Kinematic Considerations of Elite Alpine Slalom Ski Racers

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KINEMATIC CONSIDERATIONS OF ELITE ALPINE SLALOM SKI RACERS

by

David Andrew Goodwin

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
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KINEMATIC CONSIDERATIONS OF ELITE ALPINE SLALOM SKI RACERS

David Andrew Goodwin, M.A.
Western Michigan University, 1990

This study described specific kinematic parameters associated with success on the international level in alpine slalom ski racing. Sixteen male athletes representing twelve countries comprised the subject pool. Subject selection was based on finish position in the men's special slalom at the 1989 World Alpine Ski Championships in Vail, Colorado. Cinematographical records were analyzed by a method known as direct linear transformation.

The findings of the study indicated that: (a) hip and knee joint angles of the turning leg must approximate 1.80 to 1.83 radians and 1.82 to 2.21 radians, respectively, for efficiency in this turn; (b) a decrease in right knee angular velocity and a consistent right hip angular velocity tend to be associated with higher right boot toe velocities; and (c) right boot toe distance from the base of the slalom pole correlated well with velocity. Although variable relationships exist, none of the dependent variables tested could be classified as more significant than the others regarding the proper execution of an alpine slalom turn.
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David Andrew Goodwin
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Kinematic considerations of elite alpine slalom ski racers

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Western Michigan University, 1990

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CHAPTER I

INTRODUCTION

The use of quantitative biomechanical parameters as qualitative descriptors of competitive alpine ski technique is generally limited by environmental factors which influence the sport. An open environmental arena presents significant challenges to researchers, of which terrain changes, course layout, and weather problems play the most predominant roles to be overcome. Because the United States ski industry is relatively small compared to that of European nations, competitive alpine skiing is given less significance in this country than other sports for financial reasons. U.S. researchers generally divide their time between their own specialties such as mechanical engineering and ski research. The result is that a much more significant contribution to sports science research in alpine skiing comes from European scientists/engineers.

Success at the national and international levels in alpine ski racing is dependent in part, upon a skier's ability to maintain a particular line through a course. The lower extremities are primarily responsible for the ability to maintain the correct line for a given turn. Changes in the leg, thigh, and pelvic displacements, velocities, and accelerations are responsible for lower body technique, which are an axiom of turn (line) requirements. In essence, technique of the elite skier is established by appropriate lower body kinematics throughout a turn which effectively optimize speed, the criterion for success in alpine ski racing.
**Problem Statement**

This research is expected to identify specific kinematic parameters that are thought to be associated with elite alpine slalom ski performance.

1. The resultant and component velocities of skiers as they negotiate a slalom turn ultimately determine how successful the skiers are.
2. The joint angles in the lower body act as technique descriptors during the turn sequence.
3. The lower body joint angular velocities throughout the turn sequence describe how active the lower body is through the turn.
4. The position of the right boot toe in relation to the position of the base of the slalom gate indicates the line taken through the turn.

**Purpose of the Study**

The purpose of this investigation was to quantitatively explain the mechanics involved in negotiating an alpine slalom ski turn. Specifically studied were lower body location and linear and joint angular velocities, as they apply to the techniques and course line choices of international slalom ski racers competing in the men's special slalom event at the 1989 World Alpine Ski Championships in Vail/Beaver Creek, Colorado (USA). Based on kinematic considerations concerning position, joint angles, and velocity characteristics of the lower body, insight into physical attributes possessed by elite alpine skiers were made. It is the intent of the investigator that results of this study will assist national ski team coaches/programs in understanding the significant mechanical characteristics which elite alpine slalom skiers possess.
Need for the Study

While there is a preponderance of qualitative theoretically based evaluations of slalom ski racing technique, very few researchers have described competitive ski technique in quantitative terms. Superior performances are considerably more frequent during Olympic and World Championship competitions than in the laboratory. This investigator found no empirical research regarding the alpine slalom event during an actual international competition. This study makes an effort to provide a more precise quantitative understanding and to lay a foundation upon which further scientific research in the sport of alpine skiing may be made.

Delimitations

The study was delimited to:

1. Three-dimensional cinematographic records which were made by the method of direct linear transformation for both men's slalom events at the 1989 World Alpine Ski Championships in Vail/Beaver Creek, Colorado (USA).

2. Subjects who were elite male alpine skiers on national ski teams that participate in international alpine ski events.

3. Skiers who were initially classified according to their international (FIS) slalom point ranking and later rank-ordered by their post-race positions.

Limitations

The following were basic limitations to this study:

1. Visual digitization of unmarked joint centers provided the kinematic data necessary to make quantitative analyses of technique.
2. Subjective interpretations of joint centers were made when limbs were blocked from view by other limbs or spray of the snow.

3. Slope topography was estimated by a series of localized measures which were then averaged.

4. There was a possibility of digitizing error based on the processing quality of the film.

Assumptions

In this study, the following assumptions have been made:

1. It was assumed that the subjects' International Ski Federation (FIS) points were a valid indicator of ski ability in the slalom event.

2. Subjects' performance was optimal because of the importance associated with racing against the clock and other competitors.

3. The high-speed camera system functioned properly in the cold environment.

4. The camera set-up and referencing system provided a three-dimensional record of each subject over a given interval of time.

Definition of Terms

Alpine Equipment Characteristics

The physical properties of alpine skis include:

1. Camber: This describes the arched shape (convexity) in the ski as it lies unweighted on a flat surface.

2. Contact Surface: This is the amount of edge that makes contact on the snow when the ski is weighted. Pressure is applied at the tip and tail of the ski because of camber. This pressure is required to initiate and sustain all carved turns.
3. **Damping**: This is the ski quality that attempts to absorb vibrations and shocks.

4. **Flexion or Stiffness**: Resistance of the ski to bend and the variability of this resistance along the ski, determining the flex pattern of the ski.

5. **Reverse camber**: This describes the arched shape (concavity) in a ski on edge with weight applied. In this position, energy is stored in the materials of the ski which provide the capacity of the ski to recover from a flexed reverse camber position.

6. **Side-cut**: This is the amount of deviation from a straight line that the ski edge makes. The amount that side-cut varies determines the maximum reverse camber possible, and turn (arc) radius. Slalom skis have the largest side-cut allowing for short radius turns.

7. **Side-deflection**: This is a lateral flexion in a ski created by a side force.

8. **Torsion**: This describes the resistance of the ski to twisting forces.

9. **Torsional Flexibility**: This is a property which absorbs twisting and untwisting shock as the contact surface carves over undulations in the terrain.

10. **Unwinding**: The capability of the ski to recover from a twisted (torsionally deflected) position is known as unwinding.

11. **Vibration**: This describes the fluttering (oscillation) of the ski tip, and is critical at high speeds on hard snow.

A physical property of alpine ski boots is:

12. **Boot Shaft-Forward Lean**: This is the anterior inclination from a vertical axis through the boot’s center of mass. Anterior-posterior (front-back) stiffness contributes to force transfer through the ski. Harder snow conditions and the slalom event require stiffer boot shafts.
Physical properties of alpine ski bindings include:

13. Cycle speed: This describes the bindings' identification and absorption of shock and is the most important measure of a binding's performance.

14. Return-to-center (Retention): The ability of the binding to return the boot to the neutral position after an applied load to the boot is known as retention. If the external forces on the binding are too great, release occurs. Retention is measured in the toe and heel vertically, horizontally, and in some cases diagonally.

Alpine Ski Technique (Descriptive)

1. Alpine Slalom Event: Skiers compete against each other over the same course against the clock by winding through a series of slalom poles set back and forth down the hill. Slalom (SL) racing consists of two runs over different courses with the aggregate time for both runs determining the winner. Per FIS standards, a gate is made from two poles set a minimum of 4 meters and a maximum of 6 meters apart. The distance from turning pole to turning pole of successive gates may not be less than 0.75 meters and not more than 15 meters. A course consists of 55-75 gates set over approximately 480 meters with a vertical drop of 180-220 meters. Each run takes between 50-60 seconds to ski, with racers traveling 40-55 km/hr.

2. Angulation: This refers to the fact that two parts of the body are on different segmental axes from an angle where they meet. Knee angulation results from medial (inward) projection of a flexed knee creating an angle between the thigh and leg (vertical axis). Hip angulation refers to the angle formed by the axes of the upper and lower body when the waist is flexed and rotated over the outside hip joint in opposition to the turn.
3. Anticipation: This is the separation of upper body and lower body movement. As the skis come around the turn, the upper body continues to face downhill providing impulse for the next turn initiation.

4. Edge Set: By rolling the ski on edge and applying a force which creates reverse camber, the ski edge will bite into the surface and begin to carve a curved track.

5. Elite: This is a subjective classification of proficiency in alpine skiing given to those members on national ski teams who possess a top 100 ranking on the FIS point list in the alpine slalom event.

6. Fall Line: The line where the hill is decreasing most rapidly creates the slope's fall line.

7. FIS (Federation Internationale de Ski) Points: This is the International Ski Federation classification of skiers from different countries where lower points correlate with better start positions in a race. Skiers with higher FIS points can lower (drop) points by finishing ahead of skiers who have lower FIS points. Fifteen skiers make up a seed in start orders. The top fifteen skiers (lowest FIS points) are drawn randomly for start positions 1-15. Subsequent seeds are formed according to FIS points from low to high.

8. Forward Foot Thrust: Pushing the carving ski forward as it crosses the fall line is a critical movement minimizing sideslipping (centrifugal forces) and maximizing speed, and is known as forward foot thrust.

9. Lateral Forward Projection: A movement from the downhill ski to the uphill ski at the end of a turn helps establish a higher line in the course or can be used as an acceleration movement over flat terrain.

10. Traverse Direction: This is a direction across the hill which lies perpendicular to the fall line.
11. Unweighting: Turn initiation requires a reduction of contact forces between the ski and the snow. A variety or combination of upward or downward center of gravity maneuvers accomplishes unweighting the skis, with choice depending on speed, slope steepness (gradient), terrain features, and turn radius. Unweighting the ski creates a situation of nearly zero external torque and non-zero constant angular momentum on the ski, which initiates direction change.

12. World Cup Circuit: This is a season long series of ski races which determines the best technical and all-around skiers in the world. The circuit consists of slalom (SL), giant slalom (GS), super giant slalom (SGS), and downhill (DH) events.

Biomechanical Data Collection and Reduction Techniques

1. Anatomical Data: Some physical measurements are necessary to derive and validate kinetic data from film records. Segment length, mass, center of mass, and joint centers are typical anatomical data. Lower extremities pertain to the thigh, leg, and foot segments.

2. Cinematography: This is a method of measurement that employs high speed filming to determine kinematic variables. Film speed ranges from 60-200 frames per second (f.p.s.) for most sports movements. Filming may be two-dimensional or three-dimensional depending on the number of cameras used and their positioning.

3. Curvature (K): This variable defines information about the sharpness of the curve at various points and is used in turn identification and defined as the absolute value of the rate at which the angle θ changes with respect to arc length s.

4. Data Smoothing: This is an attempt to filter or reduce noise that produce errors in higher order derivative calculations (velocity, acceleration). The noise results
from extraneous signals, camera vibration from film speed, and camera platform settling.

5. Digitizing: This refers to the location and electronic storage of critical anatomical landmarks and reference points on specific frames of the film.

6. Direct Linear Transformation: This is a three-dimensional cinematographic technique based on photogrammetric methods of topographical mapping from the air.

7. Gradient (\(\nabla f\)): Slope topography or the drop in elevation over a given distance on the course is known as gradient. \(\nabla f\) can be used to find the slope of the function \(f\) at any point if survey methods are applied.

8. Kinematics: These are variables involved in movement description, independent of the forces that cause the movement. Included are linear and angular displacements, velocities, and accelerations. Displacement data is obtained for any anatomical landmark. A relative spatial reference system requires anatomical coordinates be reported relative to a fixed anatomical landmark such as body center of gravity. An absolute spatial reference system refers coordinates to an external spatial reference system. Relative angles refer to joint angles, absolute angles refer to some external spatial reference.

9. Reference System: This provides control points which develop three-dimensional coordinate interior and exterior orientations in space.
CHAPTER II

REVIEW OF LITERATURE

Introduction

The purpose of this review was to provide an overview of the biomechanical research related to alpine skiing, and more specifically, that related to competitive situations in the sport. Additionally, research concerning three-dimensional cinemagraphic methodologies and raw biomechanical data smoothing techniques are of considerable interest to this project. Familiarization with these studies formed a foundation that facilitated research in this area.

Alpine Ski Research

Alpine ski research has focused almost exclusively on the safety concerns of ski equipment. This type of basic research was justified through equipment modifications and other safety applications in a high injury risk sport, and was well suited to experimental laboratory testing.

Direct methods of measuring loads between the boot and binding, and binding movement have been made in field research (Lieu, Mote, Brown, & Ettlinger, 1982). High speed filming has also been used to identify performance parameters of the optimal line in slalom ski racing (Förg-Rob & Nachbauer, 1988). The parameters included toe position in relation to the gate, time spent and distances travelled for various defined turn phases, angle from the fall line of the binding toe during turn phases, and toe velocity in the different phases. As early as 1970 Ikai conducted a
biomechanical study of alpine skiing focusing on the indirect measurement of ground reaction force during a turn by using high-speed cinematography. A special turn course was constructed with a 14.2 meter radius. One camera was set at the center of the circle and the other at 90 degrees to the focal axis of the first. The subjects were top Japanese alpine skiers, with one athlete generating 118.22 kg of ground reaction force during a turn at a speed of 12.8 m/s. This was 81% of the athlete's maximal leg strength. The same methodology was used at the Sapporo (Japan) Pre-Olympic Games men's downhill. Gate number 4, with a 19.0 meter radius, was selected. The ground reaction forces averaged 211.3 kg for the top 10 skiers, while turn speed averaged 22.4 m/s for the same group.

While there have been papers published on recreational skiing, very few empirical studies have been applied to ski racing skills. Yatabe (1972) described a turning ski by angular and linear velocity, ski drifting angle, and the radius of curvature of the turn. Nachbauer (1986) extended recreational ski research to the competitive field of alpine skiing by investigating methods of line determination and reaction forces in the slalom and giant slalom events. In 1988, Förg-Rob and Nachbauer published a research paper which dealt exclusively with the slalom event, leading to identification of biokinematic performance parameters important to line selection.

Förg-Rob and Nachbauer (1988) investigated thirty-four elite skiers, including members of the Austrian A, B, and C Teams, the Yugoslavian Team, and the United States Junior National Team, who were tested on the glaciers in Hintertux, Austria in the Fall of 1983. Skiers were filmed at 50 f.p.s. over three gates of a five gate experimental course with a 21.5 degree slope. Reaction forces were obtained from four pressure gauges on each ski. The gauges were placed on the top surface of the skis, with two gauges under the toe and two gauges under the heel, on the medial and lateral
sides. Each turn was divided into two phases, preturning and turning. The preturning phase was subsequently subdivided into weight transfer and unweighting. The turning phase was subdivided into edge-setting and steering. Toe portions of each binding were marked with black foil tape to achieve better contrast.

Förg-Rob and Nachbauer (1988) found means and standard deviations for twelve performance parameters, as well as results of the fastest racer, were evaluated and compared. The fastest run was characterized by an early weight transfer onto the inner ski for the next turn, and a straighter, steeper line to the next gate. These characteristics provided a mean velocity of 9.43 m/s compared to the mean velocity of 8.91 m/s for the other 33 skiers. Correlation coefficients were calculated between performance parameters and the total time of performance. The critical parameters were identified as: (a) the distance of the line from Gate 2 orthogonal to the fall line (across the hill displacement); (b) toe position along the fall line at the end of the steering phase of the preceding turn, and at the beginning of the weight transfer phase; and (c) toe position orthogonal to the fall line at the end of the steering phase.

Finally, path-analysis indicated a cause and effect relationship between these parameters and ski technique. High entering velocity is the speed the skier brings into a ski turn. A high line at the beginning of a turn is established by a position farther up the fall line at turn initiation, a low line at the beginning of edge set occurs when the skier finishes the turn prior to arrival at the gate, an early edge set allows for this low line, and a short distance traveled orthogonally (perpendicular) to the fall line directly affect total time for the course. The end of a turn is greatly influenced by its initiation and edge-set, which contribute to the orthogonal distance the skier travels from the fall line.
Data Collection Techniques

While two-dimensional cinematography has been used successfully for motions that occur in a single plane, it is a limiting factor for more complex human motion studies. As a result, three-dimensional cinematographic methods using at least two cameras were developed (Anderson, 1970; Bergemann, 1974; Martin & Pongratz, 1974; Miller & Petak, 1973; VanGheluwe, 1974). While accuracy was reported as good, the procedures were difficult, lengthy, and inflexible. Also, all measures related to external camera orientations must be established by standard surveying techniques. This introduced another source of error (external layout calculations) into the procedures.

In 1971, Abdel-Aziz and Karara developed a three-dimensional cinematographic method which incorporated the application of stereo-photogrammetric techniques to situations where non-metric cameras (i.e., unknown internal camera parameters) could be used. This method, known as direct linear transformation (DLT), was originally developed for still cameras used in topographical mapping. The technique compares the same point in space, visible from two separate camera positions into three-dimensional coordinates.

The positioning of two or more cameras in random locations for three-dimensional cinematography has been evaluated (Bergemann, 1974). The only restriction to camera layout is that a common origin point must be in the field of view with the optical axes intersecting. Bergemann utilized a 17-point coordinate grid, two 8-point concentric circles and an origin which were marked on the floor. A 4 foot plumb bob was suspended over each marked point. Markers on the bob line were located at one foot intervals. The mean absolute error of X, Y, and Z coordinates was found to be about ±0.25 inches.
Shapiro (1978) determined the validity and reliability of the DLT method for high speed cinematography. Knowledge of external orientation of cameras is unnecessary with this method because all control points are designed so that their locations with respect to a fixed origin are known. As a general rule it is recommended that the relationship between camera to camera and object to camera distance be in a ratio of 1 to 3, respectively. However, small deviations do not significantly affect the overall accuracy of results. The critical limitation of this method to high speed cinematography is that only motion occurring in the field of view of both cameras can be analyzed.

Shapiro (1978) conducted a series of static and dynamic tests to evaluate the DLT method using high speed cinematographic techniques. A series of 48 stationary points were filmed at 150 f.p.s. The results of the first static test indicated average errors of 0.43 cm, 0.51 cm, and 0.44 cm for the X, Y, and Z coordinates, respectively. In the second static experiment, the calculated length of a meter stick varied 2% to 4% from the known length. The calculated kinematic parameters of a golf ball during free flight produced an acceleration of gravity which ranged from 1% to 4% of -9.81 m/s². From this data it was concluded that the DLT method met accuracy requirements for locating points in space (±0.5 cm average error on unknown spatial coordinates), and is therefore ideal for three-dimensional cinematography.

Data Smoothing Techniques

A common problem encountered when analyzing and evaluating human motion by cinematographic methods is the accurate determination of higher-order derivatives (velocity and acceleration) from displacement-time data. If an estimate of the true underlying displacement-time function is not made prior to differentiation, conse-
quential magnification of inherent noise in the raw displacement-time data seriously jeopardizes other kinematic calculations made from this data. While many methods of data smoothing have been suggested, digital filtering and spline functions are the two most generally accepted methods in use with raw biomechanical data (Phillips & Roberts, 1983).

The purpose of a digital filter, such as a second-order recursive Butterworth, is to filter out the high frequency noise while allowing the low frequency displacement signal to pass through the algorithm untouched. The spline function theory is a piecewise differentiable polynomial function $s(t)$ which satisfies continuity conditions on the derivatives of the data points examined. The problem is to find a spline function, $s(t)$, of degree $2m-1$ (m refers to the mth derivative) which will minimize the integration of the function. A set of boundary conditions control the smoothing. Vaughan (1982) found that a quintic spline function presented the best modeling strategy for smoothing of raw displacement data; however, sufficient computer core memory must be available. A significant concern with the digital filter (DF) and cubic spline (CS) methods is the invariable “zeroing” of acceleration data at the endpoints. Irrespective of actual non-zero accelerations, satisfactory results can be obtained with some form of augmentation and/or velocity smoothing on microcomputer systems.

Phillips and Roberts (1983) proposed a solution to the end-point problem of the spline function procedure. They recommended the addition of one extra dummy point at the beginning ($x_0$) and end ($x_{n+1}$) of the data set, respectively, hence an augmented cubic spline. In a comparison with the second derivative endpoints obtained by DF and natural CS functions, the augmented cubic spline (AS) provided more acceptable results for end-point accelerations suspected of being non-zero. As the AS curve passes through the dummy points, it is recommended that they be the first and last real data.
points, in order to provide the most accurate results possible. Based on Phillips and Roberts' (1983) experience, it was suggested that several dummy values be created to eliminate measurement error associated with an investigated point of interest. The main disadvantage of the AS method is the increased computer time over DF and CS methods.

Conclusion

This review of literature provided a foundation upon which further biomechanical research directed toward competitive alpine skiing could be based. While there have been many theoretical articles on technique, little empirical work on technique analysis in any of the alpine events is available. There is a need to biomechanically evaluate the specific characteristics of alpine ski technique in the different race events. Based on this empirical data, information can be disseminated to coaches of national level development programs concerning characteristics of line selection for a race course.
CHAPTER III

METHODOLOGY

The objective of the study was to identify certain kinematic parameters inherent to elite performance in men’s alpine slalom ski racing. The experimental procedures utilized for the investigation were grouped as follows: (a) subjects; (b) instrumentation; (c) filming procedures; (d) data reduction procedures; and (e) statistical analysis procedures.

Subjects

The selection process of subjects for this study was made based on race finish position at the 1989 World Alpine Ski Championships, which saw a record 43 nations take part. Ninety-eight men from 38 countries competed in the men’s special slalom event held on the International Trail of Vail Mountain, Vail, Colorado, on Sunday 12 February 1989. Figure 1 presents a three-dimensional topographical representation of the trail.

Figure 1. Three-Dimensional Representation of the International Trail from the Men’s Slalom Start.
Twenty-nine skiers from the first run and the top twenty-one skiers in the second run were scientifically filmed. Skiers from Austria (AUT), West Germany (BRD), Luxemberg (LUX), Switzerland (SUI), Sweden (SWE), Norway (NOR), Liechtenstein (LIE), Yugoslavia (JUG), Czechoslovakia (TCH), France (FRA), Bulgaria (BUL), and the United States (USA) were selected for evaluation based on their finish positions in the race. The approximate age range of the skiers was 17-32 years and the average time spent on the World Cup Circuit was 6 years.

Instrumentation

Collection Hardware

High speed cinematography was conducted using two RedLake Locam II cameras, model 51-0002, equipped with P. Angenieux No. 1399753 12-120mm zoom lenses. These 16mm intermittent pin-registered high speed motion picture cameras were capable of operating at film speeds from 2-500 f.p.s. Quick Set multi-tilt tripods were used as the camera platforms. Direct current power was supplied by portable battery packs.

During filming both cameras were set at 100 f.p.s. Simultaneous filming by both cameras was accomplished by using a telemetric remote control box. Film synchronization was achieved by timing marks placed on the exposed film from interval timing light generators operating at 100 hertz (hz). An Asahi Pentex Spotmeter V, No. 132553 provided information on lighting conditions used to set the lens f/stop. Fluctuating light meter readings resulted in f/stop settings between 8 and 11 during both runs.

A DLT octopus was used to determine the three-dimensional reference field of comparator points. This device consisted of a hinged center pole, a fourteen sided
polyhedron, and thirteen marked arms that project from the surface of the polyhedron. Arm markings constituted reference points for the objective location of subject coordinates, which helped derive kinematic variables of motion. Appendix G contains photographs and specifications of the reference system.

Specifically constructed hinge levels were used to provide topographical information necessary for orientations of the cameras into horizontal planes. Slope topography was taken to be consistent throughout the sample area. A single hinge 0.9144 meter sampling level was used on the snow at the slalom gate to generate the average slope gradient. A two-hinge (0.149 m x 0.222 m) tripod platform level set the camera platforms on parallel axes with the slope.

Two 400 feet rolls of Eastman Ektachrome Video News Film 7250 Tungsten, ASA 400, were used to record cinematographical records of the race. Colorado Industrial Colorfilm, Inc., Colorado Springs, Colorado, provided the 16mm color reversal processing.

Reduction Hardware

A Vanguard Motion Analyzer film projection system was used to display, frame by frame, the high-speed film so digital data could be obtained mechanically with the digitizing unit. Cartesian coordinates representing the digitized points of anatomical or reference landmarks were electronically located by a Neumonics Digitizing Unit, model 1224, and stored on floppy disks of an interfaced Apple II+ microcomputer having 64k memory, dual disk drives, and peripheral capacity. An electronic sensing needle is activated by depressing a key pad. Surface resolution of the digitizing unit was rated as ±0.05 inches. This is the link between the raw data (film) and manipulated data (kinematics).
Each frame over the filming interval was digitized. Appropriate software allowed kinematic data storage and analysis in three dimensions to be made. The raw data was compiled on a Zenith microcomputer, model 80386, 16 MHz, 40 Mb HD, 2 Mb RAM, 640k dual disk drives, peripherals, and was IBM compatible to run DLT software programs on the raw digitized film data. Hardcopies of output were made on a Fujitsu DL3300 printer. The software program language, PASCAL, required use with an IBM compatible system.

A VAXcluster mainframe (WINNIE) macrocomputer system was utilized to upload the raw coordinate data from the Apple II+ system, then download the data to the Zenith 1390 system for coordinate calculations and further kinematic processing. The system was manufactured by Digital Equipment Corporation and was networked by three different models of VAX computers (VAX 8700-POOH, VAX 8650-KANGA, VAX 11/780-TIGGER).

Filming Procedures

Data collection procedures were carried out in Vail, Colorado from Saturday, 11 February 1989 through Sunday, 12 February 1989. On Saturday, immediately following the conclusion of the women's giant slalom event at 1:30 p.m., both runs of the men's special slalom course were set on the International Trail. Looking down the hill, the first run was set on the left and the second run set on the right of the hill. There were 73 gates in the first run and 74 gates in the second run. Gate number 10 (blue) of the first course and gate number 9 (blue) of the second course were chosen as representative slalom turns. These gates occurred in a transition of the hill from the steep pitch of French Face onto a flat rolling section of the hill. The three objectives of this pre-race work were to determine all topographical measures, measure inter-gate
distances, and construct trenches for the camera tripods. A plumb bob and bubble level were used with the single hinge level to estimate slope of the hill. Fall line slope (FLS), diagonal slope (DS) to camera 2, and slope perpendicular to diagonal slope (PDS) were measured. FLS was 20.36° and 24.29°, DS was 5.85° and 7.17°, and PDS was 19.04° and 23.93°, for the first and second runs, respectively. The film was loaded in a warm environment Saturday night.

On Sunday, camera positions were established based on Shapiro's (1978) DLT validation research procedures. Camera 1 was placed perpendicular to the fall line at the slalom gate in both runs. Camera 2 was located on an arc below camera 1, approximately one-third of the distance from the object to the line between the cameras, in both runs. During the first run camera 1 was 20.60 meters from the slalom gate and 0.98 meters above the surface of the snow. Camera 2 was 20.68 meters away and 1.00 meters above snow level. The distance between cameras was 6.71 meters. For the second run camera 1 was 18.49 meters away and 1.09 meters above the snow. Camera 2 was 18.16 meters from the gate and 0.94 meters above the snow. Camera separation was 5.64 meters. Figure 2 illustrates the camera setup for the second run. Camera placement for both runs was right of each course looking down the hill. Due to technical problems with the camera lens and lighting conditions, only the second run was analyzed.

Camera tripod platforms were leveled with the two-hinge level to provide horizontal axes corrected from the measured slopes. Camera 1 required only a fall line leveling while camera 2 required a tripod platform tilt in both a direct line optical axis and perpendicular line optical axis. Light meter readings were taken intermittently during both runs. The f-stop setting was 9 for both cameras. Zoom lens settings for camera 1 and camera 2 were 28 and 32, respectively. The weather consisted of partly
Figure 2. Illustration of Camera Setup.
cloudy skies, occasional snow, and an air temperature of -2 °C. The course had been iced down and snow conditions were hard.

The first 29 skiers to start the second run were filmed for approximately two seconds over a three gate combination of the course. At completion of the run, the slalom gate was removed and the DLT Octopus was placed directly in the slalom pole hole and filmed to establish the reference system. Figure 3 represents a schematic diagram of the filming site, with all measured values for the second run. Curves indicate the path traveled by skiers through each section of the course. Second run

\[ \rho = \text{Radius of the Curve} \]
\[ \rho = 9.6 \text{ m} \]

Curvature (K) = 1 radian / \rho

K = 1 rad / 9.6 m = 0.104 rad/m

Figure 3. A Schematic Diagram of the Filming Site Illustrating Camera Placements and Curvature Calculations.
data collection methods were identical to the first run; however, only the first 21 skiers were filmed. There was no physical or verbal association between the skiers and the investigator. The film was secured and taken back to Western Michigan University for biomechanical analyses.

Data Reduction Procedures

Two distinct turning phases during an alpine slalom turn were established from the raw film footage. Phase 1 began when the racer's ski tips reached the base of the slalom gate and ended when his body made contact with the slalom pole. Phase 2 began when his body made contact with the slalom pole and ended when the ski tails reached the slalom pole. Phase 1 and Phase 2 made up the turn sequence which was analyzed in this research.

The investigator identified 12 dependent variables considered to be critical to efficient slalom technique. The variables were: (a) FIS slalom points; (b) intermediate time; (c) angle of the hip during the turn; (d) angular hip velocity during the turn; (e) angle of the knee during the turn; (f) angular knee velocity during the turn; (g) resultant velocity during the turn; (h) fall line velocity during the turn; (i) traverse velocity during the turn; and for line through the turn; (j) x position of the right boot toe; (k) y position of the right boot toe; and (l) z position of the right boot toe.

FIS Slalom Points

This dependent variable was determined from previous race finishes and was used to seed the racers for the current race. The fifteen best, lowest, point racers were randomly drawn for starts 1-15. The remainder of the field was ordered from low to high. Sample point calculations may be found in Appendix H.
Intermediate Time

This dependent variable was a measure of how fast the skiers completed a section of the race course. There are usually two intermediate timing lines per run which divide the course into three sections. The first intermediate timing line was used in this run because the gate under evaluation was contained in this section of the course.

Angle of the Hip During the Turn

The angle of the right hip joint was calculated for the turn sequence. The hip joint was defined as the joint between the trunk segment and the thigh segment. A line between the sternum and the pelvic midpoint defined the trunk segment. The thigh segment was defined from the greater trochanter to the lateral femoral condyles. The angle of the hip was calculated from the following equation,

\[
\theta = \arccos \left( \frac{[(x_2-x_1)(x_4-x_3) + (y_2-y_1)(y_4-y_3) + (z_2-z_1)(z_4-z_3)]}{\sqrt{(x_2-x_1)^2 + (y_2-y_1)^2 + (z_2-z_1)^2} \sqrt{(x_4-x_3)^2 + (y_4-y_3)^2 + (z_4-z_3)^2}} \right)
\]

(1)

where \(\theta\) is the angle of the hip, \(x_1, y_1, z_1\) are the coordinates of the right lateral femoral condyle, \(x_2, y_2, z_2\) are the coordinates of the right greater trochanter, \(x_3, y_3, z_3\) are the coordinates of the pelvic midpoint, and \(x_4, y_4, z_4\) are the coordinates of the sternum.

Angular Hip Velocity During the Turn

The angular hip velocity was calculated for the turn sequence. Angular hip velocities were calculated from the following equation,

\[
\omega_t = \frac{\theta_{t+1} - \theta_{t-1}}{2\Delta t}
\]

(2)
where \( \omega_h \) is the angular velocity of the hip, \( \theta_{i+1} \) and \( \theta_{i+1} \) are the angles before and after the frame in question, respectively, and \( \Delta t \) is 0.01 seconds or the time between frames.

**Angle of the Knee During the Turn**

The angle of the right knee joint was calculated for the turn sequence. The knee joint was defined as the joint between the thigh segment and the leg segment. The thigh segment has previously been defined. Distance from the lateral femoral condyles to the lateral malleolus constituted the leg segment. The knee angle was calculated from the following equation,

\[
\theta = \arccos \frac{[(x_2-x_1)(x_3-x_2) + (y_2-y_1)(y_3-y_2) + (z_2-z_1)(z_3-z_2)]}{\sqrt{(x_2-x_1)^2 + (y_2-y_1)^2 + (z_2-z_1)^2} \cdot \sqrt{(x_3-x_2)^2 + (y_3-y_2)^2 + (z_3-z_2)^2}}
\]  

(3)

where \( \theta \) is the angle knee, \( x_1, y_1, \) and \( z_1 \) are the coordinates of the right lateral malleolus, \( x_2, y_2, \) and \( z_2 \) are the coordinates of the right lateral femoral condyle, and \( x_3, y_3, \) and \( z_3 \) are the coordinates of the right greater trochanter.

**Angular Knee Velocity During the Turn**

The angular knee velocity was calculated for the turn sequence. Angular knee velocities were calculated from the following equation,

\[
\omega_k = \frac{\theta_{i+1} - \theta_{i+1}}{2\Delta t}
\]  

(4)

where \( \omega_k \) is the angular velocity of the knee, \( \theta_{i+1} \) and \( \theta_{i+1} \) are the angles before and after the frame in question, respectively, and \( \Delta t \) is 0.01 seconds or the time between frames.
Right Boot Toe Resultant Velocity During the Turn

The resultant velocity of the right boot toe was calculated for the turn sequence. Evaluation of this velocity occurred as the upper body made contact with the slalom pole. The resultant velocity was calculated from the following equation,

\[ r_{v_i} = \sqrt{\left(\frac{x_{i+1} - x_{i-1}}{2\Delta t}\right)^2 + \left(\frac{y_{i+1} - y_{i-1}}{2\Delta t}\right)^2 + \left(\frac{z_{i+1} - z_{i-1}}{2\Delta t}\right)^2} \]  

(5)

where \( r_{v_i} \) is the right boot toe resultant velocity, \( x_{i+1}, y_{i+1}, \) and \( z_{i+1} \) are the coordinates of the right boot toe after the frame in question and \( x_{i-1}, y_{i-1}, \) and \( z_{i-1} \) are the coordinates of the right boot toe before the frame in question, and \( \Delta t \) is 0.01 seconds or the time between frames.

Fall Line and Traverse Component Velocities During the Turn

The components of the right boot toe resultant velocity in the direction of the fall line and along a normal line traverse to it were calculated for the turn sequence. Evaluation of these velocities occurred as the upper body made contact with the slalom pole. The component velocities were calculated using the following equations,

\[ f_{lv_i} = \frac{x_{i+1} - x_{i-1}}{2\Delta t} \]  

(6)

\[ t_{v_i} = \frac{y_{i+1} - y_{i-1}}{2\Delta t} \]  

(7)

where \( f_{lv_i} \) is the fall line velocity, \( t_{v_i} \) is the traverse velocity, \( x_{i+1}, \) and \( y_{i+1}, \) are the coordinates of the right boot toe after the frame in question, \( x_{i-1}, \) and \( y_{i-1}, \) are the coordinates of the right boot toe before the frame in question, and \( \Delta t \) is 0.01 seconds or the time between frames.
Right Boot Toe X, Y, and Z Position

The position of the right boot toe throughout the turn sequence helped establish the line chosen by each skier through this particular section of the slalom course. The position of the right boot toe was measured in meters away from the base of the slalom gate in x, y, and z directions. While the z position between subjects could be slightly different, it was expected to remain constant in each subject because of the adjustments made to the camera platforms. Comparisons between skiers and curvature (K) of the turn were investigated.

Software Packages and Data Reduction

Overlays (plates) were made for the reference points from each camera view to assist in the accuracy of digitizing as a result of film resolution quality. The plates are presented in Figure 4 and Figure 5. The program which made the actual three-dimensional coordinate calculations (DLTM.EXE) also provided accuracy data on the coordinates. From the given x, y, and z coordinates on the DLT octopus, a set of computed x, y, and z coordinates were generated by the program. The points selected, based on the root mean square (RMS) errors, were 1, 10-16, 18, 19, 30, and 34-37. The average mean square errors for x, y, and z of the 15 points, were 0.015m, 0.074m, and 0.037m, respectively. The average mean square error for the resultant position was 0.085m. With the reference field defined, the skier data was added to each file and run through the program, generating real three-dimensional coordinates. Twelve computer programs were used to obtain the final kinematic data for the race. The programs were written in BASIC, PASCAL, FORTRAN, and C computer languages. A summary of the data flow through these programs along with the source codes for the programs may be found in Appendix F.
12.2.90
DLT Parameters
Frame # 671
Camera 1
2nd Run Slalom

Figure 4. DLT Digitizing Plate for Camera #1.
12.2.90
DLT Parameters
Frame # 692
Camera 2
2nd Run Slalom

Figure 5. DLT Digitizing Plate for Camera #2.
Pilot Study

The objective of this preliminary work was to validate the instrumentation and data collection procedures to be used in the research project. The pilot study was conducted outside the biomechanics lab, located in the Sindecuse Health Center on the campus of Western Michigan University, on Thursday, 15 December 1988, at 10 a.m. The outside temperature was -7 °C, which provided for excellent race day simulation conditions.

The camera tripods were set approximately 50 feet from the slalom gate and 20 feet apart. The tripod platforms were leveled to produce a horizontal image on the film, thus taking into account the slope of the hill. Camera 1 was positioned so a field of view perpendicular to the fall line through the slalom gate was achieved. A platform tilt of 14.0° equalled the slope grade at the slalom pole. Camera 2 was positioned 20 feet below camera 1. A 7.0° slope on a horizontal line to the gate was measured. The cameras were mounted and connected to their battery pack power supplies. The slalom gate was removed and the DLT octopus was set in the slalom gate hole and filmed. The slalom gate was then placed back in the hole and a trial run was filmed. A known distance of 48.375 inches on a board was filmed in various random planes to the cameras for validating the DLT octopus. Due to the quality of the developed film no validation or statistical analyses were possible, and Shapiro's (1978) validation research had to be accepted. Findings from the pilot study did determine that care had to be taken to insure the visibility of the arm markings on the DLT octopus and that the camera platforms were level in both horizontal and perpendicular axes to the slalom pole.
CHAPTER IV

ANALYSIS OF DATA AND DISCUSSION OF RESULTS

This project intended to identify specific kinematic parameters associated with elite (international) alpine slalom performance during an actual competitive situation. The results of the investigation were grouped under the following headings: (a) a descriptive analysis of technique; (b) results for the turn sequence; (c) the relationship between variables; and (d) discussion of results.

A Descriptive Analysis of Technique

Alpine slalom racing requires a powerful yet controlled collection of lower body movements specific to the requirements of the turn encountered. In general, as the racer approaches the slalom gate the hips begin to angulate from counter-rotation of the upper body in opposition to the lower body (anticipation). This angulation causes the downhill ski to roll into the hill and onto edge. When an edged ski is weighted from the centrifugal force acting on the skier, it develops reverse camber and carves a track through the snow in an arc dictated by the side cut of the ski. As the centrifugal forces increase toward the end of the turn, the ski may begin to vibrate and start to slip or chatter away from the arc of the turn, adversely affecting the speed developed in the beginning of the turn. In an attempt to prevent side slip or skidding of the turning ski the turning leg is pushed ahead by extending at the knee. This is known as forward foot thrust. The hip may flex slightly at this point from the centrifugal force developed on the skier. The ability to be dynamic through a turn, however, is possible only from an extended position. An upright stance is more powerful because extended limbs
provide increased lever arms for the muscles to pull against. Subsequently, a negatively correlated relationship exists between power and flexion. Finally, as the turn is completed at gate contact a quick lateral forward projection may be necessary to improve the line to the next gate, particularly if the line into the last gate was too straight. Figures 6, 7, and 8 present examples of elite alpine slalom technique.

Results for the Turn Sequence

A presentation of the calculated kinematic data with theoretical technique analysis for the alpine slalom event is made in this section. Certain variables are grouped and discussed collectively as they relate to each other. Individual subject data may be found in Appendix E.

Federation Internationale de Ski (FIS) Slalom Points

The mean for FIS slalom points was 10.63 while the standard deviation was calculated to be 9.47. This dependent (subjective) variable explains the high level of proficiency these skiers possess for the slalom event based on their past performance. FIS points, however, can not solely predict success, as can be seen by the 14th place finisher whose 40.5 points are more than three times higher than the next best skier.

Intermediate Time

The mean for the first intermediate time was 31.81 seconds while the standard deviation was calculated to be 0.73 seconds. Intermediate time measures a racer's success over the first third of the course. Considering the elite level of these skiers and
Figure 6. Photomontage of World Cup Ski Technique #1.
a well documented history of World Cup races won by tenths and hundredths of a second, it was not surprising that the times were so close.

**Right Boot Toe Resultant Velocity**

Figure 9 presents right boot toe resultant velocity curves for three groups of skiers over the turn sequence based on average magnitudes for each group. Group 1 included Subjects 2, 3, 8, 9, and 14. Their velocity ranged from 16.2 m/s to 16.9 m/s. The standard deviation ranged from 0.13 m/s to 0.29 m/s. Group 2 included Subjects 1, 6, 10, 12, 13, 15, and 16. Their velocity increased from 14.4 m/s to 15.0 m/s, then decreased to 14.9 m/s. The standard deviation ranged from 0.26 m/s to 0.65 m/s. Group 3 included Subjects 4, 5, 7, and 11. Their velocity increased from 12.2 m/s to 13.2 m/s. The standard deviation ranged from 0.59 m/s to 0.71 m/s.

![Figure 9. Right Boot Toe Resultant Velocity Curves.](image-url)
Right Boot Toe Fall Line Velocity

Right boot toe fall line velocity curves for three groups of skiers over the turn sequence, based on magnitudes, are presented in Figure 10. Group 1 included Subjects 2, 3, 8, 9, 14, and 15. Their magnitude increased from 14.5 m/s to 15.1 m/s. The standard deviation ranged from 0.24 m/s to 0.70 m/s. Group 2 included Subjects 1, 6, 10, 12, 13, and 16. Their magnitude increased from 13.4 m/s to 14.3 m/s. The standard deviation ranged from 0.29 m/s to 0.40 m/s. Group 3 included Subjects 4, 5, 7, and 11. Their magnitude increased from 11.4 m/s to 12.5 m/s. The standard deviation ranged from 0.48 m/s to 0.57 m/s.

![Figure 10. Right Boot Toe Fall Line Velocity Curves.](image-url)
Right Boot Toe Traverse Velocity

Figure 11 presents traverse velocity curves for three groups of skiers over the turn sequence based on magnitudes. Group 1 included Subjects 1, 2, 3, 9, 10, and 14. Their magnitude decreased from 4.6 m/s to 4.5 m/s. The standard deviation ranged from 0.72 m/s to 0.73 m/s. Group 2 included Subjects 8, 11, 12, and 16. Their magnitude decreased from 3.2 m/s to 3.0 m/s. The standard deviation ranged from 0.31 m/s to 0.33 m/s. Group 3 included Subjects 4, 5, 6, 7, 13, and 15. Their magnitude decreased from 1.5 m/s to 1.3 m/s. The standard deviation ranged from 0.66 m/s to 0.71 m/s.

Figure 11. Right Boot Toe Traverse Velocity Curves.
Right Knee Angle

Figure 12 displays data representing right knee angle curves for three groups of skiers over the turn sequence based on level of activity and trends in change. Group 1 included Subjects 2, 3, 8, and 9. Their magnitude increased from 1.81 rad to 2.44 rad. The standard deviation ranged from 0.08 rad to 0.19 rad. Group 2 included Subjects 1, 7, 12, 13, 14, and 16. Their magnitude increased from 1.73 rad to 2.18 rad. The standard deviation ranged from 0.06 rad to 0.09 rad. Group 3 included Subjects 4, 5, 6, 10, 11, and 15. Their magnitude increased from 1.90 rad to 2.09 rad. The standard deviation ranged from 0.08 rad to 0.12 rad.

Figure 12. Right Knee Angle Curves.
Right Knee Angular Velocity

Figure 13 presents right knee angular velocity curves for three groups of skiers over the turn sequence based on magnitudes. Group 1 included Subjects 2, 3, 9, and 14. Their magnitude increased from 7.75 rad/s to 8.16 rad/s, then decreased to 0.79 rad/s. The standard deviation ranged from 0.84 rad/s to 1.91 rad/s. Group 2 included Subjects 1, 7, 8, 11, 12, and 13. Their magnitude decreased from 3.94 rad/s to 0.55 rad/s. The standard deviation ranged from 0.47 rad/s to 0.73 rad/s. Group 3 included Subjects 4, 5, 6, 10, 15, and 16. Their magnitude increased from 0.69 rad/s to 1.34 rad/s, then decreased to 0.94 rad/s. The standard deviation ranged from 0.24 rad/s to 0.81 rad/s.

Figure 13. Right Knee Angular Velocity Curves.
Right Hip Angle

In Figure 14, right hip angle curves for three groups of skiers over the turn sequence, based on magnitudes, are presented. Group 1 included Subjects 2, 5, 7, 8, 9, 10, and 11. Their magnitude increased from 1.94 rad to 2.01 rad. The standard deviation ranged from 0.06 rad to 0.13 rad. Group 2 included Subjects 4 and 6. Their magnitude increased from 1.79 rad to 1.82 rad. The standard deviation ranged from 0.02 rad to 0.04 rad. Group 3 included Subjects 1, 3, 12, 13, 14, 15, and 16. Their magnitude increased from 1.67 rad to 1.68 rad, then decreased to 1.66 rad. The standard deviation ranged from 0.08 rad to 0.10 rad.

![Figure 14. Right Hip Angle Curves.](image-url)
Right Hip Angular Velocity

Figure 15 presents right hip angular velocity curves for three groups of skiers over the turn sequence based on magnitudes. Group 1 included Subjects 2, 7, and 12. Their magnitude increased from 0.42 rad/s to 2.42 rad/s. The standard deviation ranged from 0.09 rad/s to 0.91 rad/s. Group 2 included Subjects 1, 3, 4, 6, 8, 9, 14, 15, and 16. Their magnitude decreased from 1.03 rad/s to 0.49 rad/s, then increased to 0.74 rad/s. The standard deviation ranged from 0.23 rad/s to 0.95 rad/s. Group 3 included Subjects 5, 10, 11, and 13. Their magnitude decreased from 2.38 rad/s to 0.33 rad/s. The standard deviation ranged from 0.31 rad/s to 0.94 rad/s.

Figure 15. Right Hip Angular Velocity Curves.
Right Boot Toe Position

Finally, Figure 16 presents the lines skied through the turn by three groups of skiers over the turn sequence. Group 1 included Subjects 1, 2, 12, 14, and 16. Their distance from the slalom pole base, along the traverse axis, was 0.407 m at body contact with the pole. The standard deviation ranged from 0.04 m to 0.09 m. Group 2 included Subjects 6, 8, 9, 10, 13, and 15. Their distance from the slalom pole base, along the traverse axis, was 0.629 m at body contact with the pole. The standard deviation ranged from 0.06 m to 0.13 m. Group 3 included Subjects 3, 4, 5, 7, and 11. Their distance from the slalom pole base, along the traverse axis, was 0.202 m at body contact with the pole. The standard deviation ranged from 0.03 m to 0.08 m.

Figure 16. Position of the Right Boot Toe.
The Relationship Between Variables

The determination of groups for right boot toe resultant velocity (RBTRV), right boot toe fall line velocity (RBTFLV), and right boot toe traverse velocity (RBTTV) over the turn sequence were based on magnitude comparisons. Additional information on RBTRV was gained by examining the trends in change of the velocities. Subjects were grouped according to increasing, constant, and decreasing velocity over the course of the turn. The same trends appeared in RBTFLV and there was a slight decrease by all subjects for RBTTV. Groups formed for knee and hip angles were based on magnitude differences and trends in change of the magnitude. Groups formed for angular hip velocity were based on trends in change of magnitude alone. Finally, magnitude differences determined the groups for angular knee velocity, and groups for x (fall line) and y (traverse) positions were based on distance away from the gate throughout the turn.

Generally, excluding right boot toe position, Group 1 contained members with the highest magnitudes for all variables. Group 2 included subjects with magnitudes closer to the mean of all skiers, and Group 3 was composed of skiers with magnitudes below the other two groups. A slight exception to this occurred for the right hip angular velocity variable. Subjects in Group 1 demonstrated a steady increase in hip activity throughout the turn, Group 2 subjects decreased hip activity then increased activity to the initial level. Subjects in Group 3 showed a steady decrease in hip activity throughout the turn.

Subjects in Group 1 for the right boot toe position included skiers with positions an average distance from the base of the slalom pole, and the most round line. Group 2's subjects took a straighter line through the turn at a more distant location from the base of the slalom pole. Group 3's subjects skied a round line closer to the gate.
than the other two groups. Table 1 presents the classification of subjects with groups for each variable.

RBTRV is considered the most important variable investigated because it reflects the absolute speed of the skier through the course. The two horizontal components of this velocity, RBTFLV and RBTTV, are expected to be related inasmuch as subjects with high resultant velocities should show high component velocities. Subjects 2, 3, 9, and 14 were members of Group 1 for these three variables. Subject 8 was a member of Group 1 for RBTRV and RBTFLV, but a member of Group 2 for RBTTV. Subjects 12 and 16 were the only members common to Group 2 for all three variables. Subjects 1 and 10 were members of Group 2 for RBTRV and RBTFLV, but members of Group 1 for RBTTV. Subjects 6 and 13 were members of Group 2 for RBTRV and RBTFLV, but members of Group 3 for RBTTV. Subjects 4, 5, and 7 were members of Group 3 for all three variables, and Subject 11 was a Group 3 member for RBTRV and RBTFLV, but a member of Group 2 for RBTTV.

Considering trends in change of RBTRV, Subjects 1, 4, 5, 7, 8, 9, 10, 11, 14, and 16 made up Group 1. Their velocities all increased consistently over the turn sequence. Only Subjects 2 and 3 fell in Group 2. This group was marked by relatively constant velocity over the course of the turn. Subjects 6, 12, 13, and 15 all showed a decrease in RBTRV over the turn sequence, and made up Group 3.

The position of the right boot toe through the turn sequence governs the velocity attainable based on the requirements of the turn (K = 0.104 rad/m). Subjects 2 and 14 remained consistent in Group 1, while Subjects 4, 5, and 7 were exclusive members of Group 3. There were no other subjects who remained in one group only, for all four variables. When only RBTRV and RBTP were compared, the exclusive members for
Table 1

Subject Association with Groups for each Variable

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBTRV (magnitude)</td>
<td>2,3,8,9,14</td>
<td>1,6,10,12,13,15,16</td>
<td>4,5,7,11</td>
</tr>
<tr>
<td>RBTRV (trend)</td>
<td>1,4,5,7,8,9,10,11,14,16</td>
<td>2,3</td>
<td>6,12,13,15</td>
</tr>
<tr>
<td>RBTFLV</td>
<td>2,3,8,9,14,15</td>
<td>1,6,10,12,13,16</td>
<td>4,5,7,11</td>
</tr>
<tr>
<td>RBTTTV</td>
<td>1,2,3,9,10,14</td>
<td>8,11,12,16</td>
<td>4,5,6,7,13,15</td>
</tr>
<tr>
<td>RKA</td>
<td>2,3,8,9</td>
<td>1,7,12,13,14,16</td>
<td>4,5,6,10,11,15</td>
</tr>
<tr>
<td>RKAV</td>
<td>2,3,9,14</td>
<td>1,7,8,11,12,13</td>
<td>4,5,6,10,15,16</td>
</tr>
<tr>
<td>RHA</td>
<td>2,5,7,8,9,10,11</td>
<td>4,6</td>
<td>1,3,12,13,14,15,16</td>
</tr>
<tr>
<td>RHAV</td>
<td>2,7,12</td>
<td>1,3,4,6,8,9,14,15,16</td>
<td>5,10,11,13</td>
</tr>
<tr>
<td>RBTPyc</td>
<td>1,2,12,14,16</td>
<td>6,8,9,10,13,15</td>
<td>3,4,5,7,11</td>
</tr>
</tbody>
</table>

RBTRV = Right Boot Toe Resultant Velocity
RBTFLV = Right Boot Toe Fall Line Velocity
RBTTTV = Right Boot Toe Traverse Velocity
RKA = Right Knee Angle
RKAV = Right Knee Angular Velocity
RHA = Right Hip Angular Velocity
RHAV = Right Hip Angular Velocity
RBTPyc = Right Boot Toe Position-y direction at gate contact

Each group were subjects 2 and 14 for Group 1, Subjects 6, 10, 13, and 15 for Group 2, and Subjects 4, 5, 7, and 11 for Group 3.

Results for hip and knee joint angles and angular velocities present no clear relationships. Only Subject 2 is a member of the same group (Group 1) for all four variables. There is a stronger group relationship between right knee angle and right knee angular velocity than between right hip angle and right hip angular velocity.
Considering the knee, Subjects 2, 3, and 9 are members of Group 1 for both variables. Subjects 1, 7, 12, and 13 are members of Group 2 for both variables, and Subjects 4, 5, 6, 10, and 15 are exclusive members of Group 3. A similar comparison for right hip data shows Subjects 2 and 7 as members of Group 1 for right hip angle and right hip angular velocity. Subjects 4 and 6 are members of Group 2 for both variables. Subject 13 is the only exclusive member of Group 3. When all eight variables are considered, only Subject 2 remains in the same group (Group 1) exclusively.

Table 2 displays the Pearson product-moment correlation coefficients which were calculated for the 12 variables. Values for all variables except FIS Points and Intermediate Time are taken from the point at which contact of the upper body with the slalom pole was made. From this table, the following results are apparent:
Table 2
Correlation Matrix for the Selected Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. FIS Pts</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Intermediate Time</td>
<td>0.8773**</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Hip Angle</td>
<td>-0.1255</td>
<td>-0.2455</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Angular Hip Velocity</td>
<td>-0.1694</td>
<td>0.0097</td>
<td>0.1289</td>
<td>1.0000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Knee Angle</td>
<td>-0.1820</td>
<td>-0.1878</td>
<td>-0.2338</td>
<td>-0.1658</td>
<td>1.0000</td>
<td></td>
</tr>
<tr>
<td>6. Angular Knee Velocity</td>
<td>-0.0238</td>
<td>0.1667</td>
<td>-0.3400</td>
<td>0.2552</td>
<td>0.4012</td>
<td>1.0000</td>
</tr>
<tr>
<td>7. Resultant Velocity</td>
<td>0.2001</td>
<td>0.2372</td>
<td>-0.2473</td>
<td>0.5610</td>
<td>0.5610</td>
<td>0.5131</td>
</tr>
<tr>
<td>8. Fall Line Velocity</td>
<td>0.3043</td>
<td>0.3398</td>
<td>-0.3227</td>
<td>-0.0946</td>
<td>0.4871</td>
<td>0.3422</td>
</tr>
<tr>
<td>9. Traverse Velocity</td>
<td>-0.0332</td>
<td>-0.0266</td>
<td>0.0802</td>
<td>-0.0626</td>
<td>0.4233</td>
<td>0.6608*</td>
</tr>
<tr>
<td>10. X Position</td>
<td>-0.1881</td>
<td>-0.0891</td>
<td>0.1971</td>
<td>0.1188</td>
<td>-0.2181</td>
<td>-0.4684</td>
</tr>
<tr>
<td>11. Y Position</td>
<td>0.2178</td>
<td>0.2415</td>
<td>-0.0767</td>
<td>-0.1968</td>
<td>0.2995</td>
<td>-0.1130</td>
</tr>
<tr>
<td>12. Z Position</td>
<td>0.2887</td>
<td>0.3131</td>
<td>-0.0766</td>
<td>-0.2009</td>
<td>0.3148</td>
<td>-0.0665</td>
</tr>
</tbody>
</table>

N of cases: 16
1-tailed Signif: * - 0.01 ** - 0.001

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Table 2
Correlation Matrix for the Selected Variables

<table>
<thead>
<tr>
<th></th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-0.1658</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.2552</td>
<td>0.4012</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.5610</td>
<td>0.5610</td>
<td>0.5131</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-0.0946</td>
<td>0.4871</td>
<td>0.3422</td>
<td>0.9439**</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-0.0626</td>
<td>0.4233</td>
<td>0.6608*</td>
<td>0.6773*</td>
<td>0.4019</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.1188</td>
<td>-0.2181</td>
<td>-0.4684</td>
<td>-0.3307</td>
<td>-0.2324</td>
<td>-0.4168</td>
<td>1.0000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>-0.1968</td>
<td>0.2995</td>
<td>-0.1130</td>
<td>0.6714*</td>
<td>0.7950**</td>
<td>0.0922</td>
<td>0.1803</td>
<td>1.0000</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>-0.2009</td>
<td>0.3148</td>
<td>-0.0665</td>
<td>0.7130**</td>
<td>0.8195**</td>
<td>0.1603</td>
<td>0.1087</td>
<td>0.9861**</td>
<td>1.0000</td>
</tr>
</tbody>
</table>
Correlation levels (r values) were based on a 1-tailed significance test. Very high relationships existed if the significance level was 0.001. A moderate relationship existed if the significance level was 0.01.

1. There was a very high positive relationship (r = 0.8773) between FIS slalom points and intermediate time. As expected, FIS points tend to indicate a competitor's ability in a given event. Lower points reflect higher ability in most situations, and subsequently expected faster intermediate times.

2. There was a very high positive relationship (r = 0.9439) between resultant velocity and fall line velocity. These two variables seem to be closely associated, with consistent high velocities seen in the faster skiers. The fastest line through a course is one which generally follows the fall line.

3. There was a very high positive relationship (r = 0.7950) between y position and fall line velocity. Apparently, the fall line velocity is directly related to the skier's position moving across the hill to the slalom gate. Optimal distance away from the gate in a particular turn appeared to be critical to maintaining fall line velocity.

4. There was a very high positive relationship (r = 0.8195) between resultant velocity and z position. The interpretation of this relationship is unclear. Position based on line selection apparently is critical to this variable.

5. There was a very high positive relationship (r = 0.7130) between fall line velocity and z position. As resultant velocity and fall line velocity were highly related position also appears to be important to this component velocity.

6. There was a very high positive relationship (r = 0.9861) between y position and z position. The relationship between positional components from selection of line through the turn appear to have similar values.
7. There was a moderate positive relationship \( (r = 0.6608) \) between angular knee velocity and traverse velocity. The contribution of the knee in direction change was seen in the competitors. Dynamic lower body movements provide the tools for large turn requirements. More active knees produced higher traverse velocities.

8. There was a moderate positive relationship \( (r = 0.6773) \) between resultant velocity and traverse velocity. Thus, the skiers with the higher traverse velocities exhibited higher resultant velocities.

9. There was a moderate positive relationship \( (r = 0.6714) \) between resultant velocity and \( y \) position. Apparently the skiers who positioned themselves optimally away from the slalom pole maintained the highest speed through this turn.

A surprising fact was that there was no true relationship between either hip angle or angular hip velocity with the other variables. No strong significance was seen between the joint angles and joint angular velocity with RBTRV. At best, the strongest associations were between RBTRV and RHAV \( (r = 0.5610) \), RBTRV and RKA \( (r = 0.5610) \), and RBTRV and RKAV \( (r = 0.5131) \). There was no association between RBTRV and RHA. A turn across the fall line similar to this one would require substantial hip angulation. This investigator speculates that the lack of a relationship resulted from anatomical considerations that were not investigated. The dynamic movements at the hip are most likely unique to the individual, where as knee movements appear to be more general among the subjects.

Discussion of Results

All 16 subjects represented elite technique in the men's alpine slalom event, though slight differences in technique probably contributed to the variance seen in the kinematic data. Speed is paramount in a ski race, and maintaining that speed is critical,
particularly in transition from steep to flat sections of the course. Maintenance of speed through the course is directly related to resultant velocity of the skier. The fall line represents the steepest direction down the hill (24.3 degrees here), so maximizing the fall line component of the resultant velocity would tend to maximize the skiers' speed through the course. The line chosen through the turn should play a role in attaining maximal velocity. In this particular turn, the line chosen close to the gate appears to be slow because subjects 4, 5, 7, and 11 skied this line and had the slowest RBTFLV and RBTRV. An ideal distance away from the slalom pole base for this turn appears to be 0.400 m or farther away, as these skiers maintained the highest rate of RBTRV. Stance of a skier is considered quite individual and a wide stance would put the right boot toe of some of the skiers farther from the base of the slalom pole. The correlated value \( r = 0.7950 \) between RBTFLV and \( y \) position of the right boot toe supports this contention.

The percentage breakdown for RBTFLV and RBTTV for the subjects, taken collectively, indicated that RBTFLV increased from 85.3\% of RBTRV to 87.2\% of RBTRV over the course of the turn, while RBTTV showed a slight decrease in contribution from 4.6\% to 3.7\% of RBTRV. Therefore, only a minimal amount of side slip by these skiers through the turn probably occurred. Had they not made a cleanly carved turn, as is often the case with non-elite skiers, the RBTTV would be expected to drop off quicker due to side slip in the turning ski. The correlated value \( r = 0.9439 \) between RBTRV and RBTFLV verifies the importance of the fall line component.

Only Subjects 8, 9, and 14 associated an increase in RBTRV with high RBTRV. Subjects 2 and 3 maintained a consistently high level of RBTRV. Subjects 6, 12, 13 and 15 showed a decrease in RBTRV from association with mean RBTRV magnitudes. The low level of RBTRV for Subjects 4, 5, 7, and 11 probably did not adversely affect them, as they all were increasing RBTRV through the turn.
Forward foot thrust of the turning leg at the end of a turn helps the ski maintain a tracking arc through the snow, eliminating side slip which reduces velocity. If set up by the correct line choice and timed properly, this maneuver should occur approximately at gate contact. Newton's 3rd Law of Physics states that for every action (force), there is always an equal and opposite reaction (force). As forward foot thrust occurs below the body's center of gravity (CG), the upper body of the skier rotates forward, reducing the hip angle slightly. Subjects 1, 3, 12, 13, 14, 15, and 16 exhibit a slight decrease in right hip angle (RHA). Subjects 2, 4, 5, 6, 7, 8, 9, 10, and 11 appear more upright from the angles measured over the course of the turn, and actually show a slight increase in hip angle. Extension at the hip could possibly be a result of side slip where the skier momentarily is correcting for unexpected centripetal forces acting to flatten his skis on the snow and pull him outside the turn. Subjects 4, 5, 6, 7, and 11 had consistently low velocities through this turn suggesting some side slip was occurring.

The right hip angular velocity (RHAV) remained fairly consistent for all 16 subjects over the turn sequence. As the subjects approach contact with the slalom pole, about 0.12 seconds into the turn sequence, the variability in RHAV decreases. After contact with the slalom pole the variability increases again. This trend suggests that prior to and preceding contact with the slalom pole, slight individual differences in technique exist that are not detectable visibly.

A moderate change in RHAV is expected as the skier extends out of the turn. A carving ski provides the platform for the extension. A rapid change in RHAV would be seen when a skier moves his CG inside of a turning ski that begins to side slip. As the weight is shifted to the inside ski, the right hip angle increases because the ski is lost to the side slip.
All subjects showed an increase in the knee angle of the turning leg (right) over the turn sequence. Hip extension and forward foot thrust of the turning leg contribute to the change in this variable. Subjects 4, 5, 6, 10, 11, and 15 display only a small change over the turn sequence. Subjects 1, 7, 12, 13, 14, and 16 show a moderate change, and Subjects 2, 3, 8, and 9 demonstrate a large change in the right knee angle (RKA). Subjects 2, 3, 8, and 9 appear to have completed the turn earlier, benefiting from forward foot thrust. They also maintained the highest rates of velocity through the turn.

Right knee angular velocity (RKAV) decreases over the course of the turn, however, at different rates. Three distinct levels of activity are present. Subjects 2, 3, 9, and 14 drop from a high level of activity, Subjects 1, 7, 8, 11, 12, and 13 drop from a lower level of activity, and Subjects 4, 5, 6, 10, 15, and 16 show a constant angular velocity in the right knee joint. These large differences are seen prior to contact with the slalom pole and may reflect the position of the racer on the course or individual differences in technique. By the time the turn sequence is finishing, all three groups are very similar in activity levels. The high initial level of activity in RKAV appears to be advantageous because the subjects also had the highest levels of right boot toe velocity through the turn. A moderate correlation exists (\( r = 0.6608 \)) with RBTTV.

While there are no strong correlations between right boot toe velocity data and lower body kinematic data, limited group association does exist. Subjects 2, 3, 8 and 9 show increasing or constant right boot toe velocity and are associated with the groups of increasing or high activity levels for joint angular data. Subjects 6, 12, 13, and 15 present decreasing RBTRV's and associate more closely with the groups of lower joint angular activity. Based on subject group association and the correlation data this suggests that the following positions and levels of activity in the lower body joints are
important to maintaining high velocity through the turn. For the knee, a RKA range from 1.81 rad to 2.44 rad and a RKAV above 4.00 rad/s for this turn appears necessary. Information for the RHA is less clear, however, a constant RHAV around 1.00 rad/s appears to be ideal for this turn.
CHAPTER V
SUMMARY, FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

Summary

An attempt was made through this research to identify specific kinematic parameters associated with elite performance in the alpine slalom event. The second run of the men's special slalom at the 1989 World Alpine Ski Championships in Vail, Colorado, was filmed by high-speed cinematographic techniques. The subject pool was selected based on overall finish position. Selected for analysis were sixteen skiers, representing twelve countries. The race was held under sunny to overcast skies on Sunday, 12 February 1989.

Filming was done with the aid of two RedLake Locam II cameras, model 51-0002, each equipped with P. Agenieux No. 1399753 12 - 120 mm zoom lenses. Overlapping visual fields were captured from both cameras, positioned in such a configuration that the distance between the cameras was approximately one-third of the distance from the object to the line between the cameras (B/D 1/3) and keeping the convergence to a minimum ($\Theta = 0$). This method is known as direct linear transformation. The film speed was 100 frames per second.

The developed film was analyzed on a Vanguard Motion Analyzer, a Neumonics model 1224 Digitizing Unit, and an Apple II+ microcomputer. Nine computer programs in 3 languages were used on two Zenith microcomputer systems to reduce the raw data. The following kinematic values for a turn to the left were found: (a) the angle of the right hip during the turn; (b) the right hip angular velocity during the
turn; (c) the angle of the right knee during the turn; (d) the right knee angular velocity during the turn; (e) the right boot toe resultant velocity during the turn; (f) the right boot toe fall line velocity during the turn; (g) the right boot toe traverse velocity during the turn; (h) the x position of the right boot toe through the turn; and (i) the y position of the right boot toe through the turn.

Findings

The findings of the study were as follows:

1. High levels of right knee angular velocity early in the turn associate well with high right boot toe velocity through the turn. Four subjects who initiated the turn sequence with a RKAV of about 8 rad/s all fell in the RBTRV group which average 16.6 to 16.9 m/s through the turn. Collectively, a RKA ranging from 1.81 rad to 2.44 rad, a RKAV above 4.00 rad/s, a RHA ranging from 1.66 rad to 2.01 rad, and a constant RHAV around 1.00 rad/s associate with the highest right boot toe velocities.

2. No clear relationship was present with right hip angular velocity, as three trends were observed. The only associations to velocity were that more subjects who maintained a fairly consistent rate ranging from 0.74 rad/s to 1.03 rad/s also maintained velocities above 14.4 m/s for RBTRV, 13.4 for RBTLVL, and 3.0 for RBTTV. There was evidence to support a gradual decrease in right knee activity over the course of the left turn. This particular turn required a level of activity in the knee of 3.90 rad/s prior to gate contact, which reduced to less than 1.00 rad/s after the turn was completed.

3. Resultant velocity differences in the right boot toe may be partly attributed to the traverse velocity differences. Traverse velocity ranged from 0.52 m/s to 5.69 m/s. The resultant component, fall line velocity, appears to be at least as significant. The five subjects with the highest right boot toe resultant velocities also had the highest right
boot toe fall line velocities. Additionally, six skiers maintained velocities above the mean ranges for both fall line (13.3 m/s - 14.1 m/s) and traverse (3.1 m/s - 2.9 m/s) directions.

4. Some variability in position of the right boot toe was seen and appeared to be critical in maintaining speed. Three subjects were positioned more than one standard deviation inside the 0.455 meters mean to the slalom pole base (0.470 m, -0.050 m, -1.285 m). Each of these subjects was unable to achieve the mean velocity ranges for both fall line and traverse directions, suggesting his line was too close to the gate for this turn.

5. There were very high positive relationships between FIS slalom points and intermediate time \((r = 0.8773)\), resultant velocity and fall line velocity \((r = 0.9439)\), fall line velocity and y position \((r = 0.7950)\), resultant velocity and z position \((r = 0.7130)\), fall line velocity and z position \((r = 0.8195)\), and y position and z position \((r = 0.9861)\).

6. There were moderate positive relationships between angular knee velocity and traverse velocity \((r = 0.6608)\), resultant velocity and traverse velocity \((r = 0.6773)\), and resultant velocity and y position \((r = 0.6714)\).

Conclusions

Based upon the results of this investigation, the following conclusions were made:

1. Given the terrain gradient and the type of turn \((K = 0.104 \text{ rad/m})\), a velocity above 14.0 m/s in the RBTRV results from proper line through the turn and certain lower body kinematics.
2. To make an efficient slalom turn with a curvature and slope gradient similar to this particular turn, the hip and knee joint angles of the turning leg must approximate 1.82 and 2.06 radians, respectively, through the turn.

3. A combination of variables working in concert are necessary to perform on the elite level in the alpine slalom event. No independent variables tested proved to have clear significance over the others.

4. Angular hip and knee velocities are dependent on the choice of line through the turn, CG or balance, and lower body anatomical considerations such as limb segment lengths and muscle attachments. Specifically, knee angular velocities appear to be decreasing over the course of the turn.

5. The position of the skier as measured by the right boot toe in a left turn is critical to maintaining velocity throughout the turn. Specifically, the y (traverse) distance away from the base of the slalom gate correlated well with right boot toe velocities. Taken along with turn curvature, the more round the turn is, the sooner the skier must finish the turn and be on line toward the next gate. Skiing too straight of a line reduces the chance to maintain velocity through the turn.

Recommendations

The results of this study prompted the investigator to make the following recommendations for further study.

1. The reference field needs to be expanded so that a more complete turn sequence may be evaluated.

2. Validation of other reference systems with a viable use in this extreme environment should be undertaken.
3. An optimal camera layout should be devised and implemented for specific turns in a slalom course to allow filming the best angles of the skier, thus reducing subjective digitizing error.

4. A comparative investigation between turning and non-turning lower limb kinematics would be valuable.

5. Force generation patterns, impulse, energy, and other kinetic variables should extend from the kinematic research to provide a better understanding of elite ski racers.

6. An investigation over three or more consecutive turns would allow further conclusions to be drawn from the influence of technique and position through the turns relating to success over a section of the course.
Appendix A

Project Clearance Letter
Mr. Dave Goodwin  
3828 Grand Prairie Road  
Kalamazoo, MI 49007  
August 23, 1988

Dear Mr. Goodwin:

Your request for on-hill credentials to the 1989 World Alpine Ski Championships has been passed on to me as it involves photo bibs and press credentials.

After discussing your request with John Garnsey, we will be able to give you access to the press/photo corrals that will be positioned per the wishes of the FIS Technical Delegates. We cannot, at this time, say that we will be able to construct a separate corral for your use.

As for your request to run a wire connection between your two cameras, that is something we cannot give a definite yes or no answer to at this point. We probably will not know that until race day itself and the course is set and you make your desired position known to the appropriate people on the race crew.

Thirdly, we would suggest you concentrate your research efforts on the Men's Combined Slalom scheduled for Monday, January 30, 1989. Since you need two days to complete the research, it could be difficult to collect that with the Men's Special Slalom as that is the final event of the Championships on February 12, 1989.

Finally, we will issue no more than two on-hill credentials and a total of five for your team. Please understand that we cannot credential guests of the press for this event. Enclosed you will find five sets of credential forms that need to be returned no later than November 15, 1988. With the demand for on-course access that we anticipate, the two photo bibs will be available for the Men's Combined Slalom only.

If you have any further questions on credentials, please let me know.

Sincerely,

Chery Lindstrom

Chery Lindstrom
Media Operations

World Alpine
Ski Championships

Vail, Colorado 81658
303-776-9900
Telex 910-294-1989

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Dear Linda Bork,

The video tape enclosed was made on Thursday, 15 December 1988, at 10 AM. The temperature was 20 degrees fahrenheit, which provided for excellent race day simulation conditions for my pilot study. The following text will help explain what is being done throughout the tape. The tape runs for approximately 40 minutes, and Chris, a fellow graduate student here at Western Michigan University, is playing me since I have to oversee everything and run the video camera as well. I have the ski vest on.

To begin, the camera tripods are placed approximately 50 feet away from the gate of interest.

The tripod platforms are then leveled to the horizontal with the slope of the hill at this location. The video tape then shows the test slalom course, set to FIS standards for gate separation. The questions that my Graduate Advisor, Dr. Mary Dawson is asking me concern how we should be leveling the tripod platforms in relation to the slope of the hill. Next, the cameras are mounted and connected to their power supplies (battery packs). The DLT octopus (referencing devise, see enclosed photocopies) is set up in the foreground.

During the actual work in February at the World Championships, the DLT device will not be put together until the center bar is set in the slalom gate hole and the lower arms are on (AFTER RUN IS COMPLETED). Next, the slalom gate was removed and the DLT device was set using a steel bar (Note: a cordless drill will be used for the actual work, snow cover was only 2 inches during the pilot study). A screw hinge allows the DLT octopus to pivot so the lower arms touch the snow.

The DLT octopus is then removed and the slalom gate replaced.

The rest of the video just pertains to the pilot study. A test run is made through the course, then a known distance is filmed on a board that I'm holding to validate the accuracy of the DLT device. Dr. Dawson wanted to know if accurate data could be obtained if the DLT octopus was raised above the snow surface 4-6 inches, which is the last part of the video tape.

In summary, prior to the start of each run the tripods and cameras will be set up. Then the run will take place and I will film over the predetermined 3 gate section of the course. After the end of the run, the slalom gate will be removed and the referencing work (DLT octopus) will be done. Then the cameras will be repositioned for the second run. This procedure would be used to film both men's slalom events. For further clarifications please do not hesitate to contact me.

Sincerely,

Dave Goodwin
3823 Grand Prairie Rd.
Kalamazoo, MI 49007
(616) 349-4914

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Appendix C
Accreditation Forms
1989 WORLD ALPINE SKI CHAMPIONSHIPS
1989 CHAMPIONNATS DU MONDE DE SKI ALPIN
1989 ALPINE SKI-WELTMEISTERSCHAFTEN

Return by: **NOVEMBER 15, 1988**

To: 1989 World Alpine Ski Championships
P.O. Box 309
Vail, Colorado 81658 U.S.A.

**ACCREDITATION FORM • FORMULAIRE D'ACCREDITATION • AKKREDITIERSFORMULAR**

PLEASE FILL OUT ONE FORM PER PERSON TO BE ACCREDITED
REMPLISSEZ UN FORMULAIRE PAR PERSONNE AVANT BESOIN D'ACCREDITATION, S'IL VOUS PLAIT
BITTE EIN FORMULAR PRO PERSON. DER/DIE AKKREDITIERUNG BRAUCHT

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### 1989 WORLD ALPINE SKI CHAMPIONSHIPS

1989 CHAMPIONNATS DU MONDE DE SKI ALPIN

1989 ALPINE SKI-WELTMEISTERSCHAFTEN

---

**To be submitted together with accreditation form**

**DOIT ETRE JOINT AU FORMULAIRE D'ACCREDITATION**

**VUSS DDEM AKKREDITIERUNGSFORMULAR BEIGELEGT WERDEN**

---

**NAME**

**NOM**

**VORNAME**

**PRENOM**

**NAME OF ORGANIZATION / TYPE OF ORGANIZATION / ART DES PRESSEORGANS**

**QUOTIDIEN**

**TELEVISION**

**RADIO**

**NEWS AGENCY**

**PRESSEAGENTUR**

**MAGAZINE**

**JOURNALISTE LIBRE**

**FREELANCE PHOTOGRAPHER**

**KOMMENTATOR**

**TECHNIKER**

**FRIER PHOTOGRAPH**

---

**Press Card Number (AIPS)**

*Please attach photocopies of national and/or state cards*

---

**Primary Method of Transmission?**

**QUELS MOYENS DE TRANSMISSION UTILISEZ-VOUS?**

**MIT WELDEM Gerät ÜBERMITTELEN SIE HAUPTSÄCHLICH?**

**PHONE**

**TELEFON**

**PRIVATE LINE**

**LIGNE PRIVEE**

**PRIVATE TELEFAX**

**FAX**

**TELEX**

---

**Primary Phone Number You Will Be Calling For Transmission?**

**QUEL NUMERO TÉLÉPHONEZ-VOUS POUR VOS TRANSMISSIONS?**

**TELEFONNUMMER, DIE SIE FÜR IHRE ÜBERMITTLUNG HAUPTSÄCHLICH WAHLEN?**

---

**LOGGING LOCATION (IF KNOWN)**

**LOGEMENT (SI CERTAIN)**

**INTERKUNFT (WENN GEWUSST)**

---

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DO YOU HAVE ANY SPECIAL REQUESTS?

DO YOU HAVE ANY SPECIAL REQUESTS?

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DO YOU HAVE ANY SPECIAL REQUESTS?

DO YOU HAVE ANY SPECIAL REQUESTS?

DO YOU HAVE ANY SPECIAL REQUESTS?

DO YOU HAVE ANY SPECIAL REQUESTS?

DO YOU HAVE ANY SPECIAL REQUESTS?
Appendix D

Slalom Gate Design
The Sports Club International Inc. exists to provide you, our customer, with high quality ski racing products at a fair price. Everything we sell has been subjected to the most rigorous and demanding tests for durability, reliability, ease of use and function. We believe that you will find our products to be the best available anywhere and at any price!

Our TSC Performance flex-gate was introduced last year to wide acclaim. The Roto-Gripbase has revolutionized Slalom training and racing by making these gates virtually impossible to knock out of the snow. After thorough testing and successful trials in World Cup and Nor Am competitions, the Roto-Gripbase is now fully approved by the FIS.

Also FIS homologated, the Dalloz flex-gate continues to be our biggest seller. Several improvements have been made for this season making Dalloz better than ever! New this season will be the Dalloz Training gate, a low cost alternative for programs and race departments that do not require a FIS approved pole. Also new are Dalloz stubbies for training modern Slalom technique.

Dalloz and Roto-Gripbase have been selected as official suppliers to the 1989 World Alpine Ski Championships in Vail/Beaver Creek. Selected for use are Dalloz fixed and flex gates, as well as, Roto-Gripbase equipped TSC Performance flex gates.

In addition to the popular Bosch Cordless Hammer Drill, we now also carry the Hilti Cordless Hammer Drill. Both drills work best with the unique Maco Double Carbide Tip Bit which is finally back in stock!

Welcome to The Sports Club! We hope that we may become your supplier of Race Course Supplies and ski racing products.

---

The Dalloz Competition Flex-Gate continues to be the most durable flex gate on the market with an average breakage rate of less than 4% reported by our customers. New for this year is an improved base which is now a single piece of molded plastic. This base becomes wider at the top creating better purchase in the snow as the pole is wedged into the hole.

FEATURES:
- Official Supplier to the 1989 World Alpine Ski Championships.
- FIS homologated.
- One year guarantee on base, shaft and hinge.*
- Integrated retaining star and depth gauge.
- Top cap to prevent tip breakage.
- Protective sleeve.
- Lightweight, only 1.37 lbs. (850 g).
- World Cup proven!

D001 - Dalloz Competition Flex Gate (Red)
D002 - Dalloz Competition Flex Gate (Blue)

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*Warranty on Dalloz Flex-Gates, Dalloz Fixed Gates, Dalloz Replacement Parts (when purchased) and TSC Performance Flex-Gates or Bases: The Sports Club International Inc. will replace, free of charge, any broken shafts, hinges or bases for a period of one year from purchase. This warranty does not apply to Dalloz Protective Sleeves, Dalloz Retaining Stars or parts which have been altered in any way including painting. All broken pieces must be returned with proof of purchase. All shipping costs are the responsibility of the customer.
TSC Performance means you can coach slalom again! Never again will you spend slalom days running up and down the hill chasing gates.

The Dalloz shaft and hinge are combined with the ROTO-GRIPBASE, a.k.a. HERMANN GATE, to create the most advanced flex gate technology available today. The TSC Performance Flex-Gate is now available with either the competition or training hinge at no extra charge.

The Roto-Gripbase is made of fiberglass reinforced nylon and is again reinforced internally with aluminum. There are three 6” long sections to accommodate different snow depths and conditions. These are snapped together and held in place with couplers.

To set the pole, a 32mm or 34mm drill bit is recommended. When using all three sections of the base, the 7” drill bit extension is also recommended. The TSC Performance flex gate is then screwed into the hole with the setting wrench which is slipped over the top of the shaft and engages the Roto-Gripbase. Once properly set**, the TSC Performance is virtually impossible to knock out.

TSC Performance Flex-Gates will be used in the settling of all the Slalom courses at the 1989 World Alpine Ski Championships at Vail and Beaver Creek.

P001 - TSC Performance Flex-Gate Complete (Red).........................................................$34.95 ea.
P002 - TSC Performance Flex-Gate Complete (Blue).......................................................$34.95 ea.
P107 - Roto-Gripbase Only...............................................................................................$34.95 ea.
P010 - TSC Performance Setting Wrench.............................................................................$39.95 ea.

**For skier safety it is extremely important that the TSC Performance Flex-Gate is set so that the hinge-point of the pole is at snow level. Under no circumstances may you allow a portion of the base to protrude above snow level.
Appendix E
Subject Data
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Nation AUSTRIA (AUT)  

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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
RBTTV = Right Boot Toe Traverse Velocity  
RKA = Right Knee Angle  
RKAV = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
**Subject 2**  
**Nation** WEST GERMANY (BRD)

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**RBTRV** = Right Boot Toe Resultant Velocity  
**RBTFLV** = Right Boot Toe Fall Line Velocity  
**RBTTV** = Right Boot Toe Traverse Velocity  
**RKA** = Right Knee Angle  
**RKAV** = Right Knee Angular Velocity  
**RHA** = Right Hip Angular Velocity  
**RHAV** = Right Hip Angular Velocity  
**RBTPyc** = Right Boot Toe Position-y direction at gate contact
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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
RBTTV = Right Boot Toe Traverse Velocity  
RKA = Right Knee Angle  
RKAV = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
Subject 4  
Nation SWITZERLAND (SUI)  

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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
RBTTV = Right Boot Toe Traverse Velocity  
RKA = Right Knee Angle  
RKAV = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
Subject 5  
Nation = SWEDEN (SWE)

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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
RBTTV = Right Boot Toe Traverse Velocity  
RKA = Right Knee Angle  
RKA V = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
Subject 6  
Nation NORWAY (NOR)

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<td>RHAV (rad/s)</td>
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<td>RBTPyc (m)</td>
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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
RBTTV = Right Boot Toe Traverse Velocity  
RKA = Right Knee Angle  
RKAV = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
Subject 7  
Nation LIECHTENSTEIN (LIE)  

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<td>RHA (rad)</td>
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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
RBTTV = Right Boot Toe Traverse Velocity  
RKA = Right Knee Angle  
RKAV = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
Subject 8  
Nation YUGOSLAVIA (JUG)

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<td>RHA (rad)</td>
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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
RBTTV = Right Boot Toe Traverse Velocity  
RKA = Right Knee Angle  
RKAV = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
Subject 9  
Nation AUSTRIA (AUT)

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<td>RBTTV (m/s)</td>
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<td>RKAV (rad/s)</td>
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<td>RHAV (rad/s)</td>
<td>0.44-0.08-0.87-0.54</td>
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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
RBTTV = Right Boot Toe Traverse Velocity  
RKA = Right Knee Angle  
RKAV = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
Subject 10  
*Nation* SWITZERLAND (SUI)

| FIS Points | 14.67 |  
| Intermediate Time (s) | 32.35 |  
| **Range** | **Mean** | **Standard Deviation** |
| RBTRV (m/s) | 14.8-15.9 | 15.3 | 0.40 |
| RBTFLV (m/s) | 13.4-14.6 | 14.0 | 0.43 |
| RBTTV (m/s) | 3.9-3.8 | 3.9 | 0.03 |
| RKA (rad) | 1.77-1.96 | 1.88 | 0.06 |
| RKAV (rad/s) | 1.10-1.43-0.44 | 1.08 | 0.32 |
| RHA (rad) | 1.86-2.08 | 2.01 | 0.07 |
| RHAV (rad/s) | 3.24-0.07 | 1.30 | 1.06 |
| RBTPyc (m) | 0.421 | - | - |

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RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact

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Subject 11  
Nation CZECHOSLOVAKIA (TCH)

| FIS Points | 13.20 |
| Intermediate Time (s) | 31.98 |

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<td>RBTTV (m/s)</td>
<td>3.2-3.0</td>
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<td>RKA (rad)</td>
<td>1.76-2.17</td>
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<td>1.96-2.09</td>
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<td>RBTPyc (m)</td>
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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
RBTTV = Right Boot Toe Traverse Velocity  
RKA = Right Knee Angle  
RKAV = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
Subject 12  
Nation FRANCE (FRA)

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<td>13.7-14.2</td>
<td>14.1</td>
<td>0.23</td>
</tr>
<tr>
<td>RBTTV (m/s)</td>
<td>2.9-2.8</td>
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<td>RKA (rad)</td>
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<tr>
<td>RKA (rad)</td>
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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
RBTTV = Right Boot Toe Traverse Velocity  
RKA = Right Knee Angle  
RKA = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
Subject 13  
Nation NORWAY (NOR)  

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<td>RBTTV (m/s)</td>
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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
RBTTV = Right Boot Toe Traverse Velocity  
RKA = Right Knee Angle  
RKAV = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
Subject 14  
Nation  BULGARIA (BUL)  

| FIS Points | 40.50 |
| Intermediate Time (s) | 33.93 |

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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
RBTTV = Right Boot Toe Traverse Velocity  
RKA = Right Knee Angle  
RKAV = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
Subject 15  
Nation SWEDEN (SWE)

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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
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RKA = Right Knee Angle  
RKAV = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
<table>
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<th>Subject 16</th>
<th>Nation UNITED STATES (USA)</th>
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<td>RHA (rad)</td>
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<td>RBTPyc (m)</td>
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RBTRV = Right Boot Toe Resultant Velocity  
RBTFLV = Right Boot Toe Fall Line Velocity  
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RKAV = Right Knee Angular Velocity  
RHA = Right Hip Angular Velocity  
RHAV = Right Hip Angular Velocity  
RBTPyc = Right Boot Toe Position-y direction at gate contact
Appendix F

Software Source Codes
Software Source Codes.

Raw unsmoothed coordinate data was obtained by digitizing the research films [ DIGITIZE.V2 ]. X and Y values from camera 1 and camera 2 were stored on 5-1/4" floppy disks in Apple BASIC format sequential data files (A2.10, B2.10, etc.). The DLT octopus had known spatial coordinates which were entered from a Apple II+ keyboard [ CNTFL.DLT ]. The values may be found in Appendix G. The outfiles (dlt.x, dlt.y, dlt.z) contained either x, y, or z coordinates. Finally, coordinates on the DLT octopus were digitized for camera 1 and camera 2 views [ DLT.PTS ]. X and Y coordinates from each camera position of the DLT octopus were obtained (dlt.1). This initial set of output files was then retrieved from the bulletin board of a Apple IIe by a Zenith data systems ZMC-386-40 microcomputer. This turnover procedure converted the data files from Apple to IBM formatted files which the DLT software required for program execution.

The raw coordinate data created from the three BASIC programs was organized by three Pascal programs written to structure the information into an acceptable format for processing through the DLT program. The three known coordinate files (dlt.x, dlt.y, dlt.z) were merged [ MRG3XYZ.EXE ] into one file (dlt.xyz). Digitized information from the DLT octopus was split [ SPLIT3.EXE ] into two data files (dlt.one, dlt.two). Digitized skier data (A2.10, B2.10, etc.) was regrouped [ REGROUP2.EXE ] by x and y values for each digitized point on each frame for each camera position (A2X10.spl, B2X10.spl, etc.).

Fifteen points were selected as most representative of digitized accuracy based on the visual quality of the film. Three individual files were created from the transformed data files (head, middle, tail), excluding the skier files. A combine
program [ COMBINE.EXE ] searched through the directory of files and compiled output files (C2X10.XXX, etc.) of reference points and skier data to be directly run through the main DLT program [ DLTM.EXE ]. An INTEL 80287 math coprocessor, model 440933, 10 MHz was required by the DLTM.EXE program. This program executed camera parameters and generated three-dimensional data points from the two camera positions available to the researcher. An output file (C2X10.OUT, etc.) was developed for each skier.

The raw three-dimensional coordinate data was structured into file format [ DLTOUT.COM ], generating appropriate data files (C2X10.IN, etc.). Woltring's (1982) generalized cross-validation FORTRAN program [ GCV.EXE ] smoothed the raw three-dimensional coordinate data and calculated velocity and acceleration from time and position data (S1001.x, S1001.y, S1001.z, etc.). These files were trimmed down to 18 frames of data for each skier using a text editor on the microcomputers hard drive.

Resultant velocity was calculated for each skier [ VELACCEL.PAS ], as was joint angular velocity [ JOINTAVA.PAS ]. Selection of kinematic parameters to be studied was then made based on the researchers knowledge of the sport.
1 REM ************ CNTFL.DLT ************
2 REM
3 REM THIS PROGRAM ALLOWS KNOWN COORDINATES ON THE DLT OCTOPUS TO BE ENTERED
4 REM INTO DATA FILES FOR X, Y, AND Z.
5 REM
6 REM ************ (7,4,89) ************
7 D$ = CHR$(4)
8 DIM A(40)
9 HOME
10 INPUT "FILE NAME ";F$
11 FOR I = 1 TO 40
12 INPUT "COORDINATE ";A(I)
13 NEXT I
14 REM
15 REM WRITE THE COORDINATES TO A DATA FILE
16 REM
17 PRINT D$; "OPEN ";F$
18 PRINT D$; "DELETE ";F$
19 PRINT D$; "OPEN ";F$
20 PRINT D$; "WRITE ";F$
21 FOR L = 1 TO 40
22 PRINT A(L)
23 NEXT L
24 PRINT D$; "CLOSE ";F$
25 END

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**Program Description:**

This program allows digitized X and Y coordinates from Camera #1 and Camera #2 to be input into a file for comparison with the known dimensions of the DLT octopus. When compared with the known coordinates of the DLT octopus, these digitized points set up a 3-dimensional reference field.

**Program Code:**

```
10 Dimension Xi(100), Yi(100), X2(100), Y2(100), P(40), A$(25)
20 Home
30 D$ = Chr$(4)
40 Input "NAME OF DATA FILE " ; F$
50 Input "HOW MANY DLT POINTS USED ? "; N
60 For J = 1 To N
70 Input "DIGITIZE 1ST FILM "; P(J)
80 GOSUB 1161
90 Xi(J) = Val(X$); Yi(J) = Val(Y$)
100 Print Xi(J), Yi(J)
110 Next J
120 Print "DIGITIZE 2ND FILM"
130 For J = 1 To N
140 Print "DIGITIZE POINT NUMBER "; P(J)
150 GOSUB 1161
160 X2(J) = Val(X$); Y2(J) = Val(Y$)
170 Print X2(J), Y2(J)
180 Next J
190 GOSUB 1200
200 End
```

**Function:**

- **1161 INK 4**
- **1162 B$ = " "; A$ = " "; X$ = " "; Y$ = " ";**
- **1163 For M = 1 To 19**
- **1164 Get A$(M)**
- **1165 B$ = B$ + A$(M)**
- **1166 If A$(M) = Chr$(13) Then GOTO 1168**
- **1167 Next M**
- **1168 INH 0**
- **1169 For M = 1 To 19**
- **1170 X1$ = " "**
- **1171 X1$ = MID$(B$, M, 1)**
- **1172 If M < 3 GOTO 1174**
- **1173 If X1$ = CHR$(32) Then GOTO 1176**
- **1174 X$ = X$ + X1$**
- **1175 Next M**
- **1176 For L = M To 19**
- **1177 Y1$ = " "**
- **1178 Y1$ = MID$(B$, L, 1)**
- **1179 If Y1$ = CHR$(13) Then GOTO 1182**
- **1180 Y$ = Y$ + Y1$**
- **1181 Next L**
- **1182 RETURN**

**End of Program:**

- **1200 REM **********************
- **1201 REM WRITE THE COORDINATES TO A DATA FILE**
- **1202 REM **********************
REM
PRINT D$; "OPEN \";F$\";S6,L12,D1"
FOR I = 1 TO N
PRINT D$; "WRITE \";F$
PRINT P(I)
NEXT I
FOR J = 1 TO N
PRINT D$; "WRITE \";F$
PRINT X1(J)
PRINT D$; "WRITE \";F$
PRINT Y1(J)
NEXT J
FOR L = 1 TO N
PRINT D$; "WRITE \";F$
PRINT X2(L)
PRINT D$; "WRITE \";F$
PRINT Y2(L)
NEXT L
PRINT D$; "CLOSE \";F$
RETURN
100 REM ** DIGITIZE.V2 **
101 REM
102 REM THIS PROGRAM STORES X AND Y COORDINATES THAT ARE DIGITIZED
103 REM AT ANATOMICAL LOCATIONS ON THE ATHLETE.
104 REM
105 REM ** (7.4.89) ****
106 REM
107 REM
1000 DIM X(22,50),Y(22,50),T(50),B1$(50),A$(25)
1005 HOME
1006 D$ = CHR$(4)
1010 K = 0
1020 INPUT "DO YOU HAVE AN OBJECT? <Y,N) ";W$
1040 IF U$ = "Y" GOTO 1070
1050 IF W$ = "N" GOTO 1070
1060 GOTO 1020
1070 IF W$ = "Y" THEN N = 13
1080 IF W$ = "N" THEN N = 12
1090 INPUT "SUBJECT ID? ";S$
1095 INPUT "FILE NAME ";T1$
1100 K = K + 1
1115 RESTORE
1120 PRINT "INPUT SEGMENTAL ENDPOINTS"
1130 PRINT "FRAME NUMBER ";K
1140 FOR J = 1 TO N
1150 READ B1$(J)
1160 PRINT B1$(J)
1161 IN# 4
1162 B$ = " ";A$ = " ";X$ = " ";Y$ = " 
1163 FOR M = 1 TO 19
1164 GET A$(M)
1165 B$ = B$ + A$(M)
1166 IF A$(M) = CHR$(13) THEN GOTO 1168
1167 NEXT M
1168 IN# 0
1169 FOR M = 1 TO 19
1170 X1$ = " 
1171 X1$ = MID$(B$,M,1)
1172 IF M < 3 GOTO 1174
1173 IF X1$ = CHR$(32) THEN GOTO 1176
1174 X$ = X$ + X1$
1175 NEXT M
1176 FOR L = M TO 19
1177 Y1$ = " 
1178 Y1$ = MID$(B$,L,1)
1179 IF Y1$ = CHR$(13) THEN GOTO 1182
1180 Y$ = Y$ + Y1$
1181 NEXT L
1182 X(J,K) = VAL(X$);Y(J,K) = VAL(Y$)
1183 PRINT X(J,K),Y(J,K)
1184 NEXT J
1190 INPUT "DO YOU WANT TO REDIGITIZE THIS FRAME; <Y,N) ";W1$
1200 IF W1$ = "Y" GOTO 1115
1210 IF W1$ = "N" GOTO 1250
1220 GOTO 1190
1221 REM
INPUT "DO YOU WANT TO DIGITIZE ANOTHER FRAME? (Y,N) " ; W2*
1250 IF W2* = "Y" GOTO 1100
1260 IF W2* = "N" GOTO 1350
1280 GOTO 1250
1350 DATA "RIGHT BOOT TOE","RIGHT BOOT HEEL","RIGHT LATERAL MALLEOLUS"
1355 DATA "RIGHT KNEE JOINT CENTER","RIGHT GREATER TROCHANTER"
1360 DATA "PELVIC MID-POINT","LEFT GREATER TROCHANTER","LEFT KNEE JOINT CENTER"
1345 DATA "LEFT LATERAL MALLEOLUS","LEFT BOOT HEEL","LEFT BOOT TOE"
1370 DATA "STERNUM","BASE OF OBJECT"
1395 REM
1396 REM **************
1397 REM WRITE THE COORDINATES TO A DATA FILE
1398 REM **************
1399 REM
1400 D$ = CHR$ (4)
1410 PRINT D$;"OPEN ";T1$;",L12"
1480 FOR L = 1 TO K
1490 FOR J = 1 TO N
1510 PRINT D$;"WRITE ";T1$
1520 PRINT X(J,L)
1530 NEXT J
1540 NEXT L
1550 FOR L = 1 TO K
1560 FOR J = 1 TO N
1580 PRINT D$;"WRITE ";T1$
1590 PRINT Y(J,L)
1600 NEXT J
1610 NEXT L
1660 PRINT D$;"CLOSE ";T1$
1670 END
Program Merge_xyz;

Const
  fsize = 10;  { field size of numbers in output file }
  dimen = 3;  { number of coords to read in }
  endpoint = 39;  { plan on reading 0 to "endpoint" }

Var
  i, j: integer;
  point: real;
  spoint,
  fname,    { generic filename string }
  infilename,
  outfilename: string;
  fd: array[1..dimen] of text;  { input file var vector } 
  output: text;

{ **************************************** forward declarations ****************************************}
Function open(Var filvar: text; filnam:string; access:char): boolean; forward;
Function prompt(s: string; param: integer): string; forward;
Procedure cant(s:string); forward;
Procedure fixup(var spoint: string); forward;

Procedure main;
begin
  infilename := prompt('Input file (no extension): ', 1);
  outfilename := prompt('Output file: ', 2);

  for i := 1 to 3 do begin
    fname := infilename + exten[i];
    if not open(fd[i], fname, 'r') then cant(fname);
  end;

  if not open(output, outfilename, 'w') then cant(outfilename);

  for i := 0 to endpoint do begin
    write(output, i:2, ',');
    for j := 1 to dimen do begin  { read from x, y and z files }
      readln(fd[j], spoint);
      fixup(spoint);
      write(output, spoint, ',':(fsize - length(spoint)));
    end;
    writeln(output);
  end;
  close(output);
end;
Procedure fixup(var spoint: string);
Var
    newvec: string;
    leading, trailing: boolean;
    i: integer;
begin
    newvec := '1';
    leading := true;
    trailing := true;
    for i := 1 to length(spoint) do
        case spoint[i] of
          '-', '+': newvec := spoint[i];
          '0'..'9': begin
            newvec := newvec + spoint[i];
            leading := false;
          end;
          '.': begin
            if leading then begin
              newvec := newvec + '0';
              leading := false;
            end;
            newvec := newvec + spoint[i];
            trailing := false;
          end;
        end;
    if trailing then newvec := newvec + '.';
    newvec := newvec + '0';
    spoint := newvec;
end;

Procedure convert(spoint: string; var point: real);
var
    i, j: integer;
    digits: boolean;
begin
    i := pos(spoint, '.');
    if i <> 0 then begin
      digits := false;
      for j := i - 1 downto 1 do digits := digits or (spoint[j] in ['0'..'9']);
      if not digits then insert('0', spoint, i);
    end;
    val(spoint, point, i);
    if i <> 0 then begin
      writeln('Invalid number format, "', spoint, '" at position ', i);
      close(output);
      halt;
    end;
end;

Function prompt(s: string; param: integer): string;
Begin
    if (paramcount < param) then begin
      write(s);
    end;
readln(s);
end
else s := paramstr(param);
prompt := s;
End;

Procedure cant(s:string);
Begin
  writeln('? Error: can't open file ',s);
halt;
end;

Function open(Var filvar: text; filnam:string; access:char): boolean;
Begin
  assign(filvar,filnam);
  ($i-)
  case access of
    'r','R': Reset(filvar);
    'w','W': Rewrite(filvar);
    'a','A': Append(filvar);
    else Reset(filvar);
    end;
  ($i+)
  Open := (IOResult = 0);
  End;

Begin
  main;
  End.
($r+$)

* SPLIT - separate camera 1 and camera 2 data into filename.one and filename.two.

Written by Mike Bowden 5/9/89

```
Const
a = '.one';
b = '.two';
maxpoints = 41;

Type
string8 = string[8];

Var
endpoint,
index,
i: integer;
pointvect: array [0..300] of string8;

infile,
outfile: string;

input,
outputa,
outputb: text;

Procedure main;
begin
infile := prompt('input file: ', 1);
outfile := prompt('output file (no extension): ', 2);

if not open(input, infile, 'r') then cant(infile);
if not open(outputa, outfile+a, 'w') then cant(outfile+a);
if not open(outputb, outfile+b, 'w') then cant(outfile+b);

i := 0;
while not eof(input) do begin
  readln(input, pointvect[i]);
i := i + 1;
end;
i := 1;
end;

```

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index := endpoint + 1;
writefile(outputa, index);  \{ sets up "index" for next camera \}
writefile(outputb, index);
close(outputa);
close(outputb);
end;

Procedure writefile(var output: text; var index: integer);
var
  i: integer;
begin
  for i := 0 to endpoint do begin
    writeln(output, fixup(pointvect[index]):8, fixup(pointvect[index+1]):8);
    index := index + 2;
  end;
end;

Function intval(s: string): integer;
var
  i, err: integer;
begin
  val(s, i, err);
  intval := i;
end;

Function fixup(var spoint: string8): string8;
Var
  newvec: string;
  leading, trailing: boolean;
  i: integer;
begin
  newvec := '';
  leading := true;
  trailing := true;
  for i := 1 to length(spoint) do
    case spoint[i] of
    '1', '+': newvec := spoint[i];
    '0'..'9': begin
      newvec := newvec + spoint[i];
      leading := false;
      end;
    '.': begin
      if leading then begin
        newvec := newvec + '0';
        leading := false;
        end;
    newvec := newvec + spoint[i];
      trailing := false;
      end;
end;

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if trailing then newvec := newvec + ' . ';
newvec := newvec + '0';
fixup := newvec;
end;

Function prompt(s: string; param: integer): string;
Begin
  if (paramcount < param) then begin
    write(s);
    readln(s);
    end
  else s := paramstr(param);
  prompt := s;
End;

Procedure cant(s:string);
Begin
  writeln('? Error: can' 't open file ',s);
  halt;
end;

Function open(Var filvar: text; filnam:string; access:char): boolean;
Begin
  assign(filvar,filnam);
($i-)
  case access of
    'r','R': Reset(filvar);
    'w','W': Rewrite(filvar);
    'a','A': Append(filvar);
    else Reset(filvar);
  end;
($i+)
  Open := (I0result = 0);
End;

begin
  main;
end.
Type  string8 = string[8];

Var  
  y,
  endpoint,
  frames,
  perframe,
  i, j: integer;
  pointvect: array [0..1000] of string8;

  infile,
  outfile: string;

  input,
  output: text;

{*********************** forward declarations ***********************}
Function open(Var filevar: text; filnam:string; access:char): boolean; forward;
Function prompt(s: string; param: integer): string; forward;
Procedure cant(s:string); forward;
Procedure getint(s: string; default: integer; var retval: integer); forward;
Function fixup(var spoint: string8): string8; forward;

Procedure main;
begin
  infile := prompt('input file: ', 1);
  outfile := prompt('output file: ', 2);

  if not open(input,infile,'r') then cant(infile);
  if not open(output,outfile,'w') then cant(outfile);

  i := 0;
  while not eof(input) do begin
    readln(input,pointvect[i]);
    i := i + 1;
  end;

  endpoint := i div 2;
  getint('How many points in this file: ',endpoint,endpoint);
  getint('How many coordinates per frame: ',13,perframe);
  getint('How many frames should be kept from this file: ',14,frames);

  y := endpoint;
  j := 0;
  for i := 0 to frames * perframe - 1 do begin
    writeln(output,(j mod perframe) + 1,' ', fixup(pointvect[i]):8,' ',fixup(p
  y := y + 1;

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j := (j + 1) \mod\ p\ er\ frame;
end;
close(output);
end;

Procedure getint(s: string; default: integer; var retval: integer);
var
i: integer;
digits: boolean;
begin
write(s, '"default', ') ');
readln(s);
digits := false;
for i := 1 to length(s) do digits := digits or (s[i] in ['0'..'9'])
if digits then val(s, retval, i)
else retval := default;
end;
Function fixup(var spoint: string8): string8;
Var
newvec: string;
leading, trailing: boolean;
i: integer;
begin
newvec := ' ';
leading := true;
trailing := true;
for i := 1 to length(spoint) do
  case spoint[i] of
    '1', '.', '+': newvec := spoint[i];
    '0'..'9': begin
      newvec := newvec + spoint[i];
      leading := false;
      end;
    ': begin
      if leading then begin
        newvec := newvec + '0';
        leading := false;
        end;
      newvec := newvec + spoint[i];
      trailing := false;
      end;
    end;
if trailing then newvec := newvec + '.';
newvec := newvec + '0';
fixup := newvec;
end;
Function prompt(s: string; param: integer): string;
Begin
  if (paramcount < param) then begin
    write(s);
  end;
end;
readln(s);
end
else s := paramstr(param);
prompt := s;
End;

Procedure cant(s:string);
Begin
  writeln('Error: can't open file ',s);
  halt;
end;

Function open(Var filvar: text; filnam:string; access:char): boolean;
Begin
  assign(filvar,filnam);
  (i-)
  case access of
    'r','R': Reset(filvar);
    'w','W': Rewrite(filvar);
    'a','A': Append(filvar);
    else Reset(filvar);
  end;
  (i+)
  Open := (IOresult = 0);
End;

begin
  main;
end.
* COMBINE - Combine the two skier data files with the reference point data.

* Written by Mike Bowden 7/12/89

Uses DOS;

Type
  linevector = packed array[1..150] of string[50];

Var
  info: searchrec;
  tailsize,
  middlesize,
  headsize: integer;
  tail,
  middle,
  header: linevector;

inFile,
  outFile: string;

input,
  output: text;

(* ***************** forward declarations ***************************)
Function open(Var filevar: text; filnam:string; access:char): boolean; forward;
Procedure initialize; forward;
Procedure readFile(fname: string; var vector: linevector; var vectsize: integer);
Procedure new_file(s:string); forward;
Procedure process_file(s:string); forward;

Procedure main;

Var
  i: integer;

begin
  initialize;
  findfirst('a*.spl', Archive, info);
  DOERROR = 0 do begin
    new_file(info.name);
    process_file(info.name);
    info.name[1] := 'b';
    for i := 1 to middlesize do writeln(output,middle[i]);
    process_file(info.name);
    for i := 1 to tailsize do writeln(output,tail[i]);
    close(output);
    findnext(info);
  end;
end;

Procedure initialize;
begin
  readFile('head',header,headsize);
readfile('middle',middle,middlesize);
readfile('tail',tail,tailsize);
end;

Procedure readfile(fname: string; var vector: linevector; var vectsize: integer)
begin
  if open(input, fname, 'r') then begin
    vectsize := 0;
    while not eof(input) do begin
      vectsize := vectsize + 1;
      readln(input, vector[vectsize]);
    end;
    close(input);
  end;
end;

Procedure new_file(s: string);
Var
  i: integer;
begin
  s := 'c' + copy(s,2,length(s)-4) + 'xxx';
  if open(output, s, 'w') then begin
    for i := 1 to headsize do writeln(output, header[i]);
  end;
end;

Procedure process_file(s: string);
begin
  if open(input, s, 'r') then begin
    while not eof(input) do begin
      readln(input,s);
      writeln(output,s);
    end;
  end;
  writeln(output,'0 0.0.0.');
  close(input);
end;

Function open(Var filvar: text; filnam:string; access:char): boolean;
Begin
  assign(filvar,filnam);
  {$i-}
  case access of
    'r','R': Reset(filvar);
    'w','W': Rewrite(filvar);
    'a','A': Append(filvar);
    else Reset(filvar);
  end;
  {i+}
  Open := (IOResult = 0);
End;
begin
  main;
end.
PROGRAM DLTOUT;

TYPE
  DATARRAY = ARRAY[1..1500] OF REAL;

VAR
  INFIL, OUTFIL: TEXT;
  X, Y, Z: REAL;
  NUM, I, J, PTS, FRAMES, K: INTEGER;
  NAMEIN, NAMEOUT: STRING[14];
  START: STRING[45];
  XARRAY, YARRAY, ZARRAY: DATARRAY;

PROCEDURE MAKEFILE;

BEGIN
  K := 1;
  FOR I := 1 TO FRAMES DO
    BEGIN
      WRITE(OUTFIL, I: 3);
      FOR J := 1 TO PTS DO
        BEGIN
          WRITE(OUTFIL, XARRAY[K]:16:6, YARRAY[K]:16:6, ZARRAY[K]:16:6);
        END;
      WRITELN(OUTFIL);
    END;
END;

BEGIN
  WRITELN('WHAT IS NAME OF FILE FROM DLT?');
  READLN(NAMEIN);
  ASSIGN(INFIL, NAMEIN);
  RESET(INFIL);
  WRITELN('ENTER NAME OF OUTPUT FILE');
  READLN(OUTFIL, NAMEOUT);
  WRITELN('HOW MANY FRAMES OF DATA ARE THERE?');
  READLN(FRAMES);
  WRITELN('HOW MANY POINTS PER FRAME?');
  READLN(PTS);
  REPEAT
    READLN(INFIL, START);
    UNTIL EOF(INFIL) OR (START = 'POINT X Y Z');
  WHILE NOT EOF(INFIL) DO
    BEGIN
      READLN(INFIL);
      READLN(INFIL);
      FOR J := 1 TO FRAMES*PTS DO
        BEGIN
          READLN(INFIL, NUM, X, Y, Z);
          XARRAY[J] := X;
          YARRAY[J] := Y;
          ZARRAY[J] := Z;
        END;
    END;
END;
END;
MAKEFILE;
CLOSE(OUTFIL);
CLOSE(INFIL);
END.

The only subprogrammes to be conventionally called by a user are subroutine GCVSPL for calculating the spline parameters, and function SPLDER for calculating the spline function and its derivatives within the knot range. See the comments in the headers of these subprogrammes for further details.

The programme types out statistics on the estimation procedure and on the estimated second derivatives. If the DEBUG-lines are compiled, also the raw data and the estimated spline values, first and second derivatives at the knot positions are typed.

C**************************************************************************************

PROGRAM GCV
C REAL*8
C IMPLICIT REAL*8 (A-H,O-Z), LOGICAL (L)
PARAMETER ( K =1 , NN=500, MM=10, MM2=MM*2, NWK=NN+6*(NN*MM+1) )
DIMENSION X(NN), Y(NN), WX(NN), C(NN), WK(NWK), Q(0:MM), V(MM2)
CHARACTER*64 INFILE, OUTFILE
CHARACTER*1 PROMPT
INTEGER ERRVAL, COLUMN, POINTS, TCOLS, COUNT, COUNT2, ITEMP
DATA WX/500*1D0/, WY/1D0/
C Weights, sampling interval
SCALE = 125D-3 / DATAN(IDO)
C 1/(2*PI)

PRINT *, '2J'
80 CONTINUE
PRINT *, '1;31mWhat is the input file? '
READ 90, INFILE
90 FORMAT (a)
OPEN (UNIT=1, FILE=INFILE, STATUS='OLD', ERR=800, IOSTAT=IFERR)
PRINT *, 'Points (frames) in file (maximum = 500): ' 
READ 110, POINTS
110 FORMAT (16)
122 CONTINUE
PRINT *, 'Column to evaluate: ' 
READ 100, COLUMN
100 FORMAT (16)
PRINT *, 'Time between data points: '
READ *, AT
C*** ASSIGN KNOT ARRAY
DO 10 IX=1,NN
X(IX) = AT *(IX - 1)
CONTINUE

PRINT *, 'What is the output file?'
READ 190, OUTFILE

OPEN (UNIT=2, FILE=OUTFILE, STATUS='NEW', IOSTAT=IFERR, ERR=900)
WRITE (FMT=191, UNIT=2) INFILE, COLUMN

PRINT ('Input file: ',a, 'Column: ', I3)

LOAD DATA FROM FILE IN COLUMN 'COLUMN' TO ARRAY Y

DO 200 COUNT = 1, POINTS
READ (FMT=150, UNIT=1) ITEMP, (Y(COUNT), COUNT2 = 1, COLUMN)
PRINT *, ITEMP, Y(COUNT)

CONTINUE

GET parameters (see comments in subroutine GCVSPL) or exit

PRINT *, 'Spline degree wanted: '
READ 710, ITEMP
M = INT((ITEMP+1)/2)
IF (MOD(ITEMP,2) .EQ. 0) PRINT 705, (ITEMP-1)

PRINT ('l:32mSpline degree ',I2, ' taken. '/)

PRINT *, 'l:31mOptimization mode wanted: '

READ 711, MODE

IF (MODE.NE.2) THEN
PRINT *, 'Mode value: '
READ 712, VAL

ENDIF

WRITE (FMT=713, UNIT=2) ITEMP, MODE

IF (((POINTS.LT.2*M).OR.(POINTS.GT.NN)) POINTS = NN
IF ((MODE.EQ.0).OR.(IABS(MODE).GT.5).OR.
1 ( M.LE.0).OR.( M.GT.MH)) STOP 'ready'

ASSess spline coefficients and type resulting statistics

CALL GCVSPL (X, Y, NN, WX, WY, M, POINTS, K, MODE, VAL, C, NN, 1
W, WK, IER)

IF (IER.NE.0) THEN
PRINT 720, IER

GO TO 770

ELSE
VAR = WK(6)
IF (WK(4).EQ.0D0) THEN
FRE = 5D-1 / AT
ELSE
FRE = SCALE * (WK(4)*AT)**(-0.5/M)
ENDIF

WRITE (FMT=729, UNIT=2) VAR, (WK(I),I=1,4), FRE

END
C*** Reconstruct data, type i, x(i), y(i), s(i), s'(i), s''(i) [D]
C*** Assess and type acceleration mean and standard deviation
C
WRITE (FMT=732, UNIT=2)
732 FORMAT(1, y(i),',
1         s0(i), s1(i), s2(i)'/)
D
PRINT 740
D 740 FORMAT(10 i, y(i),',
D         1 s0(i), s1(i), s2(i)'/)

IDM = MIN0(2,M)
DACC_AV = 0D0
DACC_SD = 0D0
Q(2) = 0D0
DO 40 I=1,POINTS
J = I
DO 30 IDER=0,IDM
Q(IDER) = SPLDER (IDER, M, POINTS, X(I), X, C, J, V )
30 CONTINUE
WRITE (FMT=745, UNIT=2) I, Y(I), (Q(IDER), IDER=0,IDM)
745 FORMAT(1, y(i),',
D         1 (F18.9,''),
D         DACC_AV = DACC_AV + Q(2)
D         DACC_SD = DACC_SD + Q(2)*Q(2)
40 CONTINUE
C ACCAV = DACC_AV / POINTS
C ACCSD = DSQRT((DACC_SD - ACCAV*ACCAV)/(POINTS-1))
C WRITE (FMT=760, UNIT=2) ACCAV, ACCSD
C PRINT 760, ACCAV, ACCSD
C 760 FORMAT(' acceleration mean and sd: ','2F12.7,' m/s**2')
C
C*** Next run
C
770 CONTINUE
PRINT 775
775 FORMAT('/ 1,31mRun another evaluation (Y or N)? ')
READ 780, PROMPT
IF ( ((PROMPT.EQ.'Y').OR.(PROMPT.EQ.'y'))) THEN
PRINT *, 'Keep saved data just computed (Y or N)? ' READ 780, PROMPT
IF ( ((PROMPT.EQ.'Y').OR.(PROMPT.EQ.'y'))) THEN
CLOSE (2)
776 CONTINUE
PRINT *, 'What is the new output file? ' READ 780, OUTFILE
OPEN(UNIT=2,FILE=OUTFILE,STATUS='NEW',IOUT=IFERR,ERR=1000)
ELSE
CLOSE (2,STATUS='DELETE')
OPEN (UNIT=2, FILE=OUTFILE, STATUS='NEW')
ENDIF
GO TO 20

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ENDIF
PRINT *, 'Test a different column (Y or N)? '
READ 780, PROMPT
IF ((PROMPT.EQ.'Y').OR.(PROMPT.EQ.'y')) THEN
    REWIND (1)
    CLOSE (2)
    GO TO 122
ENDIF
PRINT *, 'Run another file (Y or N)? '
READ 780, PROMPT
IF ((PROMPT.EQ.'Y').OR.(PROMPT.EQ.'y')) THEN
    CLOSE(1)
    CLOSE(2)
    GO TO 80
ENDIF
780 FORMAT (a)
CLOSE(1)
CLOSE(2)
STOP '5:1:34mHave a good daym'
800 CONTINUE
IF (IFERR.EQ.2015) THEN
    PRINT *, '1:32mThe file is not found.1:31m'
ELSE
    PRINT 810, IFERR
810 FORMAT ('1:32mError #', I4, 'occurred opening file.1:31m')
ENDIF
GO TO 80
900 CONTINUE
IF (IFERR.EQ.2013) THEN
    PRINT *, '1:32mThe file already exists.1:31m'
    PRINT *, '1:31mDelete it (Y or N)? '
    READ 780, PROMPT
    IF ((PROMPT.EQ.'Y').OR.(PROMPT.EQ.'y')) THEN
        OPEN (UNIT=2, FILE=OUTFILE, STATUS='UNKNOWN')
        CLOSE (2, STATUS = 'DELETE')
    ENDIF
ELSE
    PRINT 810, IFERR
ENDIF
GO TO 105
1000 CONTINUE
IF (IFERR.EQ.2013) THEN
    PRINT *, '1:32mThe file already exists.1:31m'
    PRINT *, '1:31mDelete it (Y or N)? '
    READ 780, PROMPT
    IF ((PROMPT.EQ.'Y').OR.(PROMPT.EQ.'y')) THEN
        OPEN (UNIT=2, FILE=OUTFILE, STATUS='UNKNOWN')
        CLOSE (2, STATUS = 'DELETE')
    ENDIF
ELSE
    PRINT 810, IFERR
ENDIF
GO TO 776
END
Program Veloce:Velocity Acceleration;
Uses DOS;
Const
  fsize = 10;  { field size of numbers in output file }
Var
  ext: char;
  info: searchrec;
  i, j: integer;
  done: boolean;
  point: real;
spoint,
fname,     { generic filename string }
infilename,
outfilename: string;
fd: array ['x',..'z'] of text;  { input file var vector }
output: text;

{ ******************************************************* forward declarations *******************************************************}
Procedure skip_header(var fd: text); forward;
Function get_point(var fd: text; var vel, accel: real): integer; forward;
Function skip_space(var fd: text): char; forward;
Procedure read_till(var fd: text; var s: string; stop_ch: char): forward;
Function resultant(x, y, z: real): real; forward;
Function open(Var filvar: text; filnam:string; access:char): boolean; forward;
Function prompt(s: string; param: integer): string; forward;
Procedure cant(s:string); forward;
Procedure error(s:string); forward;

Procedure main(infilename:string);
Var
  ix1,ix2,ix3: integer;
  r_vel,
  r_accel,
  ax,ay,az,
  vx,vy,vz: real;

begin
  infilename := copy(infilename,1,length(infilename)-1);
  outfilename := infilename + 'vac';
  writeln('Processing "",infilename,""');
  for ext := 'x' to 'z' do begin
    fname := infilename + ext;
    if not open(fd[ext], fname, 'r') then cant(fname);
      skip_header(fd[ext]);
  end;

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if not open(output, outfilename, 'w') then cant(outfilename);
write(output, 'Filename: "', infilename, '"');
write(output);
write(output, ' R e s u l t a n t ');
write(output, ' Velocity', ':6, 'Acceleration');
write(output, '-------', ':6, '-------');

repeat
  ix1 := get_point(fd['x'], vx, ax);
  ix2 := get_point(fd['y'], vy, ay);
  ix3 := get_point(fd['z'], vz, az);
  if (ix1 = 0) then done := true
  else begin
    if (ix1 <> ix2) or (ix2 <> ix3) then
      error('X, Y, Z files must have the same number of elements');
      r_vel := resultant(vx, vy, vx);
      r_accel := resultant(ax, ay, az);
      writeln(output, ix1:3, r_vel:16:9, r_accel:16:9);
  end
until done;
close(output);
for ext := 'x' to 'z' do close(fd[ext]);
end;

Procedure skip_header(var fd: text);
Var
  i: integer;
begin
  for i := 1 to 6 do readln(fd);
end;

Function get_point(var fd: text; var vel, accel: real): integer;
Var
  frame: string;
  newint, result: integer;
  dummy: real;
begin
  frame := skip_space(fd);
  read_til(fd, frame, ' ');
  val(frame, newint, result);
  if result = 0 then begin
    get_point := newint;
    readln(fd, dummy, dummy, vel, accel);
  end
  else get_point := 0;
end;

Function skip_space(var fd: text): char;
Var
ch: char;

Begin
repeat
    read(fd,ch);
    until ch <> ' ';
    skip_space := ch;
End;

Procedure read_til(var fd: text; var s: string; stop_ch: char);
var
Begin
    ch: char;
    repeat
        read(fd,ch);
        if ch <> stop_ch then s := s + ch;
    until (ch = stop_ch) or eof(fd);
End;

Function resultant(x, y, z: real): real;
Begin
    resultant := sqrt((x * x) + (y * y) + (z * z));
End;

Function prompt(s: string; 'param: integer): string;
Begin
    if (paramcount < param) then begin
        write(s);
        readln(s);
    end
    else s := paramstr(param);
    prompt := s;
End;

Procedure cant(s:string);
Begin
    writeln('? Error: can't open file ',s);
    halt;
End;

Procedure error(s:string);
Begin
    writeln('? Error:',s);
    halt;
End;

Function open(Var filvar: text; filnam:string; access:char): boolean;
Begin
    assign(filvar,filnam);
    ($i-
    case access of
      'r', 'R': Reset(filvar);
      'u', 'U': Rewrite(filvar);
      'a', 'A': Append(filvar);
    else
      Reset(filvar);
    end;
(i+)
Open := (IOresult = 0);
End;

Begin
  findfirst('*x', Archive, info);
  While DOSERROR = 0 do begin
    main(info.name);
    findnext(info);
  end;
End.

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Program Joint_Angular_Velocity_and_Acceleration;

Uses DOS;

Const
  fsize = 10;  { field size of numbers in output file }
  top_part: string = '04050612';
  bottom_part: string = '03040405';
  pmax = 30;  { max number of frames }

Type
  flagvec = array[1..6] of integer;
  rvec = array[1..pmax] of real;

Var
  info: searchrec;
  i, j: integer;
  done: boolean;
  point: real;
  theta,
  racce, rvel: rvec;
  spoint,
  fnam, { generic filename string }
  infilename,
  outfilename: string;

  fd: array [1..4, 'x'..'z'] of text;  { input file var vector }
  output: text;

{ ************************************************ forward declarations *************************************************}
Procedure skip_header(var fd: text); forward;
function get_point(var fd: text; var point: real): integer; forward;
Function get_dif(var fd2: text; var fd1: text; var dif: real): integer; forward;
Function skip_space(var fd: text): char; forward;
Procedure read_til(var fd: text; var s: string; stop_ch: char); forward;
Function open(Var filvar: text; filnam:string; access:char): boolean; forward;
Procedure open_skipxyz(fnam: string, access: char): boolean; forward;
Procedure closexyz(fx: integer); forward;
Function prompt(s: string; param: integer): string; forward;
Procedure cant(s:string); forward;
Procedure error(s:string); forward;
Procedure Process(parts, s, infilename: string; var output: text); forward;
Procedure Process_body_part(s:string); forward;
Function equal(fl: flagvec): boolean; forward;
Function resultant(x, y, z: real): real; forward;
Procedure xform_vector(Var v_from, v_to: rvec; size, start: integer); forward;

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procedure get_acos(var theta: rvec; size: integer); forward;

Procedure main(infilename:string);

begin
  infilename := copy(infilename,1,3);
  outfilename := infilename + '.ava';
  writeln('Processing bib "", infilename,""');
  writeln('Output to file "", outfilename,""');
  if not open(output,outfilename,'w') then cant(outfilename);
  writeln(output, 'Filename: "', infilename, '"');
  writeln(output, 'Note: all values are in Radians');
  process(top_part, 'Hip', infilename, output);
  process(bottom_part, 'Knee', infilename, output);
  close(output);
end;

Procedure Process(parts, s, infilename: string; var output: text);

Var
  fx, ix: integer;

begin
  ix := 1;
  fx := 0;
  while ix < length(parts) do begin
    fname := infilename + copy(parts, ix, 2);
    ix := ix + 2;
    fx := fx + 1;
    openskipxyz(fname,fx);
  end;
  process_body_part(s);
  for ix := 1 to 4 do closexyz(ix);
end;

Procedure openskipxyz(name:string; fx: integer);

Var
  s: string;
  ext: char;

begin
  for ext := 'x' to 'z' do begin
    s := name + ', ' + ext;
    if not open(fd[fx,ext], s, 'r') then cant(s);
    skip_header(fd[fx,ext]);
  end;
end;

Procedure closexyz(fx: integer);

Var
  ext: char;

begin
for ext := 'x' to 'z' do close(fd[fx,ext]);
end;

Procedure skip_header(var fd: text);
Var
  s: string;
begin
  repeat
    readln(fd,s);
    until s = 'i y(i) s0(i) s1(i) s2(i)';
  readln(fd);
end;

Function get_dif(var fd2: text; var fd1: text; var dif: real): integer;
Var
  fcoll,
  fcoll2: integer;
  v1,
  v2: real;
begin
  fcoll := get_point(fd1,v1);
  fcoll2 := get_point(fd2,v2);
  if fcoll <> fcoll2 then error('Data files must be same length')
  else begin
    dif := v2 - v1;
    get_dif := fcoll;
  end;
end;

Function get_point(var fd: text; var point: real): integer;
var
  frame: string;
  newint,
  result: integer;
  dummy: real;
begin
  frame := skip_space(fd);
  read_til(fd,frame,' ');
  (SR-)
  val(frame,newint,result);
  (SR-)
  if result = 0 then begin
    get_point := newint;
    readln(fd,dummy,point);
    end
  else get_point := 0;
end;

Function skip_space(var fd: text): char;
Var
  ch: char;

Begin
  repeat
    read(fd, ch);
    until ch <> ' ';
    skip_space := ch;
  End;

Procedure read_til(var fd: text; var s: string; stop_ch: char);
var
  ch: char;
Begin
  repeat
    read(fd, ch);
    if ch <> stop_ch then s := s + ch;
  until (ch = stop_ch) or eof(fd);
End;

Procedure Process_body_part(s:string);
Const
  pi_180 = 0.017453293;
Var
  f1: flagvec;
  t1, t2, t3, t4,
  ix1, ix2,
  iy1, iy2,
  iz1, iz2: real;
  i, j: integer;
begin
  writeln(output, '----------------------------------------------------------');
  writeln(output, ' Joint Angular');
  writeln(output, 'Point #', ' :7', 'Theta', ' :9', 'Velocity', ' :6', 'Acceleration'
  writeln(output, '---------------', ' :7', '---------------', ' :9', '---------------', ' :6', '---------------'
  i := 0;
  repeat
    f1[1] := get_diff(fd[1,'x'], fd[2,'x'], ix1);
    f1[2] := get_diff(fd[4,'x'], fd[3,'x'], ix2);
    f1[3] := get_diff(fd[1,'y'], fd[2,'y'], iy1);
    f1[4] := get_diff(fd[4,'y'], fd[3,'y'], iy2);
    f1[5] := get_diff(fd[1,'z'], fd[2,'z'], iz1);
    f1[6] := get_diff(fd[4,'z'], fd[3,'z'], iz2);
    if not equal(f1) then error(' Data files must be same length');
    if f1[1] <> 0 then begin
      i := i + 1;
      t1 := (ix1 * ix2 + iy1 * iy2 + iz1 * iz2);
      t2 := resultant(ix1, iy1, iz1);
      t3 := resultant(ix2, iy2, iz2);
      theta[i] := t1/(t2 * t3);
    end
  end
  writeln(output, '----------------------------------------------------------');
end;
until fl[1] = 0;
get_acos(theta, i);
    xform_vector(theta, rvel, i, 2);
    xform_vector(rvel, raccel, i, 4, 3);
    for j := 1 to i do writeln(output, j:4, ',theta[j]:16:9,rvel[j]:16:9,ra
end;

procedure get_acos(var theta: rvec; size: integer);
Var
    fd: text;
    i: integer;

begin
    if not open(fd,'theta1.tmp','w') then error('Out of disk space');
    for i := 1 to size do writeln(fd, theta[i]);
    close(fd);
    exec('acos.exe','');
    if not open(fd,'theta2.tmp','r') then error('Can't open THETA2.TMP');
    for i := 1 to size do readln(fd, theta[i]);
    close(fd);
end;

procedure xform_vector(var v_from, v_to: rvec; size, start: integer);
Const
    two_dt = 0.02;  { 2 * .01 seconds }
Var
    i: integer;

begin
    for i := start to start + size - 1 do
        v_to[i] := (v_from[i+1] - v_from[i-1]) / two_dt;
end;

Function equal(fl: flagvec): boolean;
Var
    i,
    tmp: integer;

begin
    equal := true;
    tmp := fl[1];
    for i := 2 to 6 do
        if fl[i] <> tmp then begin
            equal := false;
            writeln('point file #1 and #',i,' are different');
        end;
end;

Function resultant(x, y, z: real): real;
Begin
    resultant := sqrt((x * x) + (y * y) + (z * z));
End;
Function prompt(s: string; param: integer): string;
Begin
  if (paramcount < param) then begin
    write(s);
    readln(s);
  end
  else s := paramstr(param);
  prompt := s;
End;

Procedure cant(s:string);
Begin
  writeln('? Error: can't open file ',s);
  halt;
End;

Procedure error(s:string);
Begin
  writeln('? Error:',s);
  halt;
End;

Function open(Var filvar: text; filnam:string; access:char): boolean;
Begin
  assign(filvar,filnam);
  ($i$)
  case access of
    'r','R': Reset(filvar);
    'w','W': Rewrite(filvar);
    'a','A': Append(filvar);
    else    Reset(filvar);
  end;
  Open := (I0result = 0);
End;

Begin
  for i := 1 to pmax do begin
    rvel[i] := 0;
    racce[i] := 0;
  end;
  findfirst('s??03.x',Archive,info);
  While DOSERROR = 0 do begin { do all bids }
    main(info.name);
    findnext(info);
  end;
End.
#include <stdio.h>
#include <math.h>

main() {

FILE *fdin, *f dout;
float theta;
char fnl[] = "theta1.tmp";
char fn2[] = "theta2.tmp";

fdin = fopen(&fnl,"r");
if (fdin == NULL) printf("Can't open input file\n");
unlink(fn2);
f dout = fopen(&fn2,"w");

while (feof(fdin) == 0) {
    fscanf(fdin,"%f\n", &theta);
    theta = acos(theta);
    fprintf(f dout,"%f\n", theta);
}

close(fdin);
close(f dout);
}
Appendix G

Reference System
The known DLT coordinates and their positions on the octopus are displayed above. All distances are in meters and are based on the origin, located at the center of the 14 sided polyhedran. These coordinates make up the control file for the reference field.
Fourteen sided polyhedron and arm attachment positions.
Fourteen sided polyhedron on pivoting support shaft and a collection of tools used to collect the data.
Appendix H
Sample FIS Point Calculations
# Slalom Men

## Penalty Calculation

<table>
<thead>
<tr>
<th>PL</th>
<th>CODE</th>
<th>Competitor</th>
<th>Surname</th>
<th>Points</th>
<th>Best 5</th>
<th>Race Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>05139</td>
<td>NERLICH Rudolf</td>
<td>AUT</td>
<td>6.88</td>
<td>6.88</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>20028</td>
<td>BITTNER Armin</td>
<td>BRD</td>
<td>0.14</td>
<td>0.14</td>
<td>2.11</td>
</tr>
<tr>
<td>3</td>
<td>36002</td>
<td>GIRARDELLI Marc</td>
<td>LUX</td>
<td>0.00</td>
<td>0.00</td>
<td>3.84</td>
</tr>
<tr>
<td>4</td>
<td>51001</td>
<td>ACCOLA Paul</td>
<td>SUI</td>
<td>7.66</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>50074</td>
<td>NILSSON Jonas</td>
<td>SWE</td>
<td>5.51</td>
<td>5.51</td>
<td>4.90</td>
</tr>
<tr>
<td>6</td>
<td>42059</td>
<td>FURUSETH Ole Christian</td>
<td>NOR</td>
<td>6.94</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>35005</td>
<td>FROMMELT Paul</td>
<td>LIE</td>
<td>4.84</td>
<td>4.84</td>
<td>11.96</td>
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<tr>
<td>8</td>
<td>31003</td>
<td>BENEDIK Grega</td>
<td>JUG</td>
<td>11.78</td>
<td>-</td>
<td>-</td>
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<tr>
<td>9</td>
<td>05196</td>
<td>STANGASSINGER Thomas</td>
<td>AUT</td>
<td>9.08</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>51231</td>
<td>STAUB Patrick</td>
<td>SUI</td>
<td>14.67</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Total**

- Total of Best 5: 17.37
- Total of Race Points: 22.81

**Calculated Penalty**

- Total of Best 5 x 2: 34.74
- Total of Race Points: -22.81
- \[ \frac{11.93}{10} = 1.19 \]

- Penalty Applied: 0.00

---

The Technical Delegate

B. FERRONATO (ITA)

12-02-89 / VAIL - BEAVER CREEK (USA)

Data Processing by OLIVETTI PERSONAL COMPUTER

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