Optimisation of Performance in Alpine Ski Racing with Fusion Motion Capture

A report presented to SPARC in order to disseminate the knowledge acquired during a PhD research project that was a recipient of a SPARC equipment grant

Massey University, Wellington, New Zealand

Matthew Andrew Dalhousie Brodie

2009

Abstract

Fusion Motion Capture (FMC), a wearable motion capture system was developed, and applied to the optimisation of athlete performance in alpine ski racing. In what may be a world first, the three-dimensional movements of a skilled athlete[1] skiing through a complete giant slalom racecourse were analysed.

FMC consists of multiple light weight sensors attached to the athlete. It includes inertial measurement units (IMUs), pressure sensitive insoles a global position system (GPS) receiver and pressure sensitive insoles. The IMUs contain accelerometers, gyroscopes, and magnetometers. Limb orientation and location are obtained by mathematically combining the most reliable data from each sensor using fusion algorithms developed by the author. The results obtained from ski racing were accurate, stable and relatively independent of motion type and duration unlike other inertial systems available in 2005, when the research was initiated.

It became possible to determine giant slalom race performance from the analysis of the athlete skiing through the entire course. FMC proved, therefore, to be more suitable than traditional optical systems that are practically limited to capturing small sections of a race course. Many interesting insights were obtained that could, in the future, improve both athlete performance and safety.

- The optimum race strategy is a trade off between tighter turns that result in shorter path lengths and more open turns that allow for faster turning speeds.
- The results contradict the traditional ‘going straight turning short’ race strategy. The shortest path may not always be the fastest. Instead each gate has a different optimum approach arc. Optimum turn radius increases with both increasing speed and increasing terrain slope.
- In some parts of the course optimum turn radius may be limited by the maximum ski/snow angle the athlete is able to maintain.
- The results contradict laboratory measurements of ski/snow sliding friction and suggest that snow resistance in giant slalom is of similar importance to wind drag.
- In addition to gravity, the athlete increased speed using the techniques of ‘lateral projection’ and ‘pumping’.
- The athlete experienced high and rapidly fluctuating torques about all three axes of the lower joints. This information could be useful in designing training programmes racecourses and equipment to reduce knee injuries.

The results are from multiple runs of a single athlete and so additional research may be required to confirm the initial findings.

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[1] A skilled athlete is considered to have less than 20 FIS points. Federation International Ski (FIS), the ruling body in ski racing. Less than 20 FIS points means it is likely the athlete will be ranked within the top few hundred athletes world wide.

Preface

This report contains material condensed from a PhD thesis by the author (Brodie, 2009). The thesis has been archived by Massey University and is available online:

http://muir.massey.ac.nz/handle/10179/1041

The original research objectives were to improve ski technique and training methods for New Zealand athletes with flow on effects for recreational skiing. Both performance and safety were targeted. The original research objective was:

"Optimisation of athlete movement in alpine ski racing"

The principal thesis objective was not completely achieved and was initially hampered by the technical difficulties associated with motion capture in an extreme alpine environment. If the equipment had performed to the manufacturers' specifications, out of the box, then faster progress may have been made. If everything had been easy, however, then the research may not have received the same international recognition and the novel insights into alpine ski racing may not have been obtained.

Every cloud has a silver lining. The problems encountered provided many opportunities. A new prototype motion capture system was developed, a camera-less motion capture system called Fusion Motion Capture (FMC). Using FMC for the first time it became possible to complete the biomechanical analysis of alpine skiing through a complete race course. Many new insights into ski racing performance were obtained. The research provides a novel contribution to the body of knowledge at both the theoretical and practical level.

A brief summary of part of this research became an entry to the 2008 New Zealand MacDiarmid Young Scientists of the Year Awards. The 90 second competition entry video and poster provide a useful overview of the research suitable for all audiences and are provided as supplementary material to this report (**Appendices\MacDiarmid 2008**). The video entry is also available on YouTube:

www.youtube.com/BrodieMAD

Dr Matthew A D Brodie, 2009
BrodiePhD@gmail.com

Acknowledgements

The author gratefully acknowledges the support that made this project possible.

The following people, in alphabetical order, contributed to this project through the research, the funding applications and the thesis preparation: Prof Geoffrey Anneson, Dr Bobby Cheema, Prof Philip Dickinson, Mr David Graham, Mr Ben Griffin, Mr Angus Howden, Dr Edmond Lai, Dr Rachel Page, Dr Wyatt Page, Dr John Ruck, Mr Rhys Thorpe, Mrs Judy Thorpe, Mr Mike Turner, and Dr Alan Walmsley.

This research was supported by the following institutions: The Institute of Food Nutrition and Human Health, Massey University, Mt Ruapehu Alpine Lifts, the New Zealand Academy of Sport, **Sport and Recreation New Zealand (SPARC equipment grant)**, and Volkswagen New Zealand.

This research was supported by the following awards and grants: The Foundation for Research Science and Technology, for the 2008 MacDiarmid Overall Runner Up New Zealand Young Scientist of the Year Award and the Future Science and Technology Award. The Federation International Ski, for an Innovation award at the 4th International Congress on Science in Skiing. The Royal Society of New Zealand, for the R.H.T Bates award and the James G. Hay travel award. Education New Zealand, for a postgraduate study travel abroad award. Sport and Exercise Science New Zealand (SESNZ), for the 2005 Emerging Scientist Award. The Vice Chancellors Committee, for a Claude McCarthy travel award.

Approval for the skiing experiments in this thesis was obtained from the Massey University Human Ethics Committee, Palmerston North Application 05/105.

Table of Contents

List of Illustrations

List of Videos

The supplementary videos are available on the accompanying CD (**Appendices/FMC Video**). In order to view these videos using the hyperlinks in the electronic version of this thesis first ensure that the supplementary material and the thesis are in the same folder. It may also be necessary to set the default media player to Windows Media Player.

1. Introduction: past and present

Figure 1-1: Marey's white heron, motion capture from 1884Ψ

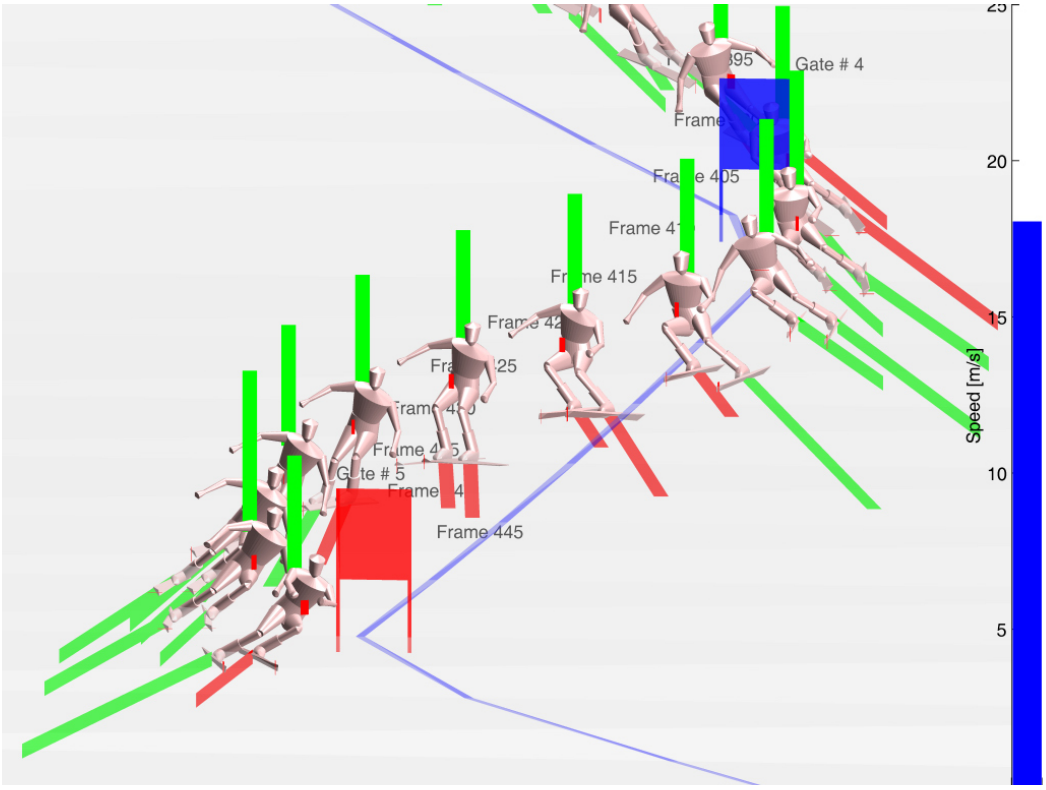


Figure 1-2: Screen shot from this research external forces 2007

1.1. Why…

…"Many skiers do not take advantage of the way modern equipment has been designed to facilitate carving turns"…(Stenmark, 1990)

From 1974-1989, Ingemar Stenmark won an incredible 86 FIS (Federation International Ski) and World Cup races. Regardless of the course conditions Stenmark would adapt his movements to the course. What can be learnt from him? In the 18 years since publication of Stenmark's article there has been a revolution in materials science and alpine ski design. Most important among many factors is the side cut radius of the 'carving' ski. (Lind & Sanders, 1997).

Do Stenmark's comments still hold true today? Do today's skiers take advantage of modern equipment design? Stenmark's comments were the motivation to begin this research because they highlighted a gap in the understanding of the scientific base for the different ski methodologies adhered to by athletes from different countries. Why did people from different countries ski differently? Was there a faster, easier or safer way to ski? How could this be proven scientifically? What makes one athlete the fastest, is it science or art?

The need to question the status quo of ski technique against the backdrop of rapidly changing ski design was further encouraged by comments in a recent book by a Slovenian ski race coach: 'Therefore the basic ski technique is unchanged relative to ski design' (Matijevec, 2003). Questions that motivated this thesis included: "Which comes first, ski design or ski technique?" Ski designers use feedback from the top athletes to design new prototypes; an athlete adapts their technique to current ski design. The recreational skier is exposed to recreational versions of this technique and equipment design. Is it possible that developments are slowly approaching a local optimal solution, but different and better optimal solutions could exist that are dependent on individual physiology?

This study is limited to measuring the athletes' movements and how they are affected by the external forces of gravity, wind drag, snow resistance and ground reaction. The implicit assumption underlying this thesis is that, in ski racing, style is not judged, so ultimately the external forces acting on the athlete completely determine the outcome of the race.

1.2. Biomechanical analysis and skiing

In recent years, the number of published papers based on the motion capture of skiing using video cameras has increased dramatically. So much so that when Erich Müller and Hermann Schwameder published a paper in 2003 that included a 'brief' description of the history of biomechanical analysis of alpine skiing, their paper included over 90 references .

Müller and Schwameder's paper contains reference to many important contemporary and historical papers, which show both the depth and high quality of previous research. Müller and Schwameder characterise the development of the biomechanics of skiing into three phases:

- 1930 – Present, Qualitative descriptions
- 1957 – Present, Quantitative
- 1980 – Present, Optimisation of Technique and Injury Prevention

The first phase contains studies that provide qualitative descriptions of skiing such as the recording of motion sequences of skilled athletes or the discussion of forces during skiing. Some contributors to the first phase include (Brandenberger, 1934; Hatze, 1966; Howe, 1983; Lind & Sanders, 1997).

The second phase contains studies that make use of biomechanical analyses in order to make objective measurements that describe the technique of skiing. The first study of this type measured ground reaction forces during skiing . Some other significant contributors to the second phase include (Eric Müller, 1994; Raschner, et al., 2001).

The third phase is characterised by using biomechanical analyses and mathematical modelling in order to measure, predict and sometimes suggest improvements. Some studies have looked at reducing course time through better aerodynamic position (Kaps, Nachbauer, & Mossner, 1996) and run line. Other studies have investigated how ski geometry affects run line (Casolo, Lorenzi, Vallatta, & Zappa, 1997; Margane, Trzecinski, Babiel, & Neumaier, 1998). Further studies have analysed musculoskeletal loading often for the purpose of injury prevention (Herzog & Read, 1992; Nachbauer & Kaps, 1994; Quinn & Mote, 1992; Senner, Lehner, Wallrapp, & Schaff, 2000).

Müller and Schwameder summarised the differences between traditional parallel skiing and 'new' carving technique, commonly employed to control modern shaped skis. Some conclusions included; smaller radius turns were possible with the new shaped skis, better sagittal plane (fore/aft) balance control and movement was required and a more equal inside/outside foot loading ratio was used. Their paper demonstrates that ski technique and equipment design are both developing and intertwined and that there are still many unanswered questions.

1.3. Is optical motion capture suitable for skiing?

Only a few researchers have questioned the suitability of optical motion capture for the biomechanical analysis of skiing, possible because there were no other practical options available. A summary of issues with optical motion capture has been extracted from the original thesis discussion (Brodie, 2009) and is presented below:

- Practical constraints on the use of contemporary video motion capture systems limit the biomechanical analysis of skiing to one or two discrete turns.
- Race performance does not depend on the performance about an isolated turn. It depends on the complete race strategy of both past and future turns.
- The three dimensional motion analyses require long post processing times for skiing. The harsh alpine environment, high speeds of the athlete and aggressive race strategies make automated marker tracking of visible markers difficult. Time-consuming manual digitising of estimated anatomical reference points on the athlete is often required.
- It is difficult to achieve high accuracy of the derived parameters such as limb angle, velocity and acceleration.

Biomechanists have already realised that in order to increase the understanding of alpine ski racing outcomes, data from multiple consecutive turns are required. Supej noted through an energy analysis that turn performance was dependant on the previous turn (Supej, Kugovnik, & Nemec, 2005). In a recent paper it was further hypothesised; ‘if turn strategy is dependent on both past and future turns, then, unfortunately, race outcome, and ultimately athlete performance, cannot be predicted from the analysis of an isolated turn sequence’ (Brodie, Walmsley, & Page, 2008a). In the same paper evidence was provided for this by analysing virtual split times through a ten-gate giant slalom course.

1.4. Motion capture using new sensing technology

The potential of a new wearable motion capture system that used small sensors attached to the athlete was investigated. The system developed through this research was based on inertial measurement units (IMUs), small sensors that contain accelerometers, gyroscopes and magnetometers.

This approach was new in 2005 and there were no previous papers detailing the use of IMU based systems for the motion capture or biomechanical analysis of skiing. While the limitations of 3D optical motion capture were well documented, the limitations of the new wearable motion capture system were, at the time, difficult to determine from the literature (Brodie, 2009). In his thesis, however, Luinge developed a Kalman filter for the inertial measurement of trunk inclination and reported errors of less than 2° (Luinge, 2002). This was similar to the errors reported to be associated with the optical motion capture systems (Schwartz, Trost, & Wervey, 2004). Such low errors appeared to make IMUs very appropriate for the biomechanical analysis of alpine ski racing.

In hindsight Luinge’s brief comment in the introduction to his thesis should have been considered more seriously:

…‘accuracy of the estimated kinematics depends on the particular movement to be performed.’…(Luinge, 2002)

Luinge's comment should have been considered more seriously because the athletic movements in alpine ski racing are very different from the quasi static trunk movements in box stacking. In order to make the new motion capture technology work for skiing the author had to develop custom motion capture algorithms. The accurate analysis of alpine ski racing is now possible because of this work. It has also improved our capacity to study complex human motion.

1.5. Optimum trajectories in alpine ski racing

In ski racing all athletes start with the same gravitational potential energy relative to their mass, so all should theoretically (in a frictionless environment) finish with the same final velocity. The winning athlete makes efficient use of gravity and has a global strategy that balances the shortest path between gates against maintaining a high velocity and avoiding injury.

Some research has focused on the path of shortest descent time commonly termed the *brachistocrone* problem (from Greek meaning shortest time). The fastest path between gates is not a straight line but the research suggests the athlete should start skiing close to the fall line to increase speed early in the trajectory (Figure 1-3). The analysis was done first without frictional forces (Reinisch, 1991) and later with 'snow cutting' forces included (Hirano, 2002).

Neither of these papers considers how the athlete should change direction at each gate. The analyses results in infinite forces required at each gate to change direction. Reinisch's and Hirano's results support one accepted tactic for skiing fast 'going straight turning short' (Lind & Sanders, 1997) and this might have impacted on the design of modern racing skis.

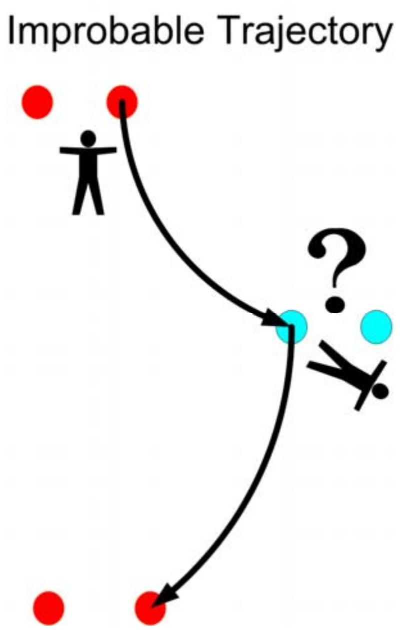


Figure 1-3: Improbable solution to the brachistocrone problem

Fortunately, considerable research has been undertaken into the analyses of the external forces acting on the athlete. External forces include gravity, wind drag, ground reaction, and snow resistance. Because style does not decide race outcome the external forces uniquely define the athlete's performance and so it follows that a survey of what is known about the external forces acting on the athlete during ski racing is required.

1.6. Forces in Alpine Skiing

Four main external forces act on the athlete as he descends the slope; gravity, ground reaction forces, wind drag and snow resistance (Figure 1-4).

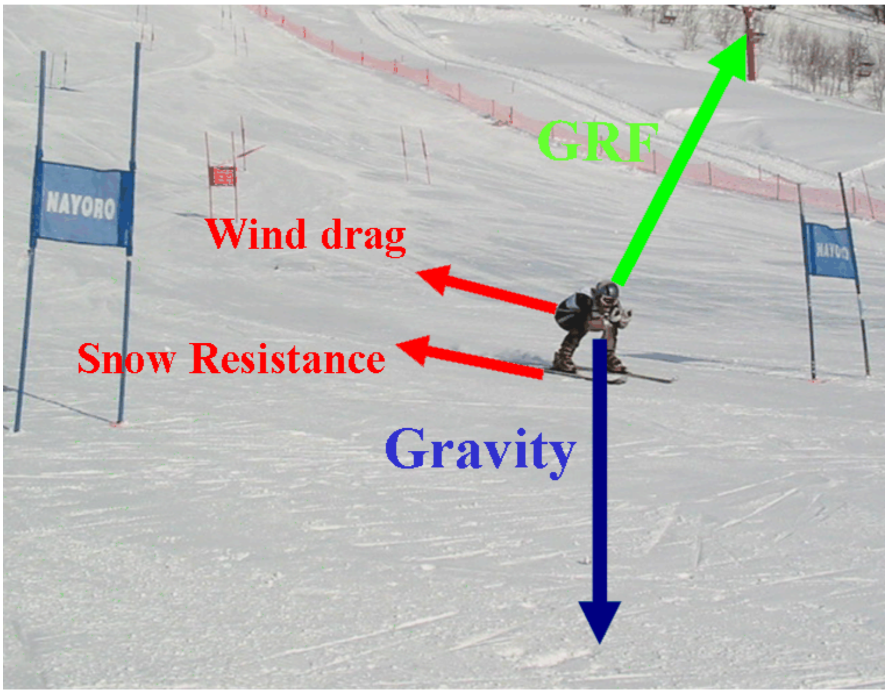


Figure 1-4: Forces affecting race outcome

1.6.1. Gravity

In alpine skiing athletes travel downhill so the primary accelerating force is gravity.

1.6.2. Ground reaction forces measurement

Ground reaction forces (GRFs) are generated between the athlete's skis and the snow surface. Athlete technique directly affects ground reactions forces, which can accelerate or decelerate the athlete and change the athlete's direction.

If the ski base is approximately parallel to the athlete's direction of travel, ground reaction forces have no effect on speed, but can change the athlete's direction (Figure 1-5). If the athlete rotates the ski tails outwards then some skidding occurs and the ground reaction forces act to reduce the athletes speed. How an athlete may be able to use ground reaction forces to increase speed through a ski run is discussed later in Chapter 3.

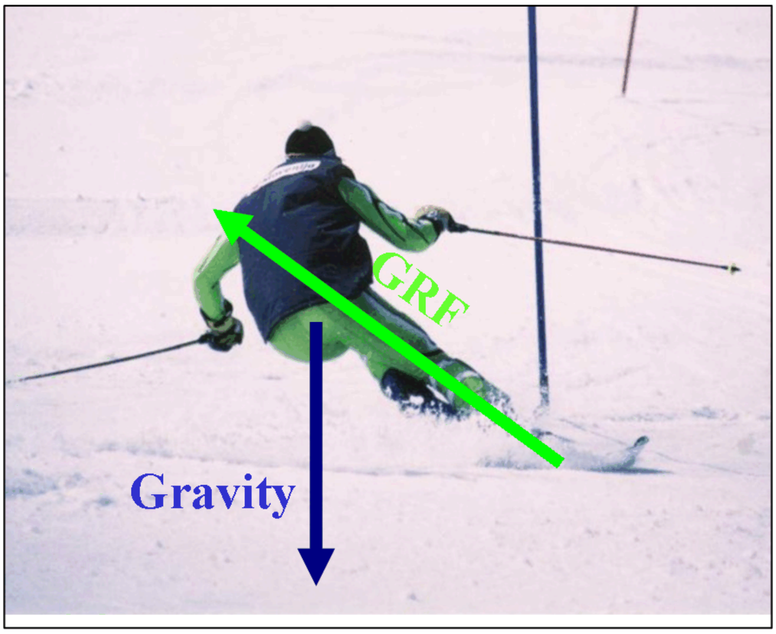


Figure 1-5: Ground reaction forces while cornering

Pressure sensitive insoles, miniature force plates and inverse dynamic analysis of video data have all been used to measure ground reaction forces. Ground reaction force data from a single turn were measured using all three methods and the data were recently published (Lüthi et al., 2005). The pros and cons of each system has been discussed elsewhere (Brodie, 2009).

The SPARC equipment grant was used to purchase a pressure sensitive insole system. Pressure sensitive insoles are easy to use affordable and do not impinge on the athletes technique or safety but are less accurate than force plates.

1.6.3. Wind resistance

Wind drag force opposes the athlete's movements through the air as they descend the slope. Barelle et al suggested that, at high speeds (>25ms^{-1}), wind drag is the most important braking force (Barelle, Ruby, & Tavernier, 2004). Wind drag can be reduced by reducing speed, cross sectional area, or wind drag coefficient. Skiers adopt aerodynamic postures and wear race suits respectively in order to reduce wind drag.

Part of this research also included the development of a pixel counting algorithm for estimating wind drag forces during the changing postures through the ski race course (Figure 1-6).

Figure 1-6: Measuring changing cross sectional area by pixel counting

Laboratory experiments report wind drag in terms of the drag coefficient (C_d) or drag area (A_c*C_d the drag coefficient multiplied by the cross sectional area). These coefficients are then used to estimate wind drag force using Equation 1.1. Reported values for drag area range from 0.15m^2 for the 'egg posture' (crouching with arms in front and poles tucked beside the torso) in skiing at 28ms^{-1} (Barelle et al., 2004) to 0.73m^2 for an upright posture in cross country skiing at less than 11ms^{-1} (Spring, Savolainen, Erkkila, Hamalainen, & Pihkala, 1988).

Equation 1.1 $$F_{Drag} = \frac{1}{2}\rho A_c C_d V^2$$

In Equation 1.1 the other symbols have the following meanings: (ρ) Density of air, (V) Relative wind velocity between the athlete's centre-of-mass (CoM) and the air.

1.6.4. Snow resistance

Snow resistance opposes the athlete's skis as they move over and through the surface layers of snow. The ski/snow interaction is very complicated and a satisfactory model that can accurately predict the snow resistance forces during ski racing remains to be developed. This research supports the hypothesis that snow resistance increases with velocity through increased displacement and compression of the snow. It is likely that snow resistance is more important than wind drag in giant slalom. The athlete should therefore ensure that his/her skis run smoothly across the snow surface with minimum skidding, vibration and penetration. It is also very important to use the most appropriate wax for the conditions to minimise snow resistance.

In ski racing the skis do not sit flat on the snow surface, but move from edge to edge between gates. The skis bend and the snow is displaced as it compresses and fractures. Federolf et al. provided evidence for a threshold process for the ski edge penetration and snow fracture in which the maximum pressure at the ski edge must exceed the mechanical strength of the snow (Federolf et al., 2007). In 1996 Kaps tried to incorporate some of these effects into a simple model and used data from skiing to fit empirical snow resistance coefficients (Kaps et al., 1996). Equation 1.2, based on Kap's research, was used in this research because it provided the best fit for the experimental data but in the future further improvements might include ski/snow edging angle.

Equation 1.2 $F_{Snow} = F_N(\mu_F + \mu_V V)$

1.6.5. How forces affect race outcome

Gravity, snow resistance and wind drag directly determine the athlete's maximum straight line speed. The athlete's speed increases until the acceleration from gravity is balanced by deceleration from snow resistance and wind drag.

Athletes can ski faster by skiing on steeper slopes, but the race course is fixed and so all athletes experience the same acceleration due to gravity and so it does not significantly affect race outcome.

Athletes can ski faster by reducing wind drag. Most athletes are of similar size and wear similar race suits and so in giant slalom the wind drag is very similar for each athlete. Wind drag is therefore unlikely to be the primary cause of race outcome unless an athlete makes a mistake and is then unable to maintain an aerodynamic posture.

Athletes can ski faster by reducing snow resistance. It is important therefore to select the correct ski design and wax for the course conditions. Ski selection is covered later in Chapter 3. Given that most athletes have access to the same skis and waxes, then, although snow resistance is important, small differences in the equipment are unlikely to significantly affect race outcome. Athletes should take care to run the skis smoothly over the snow surface, to minimise penetration into the snow surface and ski vibrations because these two factors may increase snow resistance. It was not however possible to investigate this because of the difficulties associated with accurately measuring and modelling snow resistance during a race.

This research will show that, at the elite level, ground reaction forces and therefore the athlete's technique and race strategy have the most significant effect on race outcome. These are the forces that vary most between different runs through the same course.

2. Methods

Figure 2.1: System diagnostics using a laptop from (Brodie, Walmsley, & Page, 2008b)

Figure 2.2: The author modelling the Early FMC system. (Photo Emily Ross)

2.1. Experimental, overview of data collection

The purpose was to collect data of the motion of an athlete racing through a giant slalom course. The data might then be used to complete a biomechanical analysis of alpine ski racing and therefore help athletes to ski faster and more safely.

The motion of a highly skilled athlete (less than 20 FIS points in their best discipline and mass of 78kg) was captured using the revised prototype Fusion Motion Capture (FMC) system. The athlete completed five runs, at race pace, through a ten-gate giant slalom training course at Mt. Ruapehu Ski Area (Video 2.1). The course was over 300 metres in length.

Video 2.1: Appendices\FMC Video\Ruapehu_R3_Video.avi

2.2. How FMC works

The IMU's provided the orientation of each limb. The athlete's global trajectory was measured by fusing (mathematically combining) the GPS signal (at 1Hz) with the double integral of the accelerometer signal (at 50Hz). The resulting data were used to drive the animation of a body model that approximated the subject, based on measurements made in a custom 3D anthropometric frame. The foot scan insole data were used to measure the ratio of forces under each ski, which provided essential additional information (Figure 2.3).

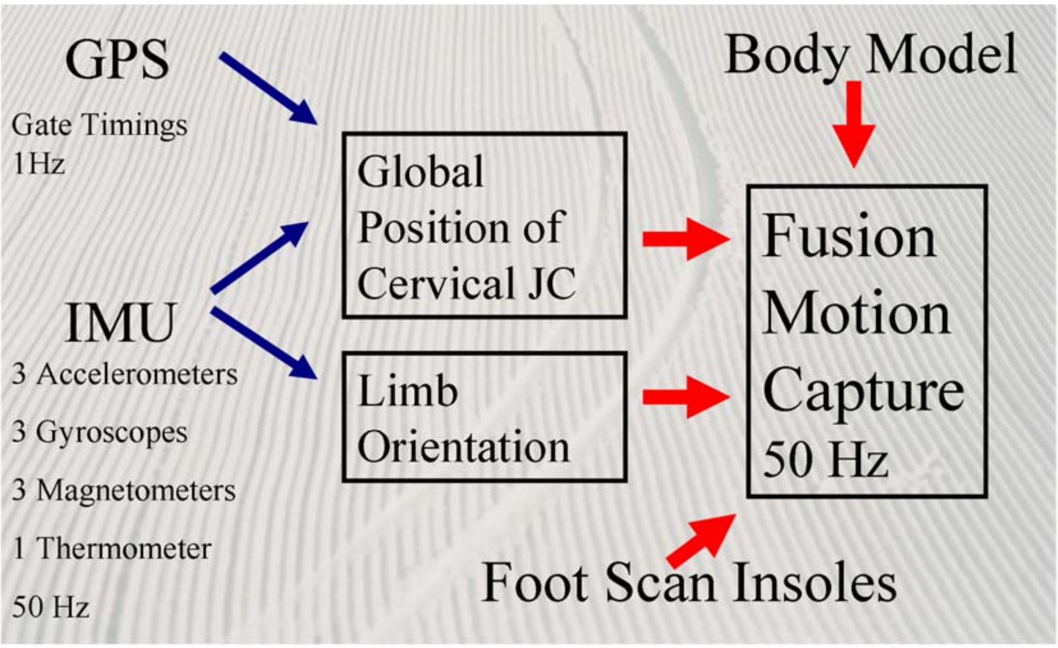


Figure 2.3: Basic overview of the FMC system

The data processing was completed in MATLAB, a technical computing language, using algorithms developed by the author. The custom algorithms gave this research a significant advantage over previous motion capture using IMUs.

2.3. Instrumentation

The data was logged to a small portable laptop strapped to the athlete's back. An RS-Scan pressure measurement system was used to determine plantar pressures and the ratio of loading between the skis. Video from a hand held digital camera, panned from a fixed position on the skiers left side of the course was used as an external reference, and to help confirm the validity of the data. A GPS receiver was attached to the athlete's helmet and a local GPS base station was positioned near the course. A theodolite and survey pole was used to measure the gate locations. The custom built 3D anthropometric frame was used to build a body model and map the IMUs to the body segments.

Equipment list

- 13 x IMUs (XSens Technologies Limited) - Specified accuracy from the manufacturers Kalman filter algorithm in dynamic situations ±3º RMS, **www.xsens.com**.
- 2 x GPS SiRFstar2, single frequency USB receivers, one base station and one rover - 1 Hz output, specified accuracy ±15m RMS in 2D, $0.1 m.s^{-1}$ 95% CI for velocity. Additional information is available at **www.sirf.com**, on the accompanying CD (**Appendices\GPS_Manual.pdf**) and in the reference manual (SiRF Technology Inc, 2005)
- A 3D anthropometric frame with on-snow stance calibration frames
- 1 x Sokkia Theodolite, Japan, **www.sokkia.co.jp**
- 2 x Sony DCR-TRV 730E Digital Video Cameras 25fps, **www.sony.net**
- RS-Scan Foot Scan insole system, 100 Hz output, **www.rsscan.com**.
- A portable data logger.

2.4. IMU placement

The IMUs were attached to each body segment in such a way to reduce skin artefacts. The placement was different from the placement used for the inline skating experiment in order to prevent direct impacts of the IMUs with the course gates. A lycra bodysuit was constructed to contain the connecting wires (Figure 2.4). The suit had apertures at the location of each IMU so the IMU could be attached directly to the athlete's skin with double-sided tape. In addition, each IMU was fastened with a firmly fitting elastic strap attached with Velcro to the suit.

The exact position of each IMU was specific to alpine ski racing as the IMUs would be damaged by aggressive race strategy if they were attached to the outside of the limbs or the athlete's back. The exact positions were:

1. Lower arms, medial surface just far enough from the wrist joints to allow free movement.
2. Medial surface of the upper arm.
3. Immediately inferior to the Sternal Notch
4. Rear of the helmet, approximating the base of the skull (Figure 2.5).

5. Between the posterior superior iliac spines.
6. Lateral surface of the thigh midway between the femoral condyle and the greater trochanter.
7. Shanks on a flat section of the tibia just below the knee.
8. Heels of ski boots, just above the binding, in a protective waterproof casing.

Figure 2.4: Lycra motion capture suit to contain the connecting wires

Figure 2.5: The author modelling the GPS and IMU attached to the helmet

The IMU for each ski was placed on the heel of each ski boot above the binding but on the part of the boot that was assumed to be rigidly attached to the ski (Figure 2.6).

Figure 2.6: IMU placement behind the ski boot, in a waterproof protective casing.

2.5. Creating the body model

In FMC the motion of IMUs is used to drive a body model of the subject. The orientation of the IMU is generally not the same as the orientation of the body segment to which it is attached. A reference posture in the calibration frame was therefore used to map each IMU to the limb to which it was attached.

The calibration frame was also used to create a subject specific body model, the 42 measurements of bony landmarks took around one hour to complete. The body model contained information about body segment lengths, posture in the reference position, and segment inertial properties such as, mass, location of segment centre-of-mass, and the inertia tensor. The body model is based on the body model proposed by Dumas and Reed (Dumas, Cheze, & Verriest, 2007; Reed, Manary, & Schneider, 1999). Further information can be found elsewhere (Brodie, Walmsley, & Page, 2006a, 2006b; Brodie, et al., 2008b).

3D frame construction and development

A 3D anthropometric frame was constructed (Figure 2.7). The entire frame was made from non-magnetic materials (aluminium, wood and plastic) as any distortion to the earth's magnetic field reduces the accuracy of the IMU to body segment calibration. The frame was designed to hold an athlete in a repeatable reference position while the measurement arms were used to measure the location of bony landmarks in 3D space. In addition, the front section of the calibration frame could be removed and placed on the snow so the athlete could replicate the calibration position on snow at the start of each run as an additional accuracy check. To our knowledge this was the first time such a frame has been constructed.

The body model was constructed from 42 measurements of the athlete and 11 measurements of the ski (Figure 2.8). The proximal joint centre and two distal landmarks are generally used to visualise each segment.

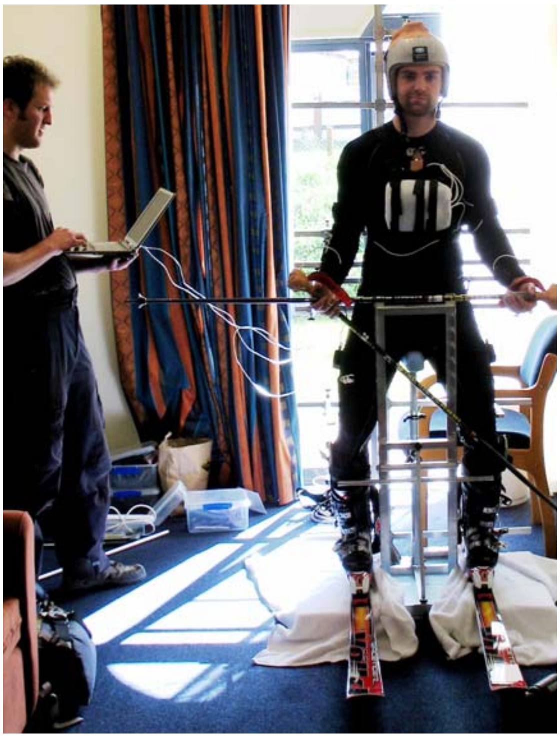


Figure 2.7: Mapping the local IMU coordinate systems to the local body segments

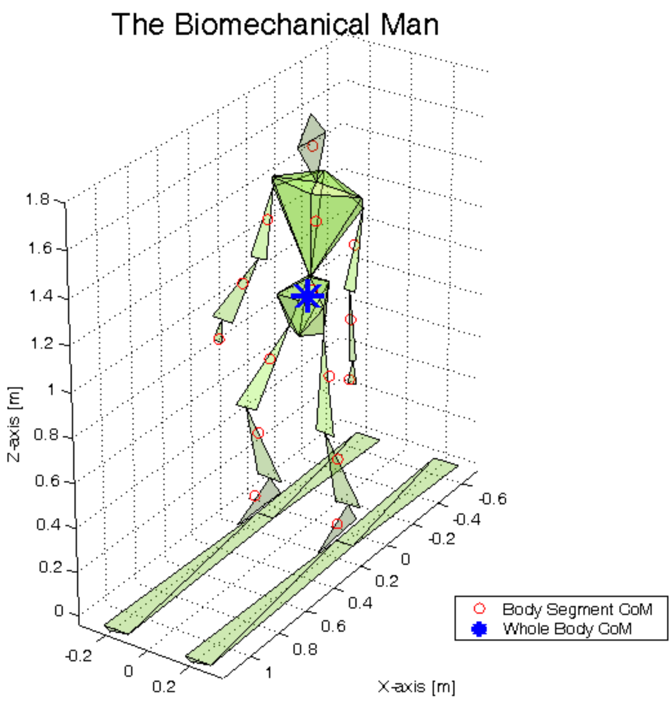


Figure 2.8: Visualisation of measurements from the 3D anthropometric frame

2.6. The Global Positioning System

GPS analysis of sports is becoming more popular so a summary of the author's findings is included in this section. In this research GPS data (at 1 Hz) were combined with the IMU data (at 50Hz) and the known gate positions to obtain a measurement of global trajectory that was more accurate than any of the measurements in isolation.

Accuracy better than 0.7m for position, $0.3ms^{-1}$ for velocity and $1.2ms^{-2}$ for acceleration was obtained (Figure 2.9). The skiing movement was highly dynamic with the typical values recorded around 30m between gates, $18ms^{-1}$ for speed and $20ms^{-2}$ for centre of mass acceleration. The unfiltered relative error for the FMC system was estimated to by 2.3% for position, 1.6% for velocity and 6.0% for acceleration. This is better than any other system developed for the motion capture of skiing to date.

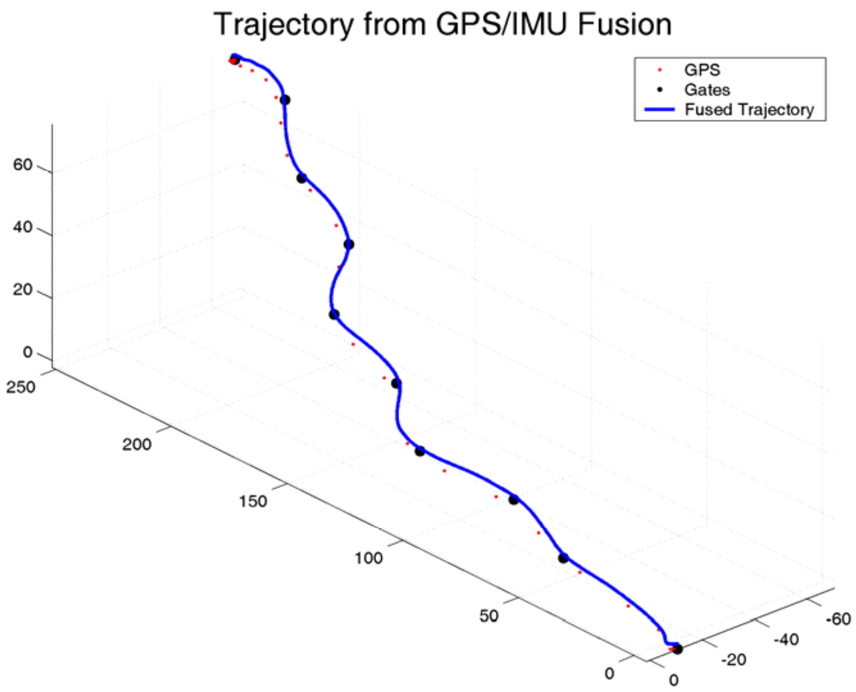


Figure 2.9: Run 3 trajectory by GPS/IMU and gate fusion

Previous experiments showed that the GPS data collected was not accurate for the biomechanical analysis of alpine ski racing (Brodie, 2009). The values provided by the GPS chip's algorithm were inaccurate when the athlete changed direction rapidly. Global trajectory errors of up to 45m, much greater than the manufacturer's specification of 15m were observed for a run through a giant slalom race course.

So how was the GPS accuracy improved from greater than 15m to less than 0.7m? Both relative speed (carrier-frequency data) and relative distance (pseudo-range data) were extracted from a single frequency GPS chip. The speed data is determined by the Doppler Effect and can be used to determine athlete velocity which is 10 to 100 times more accurate than GPS position alone. The GPS data were then combined with the IMU data (with special consideration taken to the accelerometer data) and a known start position at the first gate. More technical details are available elsewhere (Brodie, 2009).

2.6.1. Summary of GPS accuracy

The summary of accuracy is based on data from a SiRF2 single frequency GPS receiver at 1Hz with good reception and at least five satellites in continuous view. Post processing differential correction was used to improve accuracy. The data were collected to help verify the accuracy of the FMC system and more technical information on the tests is provided elsewhere (Brodie, 2009).

	Specification	Static and Walking	Dynamic skiing
Pseudo Range		1-5m	up to 5m
Location	15m RMS	~1m after 20 minutes	±3m 95% CI
Carrier Frequency		<0.01ms^{-1}	up to 0.5ms^{-1}
Velocity	0.1ms^{-1} 95% CI constant speed	<0.01ms^{-1}	±0.3ms^{-1} 95% CI
Integrated velocity		0.4m after 90 seconds	

Table 2.1: Summary of SiRF 2 GPS receiver expected accuracy

Table 2.1 shows that GPS velocity is more accurate than GPS position in both static and dynamic situations, but that accuracy deteriorates as the movement becomes more dynamic.

2.7. Gate and Course survey

The gate locations were surveyed using both GPS and measurements from a theodolite positioned at the bottom of the course.

In alpine skiing the terrain is variable and so for a first estimation, the terrain slope was estimated based on the measured gate locations. More details can be found elsewhere (Brodie, 2009). The snow surface was rendered by creating 30-metre wide contour lines perpendicular to the fall line at each one-metre change in height. The snow surface was then defined by grey triangular faces (Figure 2.10).

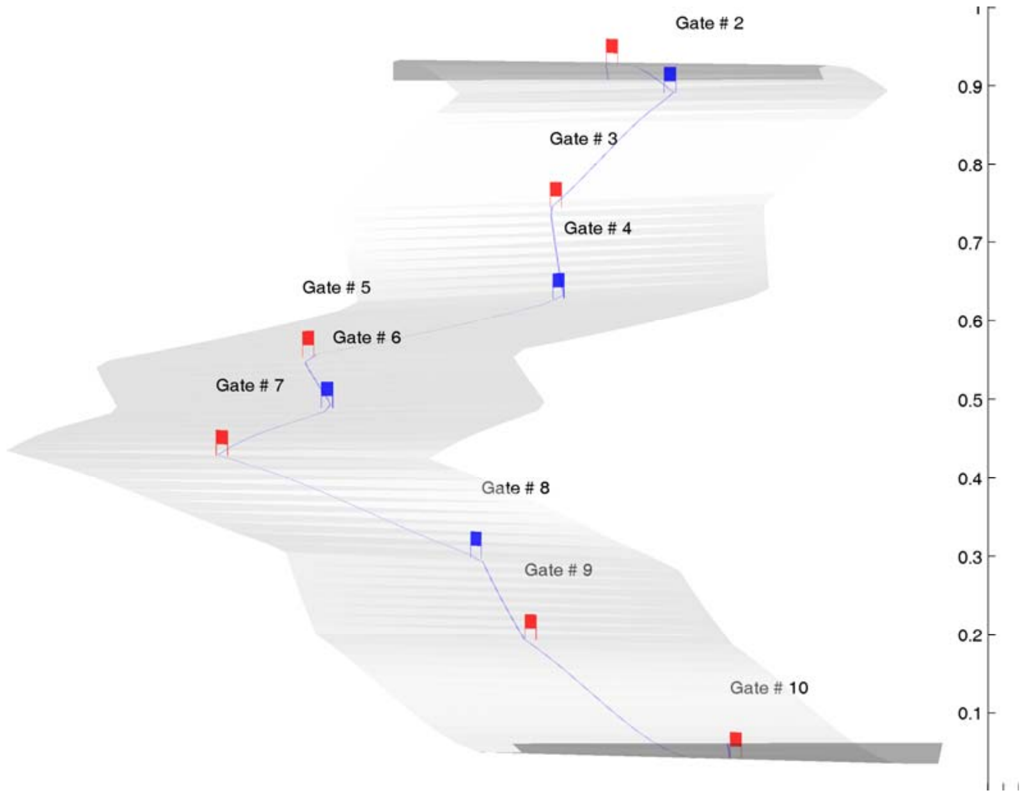


Figure 2.10: Computer model of the ski racecourse based on gate measurements

2.8. Fusion Motion Capture algorithm

The FMC algorithms used to determine athlete motion. An example of one such algorithm is presented below. More details are available elsewhere (Brodie, 2009).

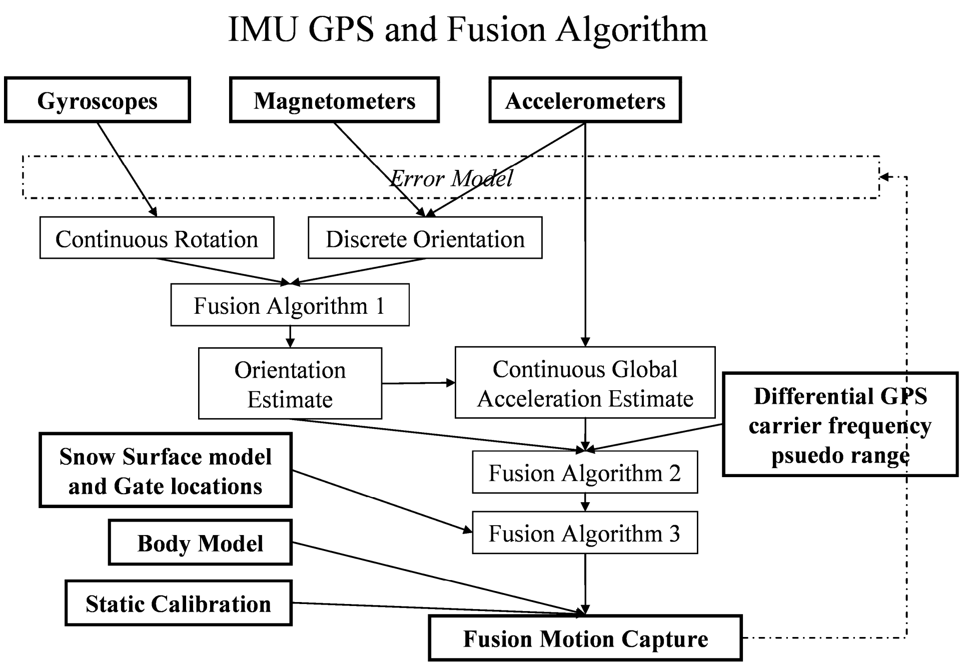
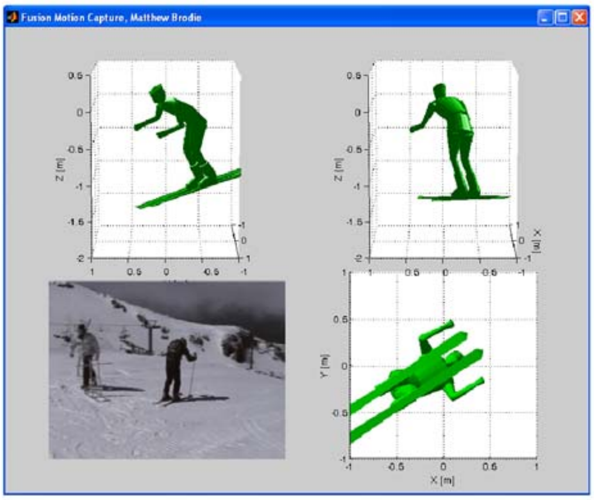


Figure 2.11: Fusion algorithm Version Four

2.9. Data driven animations of skiing

Having carried out the methods described above is was then possible to start to analyse the data. The FMC data were used to visualise the local motion data from several angles. These data driven animations were developed in order to assist with athlete feedback. The reader is invited to now view the run 5 local limb movements (Video 2.2). The ability to analyse the local limb movement from several angles becomes possible with FMC and provides additional coaching tools.



Video 2.2: Appendices\FMC Video\Ruapehu_R5_Relative.avi

The global data driven animations required additional GPS measurements (Section 2.6), the surveyed gate locations and snow surface model (Section 2.7). The FMC data driven animations can be visually compared to the video feed (Figure 2.12 and Video 2.3).

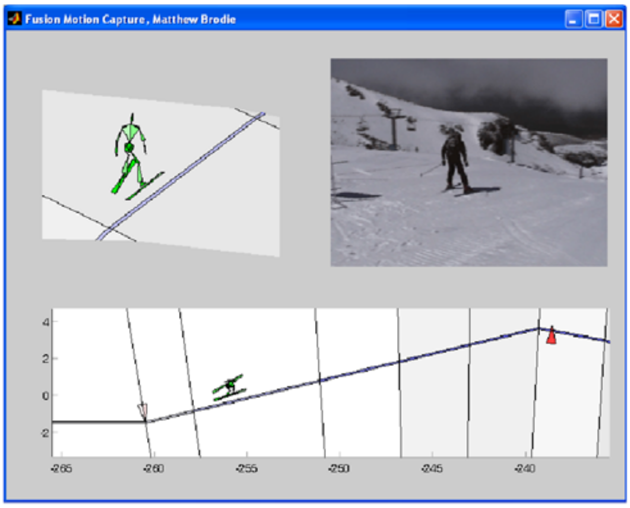


Figure 2.12: FMC data top left and bottom panels, video feed top right panel
Video 2.3: Appendices\FMC Video\Ruapehu_R5_Contours.avi

2.10. Summary of the new motion capture system

Using the FMC data it was possible to calculate many useful biomechanical parameters. The system was new and so the errors were estimated (Brodie, 2009). A summary of the estimated FMC errors is presented below.

Table 2.2: Summary of estimated FMC errors for giant slalom

Quantity	Estimated Error	Typical Value	Relative Error
Time [s]	0.04	2.0 - between gates	2.0%
Location [m]	0.7	30 - between gates	2.3%
Velocity [ms^{-1}]	0.3	18	1.6%
Acceleration [ms^{-2}]	1.2	20 for CoM	6.0%
Force [N]	110	1,800	6.0%
Power [W]	1,500	20,000	7.5%
Work [J]	Error reduced by integration of power		
Body Orientation [º]	6	up to 180	3.2%
Torque [Nm]	40	200	18.0%

Fusion Motion Capture combines data from many sensors attached to the athlete including; GPS, IMUs, and Pressure sensing insoles. These innovations have made it possible to measure the biomechanics of skiing through an entire race course with high accuracy. The data can now be used to attempt to answer the question: ‘What makes one athlete the fastest?’

3. Optimisation of Ski Race Technique

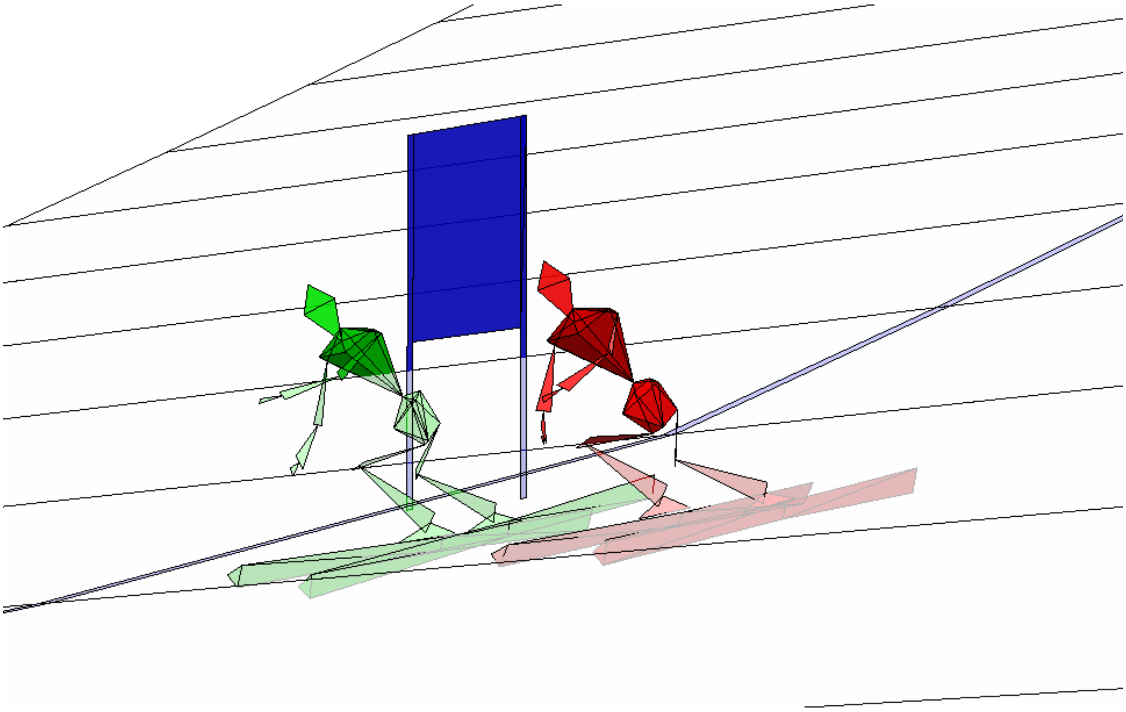


Figure 3-1: Two runs by the same athlete, green has an early lead...

What makes one athlete the fastest? In this chapter two giant slalom training runs by a skilled athlete (<20 FIS points) are compared. The analysis focuses on the external forces (gravity, wind drag, snow resistance, and the ground reaction forces normal to the ski bases), acting on the athlete and how those external forces affected race outcome.

To the author's knowledge there were no comparable analyses available in literature with which to compare most of the findings presented in this chapter. Additional data should be collected in the future in order to confirm the initial findings and to determine how the results compare to the performances of other athletes under different course conditions.

3.1. Race Analysis

Two complete runs (run 3 and run 5) through a 10-gate giant slalom training course over 250 metres in length were captured. In run 5 the athlete ran the course 0.14 second faster than in run 3, why? The video footage of run 3 is provided (Video 3.1).

Video 3.1: Appendices\FMC Video\Ruapehu_R3_Video.avi

3.1.1. Visualisation

A Ski X is a race where up to six athletes race simultaneously through a course that resembles a terrain park. The two ski runs by the same athlete (blue biomechanical man – run 3 and orange biomechanical man – run 5) can be simultaneously viewed in a single data driven animation, a virtual Ski X (Video 3.2).

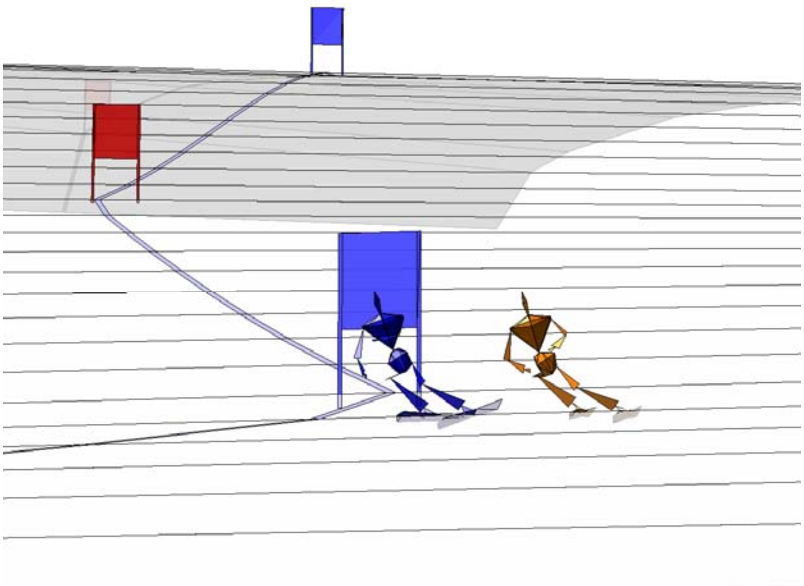


Figure 3-2: The blue man, run 3, takes the inside line about gate 4 in a virtual ski X

Video 3.2: Appendices\FMC Video\SkiX_Final.avi

Timing for virtual Ski X starts at gate 2, a blue gate, and ends at gate 9. The two runs were synchronised at the point of passing gate 2. The orange man (run 5) won the race, passing gate 9 around four frames or 0.14 seconds ahead of the blue man (run 3).

3.1.2. Chronological analysis

Course times are usually measured using timing gates. With FMC data it is possible to produce virtual gate splits, the time difference taken to pass between sequential gates. The gate splits show that if gate splits 4, 5 or 6 had been analysed in isolation it might have been erroneously concluded that run 3 was the better run (Figure 3-3). Run 5 was faster by 0.14 seconds but the lead changed several times over the course.

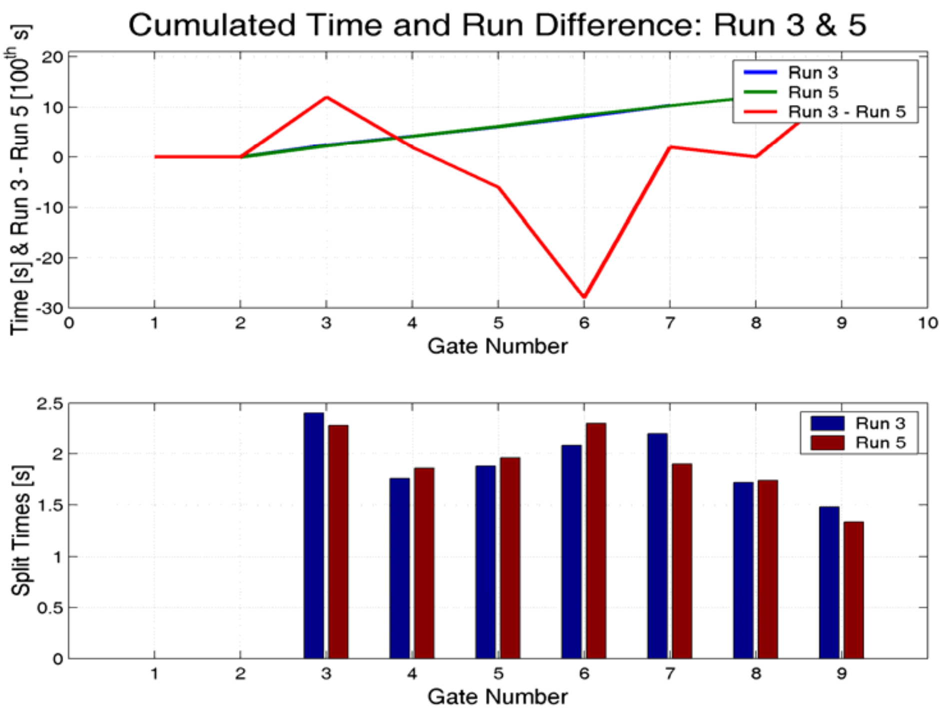


Figure 3-3: Chronological analysis using FMC

3.1.3. Course line

During the 'virtual' Ski X the lead changed twice (Video 3.2). Initially the orange biomechanical man poles more aggressively to take an early lead, then the blue biomechanical man regains the lead with an inside line about gate 4, but the orange man wins. The question is why?

The athlete's centre-of-mass (CoM) trajectories in both runs was investigated. The first lead change occurred about gate 4 when the blue avatar (run 3) took an inside line (Figure 3-4 and Figure 3-2) which resulted in a shorter path. Because the athlete was travelling at similar speeds in both runs the shorter line resulted in a faster time and blue took the lead.

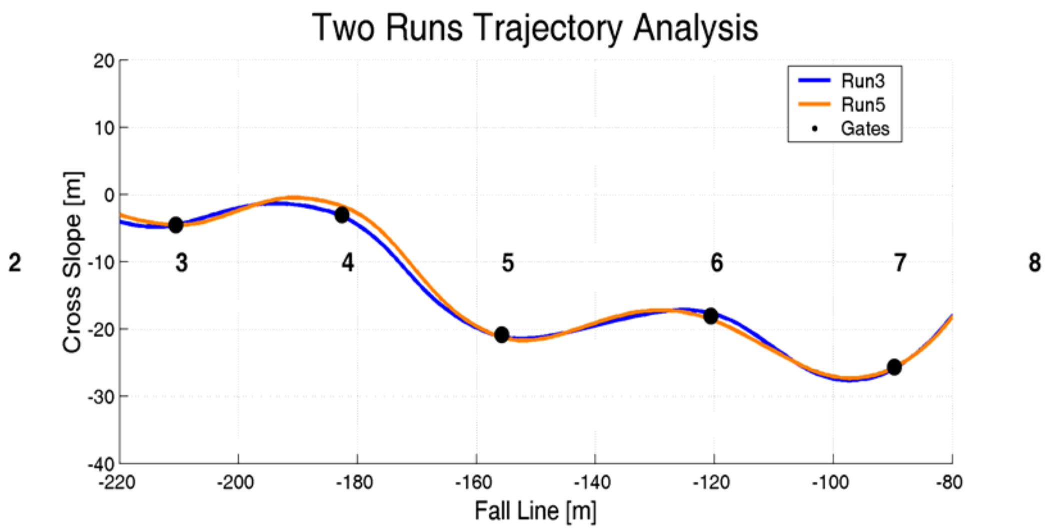


Figure 3-4: Comparison of Trajectory between gates 3 and 7

The next lead change just after gate 8 but the cause can be traced back to differences in technique about gate 6. About gate 6 in Figure 3-4 the apex of run 5 (orange line) was before the apex of run 3 (blue line), but there is very little length difference between these two trajectories. So why did the orange man win? In order to answer this question further analysis is required.

3.1.4. Speed

Examination of the speed profiles (Figure 3-5) from the two different runs shows that about gate 6 the athlete looses speed in run 3 (blue line) but gains speed in run 5 (green line). This indicates something interesting happened about gate 6.

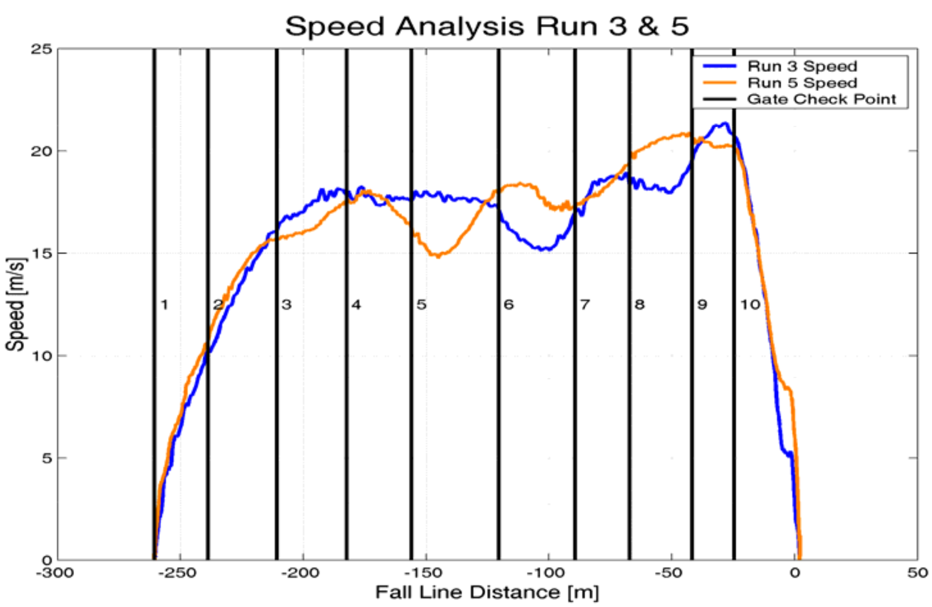


Figure 3-5: Speed profile of Run 3 (blue line) and Run 5 (green line)

3.1.5. Resultant Forces

Colour coded force vector diagrams were developed as part of this research project. The diagrams shows the athlete's CoM trajectories about gate 6 for run 3 (top panel, blue line, Figure 3-6) and run 5 (bottom panel). The resultant external forces acting on the athlete are also visualised (red vectors for periods of braking and green vectors for periods of acceleration). The CoM trajectories about gate 6 reveal that in run 3 the athlete took a 'pinch' line; going straight for the gate and then turning sharply. In contrast to the performance about gate 4, the straighter trajectory about gate 6 resulted in a slower overall time. Why?

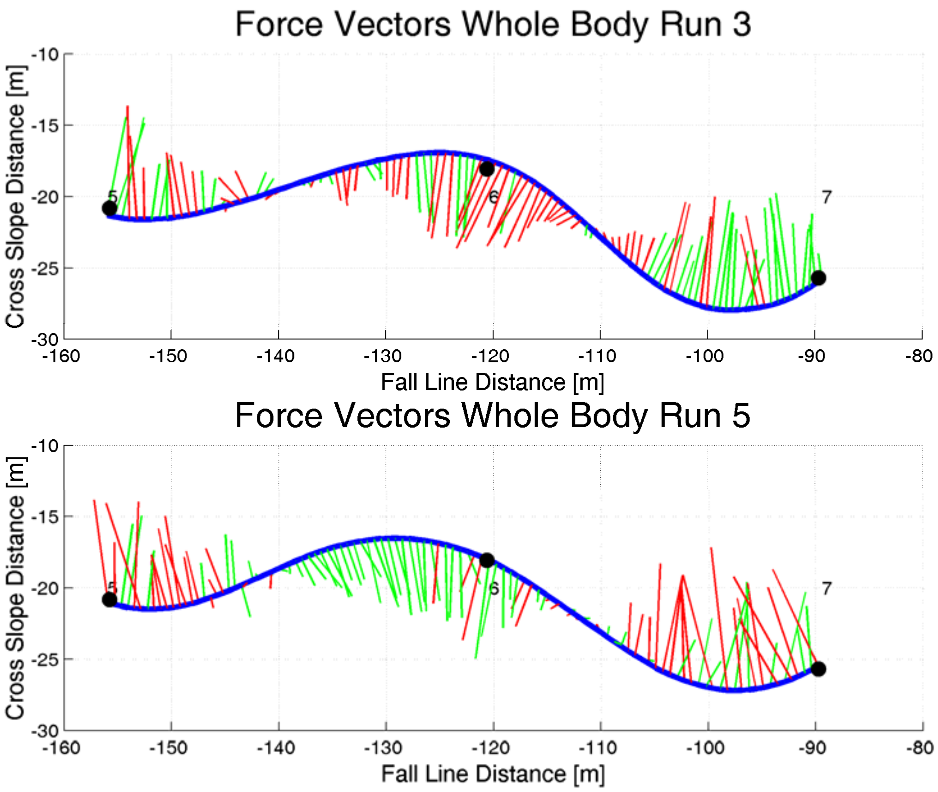


Figure 3-6: Close up force vector diagram, top panel run 3, and bottom panel run 5.

Before gate 4 the athlete was still accelerating from the start, which made the shorter radius turn of run 3 about gate 4 faster. About gate 6 however, the slightly longer radius turn of run 5 was faster (Figure 3-6, bottom panel). In run 5 the athlete generated more green accelerating forces through the turn, by leaning into the turn early and by using a clean 'carving' ski trajectory. In run 5 the gain in speed from turn 6 was maintained to the end of the course and was a major contribution to the 0.14 second lead by gate 9.

Figure 3-6 shows the resultant forces acting on the athlete, but which of the external forces (gravity, wind drag, snow resistance, or ground reaction force) were most responsible for the difference in performance between the two runs? Run 5 was also completed later in the day did this contribute? In order to answer these questions further analysis of the complete racecourse is required.

3.1.6. Ground reaction forces

Ground reaction forces in this analysis exclude the snow resistance forces parallel to the ski bases. The ground reaction forces are approximately normal to the bending ski bases. The athlete skied faster in run 5 than in run 3 because he generated more green accelerating ground reaction forces normal to the ski bases about gate 6 (Figure 3-7 and Figure 3-8).

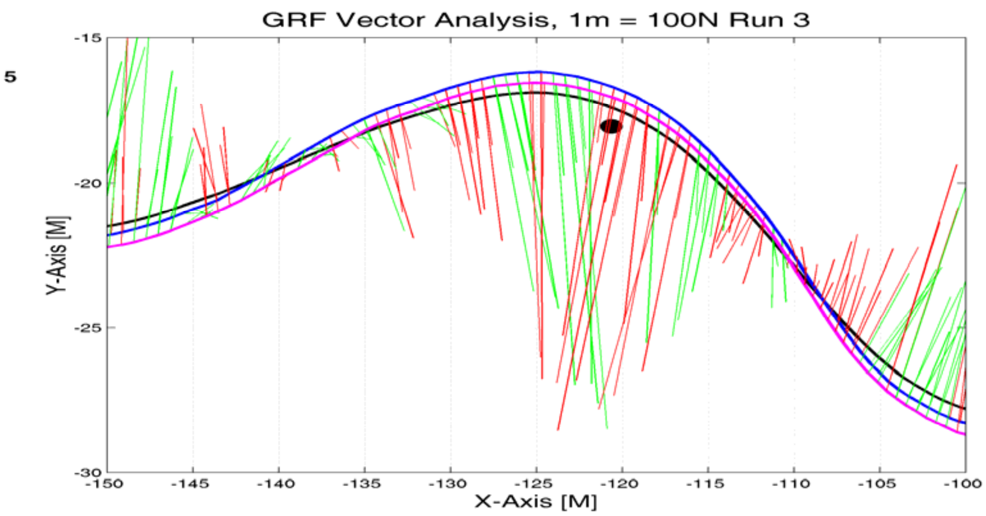


Figure 3-7: Ground reaction force vector analysis run 3

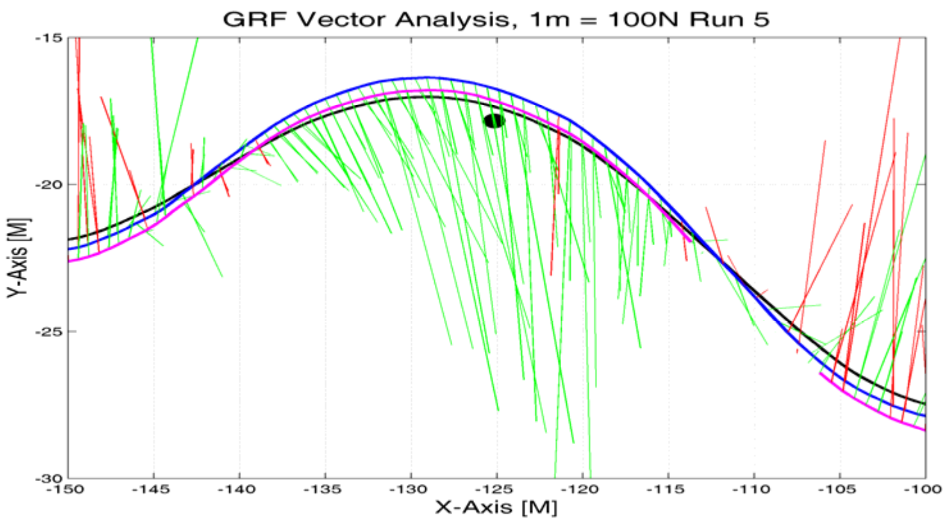


Figure 3-8: Ground reaction force vector analysis run 5

In these figures (Figure 3-7 and Figure 3-8) both skis and CoM trajectories are shown; black for the CoM, blue for the left ski and magenta for the right ski. In run 5, once again, the turn about gate 6 is characterised by a smooth and early build up of green accelerating ground reaction forces (Figure 3-8). In run 5 the force build up starts at around negative 138 metres and peaks near the gate. By contrast in run 3 the ground reaction build up begins later, around negative 130 metres, and develops more quickly (Figure 3-7). In run 3 the turn is characterised by short periods of braking ‘red’ ground reaction forces interspersed with periods of accelerating ‘green’ ground reaction forces. The fluctuating forces indicate the athlete may not have carved a smooth arc through the snow and may have slipped sideways in the turn.

In run 5 the apex of the turn was about 5 metres further from the gate than in run 3. The crossover point (where the CoM passes over the skis) before gate 6 is also earlier in run 5. This resulted in a longer path in run 5, but it also gave the athlete more room to set up the ski edges for a smooth ‘carving’ arc about gate 6 and it allowed him to accelerate more through the turn.

Video 3.3 is a data driven animation from gate 5 to gate 7 with the ground reaction forces visualised. In run 5 the athlete is an orange avatar, in run 3 he is a blue avatar. The avatars are based on anthropometric measurements of the athlete.

Video 3.3: Appendices/FMC Video/SkiX_GRF_567.avi

After viewing the data driven animation about gate 6, it is apparent the athlete maintained better contact with the snow in run 5 (orange avatar). In run 5 he was able to engage his ski edges earlier creating more positive work through regulation of ground reaction forces. Kinematic (visual) differences between the athlete’s body segments during the two runs are subtle. Close inspection shows that in run 5 after engaging the ski edges the athlete quickly abducted his outside (left) hip creating a more acute ski/snow angle. In run 3 this type of hip action occurred later on in the turn after passing the gate.

3.2. Resultant force vector analyses

The FMC data from two runs was used to create resultant force vector analyses of the athlete’s performance through the complete racecourse. The analyses are very useful in determining where the athlete lost and gained speed in each run through the course. There are interesting differences between the two runs which are now presented (Figure 3-9 and Figure 3-10).

Figure 3-9 shows in run 3 the athlete lost speed about gates 6, 8 and 10. About these gates there is a predominance of (red) retarding forces. Figure 3-10 shows in run 5 a different pattern; speed was lost about gates 5, 7 and 9. If the athlete had combined the best aspects from both runs 3 and 5 it appears he could have improved his performance; from 13.38s in run 5 to a theoretical minimum time of 12.96s, a further improvement of 0.42s or 3% and larger than the 0.14s difference between the two runs. Which of the external forces were most responsible for the observed differences gate-to-gate and run-to-run? Wind drag, snow resistance or ground reaction forces?

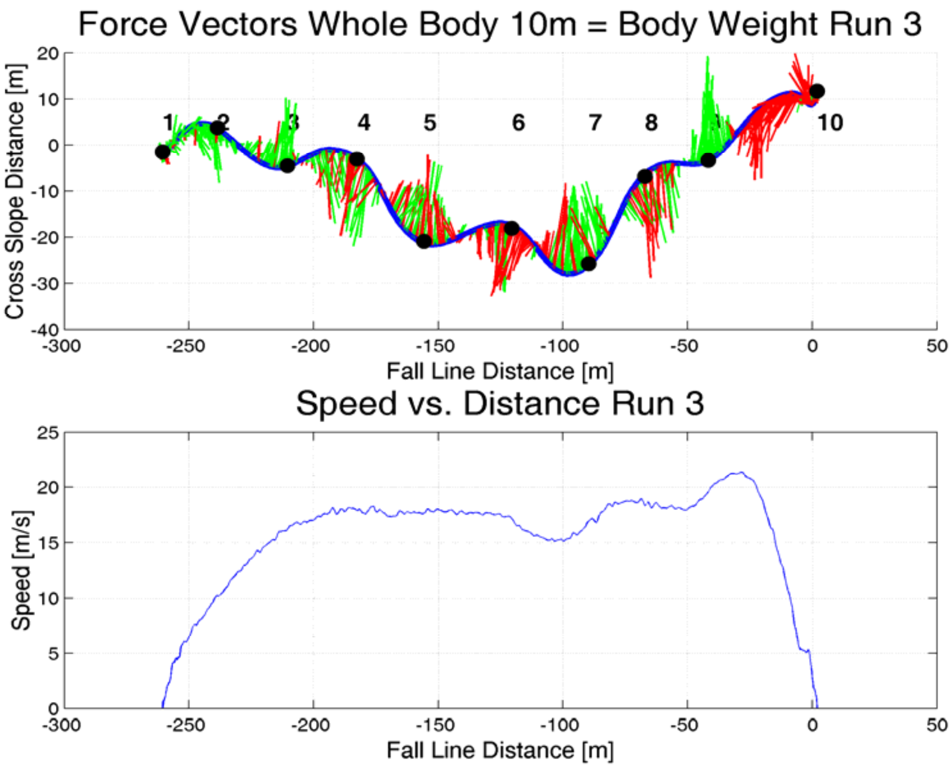


Figure 3-9: Force vector diagram resultant forces run 3

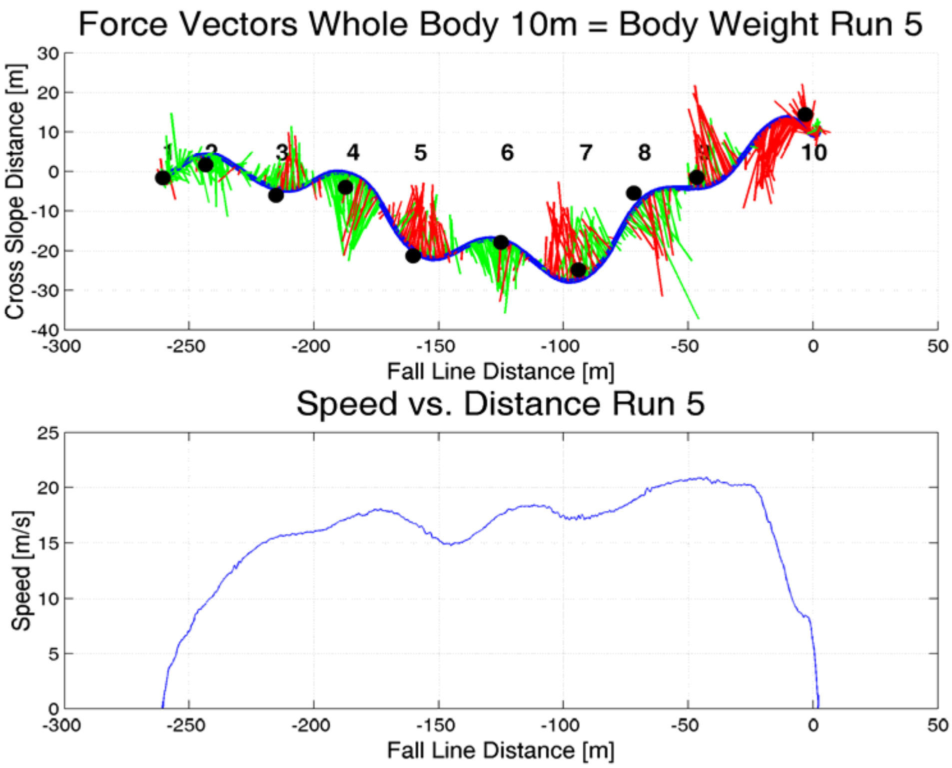


Figure 3-10: Force vector diagram resultant forces run 5

3.3. *Wind drag and snow resistance*

3.3.1. Wind drag area

Between the two runs there were only small differences between the wind drag areas, therefore it is unlikely wind drag affected race outcome. Only the data from run three is shown (Figure 3-11). In both runs, wind drag area was least about the gates as the athlete's stance was compacted (≈ $0.24m^2$ see the troughs in Figure 3-11). The athlete was not at any time completely crouched as this would have resulted in a wind drag area of around $0.15m^2$, as discussed in the introduction. The range $0.24m^2$ to $0.32m^2$ for wind drag area seems reasonable for giant slalom because sequential turns are required.

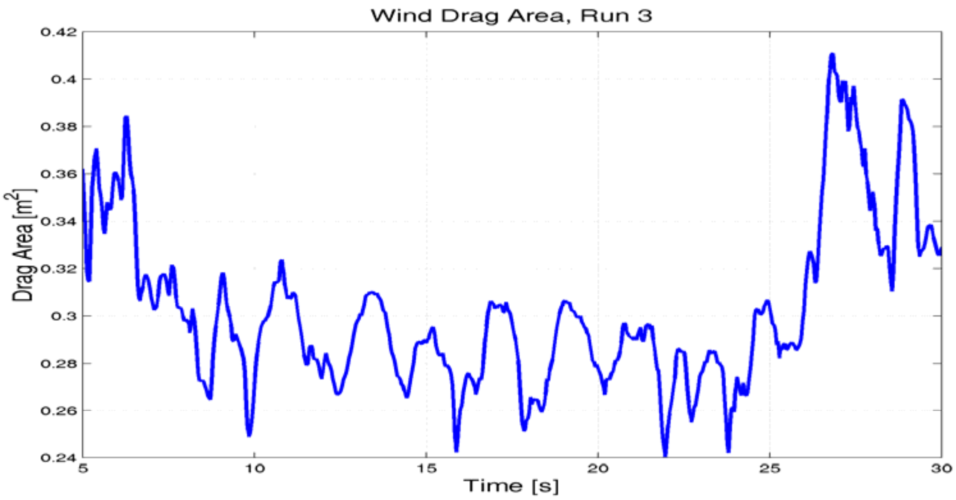


Figure 3-11: Drag area run 3, coefficient of friction *Cd* = 0.52

3.3.2. Hard and soft snow

There were small differences in snow resistances between runs 3 and 5. In both cases snow resistance appears to increase with increased velocity. The softer snow in run 5 had less resistance to displacement at high speeds but more resistance to sliding at slower speeds than the harder snow in run 3. For the speeds the athlete travelled at, surprisingly, the softer snow in run 5 slowed the athlete only slightly more the than harder snow in run 3. Run 5 was the fastest run and so snow resistance did not significantly affect the race outcome.

3.4. *Power, energy and work*

In ski racing energy analyses are required because the external forces act in all three dimensions, the athlete is changing direction constantly, and the snow surface is not flat. Figure 3-12 shows how the magnitude of the different forces change, excluding gravity which was constant (around 900N), but the figure does show how each force affected race outcome.

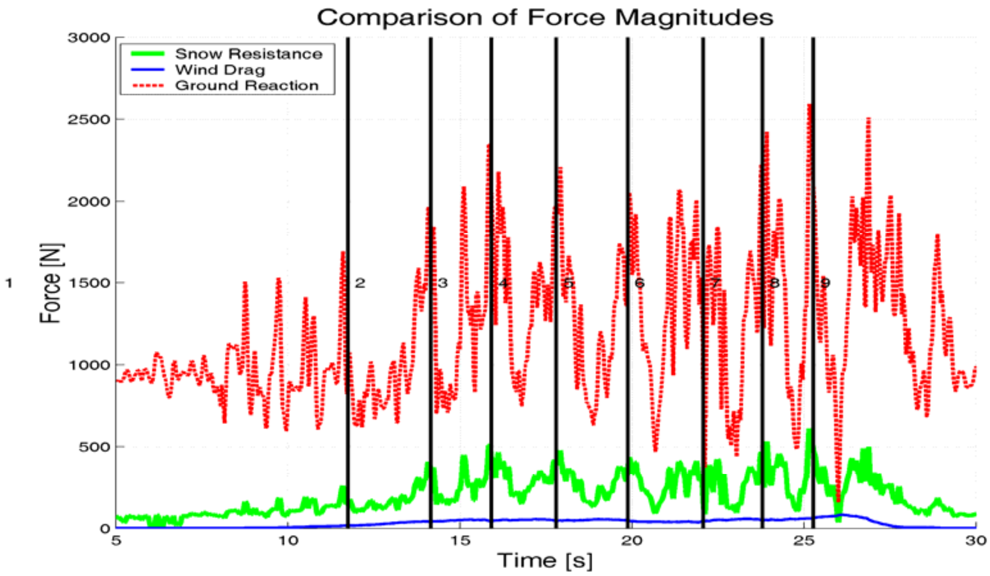


Figure 3-12: Forces in skiing

The energy analyses of runs 3 and 5 show the effects of the different external forces on the athlete's kinetic energy and therefore race outcome (Figure 3-13 and Figure 3-14). The analyses provide useful information about where and how the athlete increased speed because kinetic energy is directly related to speed. In the analysis of alpine skiing a force has a positive power and does positive work if it is acting to increase the athlete's speed. More calculation details are available elsewhere (Brodie, 2009). In summary, positive power and work are good, the athlete will go faster if the positive work done by the external forces can be increased.

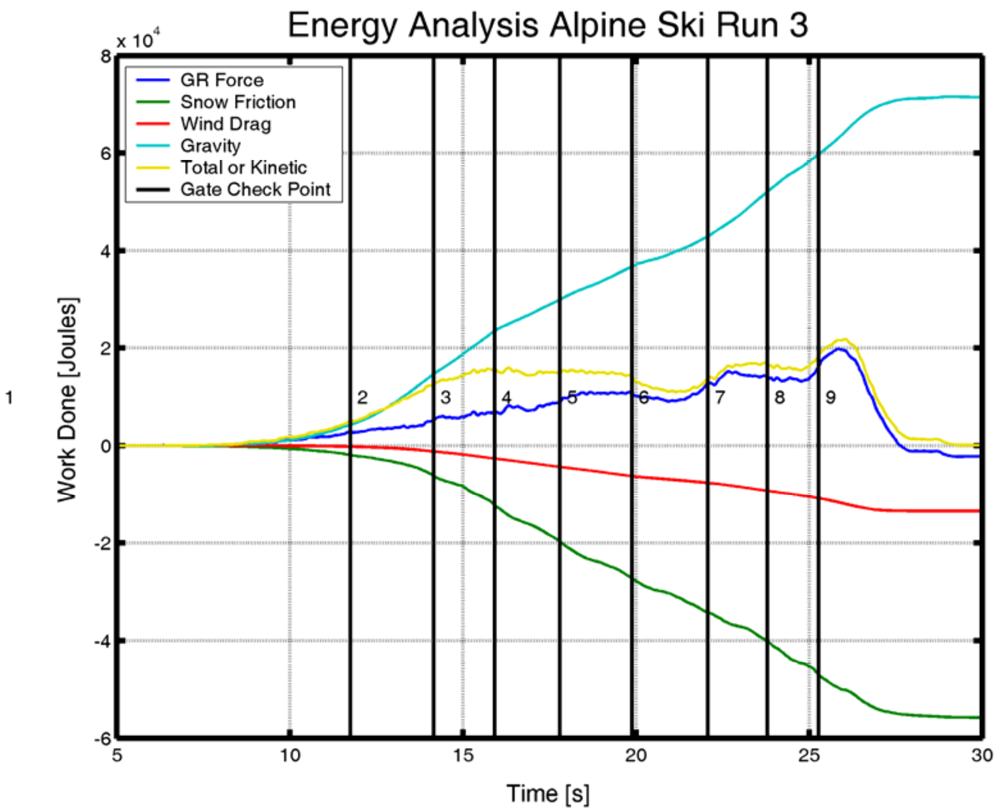


Figure 3-13: Energy Analysis of external forces for run 3

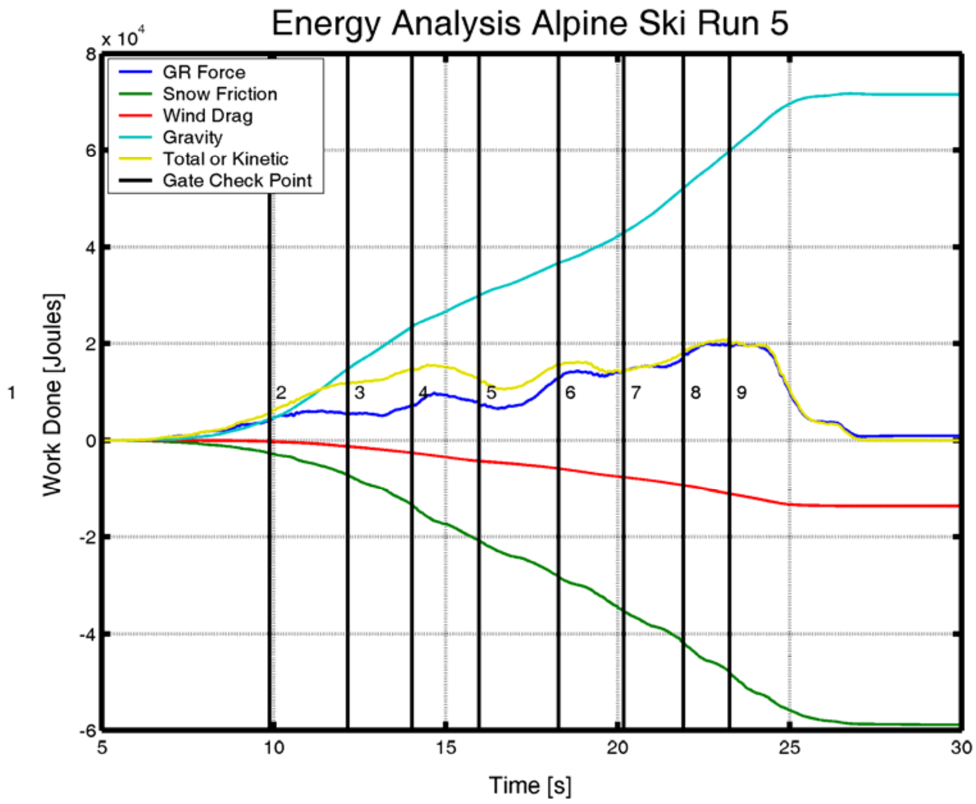


Figure 3-14: Energy analysis of external forces for run 5

Figure 3-13 and Figure 3-14 show that in runs 3 and 5 gravity acted to increase the athlete's kinetic energy (turquoise lines) and hence acted to accelerate him while wind drag and snow resistance acted to retard him (red and green lines). In both runs the work done by gravity was the same, and snow resistance (green lines) had a larger negative effect than wind drag (red lines). The snow resistance acted to retarded the athlete more in run 5, so why then was 5 was faster?

In Figure 3-13 and Figure 3-14 the shape of the total kinetic energy (yellow lines) and the work done by the athlete's ground reaction forces (blue lines) were very similar. The similar shapes suggest that the primary differences between the two runs resulted from differences in ground reaction forces. A good technique that used the reaction forces to maintain kinetic energy and therefore maintain speed was the most important difference between the two runs.

Figure 3-15 and Figure 3-16 show the work done by the athlete using either his left or right ski.

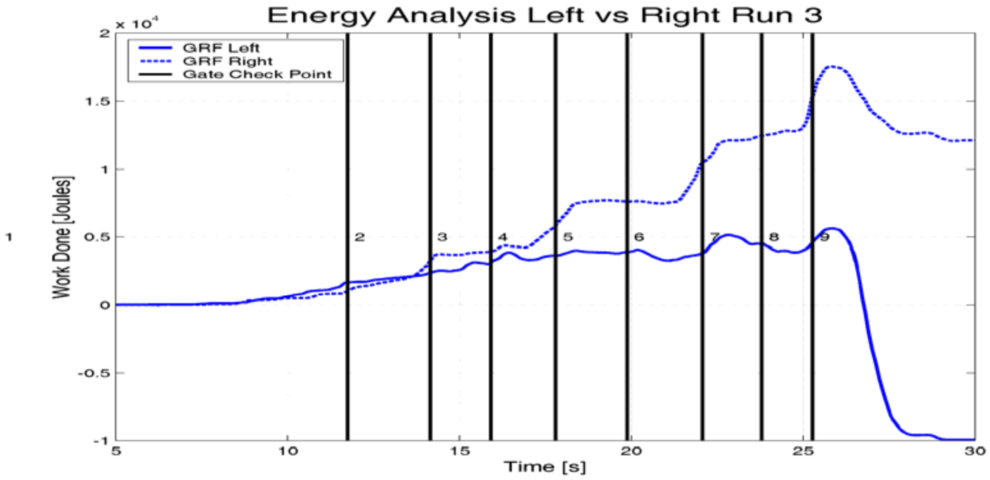


Figure 3-15: Energy analysis the work done by the left and right skis in run 3

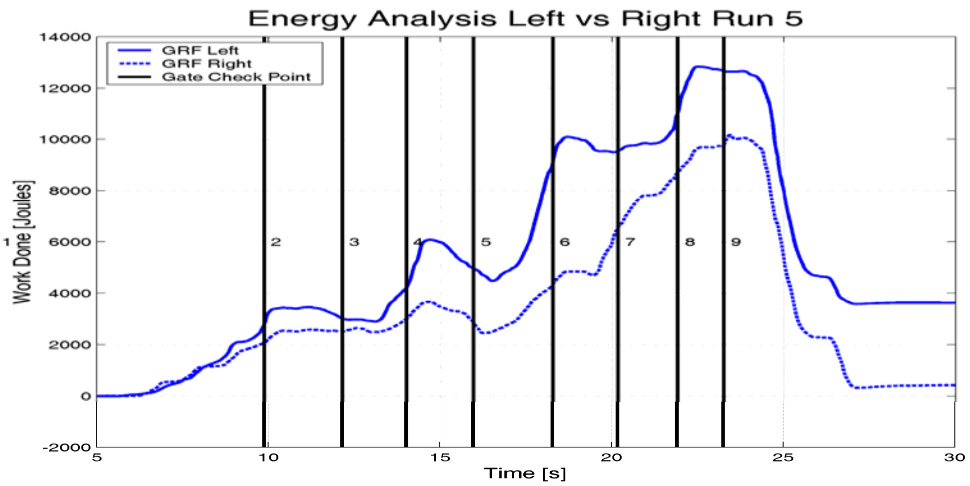


Figure 3-16: Energy analysis the work done by the left and right skis in run 5

In run 3 he did more work with his right ski. In run 5 he did a similar amount of work on both skis in the softer snow conditions, but slightly favoured his left ski. The athlete predominately used his outside leg while turning and the component foot energy analysis also demonstrates the better left turns in run 3 and the better right turns in run 5 (as discussed previously, see the previous force vector diagrams Figure 3-9 and Figure 3-10).

The component power analyses below identifies the poor turns in both runs by negative ground reaction force powers and good turns by positive ground reaction force power. The poor turns (6 and 8 in run 3 and turns 3 and 5 in run 5) can be identified by negative ground reaction force power (blue lines, Figure 3-17 and Figure 3-18). The athlete's aggressive skating and pole action before gate 2 is visible as four spikes in the ground reaction force power of run 5 (Figure 3-18). The snow resistance power is generally negatively correlated to the ground reaction force power because pushing off the snow about each turn also increases the work required to move the ski through the snow.

Figure 3-17: Power analysis of run 3

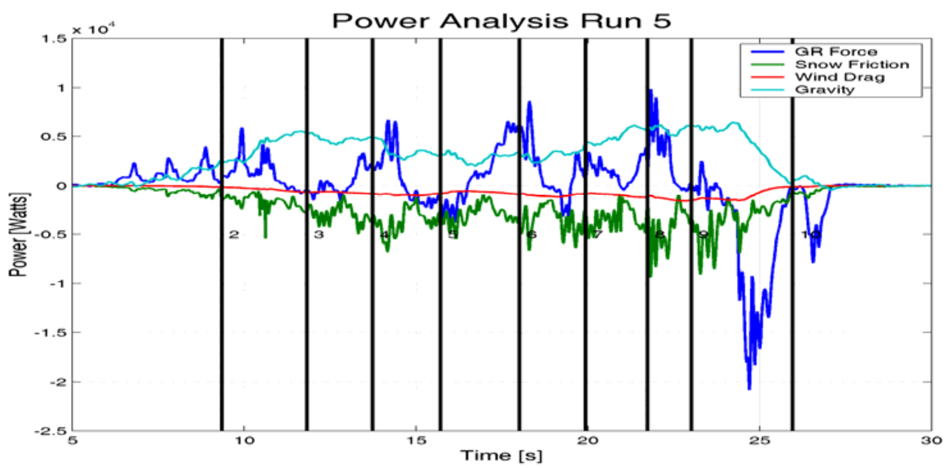


Figure 3-18: Power analysis of run 5

3.5. Data driven animation with forces

Data driven animations were used to present the complex data in a way intuitive to the athlete. The data driven animations contain a large amount of useful information for an athlete and give a good 'feeling' for the relative effects of different external forces during different parts of the course. With this type of feedback the athlete can concentrate on technique improvements that reduce the amount of red braking forces. The data driven animations show the ground reaction forces were most important to race outcome because these varied the most over the course and between runs.

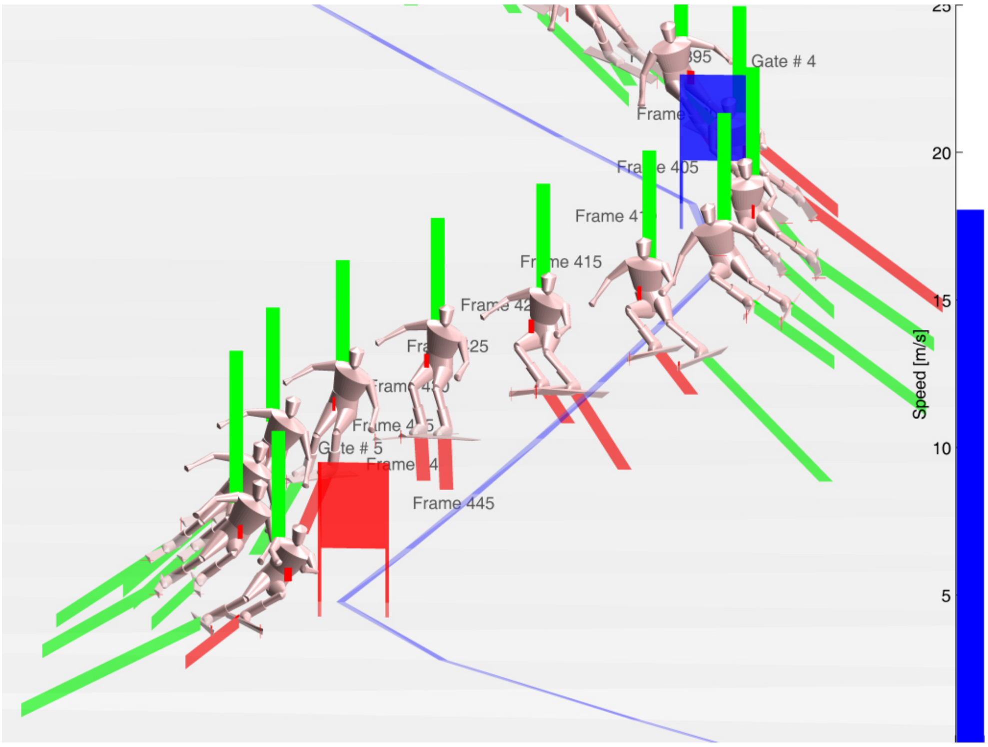


Figure 3-19: Screen shot from of run 3 using the visualisation software

The athlete's movement data were animated and the external forces of gravity, wind drag, snow resistance and ground reaction forces were superimposed as colour coded vectors (Figure 3-19 and Video 3.4). This is possibly the first time the biomechanical analysis of a complete giant slalom training run has been performed successfully and also the first time the data from giant slalom have been visualised in this way.

Video 3.4: Appendices\FMC Video\Ruapehu_R3_Force_RScan.avi
Video 3.5: Appendices\FMC Video\Ruapehu_R5_Force_Optim.avi

In these data driven animations (Video 3.4 and Video 3.5) the external forces have been visualised by vectors that represent magnitude, direction, point of contact and power. If the external force has a positive power it is acting to accelerate the athlete and it is colour coded green. Red vectors are for braking forces.

3.6. Technique optimisation

The optimal ski racing technique is athlete, course and equipment specific. The fastest possible course time depends on both local turn technique and global race strategy. The ideal athlete executes ‘perfect’ turns and selects the optimum places to make the turns. In this section FMC data are used to investigate how turn radii and inclination (leaning angle) might contribute to the execution of perfect turns. The results suggest the optimum turn radius for each gate is a trade off between tighter turns that result in shorter path lengths and more open turns that allow for faster turning speeds and also result in more acceleration earlier in the turn while travelling closer to the fall line.

3.6.1. Leaning angles

Inclination measures how far the athlete leans into the turns from a vector normal to the snow slope. The minimum inclination is 0º and corresponds to an upright stance used when running straight down the fall line. The maximum inclination angle is 90º and corresponds to the athlete lying flat on the snow, but athletes seldom incline more than 70º during races. Inclination is important in giant slalom turn technique where the athletes use inclination to maintain postural balance while cornering. The higher the inclination angles the more horizontally directed ground reaction forces (GRF) are produced and the faster or tighter the athletes can turn (as discussed previously in Section 3.1.6).

In run 5 (Figure 3-21) the athlete physically inclined between 5º and 10º further into each turn than in run 3 (Figure 3-20). The turn about gate 6 was previously identified as a key factor in race outcome (Figure 3-6). In run 5 the peak inclination angle about gate 6 was slightly earlier relative to the gate than in run 3 and this may also have contributed to the better performance in run 5.

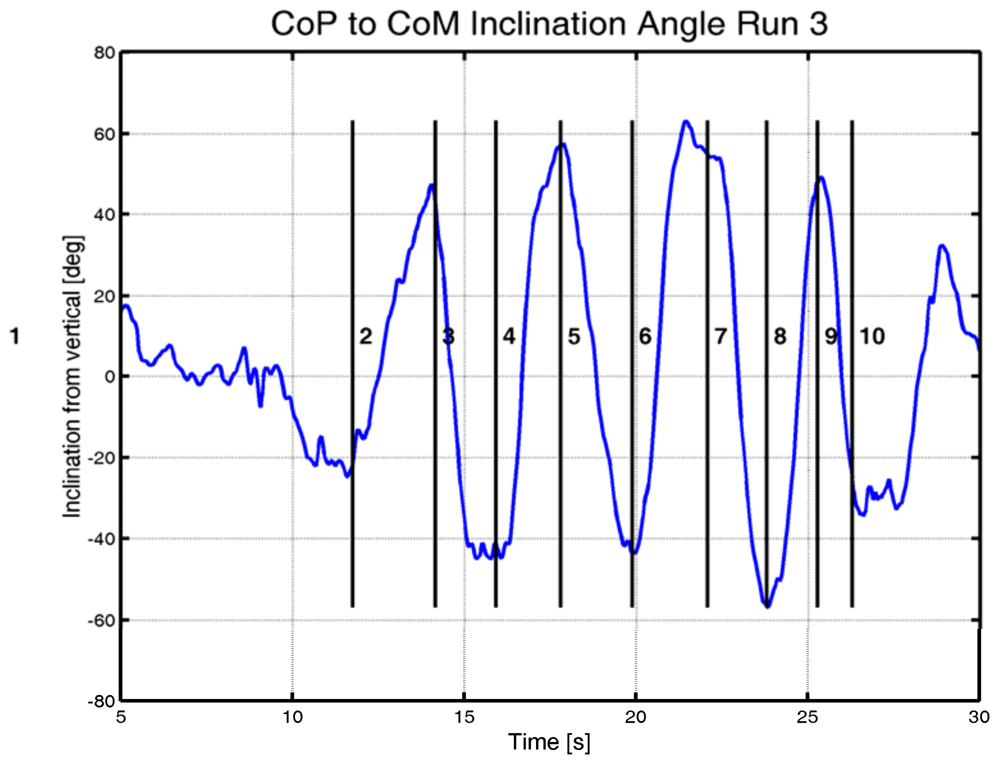


Figure 3-20: Physical inclination angle in run 3

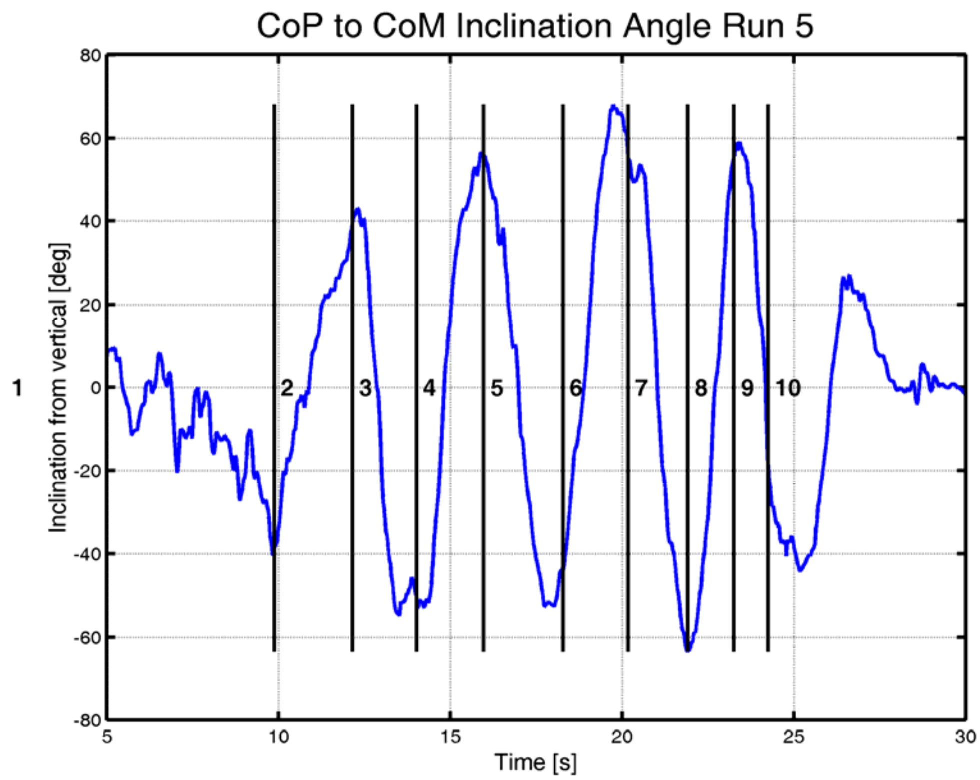


Figure 3-21: Physical inclination angle in run 5

3.6.2. Turn radii

In this section optimum turning radii for the course is investigated. Based on the athlete's CoM acceleration the instantaneous radius of curvature projected onto the plane of the snow surface is calculated for runs 3 and 5 (Figure 3-22 and Figure 3-23).

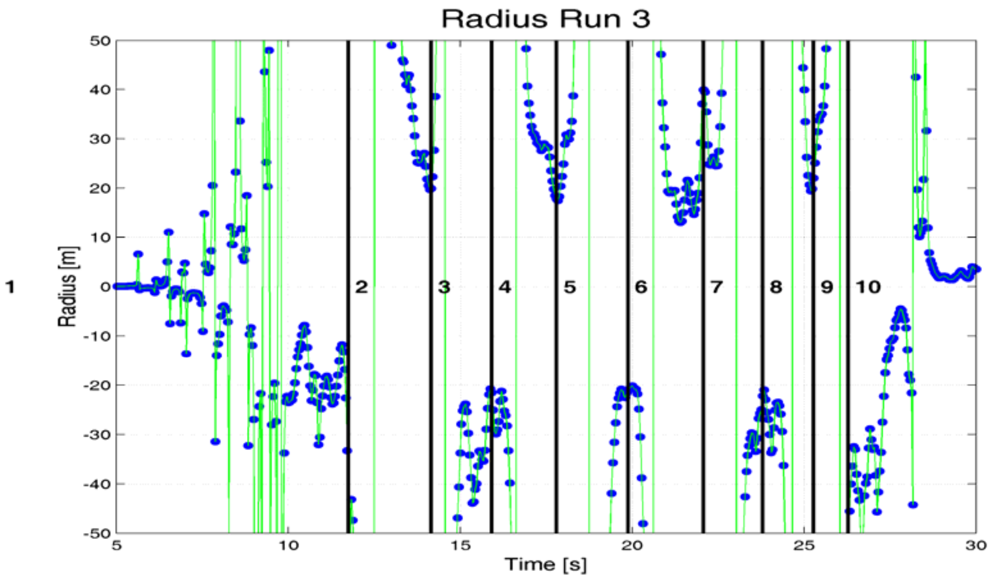


Figure 3-22: Instantaneous turn radii in run 3

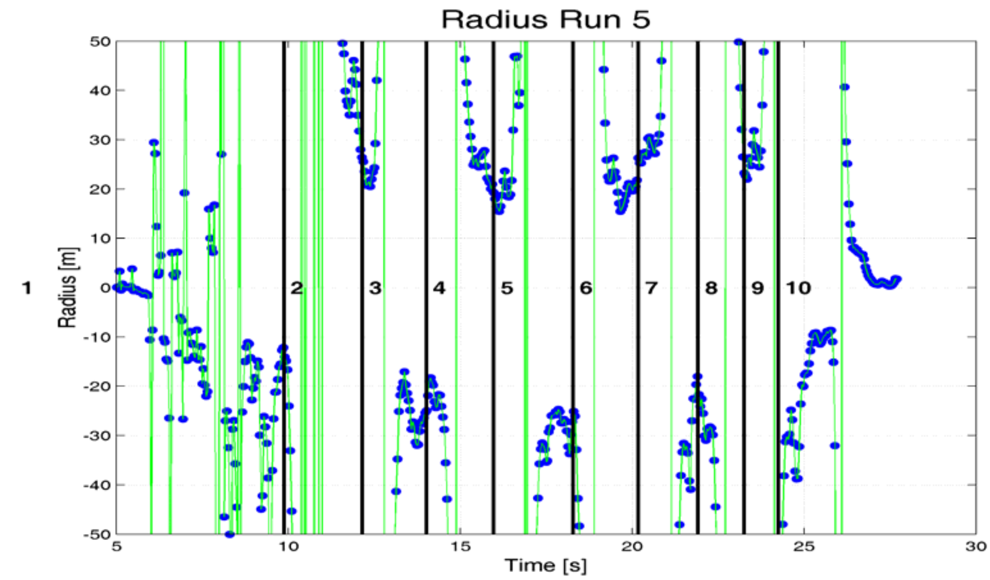


Figure 3-23: Instantaneous turn radii in run 5

Figure 3-22 and Figure 3-23 show the athlete did not make constant radius turns. Two extremes of turn technique and therefore turn radius evolution were observed during the runs. About gate 4 in both runs 3 and 5 a double minimum is observed in the graphs of turn radius, the minimum radius is observed once before the turn apex and once after the turn apex. The athlete therefore entered gate 4 with a tight turn, which set him up so he could pass safely through the gates with a more open turn, and some room for error. About gate 8 however the minimum turn radius was observed once, near the gate and probably represented a more aggressive turning strategy with less room for error.

Table 3.1: Minimum turn radii in metres taken from Figure 3-22 and Figure 3-23

	Gate 2	Gate 3	Gate 4	Gate 5	Gate 6	Gate 7	Gate 8	Gate 9
Run 3	11.8	19.7	20.8	17.4	20.1	14.6	20.9	19.4
Run 5	11.8	20.5	18.3	15.4	23.9	15.5	18.0	22.0

In general the left turns about gates 5, 7 and 9 (mean minimum radius 17.4m) were tighter than the right turns about gates 4, 6 and 8 (mean minimum radius 20.3m) indicating a cross slope and/or a difference in technique between the left and right turns.

The course line analysis (Section 3.1.3) identified that the turn about gate 4 was better in run 3 than in run 5 because of a shorter trajectory and therefore it was assumed that in run 3 a tighter minimum radius had been used. The new information from the turn radius analysis however shows that the minimum turn radius about gate 4 was unexpectedly greater in run 3 (20.8m, Table 3.1) than in run 5 (18.3m). These turn radii data contradict the "going straight, turning short" race strategy and suggests for some gates an optimum turn radius exists, which dose not result in the tightest practical paths between the gates. The hypothesis is also supported by the turn data from gate 6. About gate 6 the performance in run 5 was better than the performance in run 3 (see Section 3.1 Race Analysis) and the minimum turn radius of the 'better' turn (23.9m, run 5) was again greater than the minimum turn radius of the 'lesser' turn (20.1m, run 3).

It was possible the larger radius turns are better in some parts of the course because higher speeds can be maintained with similar inclination angles and/or ski snow angles. The larger radius turns also allowed the athlete to spend relatively more time travelling closer to the fall line (about the gates) than travelling across the fall line (between the gates). In summary; by using more open turns, the athlete might sometimes be able to reach the mid point between the gates faster even though the path length is longer. About other gates however the tighter turns were superior, such as about gate 7 in run 3.

3.7. Accelerative turn technique

Turn 6 of run 5 demonstrates how the athlete might use ground reaction forces to create positive power and increase speed through a turn (Figure 3-18). Previously David Lind hypothesised how the athlete might theoretically do this (Lind & Sanders, 1997) in his book, *"The Physics of Skiing"*. Lind compares the athlete's motion to the motion of a child on a swing or the motion of an imaginary cart on frictionless tracks making fixed radius turns. The data show that the athlete did not make fixed radius turns (Figure 3-22 and Figure 3-23) so a more general theory is required such as:

Athletes can increase speed through additional muscle work when their centre-of-mass and ski trajectories are diverging.

The theory comes with the caveat, ‘provided there is little snow resistance and that there is not too much ski skidding’.

3.7.1. Acceleration from diverging ski and CoM trajectories

The CoM and ski trajectory may diverge as indicated by the location of green arrows in Figure 3-24. The Figure 3-24 is a schematic of the athlete’s ski and CoM trajectories. Because the motion takes place in three dimensions, the CoM and ski trajectory may diverge in both the top and profile planes of view. The diagram is only a schematic and is not an accurate representation of the actual athlete’s technique.

The first opportunity to increase speed using ground reaction force work might occur during the entry phase of the turn if the athlete runs smoothly on the ski edges with appropriate physical inclination. The athlete could then use internal muscle forces to push his CoM away from his skis. The resulting motion may vaguely resemble a double footed skating stroke as the skis and CoM trajectory are diverging in the horizontal plane as viewed from the top. This type of motion can be termed ‘lateral projection’ (green arrows top view, Figure 3-24).

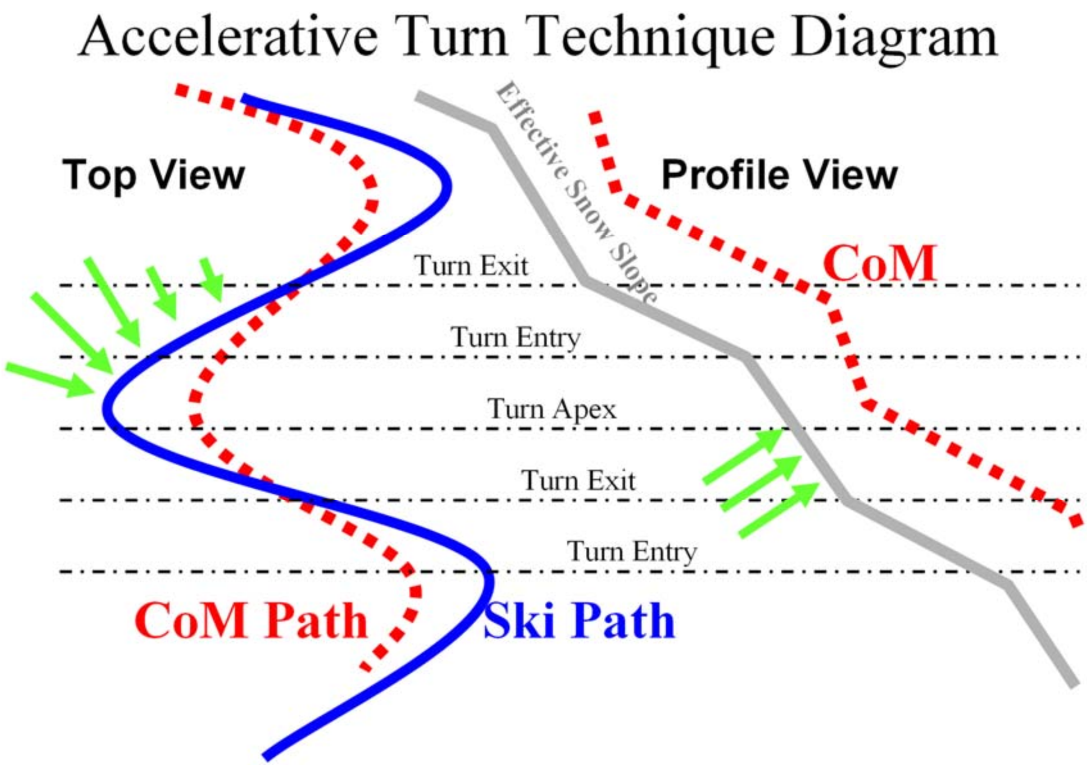


Figure 3-24: Schematic of how ground reaction forces might accelerate the athlete

The second opportunity to increase speed from internal muscle work comes from movement normal to the snow surface (green arrows profile view, Figure 3-24). This type of motion may be called ‘pumping’ and resembles the technique an athlete might use to gain additional speed in a half pipe.

Pumping might increase speed through a course if the athlete is able to create higher ground reaction forces near the turn apex where the effective snow slope is greatest and then almost becomes airborne through the transition between turns, where the effective snow slope is least. Pumping may also beneficial in combination with pre-jumping as the snow slope changes. To investigate if the athlete used pumping the effective snow slope was plotted based on the skis centre-of-pressure trajectory (Figure **3-25**).

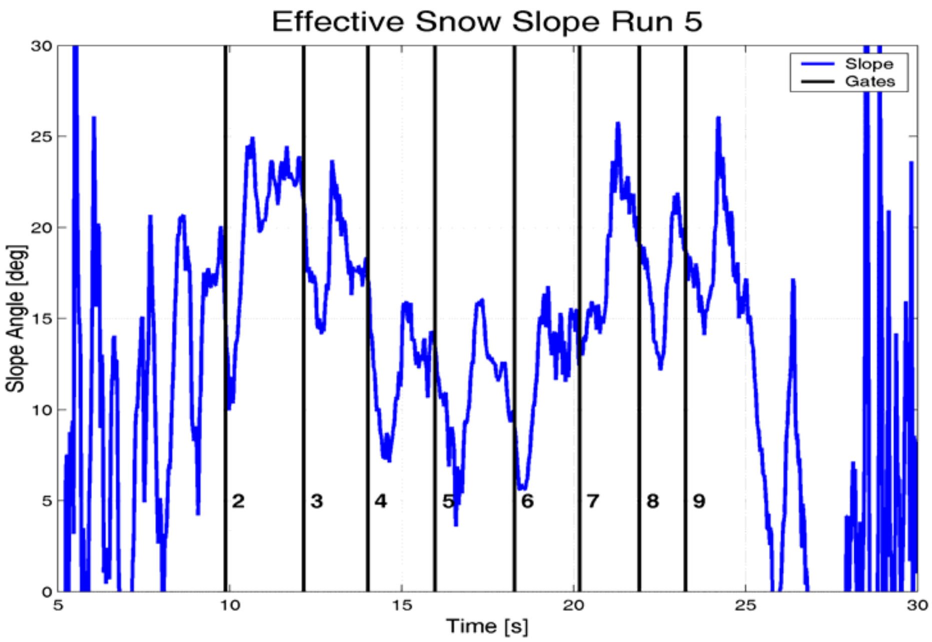


Figure 3-25: Effective snow slope changes due to athlete trajectory in run 5

Figure **3-25** shows that even though the actual snow slope (from the terrain model) was constant between the gates, the effective snow slope (as plotted) was reduced as the athlete skied across the fall line between turns. The changes in the effective snow slope were generally around 10° between gates, which is large enough to create a useful advantage. By using additional muscle work to increase ground reaction forces while travelling down the fall line athletes can go faster by ‘effectively skiing on steeper parts of the course’.

Increasing ground reaction forces, however, also increases snow resistance forces, which always act to reduce speed. The combination of snow resistance work and ground reaction force work over after the first gate is always negative and there is always far more potential to loose speed through poor technique and poor timing than to gain speed through additional muscle work.

3.8. Discussion about race strategy

The analyses presented in this chapter have shown there are many factors that might affect performance in a race. Here it is discussed that athletes may be able to improve performance by focusing on only three aspects of race strategy; choosing the optimum turn radius, turn entry point and inclination angle for each gate. These three parameters depend on multiple factors including among other things speed, terrain slope, gate setting and ski design.

3.8.1. General trends

Figure 3-26 shows that the minimum turn radius generally increased with the athlete's speed. At race pace (between 15ms^{-1} and 21ms^{-1}) the minimum turn radius ranged from 14m to 24m and was principally limited by the maximum inclination of the athlete (how far he was able to lean into each turn, Figure 3-27). At race pace the athlete's maximum physical inclination angle (between 45° and 70º) did not increase as speed increased and so speed increases resulted in turn radius increases. The athlete's maximum inclination angle was limited by the maximum ski/snow angle the athlete could sustain before the snow surfaces beneath the ski bases fractured and also the athlete's ability to rotate from edge-to-edge quickly between the turns. As discussed earlier however, maximum inclination angle did not always produce the optimum turn and therefore further analysis is required in the future.

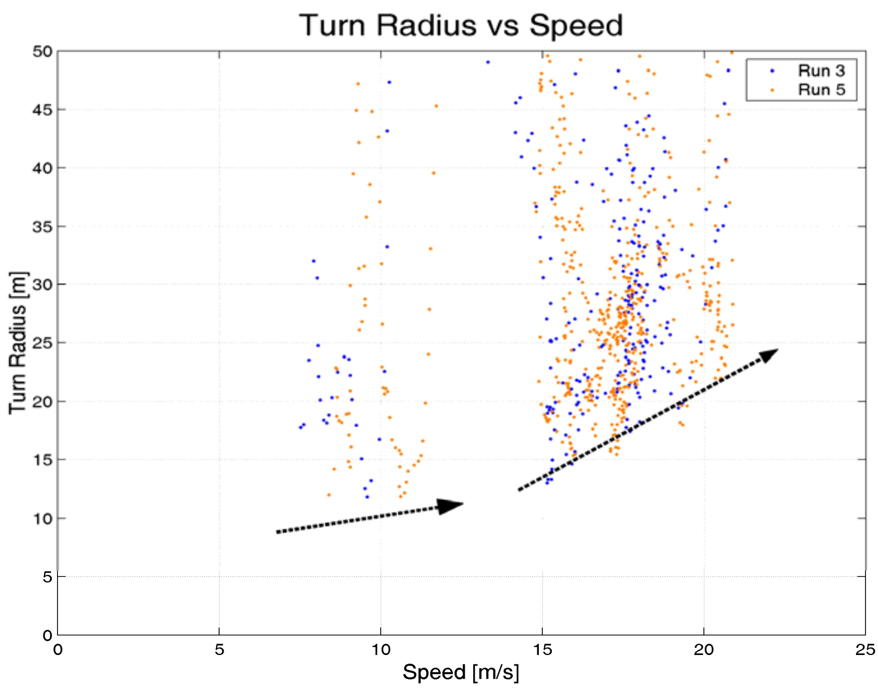


Figure 3-26: Increasing turn radius with speed

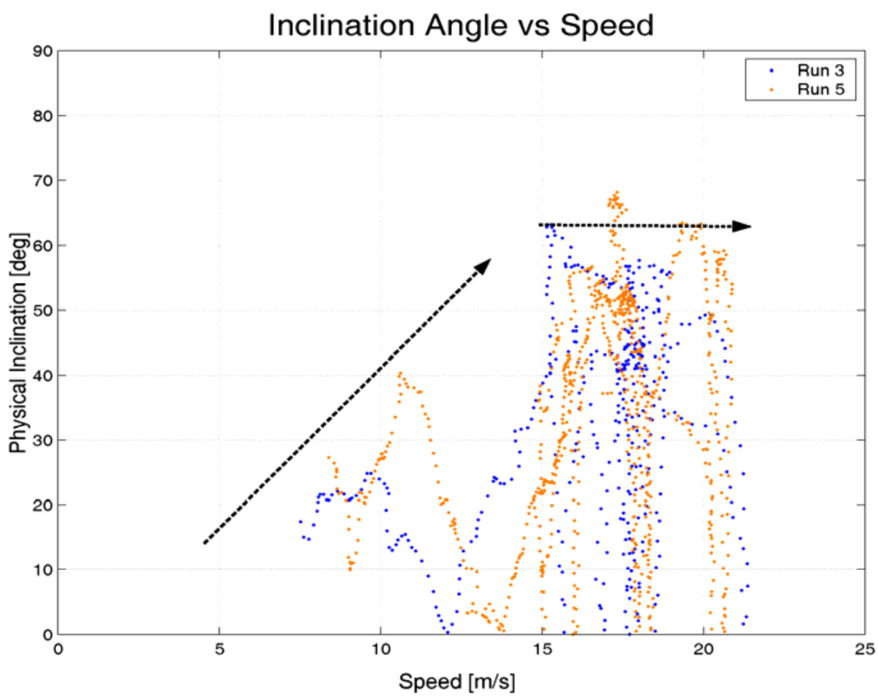


Figure 3-27: Physical inclination reaches a limit at race pace

3.8.2. Ski selection and design

Ideally, the ski should be designed by the manufacturer and/or selected by the athlete to match the specific requirements of the racecourse. Ski trajectory is a result of the ski side cut radius, the ski flex and the ski/snow angle. Theoretically the ski should carve tighter turns if it has more shape and if the ski/snow edging angle is increased by the athlete.

The ski/snow edging angle has also been plotted over the course for run 3 (Figure 3-28) where 0º corresponds to the ski sitting flat on the snow. In the figure the skating start, one stroke from the right ski and two strokes from the left ski are visible as peaks near the second gate. The figure also shows that the outside ski was edged between 10º and 20º more around each gate than the inside ski. A variety of edging angles was used and peak ski edging occurred sometime after the minimum turn radii about turn.

The ski turning radius data from the race course was then plotted against the ski edging angle data (see Figure 3-29). The ski design should be selected to best match the performance required during the turns, which generally corresponds to the area of Figure 3-29 with higher ski/snow angles (between say 30° and 70° on the horizontal axis). The mean properties of the ‘optimum’ ski (side cut radius and flex) may, for example, be determined by the trend line, while the spread of the data may determine the required versatility of the ski to perform turns of different radius with the same edging angle.

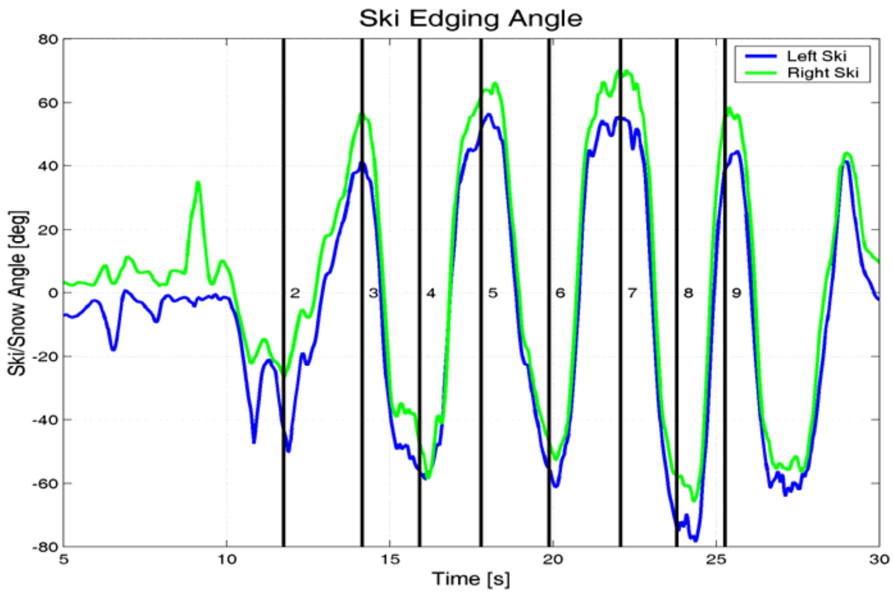


Figure 3-28: Ski/snow edging angle for run 3

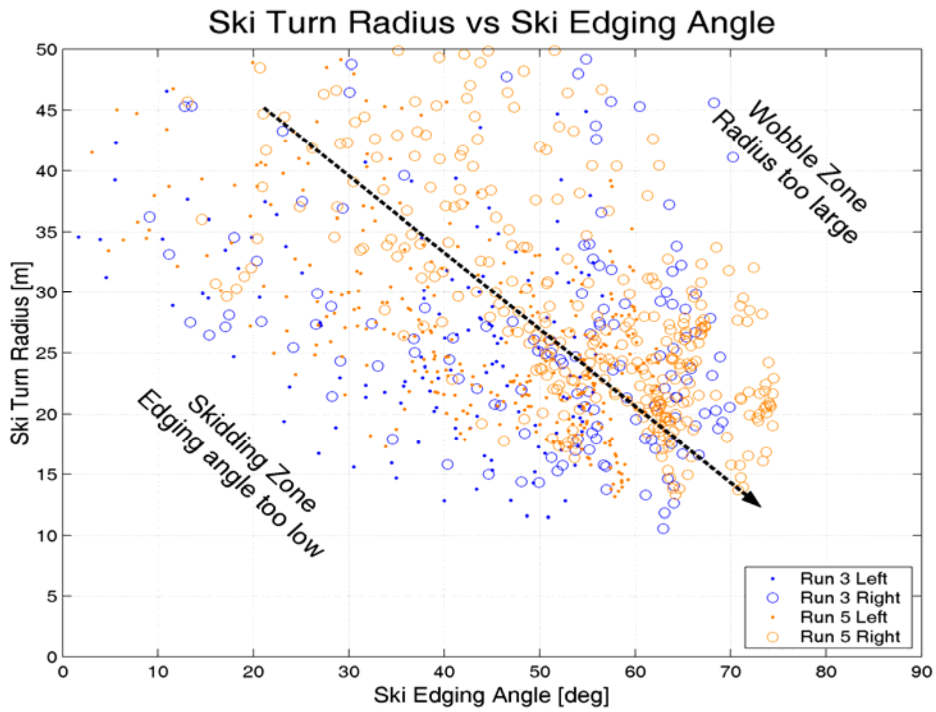


Figure 3-29: Ski turn radius vs. ski edging angle

Implications for athletes

It is important to match the ski with the course conditions. For example: On steeper terrain, at the top half of the turn, the ski/snow angle may be too small to allow the skis to carve the required tight trajectory and a skidding technique may sometimes be required to approach the gates (the skidding zone, Figure 3-29). On steeper terrain, through the bottom half of the turn the ski/snow angle is larger and the ski flexes more as a result of the ski side cut. The ski may attempt to carve a trajectory that is too tight and this may cause loss of control or increased snow resistance (the wobble zone, Figure 3-29).

Slalom skis are often designed with the rear section of the ski being stiffer and straighter than the front section of the ski. On steep terrain before the gates, the athlete may move his centre-of-pressure forwards on the ski. After the gates the athlete may maintain control by using more of the stiffer and straighter rear section of the ski.

The correct ski selection for a course and an athlete should result in both a faster and safer performance. On steep terrain with tightly spaced gates a shorter ski with asymmetrical shape and stiffness properties capable of performing turns of different radii with the same edging angle is required. On flat terrain with open gates, a longer symmetrical ski is required. Ski stiffness should increase with the athlete's weight, speed, turn tightness and snow hardness.

3.8.3. Optimum race strategy

Optimum race strategy is a trade off between tighter turns, that result in shorter path lengths and more open turns that allow for more acceleration and faster turning speeds. The athlete must, for each gate, select at least a point on the approach arc, the target turn radius, and the target inclination angle.

The optimum race strategy is different for each gate and sits between two extremes. The first strategy (the tight turn strategy) is to take the shortest practical path between the gates without skidding or losing speed. The tight turn strategy is generally limited by the athlete's maximum inclination angle and the turn apex should be located next to the inside gate. A shorter path length at similar speeds takes less time to complete.

The second strategy (the open turn strategy) is to make the longest most open turns practical while still passing between the gates. The open turn strategy is limited by the gate locations. The open turns can be run at higher speeds and provide the opportunity to accelerate earlier in the course and over longer distances while travelling closer to the fall line about the gates. The turn apex depends on both the terrain and the future gate locations, therefore, the turn apex is not always located next to the inside gate.

3.8.4. Terrain slope and turn radius

Figure 3-30 shows another general trend, the athlete's minimum turn radius increased with increasing snow slope angle. The trend line, if extrapolated, predicts an optimum turn radius of zero metres on flat terrain. This could be executed by the athlete turning on the spot on flat terrain and is impractical for a ski race. The trend line suggests, however, that when the snow slope decreases the tight turn strategy may become more suitable and as the terrain steepens the open turn strategy may become more suitable. More open turns on steeper terrain may allow the athlete to travel faster and/or accelerate down the fall line earlier and although a longer distance is travelled, the athlete may reach the midpoint between the gates earlier.

Alternatively, this relationship between increasing turn radius and increasing snow slope (Figure 3-30) may be partially explained by the athlete's maximum ski/snow edging angle limit. The same ski/snow edging angle on steep terrain results in less inclination from the vertical and therefore results in a more open turn.

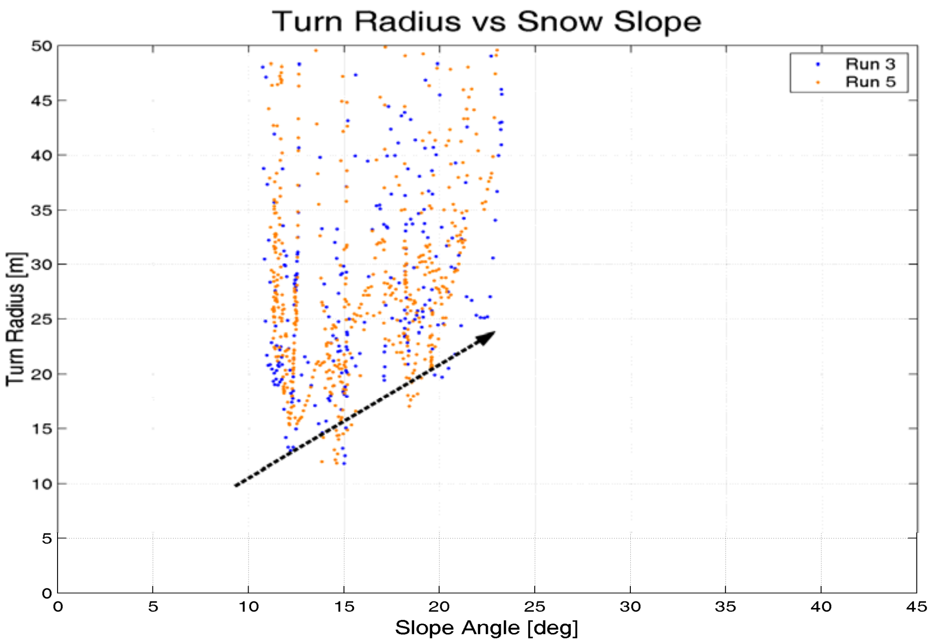


Figure 3-30: Turn radius vs. snow slope

3.8.5. Asymmetry between turns

Finally, it appears the athlete preferred at some level, symmetry between turns. In run 5 the athlete consistently inclined between 5° and 10° more than in run 3 (see Section 3.6.1) perhaps in an attempt to ski faster. The athlete might have, however, skied faster if he had been able to incline less about the left turns while inclining more about the right turns.

This hypothesis is also supported by Figure 3-29: Ski turn radius vs. ski edging angle and the figure also suggests the athlete's skis may have influenced his race strategy. In Figure 3-29 the data points corresponding to the right ski (left turns) were on average above the trend line (closer to the wobble zone) and so perhaps less ski/snow edging angle and inclination should have been used for the left turns. The data points corresponding to the left ski (right turns) were on average below the trend line (closer to the skidding zone) and so perhaps more ski/snow edging angle and inclination should have been used for the right turns. Most athletes do not have access to a large selection of different ski designs and so the naturally turning properties of their ski equipment should significantly affect their race strategy. If the naturally turning properties of the ski equipment match the race strategy and technique it might be interpreted by the athlete as a ‘good feeling’ because less effort should be required to control the ski and also the ski should create less resistance as it moves through the snow.

The fact the optimum solution is likely to be asymmetric may have been the result of a slight cross slope through the course. This could mean elite athletes may be able to improve by specifically training on asymmetrical gate sets with visual markers to guide their trajectory choice.

4. Conclusions

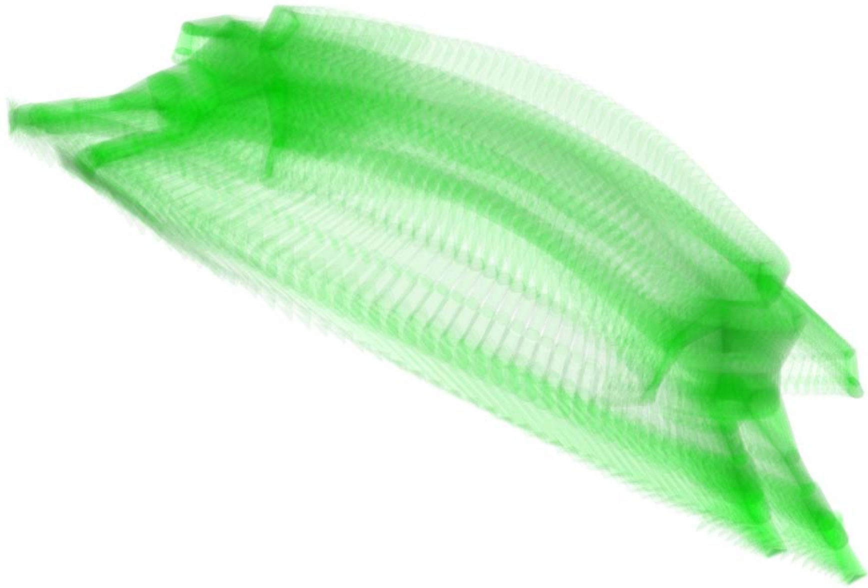


Figure 4.1: Visualisation of athlete speed in giant slalom skiing from FMC data

What makes one athlete the fastest, is it science or art? In the introduction it was discussed that the optimum strategy for passing through a series of gates was unknown. The optimum ski design for a particular gate set was unknown. The optimum envelopes of athlete movements through complete gate sets were also unknown. Steps towards finding these answers have been made.

The research shows Stenmark's comments, 'Many skiers do not take advantage of the way modern equipment has been designed to facilitate carving turns' (Stenmark, 1990), do not hold true for today's best athletes. The research demonstrates today's highly skilled athletes can make use of the way modern skis are designed to facilitate racing turns, but also shows how scientific analysis can be used to improve performance.

The practical conclusions for coaches and athletes are:

- The optimum race strategy is a trade off between tighter turns that result in shorter path lengths and more open turns that allow for faster turning speeds and also result in more acceleration earlier in the turn while travelling closer to the fall line.
- The optimum turn radius range for passing between the gates on the giant slalom racecourse is between 15 metres and 25 metres. The optimum turn radius increases with both increasing speed and snow slope. .
- Optimum physical inclination angles from the vertical are generally between 45º and 70º. Postural balance is maintained by leaning into the turns and so more inclination is required as speed increases.
- In some parts of the course optimum turn radius may be limited by the maximum ski/snow angle the athlete is able to maintain.
- A good match between the ski design, the course, and the athlete should result in both a faster and safer performance.
- Athletes may prefer to make identical turns in different parts of the course but this does not produce the fastest course time. Athletes might improve through practise dedicated to taking each course gate differently.
- Reduction of snow resistance is of similar importance or more important than the reduction of wind drag.
- Gravity does the most work in a ski race, acting to increase athlete speed, but it is ground reaction forces (a direct consequence of athlete technique) that decides the outcome of a race.
- At moderate speeds (<20m/s) and on moderate terrain (<25°) athletes may use internal muscle work, through the techniques of lateral projection and pumping, in order to increase speed.
- Dry land training should include exercises that require athletes to maintain postural balance while both subjected to both destabilising perturbations and performing lifts.
- The data visualisations and data analyses developed are useful tools for presenting complex biomechanical analyses of ski racing in a way that is intuitive to athletes, coaches and biomechanists.

Until more data is collected, it is not known if these results collected from two runs of a single athlete at moderate speeds on moderately sloping terrain can be generalised to all athletes on all terrain. In the future biomechanical analyses of alpine ski racing performance will be able to investigate previously unanswerable questions using multi-dimensional data from complete race courses. In the future it may become possible to ***optimise athlete movement in alpine ski racing***.

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