else during technique analysis." (Caldwell, 1978, p.84)

In comparing highly skilled to average skilled performance of the diagonal stride, Dillman (1978) reported the following results:

At the initiation of the thrust phase, highly skilled skiers were in a more flexed body position with the weight more forward. The trunk and shank segments were approximately 45 degrees and 60 degrees, respectively, from horizontal and the center of gravity appeared to be over the toes. Marino et al.(1980a) showed similar angles of inclination for highly skilled females. Additionally, Nigg and Waser (Dillman, 1978) reported an optimal position for the center of gravity such that it was not too much in front nor behind the base of support for most successful skiers. Thus, good body position has been shown to be an asset during the diagonal stride.

Performance and time parameters will be reviewed concurrently. Generally, qualitative analysis of these factors stresses the following technique for skilled execution of the diagonal stride:

> "In the diagonal stride, the push-off with the leg is the primary force that propels the body forward. The important characteristics of a good diagonal stride are: a smooth but forceful stride, a long smooth arm movement, and a long glide with the weight balanced on one ski." (Jensen, 1977, p.11)

> "Refinement, once you have gotten past the basics, means only the lengthening of stride, the ability to push harder and glide longer, and the development of stamina." (Tokle and Luray, 1977 p.80)

When comparing highly skilled to average skilled skiers, Dillman (1978) found that the free glide phase made up a larger proportion of the total stride (25%) for highly skilled skiers. They appeared to be better balanced and to plant the pole in a more erect position than the poorer skiers. Also, he noted that the pole implantation phase distinguished clearly that the better skiers have more effective gliding actions. The pole implantation phase, most of which is accompanied by a sliding action of the skis, accounted for approximately 60% of the difference in stride lengths. He added that the arm pull was performed by the highly skilled skiers in a more flexed arm position and appeared to be a more coordinated action.

A more extensive phase proportions study by Nigg and Waser (Dillman et al., 1979) performed on 29 racers, produced similar results for the gliding phase. It was discovered to be longer for excellent and good skiers (approximately 27% of the total stride). The pole planting phase, however, was found to be shorter for excellent and good skiers. The reason suggested for this incongruity was that the position of the center of gravity was ideal (not too much in front or behind). The pole planting phase ended for the excellent athletes in the middle of the push-off phase, whereas, for weaker skiers, it lasted longer. The horizontal velocity of the center of gravity was found to vary somewhat over the total stride. The highest velocity was shown just after the completion of the push-off phase. During the gliding phase, velocity dropped, then it levelled off or slightly increased during the pole planting phase. Other research (Jensen, 1979) showed only a slight increase in horizontal velocity at the end of the thrust phase; otherwise, it remained relatively constant throughout the stride. These findings suggest that most of the thrust phase is actually a support rather than a propulsive action. This is consistent with a previous suggestion (Dillman et al., 1979) that a relatively large vertical force called "weighting" is used to set the ski stationary in the track, but it remains unclear at what time this action occurs. Jensen (1979) also referred to a slight vertical dip in the center of gravity; however, this action has not been temporally examined. A profile of an excellent United States skier has been presented using the following parameters (Dillman, 1978):

Factors	Results
Velocity (m/s)	4.75
Stride length (m)	2.91
Stride rate (stride/sec)	1.62

Following a comparison of these results with those of poorer skiers, this conclusion was reached: More substantial differences exist in skiers' stride lengths than stride rates. It was emphasized that there is probably an optimal stride length; longer strides would likely be less efficient once this optimum is reached. Thrust time is shorter for excellent skiers, and glide time is longer. Some opposition for these conclusions has been found in a study of highly skilled female cross-country racers (Marino et al., (1980a); a higher stride frequency (1.98 strides/sec) combined with a shorter stride length (1.91 m) was discovered.

Although there is general agreement among authors, coaches, and researchers about skilled performance of the diagonal stride, there is a degree of uncertainty and contradiction concerning the relative importance and magnitudes of parameters involved with the production of an efficient stride pattern. Kinematic evaluation of a wide range of parameters would be more beneficial at this time.

Summary:

The diagonal stride in cross-country skiing is a form of locomotion bearing similarities to walking and running. Similar to other forms of body movement, this skill may be divided into logical phases. These may be accurately analyzed in a quantitative fashion using biomechanical principles and computerized data analyses. A limited number of kinematic parameters important to high calibre execution of the diagonal stride has been identified and quantified by scientific investigations. However, biomechanical analysis of cross-country skiing is still in its preliminary stages and further kinematic investigation is necessary to solve existing problems.

CHAPTER III

METHODOLOGY

The purpose of the study was to quantify the kinematic parameters of high caliber performance of the diagonal stride technique. In order to obtain a permanent, accurate record of the performances, high speed cinematography coupled with a computerized analysis of data was utilized. Following is a detailed description of the specific methods employed.

Filming Procedures

The racers used as subjects were those comprising the senior men's division competitors in the 30 kilometer race at the 1979 North American Cross-Country Skiing Championships. Each skier was over age 21 and was a considerably experienced racer; also, the group appeared to produce excellent performances of the diagonal stride technique. There was little requirement for subject preparation, as typical racing attire included an extremely close-fitting racing suit which provided an unobstructed view of body segments and joint locations. Considering that the objective was to examine the diagonal stride performance during an actual racing situation, it was considered more advantageous to examine the skiers without familiarizing them with experimental procedures. Thus, the subjects were filmed with no previous knowledge of the study.

A filming area was selected approximately 100 meters from the starting position and the camera was located such that the following requirements were satisfied: Its location allowed sufficient time for attainment of a smooth stride and a constant velocity. There was an even surface situated on a slight incline to ensure that all racers employed the diagonal stride technique. Also, the area allowed an unobstructed lateral view of the skiers' entire bodies, silouetted against a background of snow. The subjects were filmed at one minute intervals as they skied along the single, prepared track. Thus, a film of each competitor was individually obtained through the use of a Locam 16 millimeter high speed camera (model 51-0002). It was equipped with a 10 millimeter wide view lens and loaded with Kodak 4X film (outdoor ASA400). The camera was set to operate at 100 frames per second; combined with a shutter factor of 6, this produced an exposure time of 1/600 second. The filming position was stationary at a height of approximately 1 meter and a perpendicular distance of 10 meters to the side of the track. Additionally, the camera's optical axis was aligned at right angles to the racing track. This stationary camera location allowed each subject to complete a minimum of three strides while crossing the field of vision. Thus, the provision of a suitable filmed image of each subject was ensured.

A prepared length of wooden dowling with distinctive markings spaced 1 meter apart was filmed while being held in two positions -- horizontally in the vertical plane of the track center and vertically suspended from one of its ends. This procedure provided a vertical reference line as well as a previously known distance which was used to calculate the conversion factor for the film analysis.

Film Analysis Procedures

A time factor was calculated from the film according to the following procedures: Exposure marks had occurred as a result of a timing pulse generator driven by a quartz crystal oscillator (light emitting diode). Since these exposure marks had occurred at accurate .01 second intervals, they were used to determine the elapsed time per frame by counting the numbers of frames and exposures in a length of film. To ensure accuracy and reliability, this procedure was performed during the middle portion of each subject's performance. The exposure to the light emitting diode had occurred during a constant filming speed; thus, filming rate was determined using the following formula:

$$\text{filming speed} = \frac{\text{number of frames}}{\text{number of exposures}} \times 100 \ \frac{\text{exposures}}{\text{second}}$$

The constant value produced for each subject's portion of the film was 97.6 frames per second. Accordingly, the inverse of filming speed produced a time per frame of .0102 second. This time factor was subsequently used for calculating total time elapsed during the completion of particular movements.

Displacement data were collected through the use of a Vanguard Motion Analyzer (model M - 16C / C - 11). This unit enlarged the image by a magnification factor of 25 and projected one frame on its screen, locked into position by pin registration. On this projection, the operator manually positioned the X and Y coordinate cross-hairs at the desired points, producing accurate two-dimensional locations measured to the nearest Vanguard Unit (.0009 meters in real life conversion). A reliability check regarding location of points was performed using the coordinates of fifteen joint center locations. The values were recorded, then the film was advanced several frames. Following a return to the exact frame, the values for the identical joint centers were again recorded. A correlated samples T-test was performed on the two sets of recordings in order to determine whether the difference between the paired observations was significantly different from zero. This calculation produced a T-value of 1.63, indicating that no significant difference was discovered between the test and retest recordings ($P < .05$). The conversion factor for the film was determined by recording the difference between the distinctive markings from the image of the length of dowling. This difference was equated with a real life measure of 1 meter, which produced the following conversion:

1 Vanguard Unit = .0009 meters.

For each subject, the joint center coordinates were typed directly onto Fortran computer cards using a standard keypunch. Thus, the X and Y data describing the position of the following points were collected from every second frame of film (time interval = .0204 seconds): Right toe, right ankle, right knee, hip, shoulder, top of the head, right elbow, right wrist, tip of the right hand, left toe, left ankle, left knee, left elbow, left wrist and tip of the left hand. This recording order complied with the requirements of a computer program which was used to determine centers of gravity (Widule, 1977). The program used segmental weight and body weight ratios combined with segmental center of mass locations derived from several cadaver studies. Thus, the locations of joint centers were used in direct calculations of the theoretical point at which the total body mass was represented. The theory underlying this calculation is that the sum of the segmental moments of force equals the total body moment of force tangential to the X and Y axes.

Additionally, the computerized joint center coordinates were used to calculate selected body segment angles through manipulation of the computer program. For example, the trunk angle (T) relative to horizontal was calculated using the coordinates of the shoulder (X_2, Y_2) and the hip (X_1, Y_1):

$$\text{Angle } T = \tan^{-1} \frac{Y_2 - Y_1}{X_2 - X_1} .$$

Similar trigonometric relationships were constructed to facilitate computerized determinations of each body position parameter.

Selected Parameters

The following body movement parameters were selected and categorized on the basis of their suitability to the present study. For each subject, the parameters were calculated throughout one complete diagonal stride.

(a) Performance parameters:

1. Stride length.
2. Stride frequency.
3. Horizontal displacement of the center of gravity.
4. Horizontal velocity of the center of gravity.
5. Vertical displacement of the center of gravity.
6. Vertical velocity of the center of gravity.

These parameters were considered to be of prime significance for the analysis of diagonal stride technique. The information was used to relate the subject's movement to the major objective of the race, high horizontal velocity. Since the product of stride length and stride frequency is horizontal velocity, these parameters are the fundamental determinants of the performance objective. More specifically, the center of gravity analysis provided a quantitative description of the precise position and direction in which each skier had moved his total body mass. This description was useful in two respects; firstly, it allowed comparisons of the vertical versus horizontal displacements of each skier's mass throughout the complete stride. Secondly, it was valuable in providing a temporal assessment of the instantaneous values of displacement and velocity of the center of gravity. These results were visually represented by constructing both vertical and horizontal displacement versus time graphs.

(b) Stride phase parameters:

1. Phase length and percentage of total stride length.

2. Phase time and percentage of total stride time.

The calculation of phase lengths and times was performed utilizing the specific times at which certain events occurred throughout the stride. Following is a list of the times and corresponding events which were designated to visually separate the stride phases:

TIME	EVENT
t5L	The center of the left ski lost contact with the track.
t1	The tip of the recovery pole contacted the snow.
t2	The support ski became stationary in the track.
t3	The left and right legs gained parallel positioning.
t4	The pole tip lost contact with the snow.
t5R	The center of the right ski lost contact with the track.

Phase times were calculated for each subject through the use of these identifying events. The selected phases and corresponding time differences have been listed below:

Phase	Time Difference
Total Stride	t5R - t5L
Pole Implantation	t4 - t1
Foot Stationary	t5R - t2
Leg Thrust	t5R - t3
Free Glide	t1 - t5L

Phase lengths were determined for each subject by calculating the difference between the horizontal displacements of the center of gravity at the times bordering each phase.

These stride phase parameters provided a time basis for description of specific aspects of the diagonal stride. Also, they were useful in comparing aspects of performance among subjects. The phases separated the various movements involved in the skill; thus, temporal and spatial assessments were conducted regarding their importance to the total stride.

(c) Body segment angles:

G = slope of the line joining the center of gravity and the toe of the support foot; angle relative to horizontal.
L = shank angle; relative to horizontal.
T = trunk angle; relative to horizontal.
P = pole angle; relative to horizontal.
A = ankle angle; shank relative to foot.
K = knee angle; thigh relative to shank.
H = hip angle; trunk relative to thigh.
C = thighs angle; right thigh relative to left thigh.
E = elbow angle; forearm relative to upper arm.
S = shoulder angle; upper arm relative to trunk.

Figures 1, 2 and 3 illustrate the exact locations of body angles. The leg and arm which were providing support and propulsion were the segments studied, while the recovery leg and arm were not evaluated. An additional calculation was performed to determine the horizontal distance between the tip of the ski and the toe of the support leg at the beginning of the pole implantation phase.

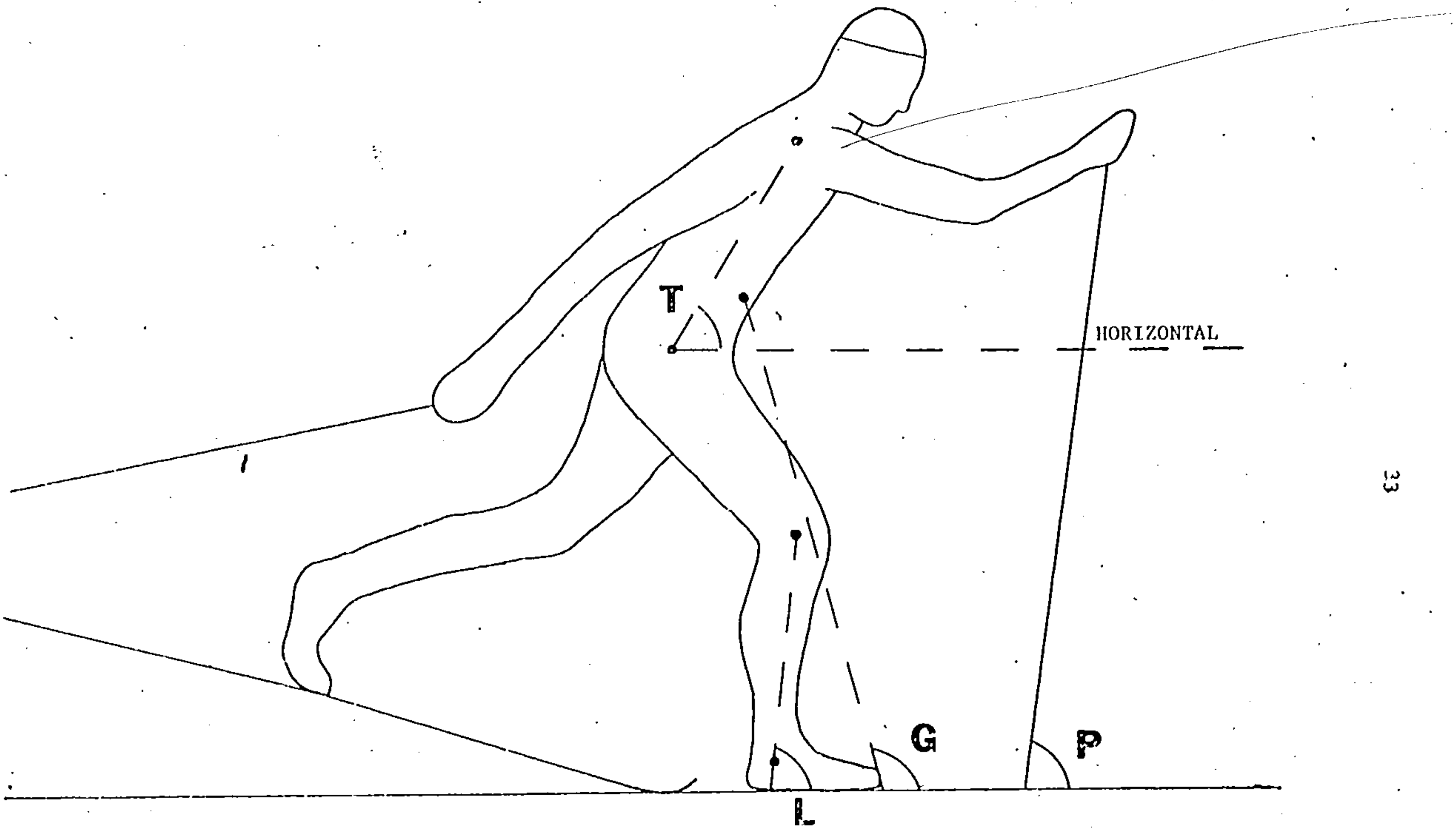

FIGURE 1: LOCATIONS OF BODY POSITION ANGLES

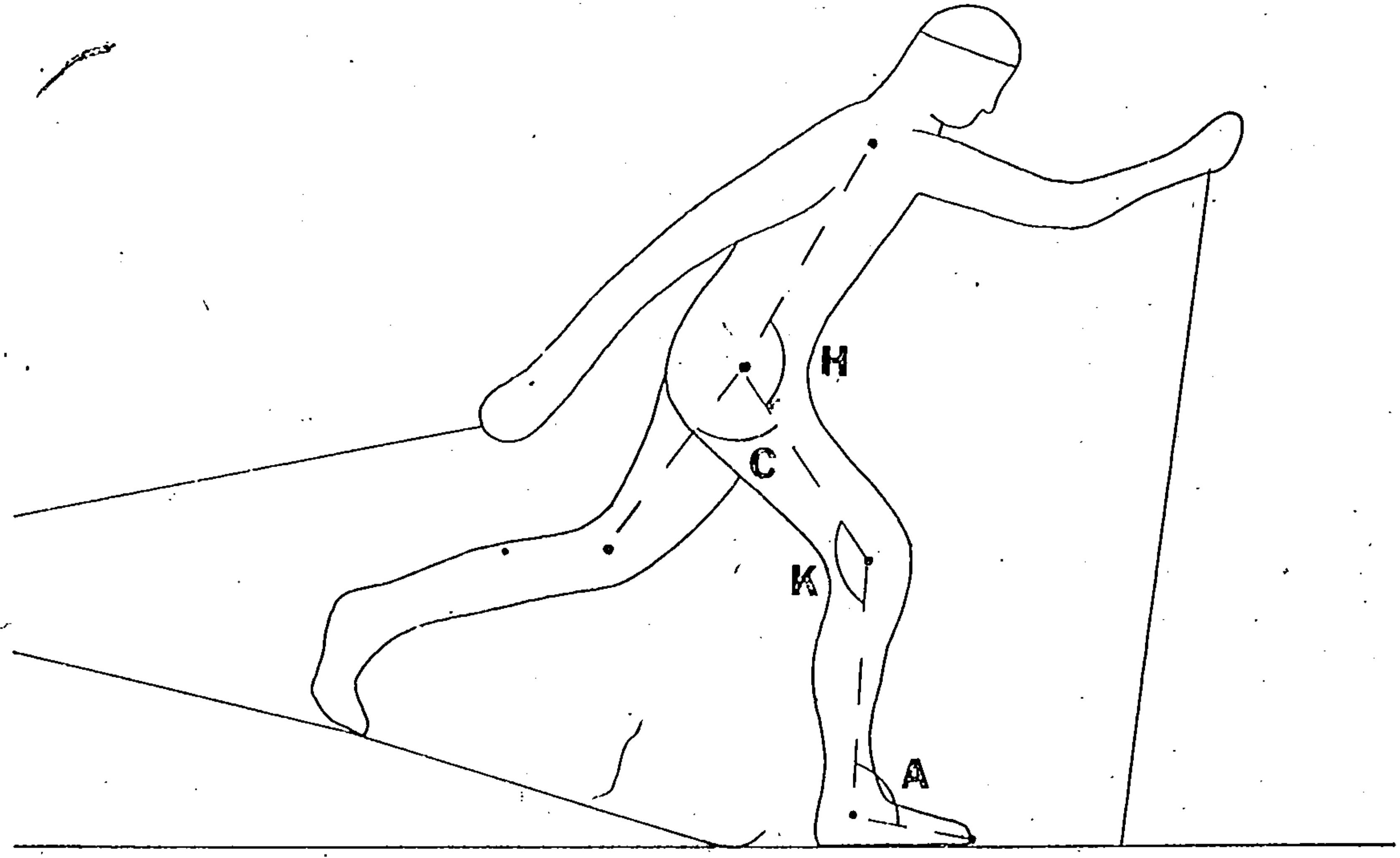

FIGURE 2: LOCATIONS OF LEG SEGMENT ANGLES

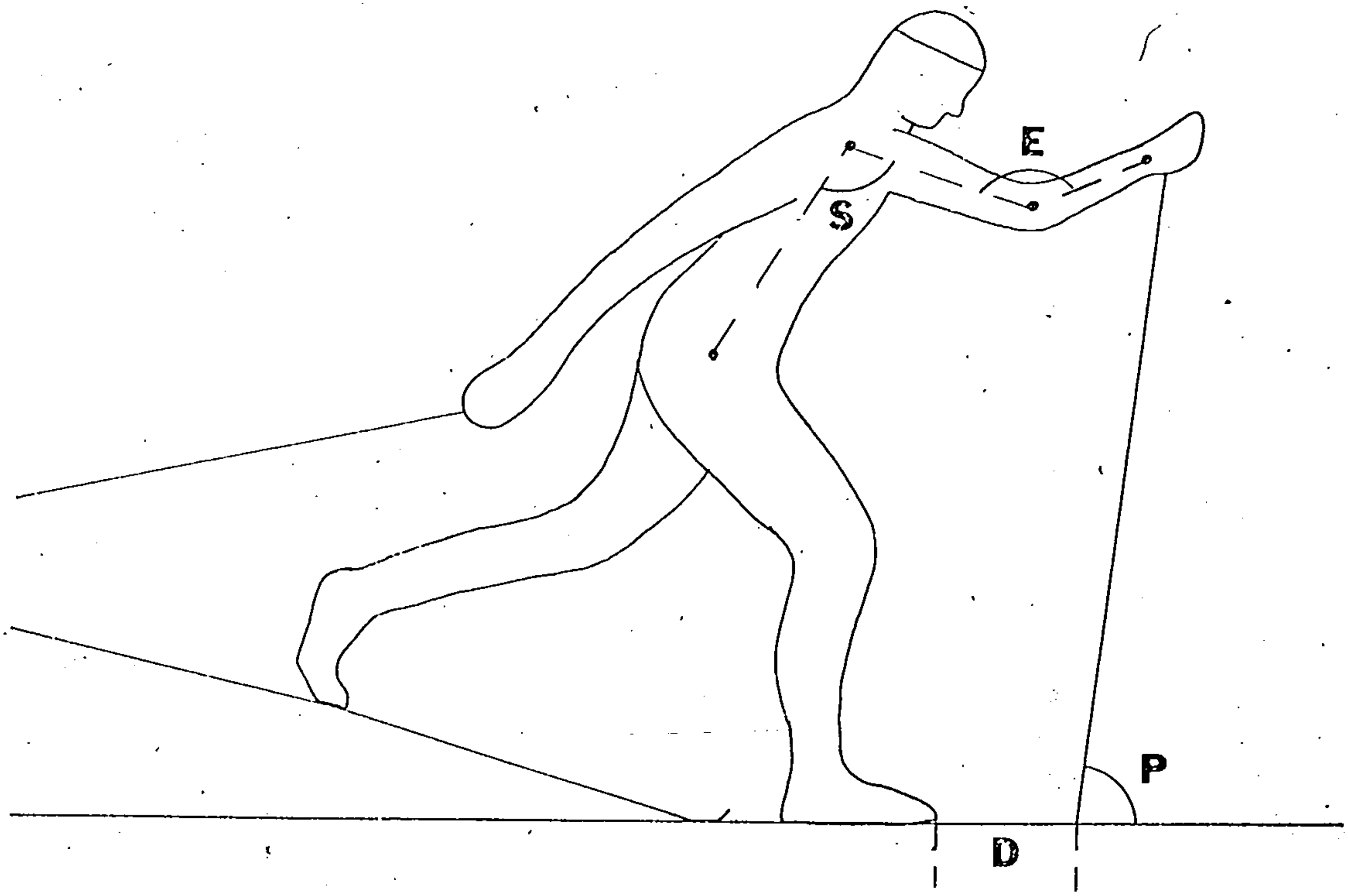

FIGURE 3: LOCATIONS OF ARM SEGMENT ANGLES AND POLE POSITION

The body segment parameters provided various types of information. Firstly, exact configuration of the body segments at various times throughout the stride were illustrated. This allowed comparisons with the findings of previous studies. For example, Dillman (1978) showed that position at the beginning of the leg thrust phase was an important factor. The present study examined total body configuration during the entire stride; thus, the next logical step was provided in the analysis of the importance of other body segment positions to highly skilled performances. Secondly, these parameters quantified the temporal and spatial relationships among body segments. This information was useful in the determination of the exact coordination of rotational movements of various segments involved in producing total body translation. Such quantitative descriptions of technique were used to form comparative evaluations of individual styles.

Analysis of Data

(a) Data Smoothing:

Experimental methods of cinematographical analysis produced a degree of unavoidable error. Therefore, the raw data provided by filming and measurement procedures were treated prior to analysis. Such treatment has been shown to be effective in reducing error while retaining meaningful changes (McLaughlin, 1977a). Thus, the reliability of the data was increased before comparative analysis and statistical treatment were undertaken. The present study utilized the computerized Cubic Spline data smoothing procedure (International Mathematical and Statistical Library, 1976). This program produced smoothed curves for vertical and horizontal displacement and velocity of the centers of gravity. However, the smoothed acceleration derivatives in the vertical direction were extreme and unrealistic, appearing to fluctuate meaninglessly. Thus, the second derivative calculation by the cubic spine was unsatisfactory.

(b) Performance profile:

Appropriate tables and graphs were constructed for the stride characteristics, phase percentages and body angles. Also, group means and standard deviations were calculated for each parameter. Thus, the quantitative description of performance, percentage times and lengths of stride phases and body configuration angles were grouped to form a profile of high caliber execution of the diagonal stride. Vertical and horizontal displacements and velocities were plotted versus time of stride for selected subjects to visually illustrate typical group patterns.

(c) Comparative analysis:

Individual performances were compared to the group profile. This comparison was used to determine differences among aspects of individual styles. Also, an attempt to identify relationships among selected parameters was undertaken through the use of the Pearson Product-Moment Correlation. Finally, a T-test for significant differences between means was performed to reveal significant differences between the performance means of the first five and the last six rankings in the race results.

Summary

The present study was concerned with the accurate quantitative analysis of the diagonal stride technique of high caliber cross-country skiers. Through the use of cinematographical analysis and computerized data smoothing, technique profiles were listed, described and compared in an attempt to provide useful knowledge regarding improvement for poorly skilled skiers. The importance of such a kinematic evaluation of technique was reflected by the lack of published material related to this topic. Thus, a detailed biomechanical investigation was undertaken. It was the author's intention to provide the next logical step in progressing toward the advancement of the body of knowledge which is available to instructors and coaches presently involved with cross-country skiing.

CHAPTER IV

RESULTS AND DISCUSSION

The purpose of the investigation was to quantify the kinematic parameters related to the diagonal stride technique of highly skilled cross-country ski racers. An analysis of selected results obtained from the study follows. Additionally, completed results have been presented in tabular form. Included in the main body is a detailed interpretation of pertinent results as well as a comparative discussion of the findings of the present study with references to related research.

Detailed race results have been listed in Table 1. Eleven of the twelve skiers completed the race; the competitor who dropped out had been tied for seventh place at the 15 km point. The top five finishers were also the five leading racers at the half way point. Their finishing times had a range of 5.22 min (5.1% of the winning time) while the overall range in completion times for the 30 km race was 14.57 min (14.2%). The first and second place racers were separated by 3.15 min (3.1%), which represents the largest difference between successive rankings. Interestingly, only the second ranked skier improved his average speed over the second half of the race. Therefore, the subjects chosen for the study appear to have exhibited a relatively narrow range in ability; also, there is a degree of consistency among the subjects' performances in the two sections of the race. This relative homogeneity was a consideration during the

TABLE 1

SENIOR MEN'S 30 KM RACE RESULTS

Subject Number	Half-way Point		Finish	
	Rank	Time (min)	Rank	Time (min)
1	1	50.07	1	102.88
2	5	53.07	2	106.03
3	4	52.97	3	106.40
4	2	52.67	4	108.03
5	3	52.75	5	108.10
6	7	53.67	6	108.95
7	6	53.42	7	109.83
8	9	54.72	8	110.25
9	10	55.42	9	112.82
10	11	55.98	10	115.00
11	12	57.73	11	117.45
12	7	53.67	12	Did Not Finish

subsequent discussion of the similarities and differences among performance aspects.

Diagonal Stride Characteristics

A summary of the rate and length characteristics of the skiers' diagonal strides is presented in Table 2. Also listed are the average horizontal velocities of their centers of gravity. Table 3 shows Pearson Product-Moment correlation coefficients for various pairs of stride and race parameters. The mean horizontal velocity of the centers of gravity for the strides analyzed was 4.29 m/sec (S=.47) produced by a mean stride length of 2.41 m (S=.22) and a mean stride rate of 1.78 st/sec (S=.15). These results are somewhat different from those presented by other studies. The mean stride length is shorter and the mean stride rate is more frequent than those shown by Dillman (1978) 2.88 m; 1.61 st/sec; and Komi et al. (1980) 2.96 m; 1.63 st/sec. Conversely, the values are longer and less frequent, respectively, than similar data reported for female skiers by Marino et al. (1979) 1.91 m; 1.98 st/sec. Dillman (1978) reported that increased horizontal velocity was achieved more by increasing the stride length than by increasing the stride rate. He suggested, however, that there is likely an optimal stride length and that strides larger than this are likely to be less efficient. Komi et al. (1980) agreed partially, stating that the increased mean horizontal velocity over that shown by Dillman (1978) was more of a result of increased stride length (2.8%) than a result of increased stride rate (0.6%). However,

TABLE 2

DIAGONAL STRIDE CHARACTERISTICS

Rank	Stride Length (m)	Stride Rate (per sec)	Horizontal Velocity (m/sec)
1	2.64	1.96	5.17
2	2.80	1.64	4.59
3	2.21	1.96	4.33
4	2.34	1.69	3.95
5	2.39	1.85	4.42
6	2.42	2.04	4.94
7	2.17	1.69	3.67
8	2.27	1.72	3.90
9	2.59	1.54	3.99
10	2.26	1.82	4.11
11	2.13	1.75	3.73
12	2.67	1.69	4.51
$\overline{X}$	2.41	1.78	4.29
S	.22	.15	.47

TABLE 3

CORRELATIONS BETWEEN SELECTED PARAMETERS

r	Parameters
.64*	Horizontal Velocity vs. Stride Length
.61*	Horizontal Velocity vs. Stride Rate
-.51	Rank vs. Horizontal Velocity
-.37	Rank vs. Stride Rate
-.27	Rank vs. Stride Length
-.21	Stride Rate vs. Stride Length
-.35	Rank vs. Percent Time of Free Glide
.04	Rank vs. Percent Time of Pole Implantation
.09	Rank vs. Precent Time of Foot Stationary
.11	Rank vs. Percent Time of Leg Thrust

$^*P < .05$

Komi et al. (1980) concluded that skiers achieve their horizontal velocities in different ways, since he noted that many excellent skiers achieve a greater velocity through an increased stride rate. The present data concur in that the subject ranked first had the second highest stride rate as well as the second longest stride length. Also, subjects ranked third, fifth, sixth and tenth have relatively high stride rates and short stride lengths producing their high horizontal velocities. Additionally, no significant relationship was discovered between finishing rank and horizontal velocity ($P < .05$). Thus, these high caliber skiers produced their horizontal velocities in different ways. Marino et al, (1980a) found that more successful female skiers had significantly higher stride lengths ($P < .05$). The results of the present study did not support this finding. Significant relationships were discovered between horizontal velocity and stride rate as well as between horizontal velocity and stride length ($P < .05$). However, no other significant relationships among stride parameters were discovered. It appears, then, that high caliber cross-country racers achieve their horizontal velocities through different methods during the diagonal stride.

Stride Phase Characteristics

Tables 4 and 5 list times and lengths of stride phases. The mean phase times, represented as a percentage of the total stride time, were 18% for the free glide phase; 74% for the pole implantation phase; 36% for the foot stationary phase; and 27% for the leg thrust phase. The mean phase lengths, represented as a percentage of the

TABLE 4

TIME COMPONENTS OF STRIDE PHASES

Rank	Free Glide Phase (sec)	Free Glide Phase (%)	Pole Implantation Phase (sec)	Pole Implantation Phase (%)
1	.13	26	.37	72
2	.16	27	.41	67
3	.05	10	.41	80
4	.11	19	.46	78
5	.12	23	.39	72
6	.06	13	.35	71
7	.11	19	.45	76
8	.11	19	.43	74
9	.12	19	.46	70
10	.07	13	.38	69
11	.05	9	.47	82
12	.14	24	.43	72
$\bar{X}$	.10	18	.42	74
S	.04	6	.04	5

Rank	Foot Stationary Phase (sec)	Foot Stationary Phase (%)	Leg Thrust Phase (sec)	Leg Thrust Phase (%)
1	.18	36	.14	28
2	.19	32	.14	23
3	.21	42	.17	34
4	.21	36	.13	22
5	.17	32	.13	25
6	.18	38	.13	27
7	.30	43	.18	31
8	.19	33	.13	23
9	.22	34	.18	28
10	.20	37	.17	32
11	.22	39	.17	30
12	.18	31	.14	24
$\bar{X}$	.20	36	.15	27
S	.03	4	.02	4

TABLE 5

LENGTH COMPONENTS OF STRIDE PHASES

Rank	Free Glide Phase (m)	Free Glide Phase (%)	Pole Implantation Phase (m)	Pole Implantation Phase (%)
1	.68	26	1.91	72
2	.75	27	1.86	67
3	.21	9	1.76	80
4	.45	19	1.81	77
5	.52	22	1.73	73
6	.29	12	1.72	71
7	.41	18	1.63	75
8	.44	19	1.67	74
9	.49	19	1.81	70
10	.29	13	1.52	67
11	.19	8	1.73	81
12	.64	24	1.93	72
$\overline{X}$	.45	18	1.76	73
S	.18	6	.12	4

Rank	Foot Stationary Phase (sec)	Foot Stationary Phase (%)	Leg Thrust Phase (sec)	Leg Thrust Phase (%)
1	.93	35	.72	27
2	.90	32	.66	23
3	.96	43	.78	35
4	.87	37	.55	24
5	.82	34	.65	27
6	.92	38	.66	27
7	.97	45	.71	33
8	.78	34	.54	24
9	.92	36	.76	29
10	.87	38	.75	33
11	.87	41	.67	31
12	.89	33	.69	26
$\overline{X}$	.89	37	.68	28
S	.05	4	.08	4

total stride length, were 18% for the free glide phase; 73% for the pole implantation phase; 37% for the foot stationary phase; and 28% for the leg thrust phase. These data show that proportions of time spent and distance covered during each phase are approximately equal. This statement is consistent with a subsequent finding of this study that horizontal velocities of the skiers' centers of gravity were constant or only slightly varying.

Figure 4 is a visual representation of time proportions for each phase of the stride. There is evidence of considerable overlap among the phases, explained by the fact that they were chosen as distinct body actions rather than a sequence of events. The exact instants by which the phases are delineated are also depicted. The diagonal stride appears to be comprised of a series of distinctly timed body movements and events. Well over half of the total stride time was consumed by the action of the support ski(s) sliding in the track (64%). These results concur, in part, with previous findings. Dillman et al. (1979) reported a free glide phase length of 25% of the total stride length for excellent skiers while Nigg and Waser showed 27% for an identical measure (Dillman et al., 1979). These reports are considerably higher than the present results for the free glide phase. The differences can possibly be accounted for by the higher horizontal velocities of the racers in the previous studies. In addition, previous data stems from a study of racers performing on flat terrain whereas the portion of race on which this study is based had a slightly upward sloping track. This may account for the shorter mean stride length and shorter glide phase reported in this study.

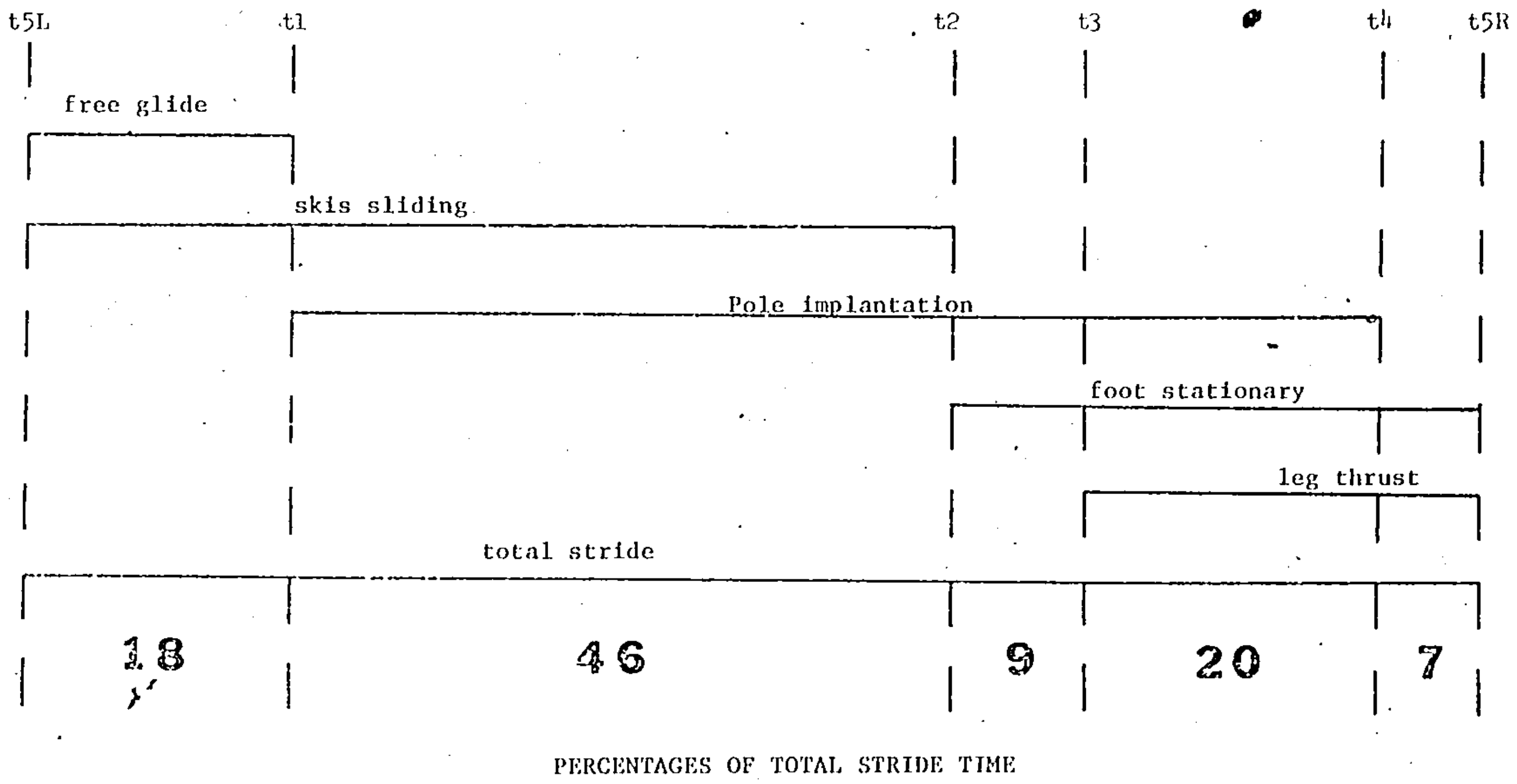

FIGURE 4: MEAN TIME PROPORTIONS FOR STRIDE PHASES

The mean pole implantation phase constituted an extremely large portion (74%) of the total stride time. The relative amount of propulsion provided by the pole action compared to the leg thrust could not be determined by this study. However, Nigg and Waser (Dillman, 1978) reported that excellent skiers have shorter pole implantation lengths than do lesser skilled skiers. Conversely, Marino et al. (1980a)showed that better ranked skiers covered considerably more distance during the pole implantation phase than did their poorer ranked counterparts. The present study found support for neither argument, since no significant relationships were discovered between race rank and the various stride phases (Table 3).

By comparison, the leg thrust portion of the total stride was relatively small (27%). It comprised most of the foot stationary phase, during which the support ski (thrust leg) was in a fixed position in the track. This stationary phase accounted for 36% of the total stride time. In this study, it was not possible to determine the exact times at which thrust began. Although the beginning of the leg thrust phase was described as the instant when left and right legs became parallel (lateral view), thrust may well have begun at any time after the ski became stationary in the track. Dillman et al. (1979) suggested that the leg thrust began when the legs came together and that highly skilled skiers seemed to get a greater thrust in a shorter time. Clearly, there is a possibility that horizontal thrust may have occurred during the time the body rotated over the stationary support ski in order to attain a more mechanically advantageous position from which to "push off". Thus, further data are required to assess the exact beginning of the leg thrust phase, while the foot stationary phase has been shown to comprise approximately one-third of the total stride time.

The phase time and phase length study provided information regarding proportions of body actions necessary for an excellent diagonal stride. Results indicated that the diagonal stride is comprised of a distinctly timed sequence of events, composed of a relatively large proportion of sliding on the ski(s) and a smaller proportion with one ski "set" stationary in the track. There were no significant relationships found between the performance of the racers and the stride phase characteristics. However, it must be considered that these results were obtained from a small sample (n=12). Further study is required to clarify the relative importance of individual stride phases.

Center of Gravity Analysis

A distinctive pattern was produced by the vertical displacements of the racers' centers of gravity. The displacement curves for subjects 1 and 8 are shown in figures 5 and 6; these are representative of the patterns produced by all subjects. The center of gravity continued to rise throughout the free glide phase and reached its high point at approximately the time at which the pole implantation phase began. Then, it dropped continuously and reached it's low point at approximately the time at which the legs became parallel. From this point,

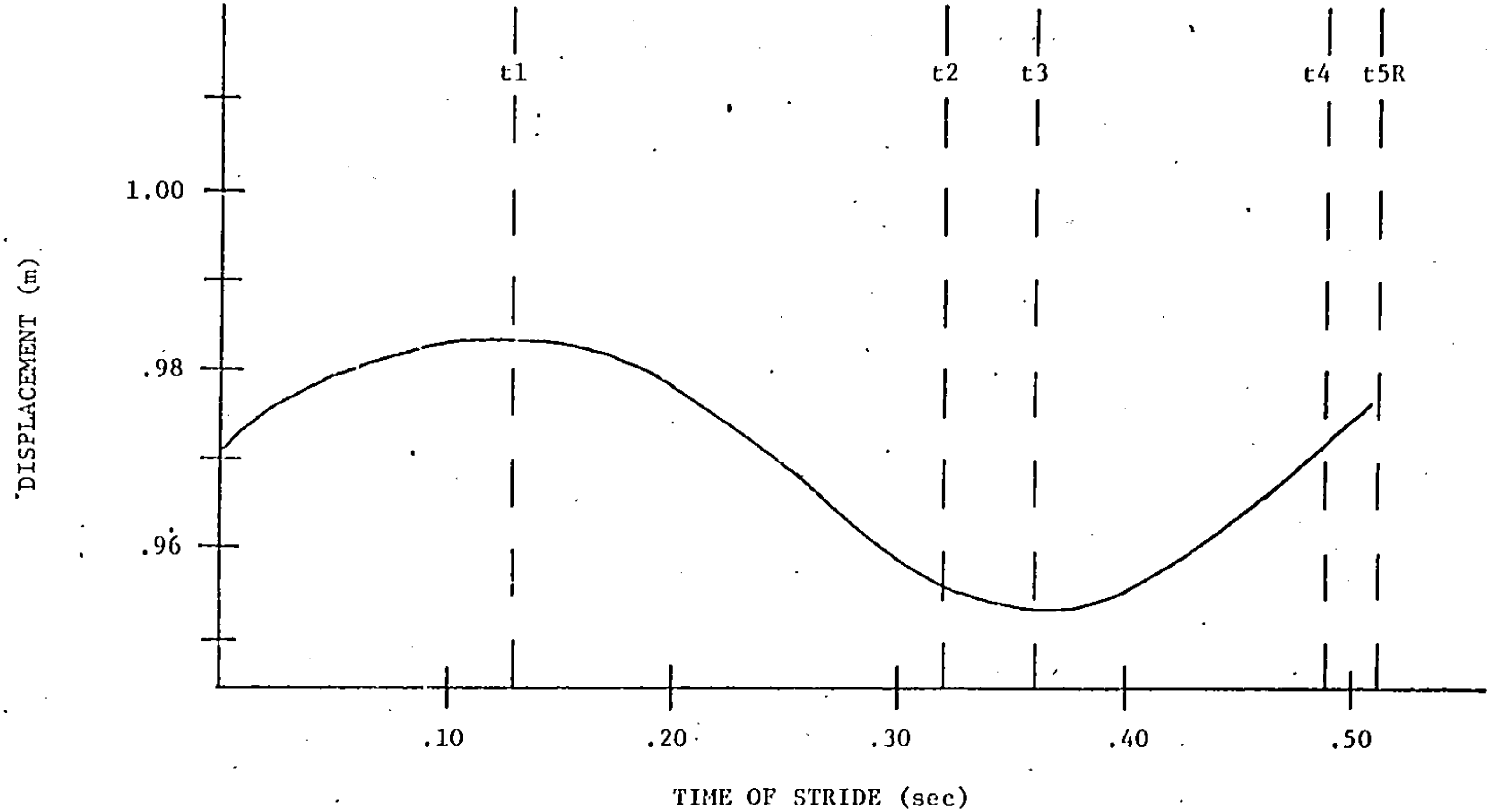

FIGURE 5: VERTICAL DISPLACEMENT OF THE CENTER OF GRAVITY (FOR SUBJECT 1)

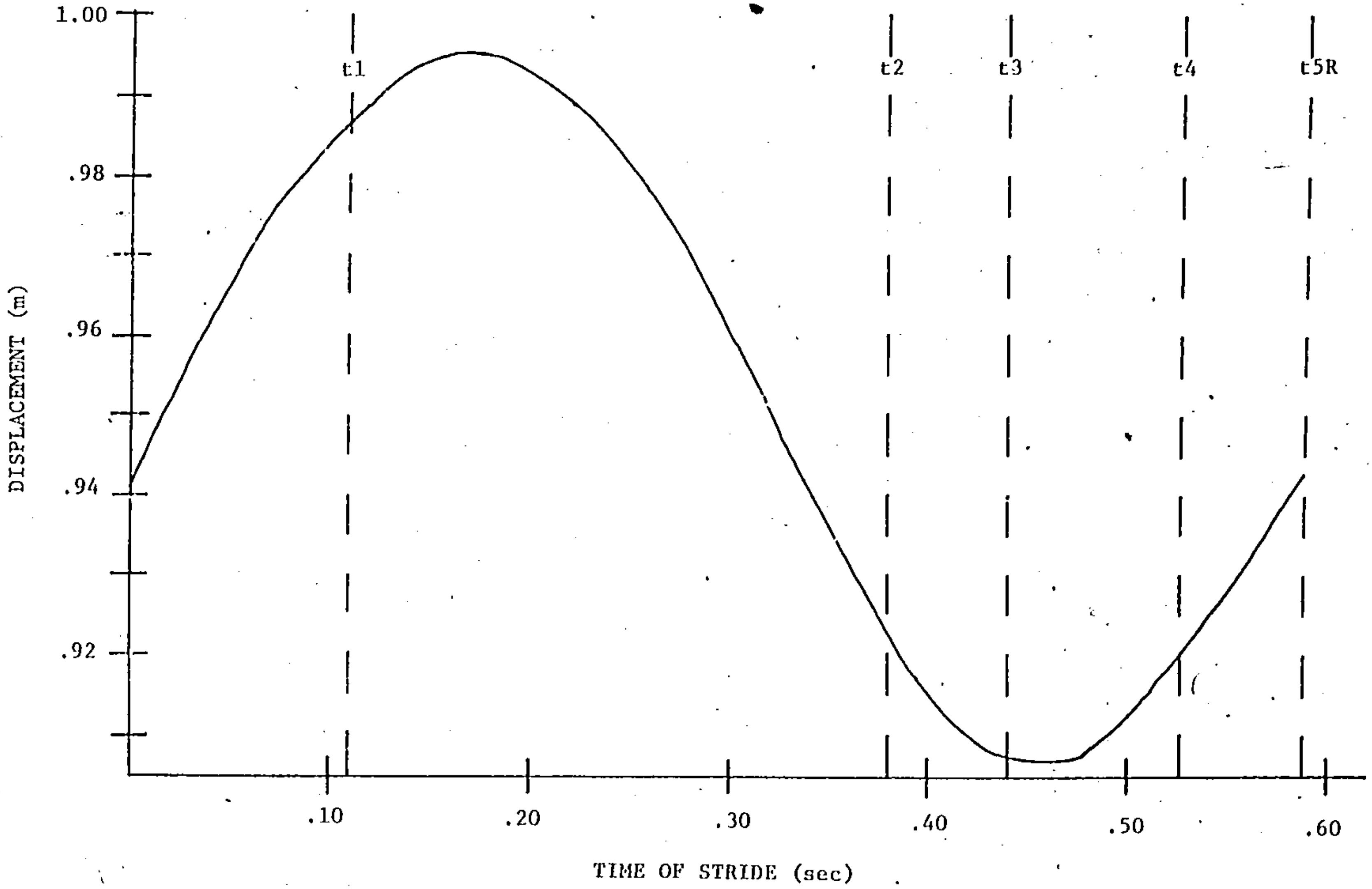

FIGURE 6: VERTICAL DISPLACEMENT OF THE CENTER OF GRAVITY (FOR SUBJECT 8)

the center of gravity rose continuously, reaching approximately the same height at take-off at which it had begun the free glide phase. This sequence is logically consistent with previously described actions performed by skiers throughout the stride cycle (Dillman et al., 1979). For example, at the center of gravity high point, the racers were in an extended position with arms held forward and backward at approximately shoulder height. Also, the rear leg was held in a high position and the support leg was relatively straight. The combined effect of these factors accounts for the high point just following the completion of the free glide phase. Conversely, at the center of gravity low point, the racers were positioned in a somewhat crouched stance with legs together. Also, the arms were positioned relatively low and to the sides of the skiers. These factors account for the low point occurring just after the legs became parallel. Similarly, the continuous rise found between the beginning of the thrust phase and the end of the free glide phase may be accounted for by the change from a semi-crouched to an extended body position. Comparably, the continuous fall of the center of gravity may be accounted for by a return to the semi-crouched position for the subsequent thrust phase of the stride cycle.

The amplitudes of vertical displacement of the center of gravity varied greatly. For example, subject 1 (Figure 5) produced a vertical displacement of .030 m; whereas, subject 8 (Figure 6) experienced a vertical displacement of .089 m. Additionally, the mean vertical displacement of the centers of gravity was .061 m (S=.032) while the range was .114 m. Therefore, there was considerable variation discovered concerning the extent to which subjects raised and lowered their centers of gravity. However, these vertical displacements are consistent with findings of previous studies. Jensen (1979) noted a slight vertical dip in the center of gravity displacement curves, while Dillman et al. (1979) postulated that a relatively large force known as "weighting" was used to set the stationary ski in the track. This action, he reasoned, was used to increase the friction between ski and snow, allowing for a horizontal "push" against the stationary ski. The required normal force could be produced by upward accelerations of body segments involved in the leg thrusting action. Ekstrom measured this vertical component of force and found its maximum values to be three times the body weight for a competitive skier (Dillman et al., 1979). Upward accelerations of the body segments could cause relatively rapid increases in the vertical displacement and velocity of the center of gravity. In the present study it was not possible to evaluate the extent to which these vertical accelerations affected the "weighting" of the stationary ski; however, the timing of the upward accelerations appears to show support for the previous statement. Graphs of vertical velocity vs. time of stride (Figures 7 and 8) indicate that upward acceleration began to occur just before the sliding ski stopped in the track. This fact is evidenced by the positive slope of the velocity curve at this instant. Acceleration increased until just after the legs had come together, then it remained positive, but decreased throughout the remainder of the leg thrust phase. During the free glide phase which followed,

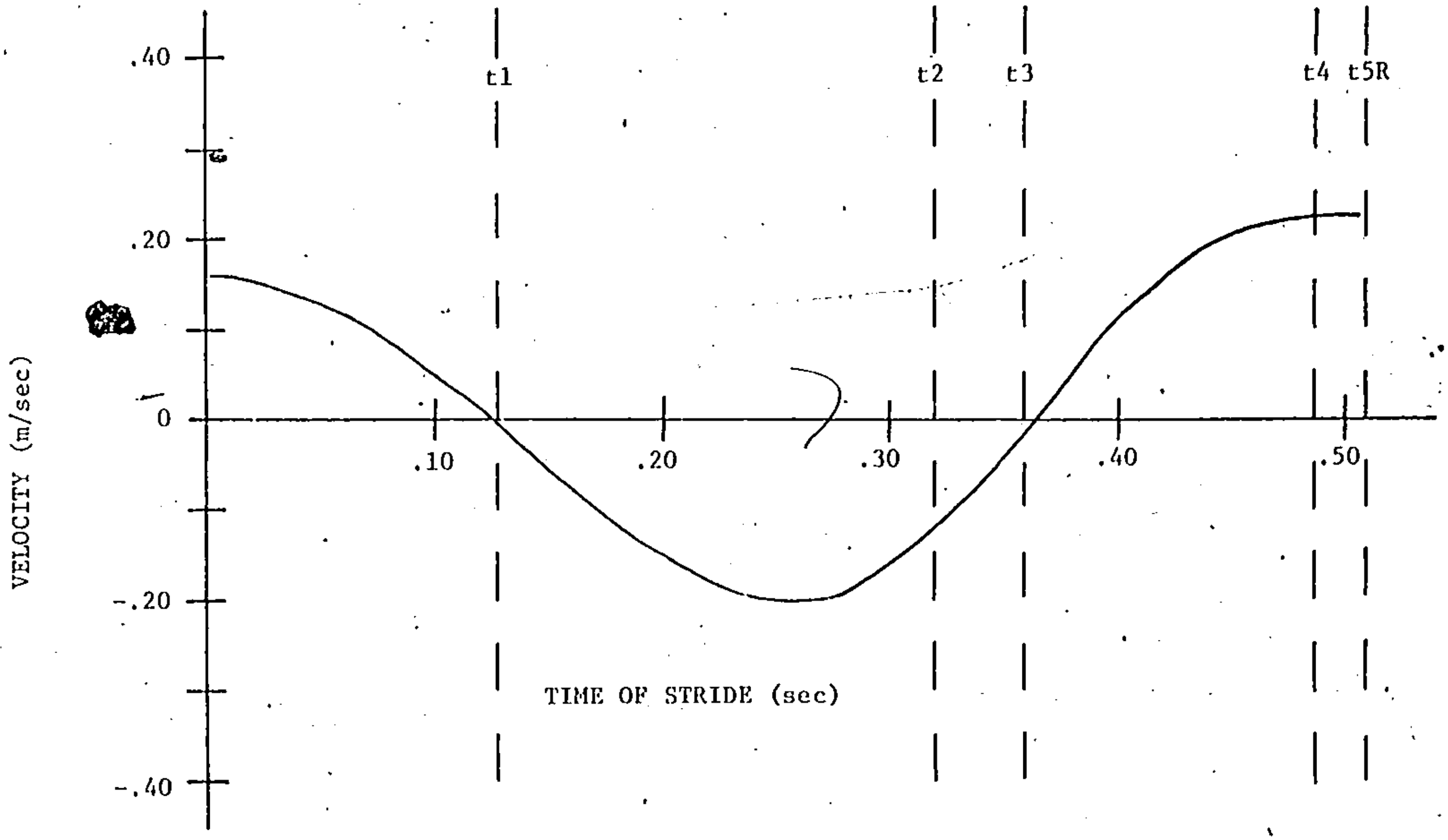

FIGURE 7: VERTICAL VELOCITY OF THE CENTER OF GRAVITY FOR SUBJECT 1

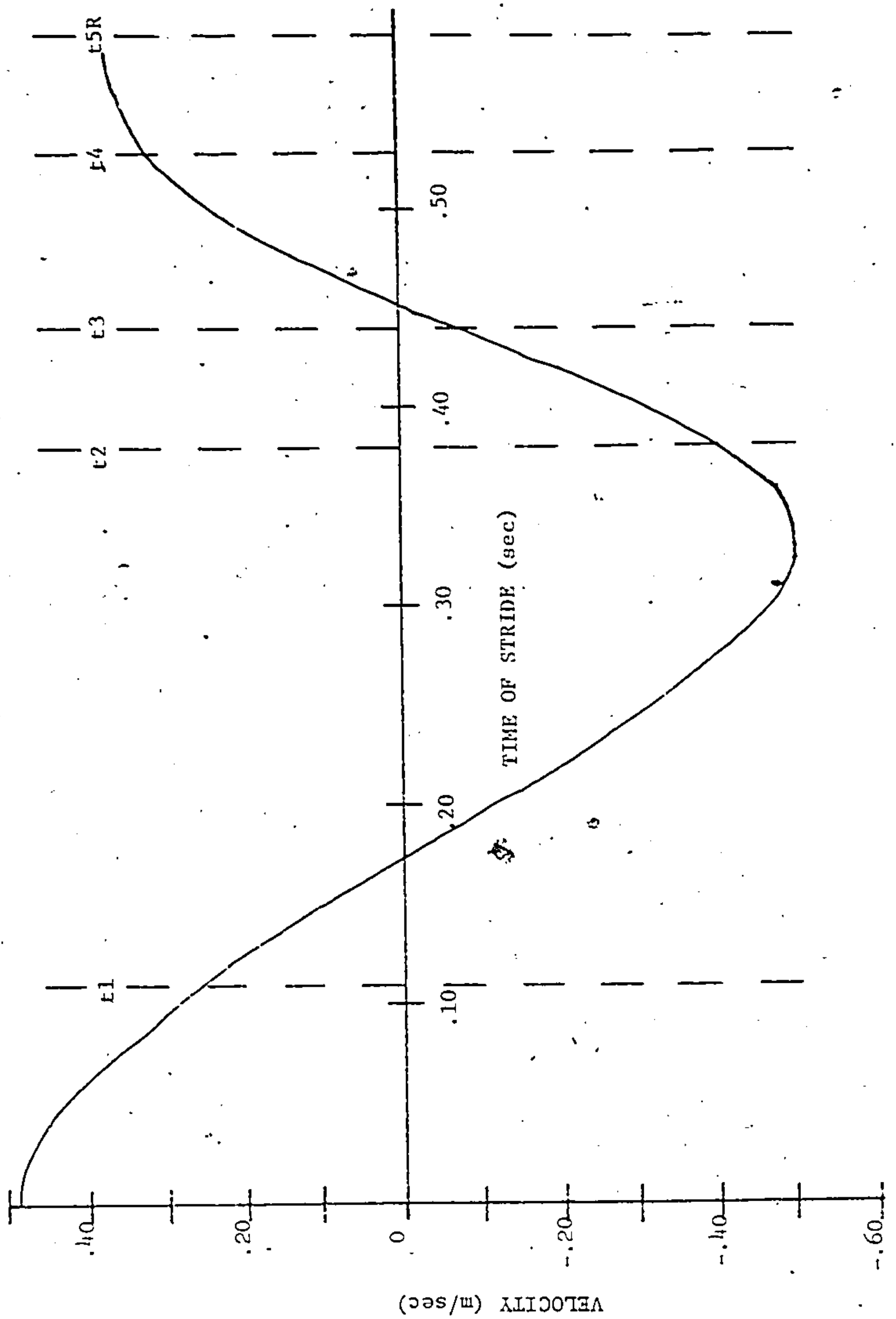

FIGURE 8: VERTICAL VELOCITY OF THE CENTER OF GRAVITY FOR SUBJECT 8

negative acceleration occurred (downward direction), evidenced by the negative slopes of the velocity-time graphs. Acceleration of the center of gravity reached its highest negative value just following pole implantation, then it remained negative but became smaller in magnitude throughout the majority of the sliding portion of the pole implantation phase. Thus, there appears to be a logical pattern in which racers create upward and downward velocities of their centers of gravity. This pattern coincides with previously suggested information regarding the body movements integral to various stride phases.

The subjects whose vertical velocity results were described were not atypical subjects from the total group; however, there were differences in the magnitudes of the vertical velocity variations during the stride pattern. The mean velocity change was .81 m/sec (S=.44) and the range was 1.45 m/sec. It was apparent that an attempt to find the mean vertical velocity of the centers of gravity to produce an "average" pattern would have resulted in an unrealistic curve. Further analysis revealed no significant relationships between rank and each of vertical displacement and velocity. Additionally, the vertical acceleration values generated by the cubic spline error reduction technique were extremely high and the variations throughout the stride appeared unrealistic. This is probably due to a distortion caused by the interaction of the error estimate and the double mathematical derivation methods necessary for the determination of acceleration curves. Thus, the vertical acceleration data appeared meaningless; further investigation is required using different methods of derivation. Overall, the evaluation of the vertical movement of the center of gravity during the stride cycle appears to provide a consistent, realistic assessment of the temporal and spatial qualities of movement in the vertical plane.

Unsmoothed horizontal displacement vs. time data for the centers of gravity during the diagonal stride have been graphically represented in Figure 9. The examples shown are data for subjects 1 and 9; these data are representative of the remainder of the skiers with the exception of subject 5. Clearly, all of the data points closely conform to a straight line drawn through them; the only difference between the two subjects is the slope of the line. Figure 10 is a graphic representation showing horizontal velocity vs. time of stride for selected subjects. Eight subjects produced constant velocities throughout their strides, exemplified by the straight, horizontal line revealed by subject 1. Three others produced a constant velocity which slightly increased (.10 m/sec) throughout the last half of the stride time. Subject 5 experienced a slight increase just after the pole was implanted followed by a sharper increase (.60 m/sec) beginning at approximately the time his support leg stopped sliding in the track. It is evident from these data that most subjects produced constant or only slightly increasing horizontal velocities throughout the total stride pattern. This argument is supported by the fact that unsmoothed displacement vs. time data points conform very closely to a straight line. Thus, the error reduction process did not obscure actual inflections in the data. These results support findings by Marino et al. (1980a) and by Jensen (1979) that the

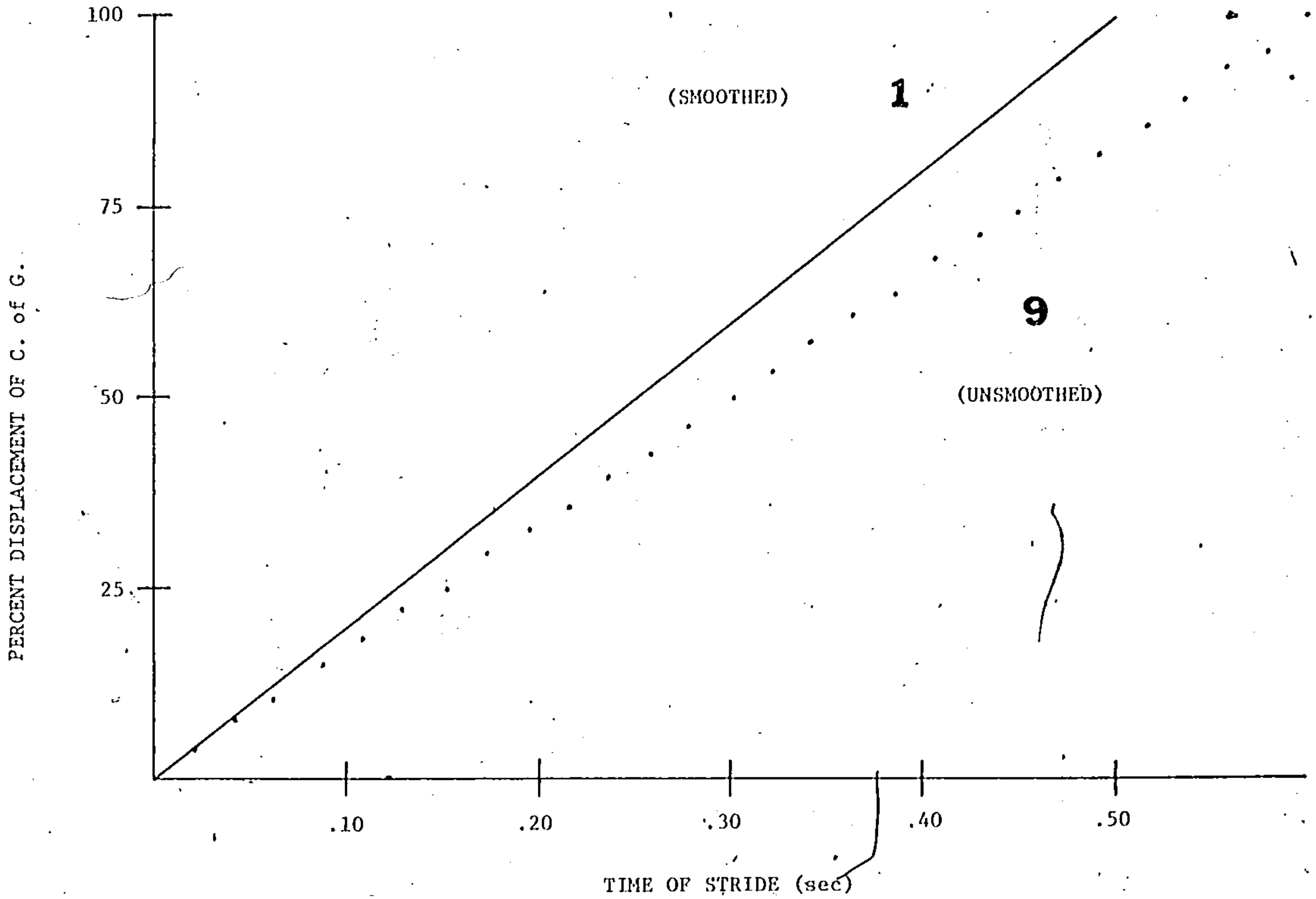

FIGURE 9: HORIZONTAL DISPLACEMENTS OF THE CENTER OF GRAVITY FOR SUBJECTS 1 AND 9

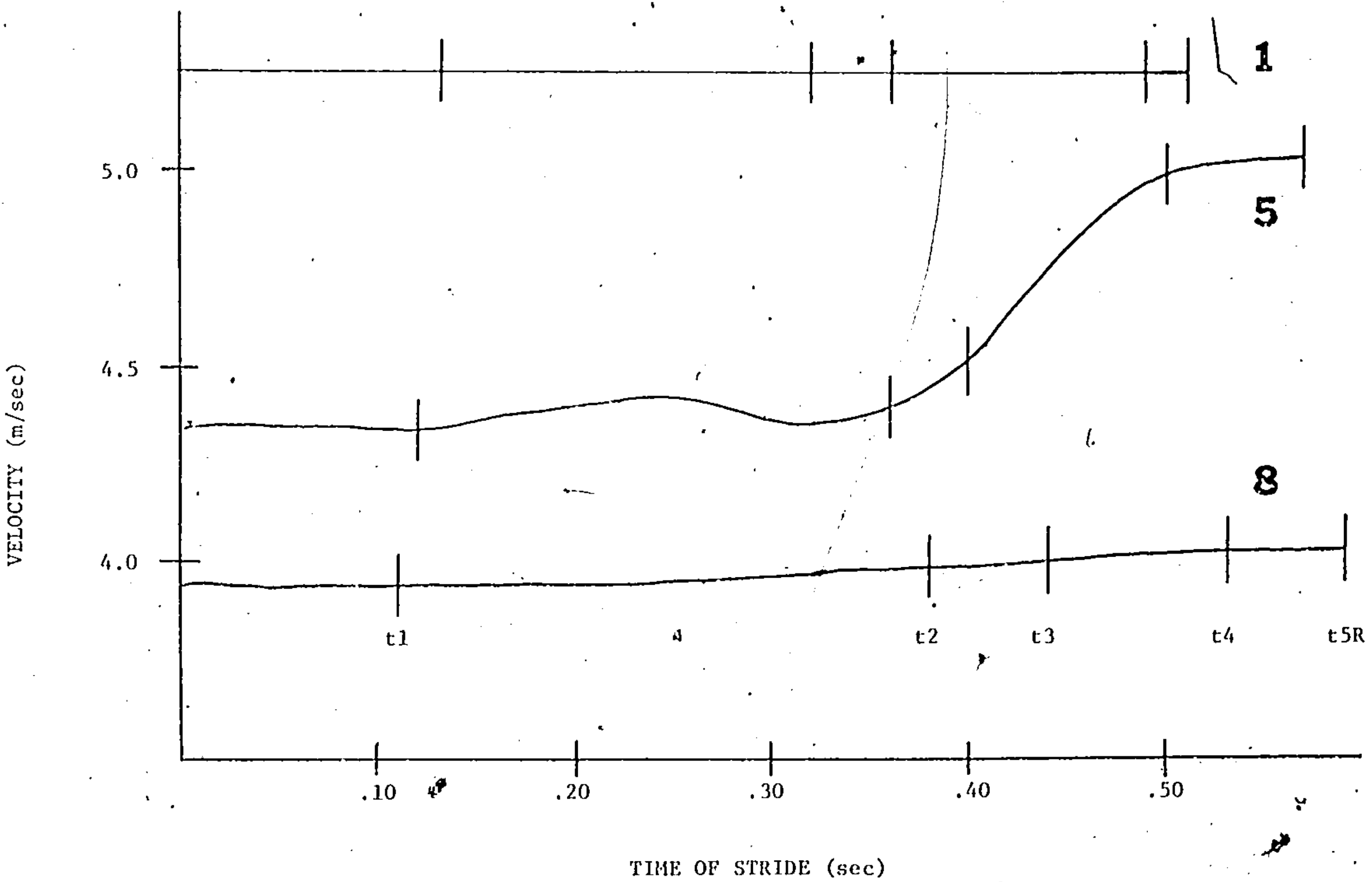

FIGURE 10: HORIZONTAL VELOCITY OF THE CENTER OF GRAVITY FOR SUBJECTS 1, 5 AND 8

horizontal velocity remains relatively constant throughout most of the stride, with some skiers producing a slight reduction during the free glide phase and a slight increase during the pole implantation and thrust phases. The results are also consistent with the suggestion that the objective of the leg thrust phase is to produce a relatively small horizontal force with which to maintain horizontal velocity of the body (Dillman et al., 1979). However, a conflicting report was presented by Komi et al. (1980). He found a mean maximum velocity range of .31 m/sec, occurring during the leg thrust phase for three skiers, but during the free glide and pole implantation phases for two skiers. These differences could possibly be attributed to different race conditions; a track producing a greater coefficient of friction between snow and skis could cause greater increases and decreases in horizontal velocity during the stride cycle. Overall, the majority of evidence supports the finding that a nearly constant horizontal velocity of the center of gravity is maintained; otherwise, slight increases toward the end of the stride may occur.

Body Segment Configuration

A qualitative description of the body actions during the diagonal stride has been presented in the Review of Literature. A quantitative analysis, however, illustrates more clearly the distinctive patterns of movement and allows comparisons to be objectively drawn. Thus, body position angles relative to horizontal and body segment angles were measured at specific instants during the diagonal stride to illustrate the exact relationships among various body segments during the movements required by the skill. The angles for the instant at which pole implantation began have been presented in Tables 6, 7 and 8. Figures 1, 2 and 3 (pages 33-35) show the locations of the body angles on diagrams of a skier's typical body configuration. Angles G, L and T were measured relative to horizontal. Angle G has a mean of -69.0 degrees (S=3.0), indicating a considerable backward lean relative to the base of support. Pole implantation occured after the free gliding phase; also, sliding of the support ski continued for a considerable distance (46% of the total stride) before the ski became stationary in the track. Therefore, the subjects appear to be weighting the rear of their sliding skis in order to enhance the gliding effect. This technique was noted by Dillman et al. (1979), who suggested that body weight should be kept slightly behind the ball of the foot during the gliding phase. These results concur in that the center of gravity was positioned well to the rear of the toe of the support leg. The mean trunk angle (T) was 58.5 degrees (S=5.2) and the mean lower leg angle (L) was 87.1 degrees (S=1.7). These results indicate a relatively upright shank and a considerably forward leaning trunk. The mean knee angle of 142 degrees (S=8.0) is evidence of a relatively bent support leg. Additionally, the mean angle between the subjects' left and right legs (C=77.4; S=5.2) implies that the recovery leg was held in a relatively high position to the rear. This body configuration parallels previous advice that skiers should maintain a good, balanced body position during the sliding action (Dillman et al., 1979). The forward leaning trunk combined with the high rear leg could help to create a well-balanced configuration of

TABLE 6

BODY POSITION ANGLES AT THE INSTANT OF POLE IMPLANTATION

	Rank	Angle G (rad)	Angle L (rad)	Angle T (rad)
	1	-.85	1.52	.88
	2	-.87	1.57	.86
	3	-.86	1.49	1.00
	4	-.93	1.45	.99
	5	-.92	1.54	1.18
	6	-.84	1.56	1.04
	7	-.91	1.54	.99
	8	-.94	1.49	1.06
	9	-.93	1.54	1.09
	10	-.96	1.49	.99
	11	-.96	1.51	1.10
	12	-.83	1.51	1.02
(rad)	$\overline{X}$	-.90	1.52	1.02
	S	.05	.03	.09
(degrees)	$\overline{X}$	-51.6	87.1	58.5
	S	2.8	1.7	5.2

TABLE 7

LEG SEGMENT ANGLES AT THE INSTANT OF POLE IMPLANTATION

	Rank	Angle A (rad)	Angle K (rad)	Angle H (rad)	Angle C (rad)
	1	1.72	2.30	1.66	1.52
	2	1.88	2.68	1.90	1.29
	3	1.82	2.29	1.80	1.44
	4	1.76	2.42	1.97	1.33
	5	1.84	2.59	2.23	1.30
	6	1.85	2.46	1.87	1.42
	7	1.73	2.52	1.96	1.31
	8	1.97	2.65	2.06	1.32
	9	1.78	2.66	2.09	1.33
	10	1.72	2.38	1.88	1.18
	11	1.82	2.35	1.93	1.37
	12	1.84	2.45	2.01	1.42
(rad)	$\bar{X}$	1.81	2.48	1.95	1.35
	S	.07	.14	.15	.09
(degrees)	$\bar{X}$	103.7	142.0	111.8	77.4
	S	4.0	8.0	8.6	5.2

TABLE 8

ARM SEGMENT ANGLES AND POLE POSITION AT THE INSTANT OF POLE IMPLANTATION

	Rank	Angle S (rad)	Angle E (rad)	Angle P (rad)	Distance D (m)
	1	1.50	2.13	1.25	-.10
	2	1.21	1.99	1.20	-.16
	3	1.86	1.98	1.25	-.15
	4	1.25	1.78	1.28	-.08
	5	1.73	2.66	1.31	.09
	6	1.22	2.07	1.17	-.29
	7	1.26	2.03	1.24	-.12
	8	1.03	2.12	1.13	-.35
	9	1.44	2.22	1.28	.03
	10	.77	1.61	1.12	-.43
	11	1.33	2.34	1.14	-.27
	12	1.07	1.98	1.21	-.22
(rad)	$\overline{X}$	1.31	2.08	1.22	-.19
	S	.30	.26	.06	.12
(degrees)	$\overline{X}$	75.1	119.2	69.9	
	S	17.2	14.9	3.4	

body segments. Also, it may allow the skier to reach well in front of his body to begin pole implantation and arm pull. This is an action consistent with the report that the pole should be planted well in front of excellent skiers (Dillman et al., 1979). In this study, pole implantation occurred a mean distance of .19 m (S=.12) behind the toe of the support leg, with only two subjects found to have planted the pole tip in front of the toe. Also, the pole angle relative to horizontal produced a mean of only 69.9 degrees (S=3.4), considerably less than the vertical angle which was previously suggested. Perhaps the differences may be accounted for by the condition and slope of the respective racing tracks, and a subsequent skill modification by the skiers in order to achieve best results. For example, since this study filmed a gradually sloping uphill section rather than a flat portion of the course, some comparisons may be ill-founded. However, the pole implantation positions and angles are within the range of expectations for highly skilled skiers. The mean shoulder angle was 75.1 degrees (S=17.2) and the elbow was 119.2 degrees (S=14.9). Their relatively high standard deviations indicate a considerable degree of variability. The measures indicate that the racers began their pole actions with rather outstretched, yet flexed arms. This position would enable them to take advantage of a shorter resistance arm in performing the skill. Dillman et al., (1979) concluded that highly-skilled skiers use more of a bent arm action for the "pulling" portion of the pole implantation phase. Thus, it would appear that these skiers combined a balanced "gliding" position with a biomechanically effective position for use of the pole at this instant during the diagonal stride.

Table 9, 10 and 11 present similar data for body configuration at the beginning of the leg thrust phase. During this instant, the legs were positioned in a parallel fashion almost directly beneath the body. The legs were slightly more flexed than at the instant of pole implantation, illustrated by a mean knee angle of 135.1 degrees (S=4.7). Also, both the shank and trunk segments were positioned at a more forward angle than in the previous position, as evidenced by mean angles of lean of 62.5 degrees (S=19.5) and 53.3 degrees (S=5.7), respectively. Additionally, the position of the center of gravity was clearly in front of the base of support, shown by a mean angle G of 88.6 degrees (S=4.3). It appears that the subjects had prepared themselves for a "thrusting off" action against the support ski. The forward leaning segments, flexed body angles and forward position of the center of gravity all contribute to a mechanical readiness for this horizontal "push". It was not possible to quantify the "push" in this study; however, corroborative evidence was shown by Dillman et al., (1979). He reported that a 60 degree shank angle and a 45 degree trunk angle were important factors in contributing to a good leg thrust.

The upper body angles produced means of 7.4 degrees (S=5.2) and 131.2 degrees (S=18.1) for the shoulder and elbow joints, respectively. The pole angle had been reduced to a mean of 36.7 degrees (S=5.2) by this stage of the stride. These results show that the pulling arm was close to the trunk, yet the elbow remained flexed for this portion of the poling action, probably to maintain the more effective thrust of a shorter resistance arm. There is also evidence of a considerable degree of variability among the subjects' arm actions.

TABLE 9

BODY POSITION ANGLES AT THE BEGINNING OF THE LEG THRUST PHASE

	Rank	Angle G (rad)	Angle L (rad)	Angle T (rad)
	1	1.49	1.23	.89
	2	1.48	1.29	.78
	3	-1.51	1.23	.88
	4	1.52	.98	1.03
	5	1.47	1.11	.92
	6	1.49	1.11	.90
	7	1.56	1.22	.96
	8	1.47	1.15	1.04
	9	-1.54	1.33	.80
	10	-1.47	.06	.84
	11	-1.48	1.19	1.08
	12	1.53	1.22	1.00
(rad)	$\bar{X}$	1.55	1.09	.93
	S	.07	.34	.10
(degrees)	$\bar{X}$	88.6	62.5	53.3
	S	4.3	19.5	5.7

TABLE 10

LEG SEGMENT ANGLES AT THE BEGINNING OF THE LEG THRUST PHASE

	Rank	Angle A (rad)	Angle K (rad)	Angle H (rad)	Angle C (rad)
	1	1.76	2.33	2.11	.20
	2	1.60	2.47	1.99	.06
	3	1.52	2.37	2.03	.03
	4	1.35	2.27	2.32	.00
	5	1.57	2.37	2.17	.01
	6	1.45	2.38	2.18	.02
	7	1.54	2.30	2.12	.17
	8	1.44	2.23	2.21	.09
	9	1.64	2.52	2.04	.02
	10	.36	1.40	2.18	.16
	11	1.51	2.36	2.26	.05
	12	1.49	2.34	2.14	.24
(rad)	$\overline{X}$	1.44	2.36	2.15	.09
	S	.35	.08	.10	.08
(degrees)	$\overline{X}$	22.5	135.1	123.2	5.2
	S	20.1	4.7	5.7	4.6

TABLE 11

ARM SEGMENT ANGLES AND POLE POSITION AT THE BEGINNING OF THE LEG THRUST PHASE

	Rank	Angle S (rad)	Angle E (rad)	Angle P (rad)	Distance D (m)
	1	.23	1.97	.68	-.77
	2	.19	2.43	.60	-1.06
	3	.08	2.00	.66	-.99
	4	.14	2.33	.60	-.98
	5	.34	2.18	.72	-.67
	6	.01	2.54	.54	-1.10
	7	.07	1.80	.77	-.79
	8	.09	2.85	.68	.98
	9	.01	2.06	.65	-.90
	10	.13	2.63	.45	-1.34
	11	.16	2.49	.65	-1.17
	12	.15	2.20	.72	-1.11
(rad)	$\bar{X}$	.13	2.29	.64	-.99
	S	.09	.31	.09	.19
(degrees)	$\bar{X}$	7.4	131.2	36.7	
	S	5.2	18.1	5.2	

The leg thrust phase ended when the center portion of a subject's thrust ski lost contact with the track. At this distinctive instant, body segment angles were calculated. Tables 12, 13 and 14 present a summary of the data for all subjects. Mean angles of the trunk and hip had increased to 61.9 degrees (S=5.7) and 170.2 degrees (S=6.9), respectively. This is evidence of an extended body position which maintained the forward lean of the trunk segment. Additionally, the knee and ankle joints showed increased angles over the beginning of the leg thrust phase, with respective means of 163.7 degrees (S=6.6) and 120.3 degrees (S=6.3). Thus, the thrust leg was extremely extended at the end of the leg thrust phase and the ankle was plantar-flexed, indicating that the heel had been lifted to a considerable extent off the ski platform. The shoulder and elbow angles produced respective means of 33.8 degrees (S=8.6) and 166.2 degrees (S=80). These angles typify an extreme extension of these joints. This result was expected since the pole implantation phase had ended at the time of takeoff for all subjects tested. The extension likely constitutes a following through action of the arm segments; however, recovery of the arm and pole may have already begun, since the joints were not in a fully extended position.

In summary, body segment configuration appears to be an important factor at various phases during the stride. These subjects exhibited strikingly similar patterns for such measures as body lean and position of the center of gravity relative to the base of support. The diagonal stride appears to be composed of a distinctly timed sequence of body segment rotations.

TABLE 12

BODY POSITION ANGLES AT THE INSTANT OF TAKE-OFF

	Rank	Angle G (rad)	Angle L (rad)	Angle T (rad)
	1	.85	.64	1.07
	2	.87	.61	1.00
	3	.86	.64	.96
	4	.93	.73	1.20
	5	.92	.61	.99
	6	.84	.58	1.13
	7	.91	.70	1.10
	8	.94	.67	1.12
	9	.93	.67	.94
	10	.96	.62	1.02
	11	.96	.55	1.27
	12	.83	.55	1.12
(rad)	$\overline{X}$	.90	.63	1.08
	S	.05	.06	.10
(degrees)	$\overline{X}$	51.6	36.1	61.9
	S	2.8	3.4	5.7

TABLE 13

LEG SEGMENT ANGLES AT THE INSTANT OF TAKE-OFF

	Rank	Angle A (rad)	Angle K (rad)	Angle H (rad)	Angle C (rad)
	1	2.20	2.90	2.95	1.35
	2	2.08	2.84	3.05	1.31
	3	2.14	2.92	3.04	1.44
	4	2.19	3.07	2.75	1.33
	5	2.01	2.76	3.14	1.30
	6	2.10	2.90	2.82	1.44
	7	2.12	2.99	2.89	1.38
	8	2.18	2.87	2.95	1.26
	9	2.08	2.85	3.11	1.28
	10	1.90	2.65	3.05	1.09
	11	1.92	2.71	2.93	1.17
	12	2.27	2.82	2.90	1.41
(rad)	$\overline{X}$	2.10	2.86	2.97	1.31
	S	.11	.12	.12	.11
(degrees)	$\overline{X}$	120.3	163.7	170.2	75.1
	S	6.3	6.6	6.9	6.3

TABLE 14

ARM SEGMENT ANGLES AND POLE POSITION AT THE INSTANT OF TAKE-OFF

Rank	Angle S (rad)	Angle E (rad)	Angle F (rad)	Distance D (m)
1	.53	2.63	.63	.83
2	.32	3.04	.57	.86
3	.55	2.99	.58	.89
4	.63	2.96	.62	.90
5	.42	2.81	.68	.67
6	.58	3.04	.57	.87
7	.71	2.63	.66	.78
8	.68	2.84	.65	.98
9	.44	3.02	.56	.87
10	.69	2.96	.57	.12
11	.88	2.95	.60	1.07
12	.70	2.93	.63	.91
(rad) $\bar{X}$	.59	2.90	.61	.81
S	.15	.14	.04	.24
(degrees) $\bar{X}$	33.8	166.2	35.0	
S	8.6	8.0	2.3	

The T-test for significant difference between the mean performance of the first five and the last six rankings produced a value of 3.51, indicating a significant difference ($P < .01$). No significant relationships, however, were discovered between finishing rank and various performance parameters. Therefore, variations in style utilized in producing successful performance appear to be present. Determination of the specific causes of the significantly different performances awaits further study.

CHAPTER V

SUMMARY AND CONCLUSIONS

The purpose of the study was to quantify the kinematic parameters involved in the diagonal stride in order to develop a performance profile of high caliber execution of this aspect of cross-country skiing technique. Analysis included an investigation of stride rate and length, both vertical and horizontal displacements of the center of gravity, phase proportions of the stride, and body segment configuration at various stages of the total movement pattern. The results indicated that the diagonal stride technique is composed of a distinctly timed sequence of actions; thus it was possible to create a descriptive profile of highly skilled performance. Based on this quantitative description, the following conclusions were warranted:

(1) High caliber racers achieve horizontal velocity through different combinations of stride lengths and stride rates.

(2) A relatively large proportion of the stride consists of the skiers' leg(s) providing only a body support function while a small component is comprised of a leg thrusting action. The majority of the former portion is characterized by a sliding action of the support ski(s).

(3) During a great percentage of the sliding proportion of the stride, assistance is gained through the use of the pole. It appears that this pole action is a factor involved with the maintenance of a relatively constant horizontal velocity.

(4) During a single diagonal stride, the horizontal velocity fluctuates very little. A majority of skiers maintain velocity

throughout the stride, while a few experience slight increases during the leg thrust phase.

(5) The vertical displacement of the center of gravity during the stride exhibits a distinctive temporal pattern; it reaches its high point at approximately the time the pole is planted and its low point at approximately the beginning of the leg thrust phase. There appears to be no rapid change in the vertical velocity of the center of gravity; upward acceleration begins just prior to the time when the support ski becomes stationary.

(6) Racers exhibit a relatively flexed body position before the leg thrust, while an extremely extended position is maintained during the sliding portion of the stride. A bent arm pulling action is utilized throughout the majority of the pole implantation phase. There is considerable variation, however, among the positions of specific body segments.

(7) During the sliding portion of the stride, the center of gravity is positioned well behind the toe of the support leg. Its relative location moves forward in preparation for the initiation of the leg thrust phase; during the leg thrust the center of gravity is positioned well in front of the toe of the thrust leg.

Thus, movement parameters describing the diagonal stride technique have been quantified in order to provide a profile of the distinct movements performed by highly skilled skiers. This profile may be considered indicative of the performance objectives for poorly skilled skiers. Additionally, instructors and coaches of cross-country skiers may base practical recommendations for improvement upon these findings.

It was the author's intention to provide a quantitative profile on which to base further study. Although performance times of the first five and the last six rankings were found to be significantly different, no significant relationships were discovered between finishing rank and various performance parameters. Thus, successful cross-country ski racers appear to exhibit subtle variations in style which prevent a valid prediction of success based on specific body movement parameters. Therefore, future research should be directed toward the identification of combinations of factors which produce successful performance of the diagonal stride, perhaps through linear regression analysis. It will be necessary, also, to examine the forces involved with leg thrust and arm pull in order to assess their relative contributions to average horizontal velocity. Further kinetic study should be undertaken to determine the optimum weighting or normal force required to increase the friction necessary to "set" the thrust ski in the track. Additionally, the diagonal stride should be examined under the varying racing conditions presented by the incline of the track, snow characteristics and tactical requirements of the race. Finally, investigation of the remaining cross-country skiing techniques should be undertaken to determine the relative contributions of each skill component to the total performance. Only upon completion of this research will biomechanicians be capable of providing coaches and instructors with a complete set of recommendations for the production of optimum mechanical performance in cross-country skiing.

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