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Fusion motion capture: a prototype system using inertial measurement units and GPS for the biomechanical analysis of ski racing

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In this pilot study fusion motion capture (FMC) has been used to capture 3-D kinetics and kinematics of alpine ski racing. The new technology has overcome the technological difficulties associated with athlete performance monitoring in an alpine environment. FMC is a general term to describe motion capture when several different streams of data are fused to measure athlete motion. In this article inertial measurement units (IMU), global positioning system (GPS) pressure sensitive insoles, video and theodolite measurements have been combined. The core of the FMC is the fusion of IMU and GPS data. IMU may contain accelerometers, gyroscopes, magnetometers and a thermometer, and they track local orientation and acceleration of each limb segment of interest. GPS data are fused with local acceleration data to track the global trajectory of the athlete. Fusion integration algorithms designed by the authors [1] were used to improve the accuracy of the independent Kalman filter solutions provided by the vendors of both the GPS and IMU. The GPS accuracy was improved from a dilution of precision of ± 5 m (meaning 50% of the measurements will be within 5 m of the true value) to a maximum error of ± 1.5 m over the race course, while the IMU orientation error was reduced from over 20° to less than 5° . The reader is invited to assess the validity of these results by comparing videos of the motion to the fusion motion capture output in the electronic version of this manuscript. Accuracy in laboratory situations has been validated, [2,3] but because such systems are becoming more popular, this system needs to be validated on the snow. As more accurate dual frequency GPS systems become less expensive this type of system will become more accurate and affordable. A biomechanical analysis was undertaken of a New Zealand Alpine Ski Racing Team member negotiating a 10-gate giant slalom course over 300 m in length. The abundant data in the results were used to create new tools for measuring alpine ski racing technique, such as colour-coded force vector analysis. The new parameters introduced in this article, such as effective inclination and ground reaction force power, are independent of the stylistic constraints often imposed by the coach or athlete. Two ski runs have been compared. Although the difference between the two run times was only 0.14 s or 1%, FMC and force vector analysis were able to

Keywords:

- GPS
- ski racing
- fusion motion capture
- biomechanical analysis
- inertial measurement units

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pick up the subtle changes in technique between the two runs. It is believed the analyses will provide useful design parameters to ski equipment engineers and will allow athlete feedback through augmented reality animations about variables, including limb dynamics, centre of mass (CoM) trajectory, CoM velocity, and external forces. In-depth analysis of the changes in net joint torques with changes in athlete posture may be useful for coaching athlete specific technique changes to improve performance and reduce injury potential. In addition, it is possible to extract key performance indicators about the athlete's physical and physiological limits, such as the mean coefficient of wind drag and the maximum inclination angle while turning, which may be used to optimise race strategies. There are tentative plans to use an improved version of a similar motion capture system to analyse forerunners on the FIS world cup race circuit. The purpose is to reduce knee anterior cruciate ligament (ACL) injuries and provide a visual biomechanical analysis of an athlete running the course to enhance the experience of the television audience. In alpine ski racing, forerunners ski the course before the first athlete to set ski tracks through the gates and check the safety of the course. © 2008 John Wiley and Sons Asia Pte Ltd

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1. INTRODUCTION

Biomechanical analysis of alpine ski racing is challenging because of the technological and practical difficulties associated with the resolution and accuracy of 3-D video analysis through large volumes. Because an improvement of as little as one-hundredth of a second between gates is significant to race outcome, performance enhancement for elite athletes may involve technique adjustments that are beyond the capabilities of video-based systems and instead must rely on coach and/or athlete intuition. Most biomechanical research to date has focused on the analysis of short turn sequences through two or three gates representing only part of a race course [4–6]. However, Supej, through an energy analysis, noted that athlete turn performance was dependent on the previous turns. Therefore, we hypothesise that, if turn strategy is dependant on both past and future turns, then, unfortunately, race outcome, and ultimately athlete performance, cannot be predicted from analysis of an isolated turn sequence.

The purpose of our project was to overcome the technological difficulties associated with athlete performance monitoring in an alpine environment by using a new system, FMC. The success of FMC proves that it is possible to capture the motion and dynamics of alpine ski racing through an entire ski run; in some cases over 1 km in length while maintaining high resolution. Previous work indicates that changes of less than 1° in local limb orientation can be tracked successfully [2]. In contrast, contemporary 3-D optical systems would require at least four cameras per gate, and a 10-gate training course may require up to 40 synchronised and calibrated cameras. In addition, the post-processing required to digitise the data from so

many cameras has had in the past limited video motion capture of at most two giant slalom turns. The set-up time for FMC varies from 15 minutes to three hours, depending on the accuracy required, and the previous experience of the athlete. The system requires between one and three people to operate and the results presented in this article could have been returned to the athlete within a few minutes of completing each run.

FMC is a composite system that fuses data from IMU (Inertial Motion Unit), video, GPS (Global Positioning System), and an RS-Scan insole system to determine segmental and whole-body kinematics and kinetics. IMU contain three gyroscopes, three accelerometers, three magnetometers and a thermometer in a 35-g box about the size of a matchbox. In the past, both instrumented skis and pressure sensitive insoles have been utilised to measure ground reaction forces for entire ski runs. Unfortunately without kinematic data from video analysis, the measured local forces cannot be interpreted in the global coordinate system. GPS has also been used to track athlete movement in ski racing [7].

In the past, each measurement system was used in isolation and because the resolution of each system is relatively low, it was not possible to pick up the subtle differences that may decide race outcomes. FMC (Fusion Motion Capture) uses low-level communication protocols to extract the unfiltered binary data from each measurement system and then fuses the data streams to improve accuracy. For example, by fusing the integral of the accelerometer output with the raw GPS pseudo range and carrier frequency data, it is possible to obtain a total trajectory estimation of position, velocity and orientation over the entire course, that is both continuous and more accurate than either instantaneous measurement in isolation. An

example of using fusion integration to obtain CoM trajectory from force platform data explains some of the principals of the data fusion algorithms used [1].

The question now is not 'How do we collect biomechanical data on an athlete's performance?' Rather it is 'How can we use biomechanical information to improve the athlete's performance?'

2. METHODS†

2.1 Data Collection

A 20-year-old male member of the New Zealand national team (body mass 78 kg) completed five runs through a 10-gate giant slalom training course at Mt Ruapehu Ski Area, North Island, New Zealand. The course was over 300 m in length. The athlete's body segment kinematics, including angular velocity and local acceleration were obtained from 13 IMU attached to the following body segments: head, torso, pelvis, upper and lower arms, thighs, shanks, and ski boots.

The IMU were attached to each body segment in such a way as to reduce skin artefacts; a lycra bodysuit was constructed to contain the connecting wires. The suit had apertures at the location of each IMU so that it could be attached directly to the athlete's skin with the use of double-sided tape. 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 IMU would be damaged by aggressive racing strategy if they were attached to the outside of the limbs or the athlete's back. The exact positions were:

- Top of the ski poles on the hand grip.
- Lower arms, medial surface just far enough from the wrist joints to allow free movement.
- Medial surface of the upper arm.
- Sternal notch.
- Top of the helmet, approximating the apex of the skull.
- Between the posterior iliac spines.
- Lateral surface of the thigh, midway between the femoral condyle and the greater trochanter.
- Shanks, on a flat section of the tibia just below the knee.
- Heels of ski boots, just above the binding.

For the purposes of this analysis the ski and boot was then modelled as a single rigid body and 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.

An RS-Scan pressure measurement system was used to determine plantar pressures and the ratio of loading between the skis. Absolute forces could not be accurately measured by the

RS-Scan system, but were determined through inverse dynamics based on the CoM trajectory. Video from a hand-held digital camera, panned from a fixed position on the skiers on the left side of the course was used as an external reference and to confirm validity of the data. A GPS was attached to the athlete's helmet and a local GPS base station was positioned near the course. Only two complete data sets were collected (run 3 and 5) because the prototype system suffered some damage during testing. Run 3 was completed in the morning on hard snow, while run 5 was completed on soft snow in the afternoon.

2.1.1 Equipment list

Fifteen IMU, XSens Technologies Limited, 512 Hz maximum output for one sensor, (50 Hz for 16 sensors), specified accuracy from the manufacturer's Kalman filter algorithm in dynamic situations $\pm 3^\circ$ RMS (www.xsens.com)

Two GPS SiRFstar2 USB receivers, one base station and one rover, 1 Hz output, specified accuracy ± 10 m RMS in 3-D or Dilution of Precision (DoP) ± 5 m. Single frequency (www.sirf.com)

- One Sokkia theodolite, Japan (www.sokkia.co.jp)
- Two Sony DCR-TRV 730E digital video cameras, 25 fps (www.sony.net)
- One RS-Scan Foot Scan insole system, 100 Hz output (www.rsscans.com)

2.1.2 Data processing

Limb orientation: The data were processed using fusion integration algorithms [1] and the Biomechanical Man body model implemented in MATLAB [8]. The athlete's limb orientation was determined by thirteen IMUs attached to the athletes' body segments. The IMU manufacturer supplied a Kalman filter algorithm which could be used to extract orientation information from the raw data. However, it was found that this algorithm produced errors of over 20° in orientation for a simple pendulum experiment that was used to simulate sustained arm swings in athletic activity [2]. Instead of the Kalman filter algorithm, the author used a custom fusion integration algorithm suitable for measuring the athletic movements in skiing (Figure 1). The fusion algorithm has an RMS error of less 1° in the laboratory. In the field measurement errors may be higher than 1° , but from the authors' experience an error of greater than 5° in limb orientation causes the subsequent animation of the athlete's movements to appear visually different from the video data, and physically impossible (e.g. the ski tips may be crossed). Therefore, in this analysis of skiing the system has an unconfirmed error of less than 5° .

The authors believe that the worst limb orientation accuracy occurs when the athlete passes gate 7 in run 3, where the skis appear to be too close together. The reader is invited to validate the accuracy in this turn by viewing the animations supplied in the electronic version of this document. The error may be a result of high angular acceleration from shock loading as the leg sensors impacted the gate, skin artefact because the sensors are not rigidly attached to the athlete's

†Part of this section '2. Methods' is based on Brodie M, Walmsley A, Page W. Fusion Motion Capture: Can technology be used to optimise Alpine ski racing technique? In: Fuss FK, Subic A, Ujihashi S (Eds.) *The Impact of Technology on Sport II*, pp. 825–831, Taylor and Francis Group, London 2008. By kind permission of Taylor and Francis.

Fusion Motion Capture Algorithm

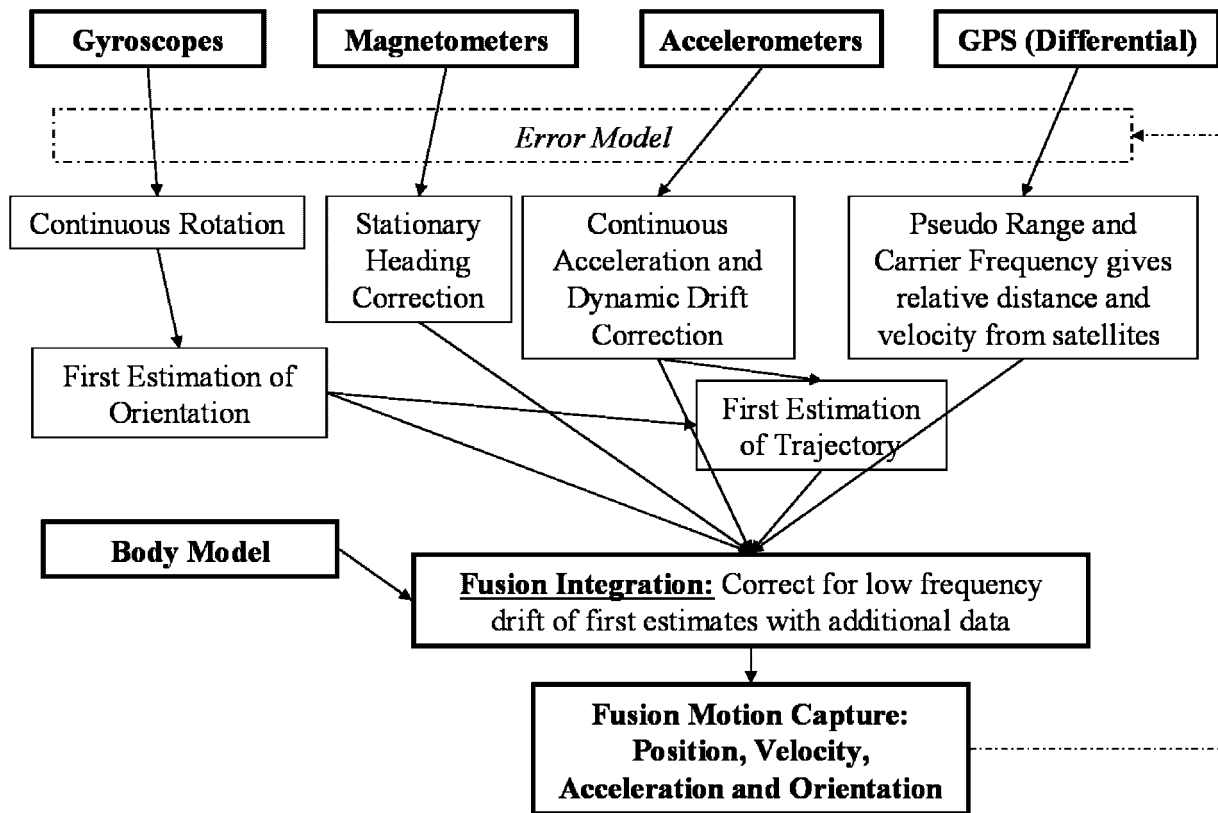


Figure 1. Block diagram of the fusion integration algorithm for IMU and GPS measurements. Raw data are fused to produce a continuous estimate of position, velocity, acceleration and orientation.

bones or the vibrations from the skis skidding over the hard snow. Errors in orientation tend to get worse in the distal segments because the animation is built up from the body model starting with the GPS receiver located on the athlete’s helmet. In addition the skis magnify any small orientation error because of their length. These errors may be reduced in subsequent tests through better sensor placement, protecting the sensors from gate strikes and vibrations, the use of multiple sensors on a single limb, and/or software capable of modelling skin artefacts.

Unfortunately, in the past there has been no way available to the authors to validate the system’s accuracy on the snow, other than audience validation of the recreated motion supplied in the electronic version of this document. However, there are tentative plans to validate the system against the PEAK optical system already validated on snow by researchers at Salzburg University [4].

Global trajectory: The trajectory of the athlete’s helmet was calculated by fusing the GPS data at 1 Hz (both base station and helmet) with the data from the IMU attached to the helmet and sampled at 50 Hz. The precise start and finish locations of the athlete and each gate position were surveyed using a theodolite and a GPS. Because GPS velocity, calculated by Doppler effect from the carrier frequency, is more accurate than position, calculated by the time of flight from the pseudo

range data, it was important in the fusion process that the athlete always started and finished the run at the surveyed points. Instantaneous athlete position was calculated by hanging distal segments of a known orientation from the appropriate proximal joint centre. In this case the location of the GPS receiver on the athlete’s head was defined as the most proximal joint centre. The next most proximal joint centre was C7, followed by shoulder and lumbar joint centres. CoM trajectory was calculated using a weighted sum of the known location of the individual limb segment CoMs.

The accuracy of trajectory can only be validated against the video in the electronic version of this document, in which it appears that the athlete contacts each gate synchronously with the video. Where there is a discrepancy it is not known if the athlete’s trajectory contains error, or the gate position was surveyed incorrectly. In any case, the error appears to be a maximum of ± 1.5 m over the entire 300-m course. The snow terrain was estimated by interpolating between the surveyed positions of the gates; the gates were surveyed by both GPS and a theodolite. However, the GPS used for the gate survey was less accurate than the theodolite, and only those gates that could not be seen from the theodolite position were surveyed with the GPS using a relative GPS movement from a gate surveyed with the theodolite. The largest discrepancy in global trajectory can be observed at the gates surveyed by the GPS.

The snow terrain model in this study also suffers from the fact that the true terrain is not constant between the giant slalom gates, which are in some cases over 20 m apart. In future, the course will be surveyed with a mobile sled that samples the terrain surface at 50 Hz. It is believed that these alterations will improve the accuracy of the system. The maximum estimated error of the system, ± 1.5 m, is much better than the stated accuracy of the GPS, dilution of precision (DOP) ± 5 m, where DOP indicates the range in which 50% of the measurements will fall. The authors believe this is still useful for the analysis of ski racing because the errors of the system result in a slow drift of position over time which can be easily corrected.

The FMC system errors are different from camera-based system errors because velocity and acceleration, measured directly, are more accurate than position, which is derived partly from acceleration and velocity measurements. Further improvements in accuracy could be obtained with a more expensive GPS system, or by constraining the athlete to the snow surface or to known checkpoints through the course, such as times of gate contact or split times measured with optical gates. In the animations provided online, the authors decided not to apply these additional constraints but chose to display the raw data so that assessment of the underlying accuracy of the system is possible.

The calculation of limb orientation and CoM trajectory are closely coupled and the fusion integration approach calculates the solution for the entire run rather than a discrete solution based on a single measurement instance. This complex approach represented in a simplified diagram (Figure 1) may be more accurate than traditional approaches because all data affect each solution at each time instance, and result in the unusual aspect that accuracy may improve with more varied measurements made over longer durations and longer ski runs.



Figure 2. 3-D anthropometry with the custom frame.

3-D anthropometry: To calculate net joint torques a body model of the athlete is required. Athlete inertial parameters are obtained from the athlete's mass, including ski boots, helmet and 3-D anthropometry using a custom-built frame (Figure 2). The measurements are appropriately scaled as suggested by Dumas *et al.* [9] and Reed *et al.* [10]. In addition, the estimated inertial properties of the helmet are added to the head segment, and the estimated inertial properties of the skis and boots are added to the foot segments. This system is required both to model the athlete's inertial parameters and to calibrate the attached IMU. The local coordinate system of each IMU is mapped to the local coordinate system of the athlete's limb (to which the IMU is attached) in the calibration process.

Calibration calculations: In FMC the athlete is free to move unbounded through global space while the motion of an IMU attached to each body segment (Figure 3) is captured using fusion integration. The motion of the IMU is mapped to the body segment it is attached to by a constant 3×3 rotation matrix, $R_{IL \rightarrow BL}$, which transforms measurements from the IMU local (IL) coordinate system to the body segment local (BL) coordinate system.

During calibration the orientation of body segments is measured by the 3-D anthropometric frame, while data from the attached IMU are recorded. The orientation of the 3-D anthropometric frame (F) with respect to the global (G) coordinate system ($R_{F \rightarrow G}$), the orientation of body segments with respect to the frame ($R_{BL \rightarrow F}$) and the orientation of the attached IMUs ($R_{IL \rightarrow G}$) are used to calculate the calibration matrices $R_{IL \rightarrow BL}$ for each body segment according to Equation 1.

$$R_{IL \rightarrow BL} = R_{BL \rightarrow F}^{-1} * [R_{F \rightarrow G}^{-1} * R_{IL \rightarrow G}] \quad (1)$$

The motion of all body segments is transformed into the global coordinate system by the instantaneous matrices $R_{BL \rightarrow G}$, calculated according to Equation 2. Where $R_{IL \rightarrow BL}$ are the constant calibration matrices from Equation 1 and $R_{IL \rightarrow G}$ are the instantaneous orientations of the IMU.

$$R_{BL \rightarrow G} = R_{IL \rightarrow G} * R_{IL \rightarrow BL}^{-1} \quad (2)$$

An automated calibration can be performed by the athlete performing a precise set of movements on a force plate while data are simultaneously recorded from the IMU. This allows the athlete's specific body segment parameters, segment length and inertial properties, to be estimated, and the relative orientation of each IMU to its attached limb to be determined. Currently, the accuracy of such a procedure has not been determined and so in this case the calibration frame described above was used.

Ground reaction force calculations: The magnitude and direction of the major component of the ground reaction force perpendicular to each ski was calculated from the foot loading ratio (calculated from the RS-Scan data), the measured orientation of the athlete's skis (measured by the IMU attached to the athlete's ski boot heel), and the athlete's CoM trajectory (Figure 5). Greater accuracy could have been obtained using skis instrumented with force transducers, but at present these are heavy and too thick to pass FIS regulation. In addition the transducers are unacceptable to most athletes in racing situations. Unfortunately, the RS-Scan data were found to



Figure 3. The author modelling an early version of the Fusion Motion Capture System with inertial measurement units attached to limbs.

underestimate the athlete’s ground reaction forces; however, it was assumed the data could give a reasonable estimate of the ratio of loading between the skis. Without the RS-Scan data it would be impossible to resolve the kinetics of the lower body as skiing is predominantly a dual stance activity.

In the first step the resultant force ($F_{Resultant}$) was calculated by twice differentiating the CoM trajectory to get acceleration (A_{CoM}), which was multiplied by the athlete’s mass (m), including ski equipment. This method contains less high frequency noise than similar inverse dynamic calculations based on optical motion capture because accelerometers are used. The high frequency component of the CoM trajectory is based on the integral of the measurements from accelerometers attached to the athlete’s helmet (Figure 4) and the gyroscopes attached to the athlete’s limbs. Therefore the differentiation process to obtain acceleration from the CoM trajectory, if carefully chosen to be the mathematical inverse of the previous integration process, does not introduce excessive high frequency noise into the resultant force calculation.

The following assumptions for ground reaction force calculation refer to Figure 5:

The resultant force plus gravity perpendicular to the CoM trajectory ($F_{Total\perp}$) was assumed to be equal to the ground reaction force perpendicular to the CoM trajectory ($GRF_{L\perp} + GRF_{R\perp}$). This assumption requires that both wind drag and ski/snow friction act parallel to the CoM velocity vector. This assumption ignores the aerodynamic lift force and the fact that the ski trajectory is not the same as the CoM trajectory.

The R-Scan data were assumed to give an accurate estimation of the ratio of ground reaction forces perpendicular to the ski surface. This ignores any bending of the ski boot, relative movements between the boot and the ski, bending of the ski base; and assumes the RS-Scan insole is capable of accurately measuring the loading ratio.



Figure 4. Diagnostic checking of the fusion motion capture system before a trial. Mt Ruapehu ski area.

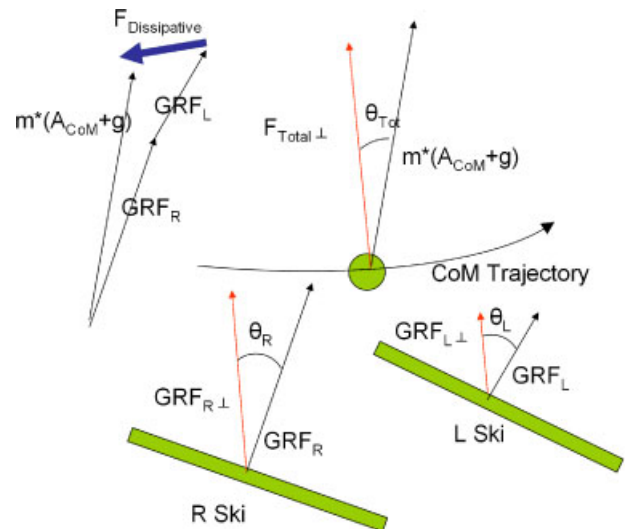


Figure 5. Free body diagram showing how the ground reaction force under each ski is calculated from the CoM trajectory, the known orientation of each ski, and ratio of loading between the skis as measured by the insoles.

From the previous assumptions Equation 4 was derived, the angles (θ_{Tot} , θ_L and θ_R) were calculated from the known orientations of the skis, and direction of the reaction force vector. The direction of the total reaction force vector ($F_{Total\perp}$) perpendicular to the CoM velocity vector (Vel) was calculated by taking multiple cross products of the normalised CoM velocity, Equation 5. Ratio is the ratio as measured by the foot scan insole system.

$$GRF_L = \frac{GRF_R}{1 - Ratio} \tag{3}$$

$$GRF_R = \frac{m * (A_{CoM} + g) * \cos \theta_{Tot}}{\cos \theta_R + \frac{\cos \theta_L}{1 - Ratio}} \tag{4}$$

$$\frac{F_{Tot\perp}}{|F_{Tot\perp}|} = \left(\frac{Vel}{|Vel|} \times \frac{m * (A_{CoM} + g)}{|m * (A_{CoM} + g)|} \right) \times \frac{Vel}{|Vel|} \tag{5}$$

Dissipative force calculations. In ski racing the dissipative forces of wind drag and ski–snow friction have a large effect on athlete performance. It was proposed that the dissipative forces ($F_{\text{Dissipative}}$) could be estimated from the residual between the first estimate of the ground reaction forces (as calculated in Equations 3 and 4) and the sum of acceleration and gravitational forces (Figure 5). Ski–snow friction is parallel to, but opposing the direction of travel of the ski. Based on the measured trajectory of the ski boot centre it was modelled by Equation 6, where GRF is the ground reaction force component normal to the athlete's foot obtained from Equations 3 and 4. K_{Friction} is the coefficient of friction due to sliding resistance, and $\mathbf{NV}_{\text{Foot}}$ is the normalised velocity vector of the athlete's feet, the normalisation process results in a unit vector describing the direction of the instantaneous velocity of the ski boot centre and is required to transform the one dimensional friction force calculated in the local orientation of the ski to the global coordinate system of the ski course in three dimensions. Wind resistance was modelled by equation 7, where \mathbf{V} is the CoM velocity vector and K_{Drag} the lumped coefficient of wind drag; in this case frontal area and air density are assumed to be constant and lumped in with the wind drag coefficient.

$$\mathbf{F}_{\text{Friction}} = F_{\text{GRF}} K_{\text{Friction}} \mathbf{NV}_{\text{Foot}} \quad (6)$$

$$\mathbf{F}_{\text{Drag}} = -\mathbf{V}^2 K_{\text{Drag}} \quad (7)$$

MATLAB's nonlinear constrained minimisation tool was used to select the run-specific coefficients for ski–snow friction and the day-specific coefficient for wind drag that minimised the residual forces between the model forces, equations 6 and 7 and the previously calculated dissipative force ($F_{\text{Dissipative}}$).

This approach had several problems:

1. In reality, the frontal area of the skier is not constant over the run and neither is the drag coefficient as it is a function of air flow, which depends on both body shape and velocity.
2. The ski friction model does not include the non-linear ski–snow interactions, such as compression, cutting and displacement of snow.
3. The optimal solution for K_{Drag} was correlated to the optimal solution for K_{Friction} . In the future, the instantaneous frontal area of the skier will be included in calculations and the coefficients will only be optimised for sections of the course where the athlete is travelling in a straight line near the mean velocity for the course. However, despite the shortcomings of this approach the optimised coefficients calculated for wind drag (K_{Drag}) and sliding friction (K_{Friction}) were in good agreement with values from literature [11, 12]. K_{Drag} for both runs was found to be $0.4 \text{Ns}^2/\text{m}^2$, while the K_{Friction} for run 3 on harder snow in the morning was 0.03 and the K_{Friction} for run 5 on softer snow in the afternoon was 0.05.

Residual force calculations: After the dissipative forces had been modelled, small residual forces remained that were assumed to be due to extra snow compression, changes in the

athlete's frontal area or errors in the system. It was decided that these residual forces would be added to the first estimate of ground reaction forces divided between the two feet according to the ratio as measured by the RS-scan insole system. The advantage of this approach may be that ground reaction force now contains most of the information that separates the technique of one run from another and that the calculated external forces from different components matches the resultant force calculated from the athlete's CoM acceleration. The disadvantage may be that reduced wind drag from reduced frontal area may be misinterpreted as an increase in velocity as a result of improved application of ski pressure or ground reaction forces in the turn.

Finally, the resulting data allowed the determination of the full kinematics and kinetics of the athlete, including limb kinematics, ground reaction forces, CoM trajectory, ski orientation, net joint torques, and net joint powers.

Component power calculations: Power in watts is a scalar quantity and from 3-D forces power is calculated from the dot product of force and CoM velocity vectors. The power of different external forces throughout each run can be calculated in this way; a positive power means that the particular force is acting to increase the athlete's CoM velocity at that instance in time.

Component energy calculations: Energy change from each force is calculated by the integral of the power for each force. In this way forces that act in three dimensions can be given a scalar value describing the energy contribution to the motion in joules. A positive energy means that the force has done work that has acted to increase the athlete's kinetic energy, and therefore the athlete's velocity. In this analysis of the CoM trajectory of the skier the rotational kinetic energy has not been computed; however, this is also possible if required. When integrating the power to obtain energy it is important to use the reverse of the numerical differentiation process used to compute velocity from CoM position, otherwise, numerical artefacts will be introduced. Two checks were carried out on the component energy calculations. First, the gravitational energy as calculated by integration of the power, this was checked for consistency against the gravitational energy calculated by mass * gravity * Δ height. Second, the kinetic energy calculated by addition of the energy from each external component was checked for consistency against the kinetic energy calculated by $1/2 * \text{mass} * \text{velocity}^2$.

3. RESULTS

The results presented in this section are part of an extremely large digital data set and so the authors find themselves in the unusual position of being 'data rich'. The challenge now becomes how to process these data to extract important information and present it in a way that is useful to coaches and athletes. For example, Figure 6 is a freeze-frame from an animation of the Biomechanical Man negotiating the giant slalom course. The animation may be used to present the complex information in an understandable way to a general audience.

The following results are concerned with the comparison between run 3, in the morning and run 5, in the afternoon

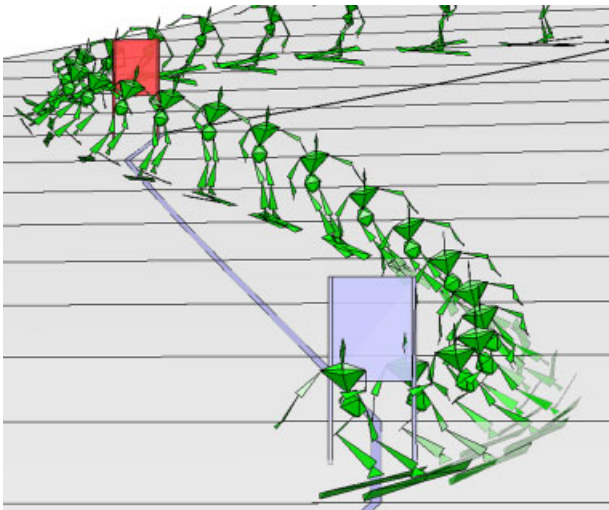


Figure 6. Fusion Motion Capture Output, a New Zealand National Team Member Skiing Giant Slalom.

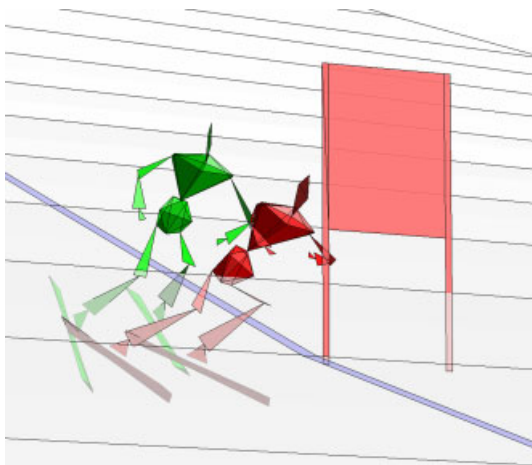


Figure 7. Virtual ski cross. Run 5 (darker red) athlete, leads run 3 (lighter green) at this gate.

(Figures 7 and 10). Race outcome is decided by minimum time to complete the course. The first panel shows the cumulative time of each run in seconds and the difference between the times for each run in hundredths of a second. The gate split times are shown in the second panel. Time zero corresponds to gate 2. Although the lead changes several times, run 5 was faster than run 3 by 0.14s.

A force vector analysis of turn 6 is presented in Figure 8, comparing run 3 and run 5. Turn 6 was chosen because there was large variation in its appearance between the two runs. The black dots represent gate locations. The solid dark blue line is the centre of mass trajectory. The thin lines represent the magnitude and direction of the resultant force vector acting on the athlete's centre of mass. The force vectors are colour-coded; dark red for retarding and light green for accelerating. There are more force vectors in run 5 as it was sampled at 50 Hz, while run 3 was sampled at 25 Hz.

Energy analysis: Table 1 shows the cumulative kinetic energy change produced by each of the external forces acting on the athlete. The table shows that while gravity does positive

work that accelerates the skier; wind drag, ground reaction forces and ski sliding friction do negative work and slow the athlete down.

Contributions of external forces to the athlete power are shown in Figure 9 for run 5. The gate locations are indicated by the numbered vertical lines (dotted). Any force that produces a positive power is desirable as it accelerates the athlete. Gravity always accelerates the athlete in alpine skiing because the athlete always travels down the slope and therefore always has a positive power, while ski friction and wind drag retard the athlete and therefore have negative power. Ground reaction force can produce either positive or negative power depending on technique and course location, which changes the relative angle between the ground reaction force and the velocity vector.

4. DISCUSSION

Is FMC technology a useful tool to optimise an athlete's performance in alpine ski racing?

Race outcome is decided by the time taken to ski the entire course. Figure 10 derived from the athlete's centre of mass trajectory, contains detailed information about the athlete's time profile for each run. The difference between the two run times, (the red line) is scaled by a factor of 100 so the difference of 1% is visible. Run 5 is faster than run 3 by 0.14s, or 1%. A 1% change between gates corresponds to about 0.02s as shown in panel 2 of Figure 10. This is a subtle difference to measure and if turns 4, 5 or 6 were analysed in isolation we would have assumed erroneously that run 3 was faster (see the split times, panel 2 of Figure 10).

The following analysis of the comparison between the two runs is enhanced if the reader views the virtual ski cross animation (timing starts from gate 2). Between gates 2 and 3, run 5 is quicker as the athlete uses an aggressive start, with more skating. The additional skating in run 5 reduces the net negative work done from ground reaction forces by gate 3, (from -4 kJ in run 3 to -2 kJ in run 5 [see Table 1]). It is important to remember that less negative work means less braking from that component of force.

However, between gates 3 and 6, run 3 is faster; a consequence of harder snow conditions for this earlier run, producing less sliding friction. Confirmation of this is found again in Table 1; the difference in the negative work of sliding friction by gate 6 is significant, (-4 kJ for run 3 and -8 kJ for run 5). Negative work, or braking, is performed by forces acting against the direction of motion. After gate 7 the lead changes again, and from gates 7 to 9 run 5 is faster. There are two reasons for this: a different race strategy between gates 5 and 6; and the exceptionally good turn technique the athlete used about gate 6 in run 5. This demonstrates a general time lag between cause and effect often observed in the analysis of gate split times [7].

Even though the snow is slower in the afternoon during run 5, the differences about turn 6 cause run 5 to be faster overall. The colour-coded force vector diagram (Figure 8) was able to pick out the subtle difference in race strategy and technique between the runs around gate 6 (Figure 8). There are

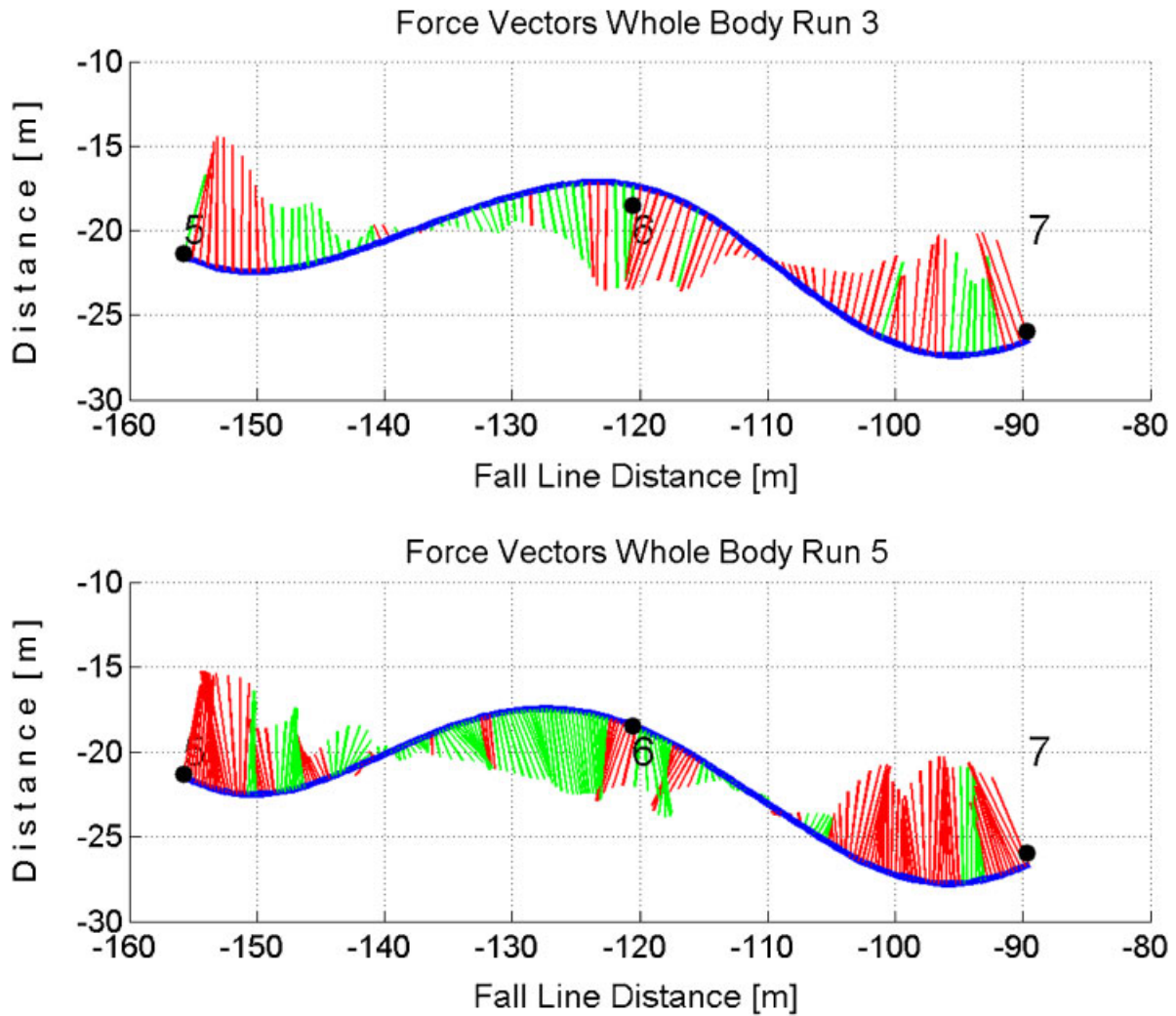


Figure 8. Top: CoM trajectory and force vector analysis of turn 6. The curves are the athlete’s measured CoM trajectory through the gates. The vectors (straight lines) represent the magnitude and direction of net resultant external force acting on the athlete, to simplify the diagram the resultant force is plotted from the CoM even when components of it may originate at the ski/snow interface or centre of wind drag pressure. Red vectors indicate periods of braking and green vectors indicate periods of acceleration. Force vector scale: 4 m ~ 1 g.

Table 1. Energy analysis, cumulative work [kJ] at each gate, comparison between runs 3 and 5.

Gate	Wind drag		Sliding friction		GR forces		Gravitational		Total kinetic	
	Run 3	Run 5	Run 3	Run 5	Run 3	Run 5	Run 3	Run 5	Run 3	Run 5
1	0	0	0	0	0	0	0	0	0	0
2	0	0	-1	-1	-2	-1	6	6	3	4
3	-1	-2	-1	-2	-4	-2	15	15	9	9
4	-4	-4	-2	-4	-4	-4	22	22	12	11
5	-6	-6	-3	-6	-6	-5	27	27	12	10
6	-9	-9	-4	-8	-7	-5	33	33	12	12
7	-11	-11	-6	-9	-11	-6	38	38	10	11
8	-13	-14	-6	-11	-12	-7	45	45	13	13
9	-16	-16	-7	-12	-14	-7	52	52	15	16
10	-19	-20	-9	-16	-33	-26	61	62	0	0

differences in both overall race strategy and turn technique. In run 5, the athlete makes the apex of the turn well before gate 6 and although the result was a longer centre of mass (CoM) trajectory than run 3, it allowed the skier to ski straighter after the gate and accelerate out of gate 6 where the snow rolled over into steeper terrain, (compare the two curves in the two panels of Figure 8, the smoother curve, representing the measured CoM trajectory of run 5, is better than run 3). In comparison, the apex of run 3 is closer to the gate and the athlete almost skis straight into the gate and is then forced to make a very small radius turn after the gate. This strategy is commonly known as a ‘pinch’ and appears to be a poor strategy for gate 6.

The force vector diagram (Figure 8) contains vectors (straight lines) that represent the resultant of the external forces acting on the athlete. This includes ground reaction forces, gravity, wind drag and sliding friction. To simplify the

diagram the resultant external force is graphically plotted from the CoM at each time step and not the locations on the athlete where each component was generated. Because the calculation procedure presented in section 3, Data Processing, is consistent, the resultant external force is also equal to the acceleration vector times the athlete's mass. Both the magnitude and direction of external force applied to the athlete is represented; the red vectors represent periods of braking, while the green vectors represent periods of acceleration. The green accelerating vectors are always inclined slightly forward of 90° to the direction of travel, this means the resultant force has a positive power and will increase the athlete's velocity as well as cause the athlete to make turns through the gates.

Turn 6 contains a high component of 'carving technique' whereby instead of skidding through the snow the front section of the edge of the ski in contact with the snow cuts a banked curve in the snow, the middle and rear sections of the ski then run round on the banked snow track, with some similarities to how a bobsled corners on ice where there is virtually no friction between the bobsled blade and the ice surface.

The kinetically superior turn technique about gate 6 in run 5, results in smoother earlier development of horizontal ground reaction forces. Most of this ground reaction force is turning the athlete, but some of it also increases the ski velocity, (see the difference between the location, length and colour of the vectors just before gate 6 there are more green accelerative vectors in run 5 than run 3, Figure 8) The horizontal component of the ground reaction force in run 5 is developed much earlier in the turn and it is maintained for a larger proportion of the turn and is directed slightly forward of perpendicular to the direction of travel. All these factors combine to give turn 6 a positive ground reaction force power, as shown in Figure 9 by the solid blue line. A positive ground reaction force power around turn 6 in run 5 means that as the athlete leans into the turn the ground reaction forces as well as turning the athlete are actually accelerating the athlete in the direction of travel. An explanation of how the radially directed ground reaction forces can increase the athlete's speed is given below. The advantage of using ground reaction force power to distinguish good technique is that turns on different slope angles and at different velocities can be compared. If only the resultant force acting on the athlete were used then turns on steeper terrain would have a higher acceleration due to gravity and would be erroneously considered always better than a turn on moderate terrain. Similarly, wind drag is higher at higher velocities and therefore turns performed at higher velocity would erroneously be considered worse than turns performed at low velocity because there would be a lower net accelerating force.

The energy analysis confirms that the difference lies mainly in ground reaction forces, which do less negative work between gates 5 and 7 (-1 kJ for run 5 compared to -5 kJ for run 3, Table 1). Figure 9 demonstrates that while gravity always has a positive power and accelerates the athlete, wind drag and ski/snow sliding friction always have a negative power and decelerate the athlete. The horizontal ground reaction forces can have a positive or negative effect, depending on the terrain and ski technique; the reason for this is discussed in the next paragraph.

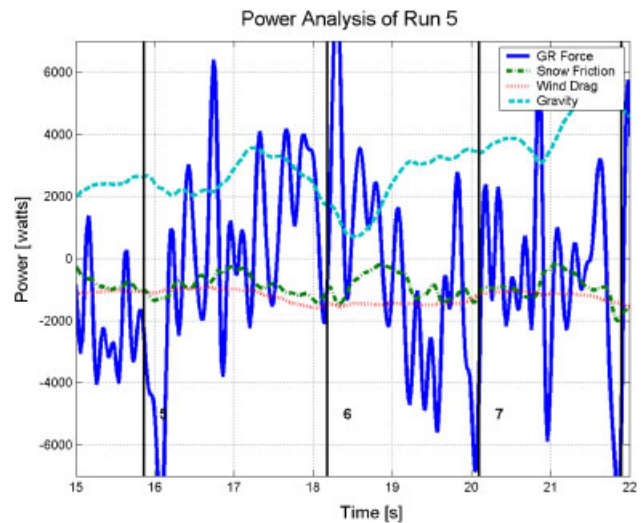


Figure 9. Power analysis of alpine ski racing run 5, gates 5–7. The figure shows a net positive ground reaction force power at gate 6, the result of exceptional technique.

Turn 6 of run 5 demonstrates how an athlete may use ground reaction forces to increase linear velocity through a turn. This is only possible when the athlete's CoM and ski trajectory are diverging as indicated by the location of the arrows in Figure 11. Because the motion takes place in three dimensions, the CoM and ski trajectory may diverge in both the top and profile planes of view. Even if the snow surface is of constant slope, the effective snow slope is reduced as the skier crosses the fall line between turns. The diagram is only a schematic and is not an accurate representation the actual athlete's technique.

There are two opportunities to use ground reaction forces to increase speed through a turn. The first occurs if the athlete has a high effective inclination during the entry phase of the turn. The resulting motion may vaguely resemble a skating stroke as the skis and centre of mass trajectory are diverging in the horizontal plane as viewed from the top. The second occurs if the athlete creates higher ground reaction forces near the turn apex (where the effective snow slope is greatest) and then becomes almost weightless, (in this context weightless means applying very little pressure to the skis and therefore generating relatively small ground reaction forces) through the transition between turns, where the effective snow slope is least and a turn is not required. The increased velocity from regulating ground reaction forces through terrain changes may resemble the 'pumping' an athlete uses to gain speed in half-pipe competitions.

In many situations potential gains from changing technique in order to increase ground reaction force power may be counterintuitive as the perception of increased effort may end up slowing the athlete due to increased ski edge slippage, loss of balance, increased wind drag and poor timing. After the first gate it is possible that the question should be 'How not to lose too much energy though ground reaction forces in a complete turn sequence?', rather than 'How to gain energy in some parts of a turn cycle?' because at high speed there is far more potential to lose energy through poor technique changes than there is to gain energy. It should also be noted that increasing ground reaction forces through flexion and extension of the

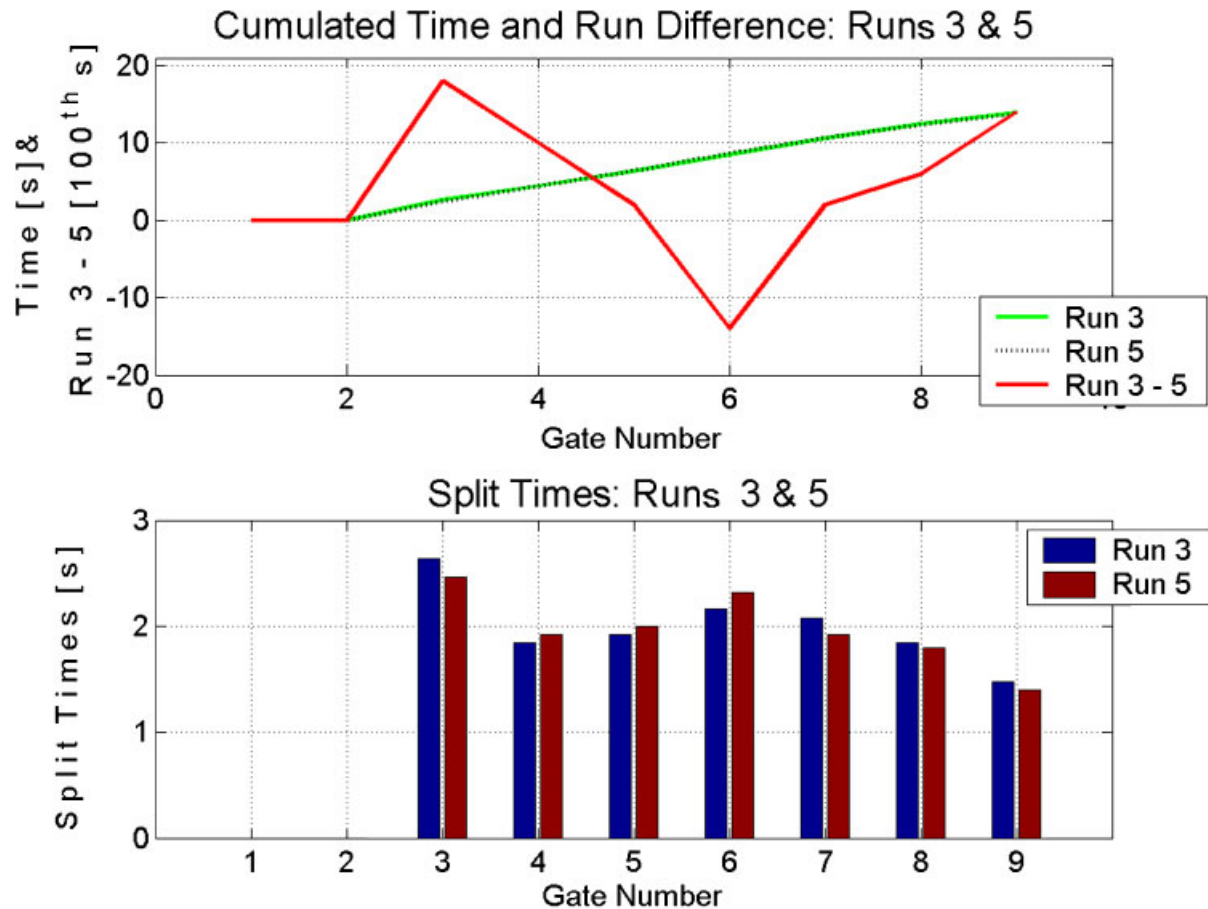


Figure 10. Time analysis, cumulated, difference and gate splits. For gates 4, 5 and 6, run 3 is faster. For gates 3, 7, 8 and 9, run 5 is faster.

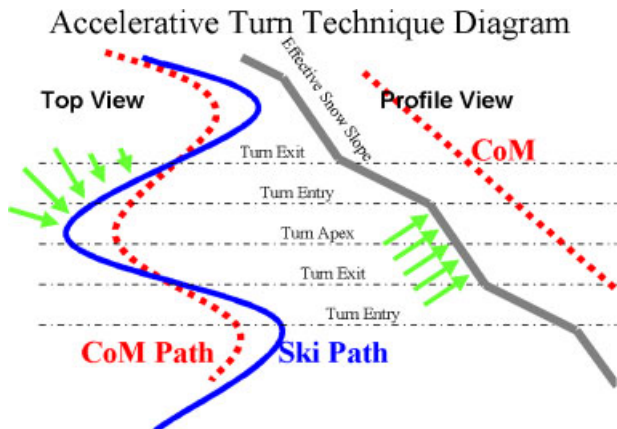


Figure 11. The athlete can use his diverging CoM and Ski path to increase velocity through a turn. The top view is perpendicular to the mean slope area.

knee and hip joints in skiing has limited effect because the length of travel of the CoM relative to the ski centre of pressure is small relative to the large global movements performed. A more effective way to increase ground reaction forces may simply be to use more inclination at the apex of each turn, and further analysis is required to determine the fastest and safest techniques to use dependant on the individual athlete and course constraints.

A kinematic or visual observation of the virtual ski cross animation reveals that the athlete uses a similar leg/snow angle through turn 6 in both runs. However, in run 3 during the entry phase of turn 6, the athlete had less pressure on the skis, resulting in a high leg snow angle and also ski edge slippage. Therefore, very little effective inclination or horizontal force development occurs.

5. CONCLUSION

FMC has been successful in capturing the motion of alpine ski racing through a 10-gate giant slalom course. The validity of the captured data is confirmed by agreement between computed kinematics presented in animated form and video images. It appears the subsequent analysis will be able to improve athlete performance in the future.

Other possibilities include virtual animations of the athlete's optimum performance prior to competing on a specific course, or some sort of acoustic feedback during training. In acoustic feedback the skier might 'hear' a positive acceleration as a high-pitched tone, and any deceleration as a low pitch with the magnitude of the accelerating force represented by tone volume, which could help fine tune the motions required for maintaining a constantly high velocity. The acoustic feedback might be an

audible interpretation of the force vector diagrams presented here.

FMC and force vector analysis appear to be useful tools for the analysis of alpine ski racing. The motion from two giant slalom runs was captured and compared successfully. Although the difference between the runs was less than 1% in time, the analysis was able to pinpoint the essential subtle differences between the two runs. A race is won by a combination of good overall race strategy, an aggressive start, a good choice of wax and the harder snow conditions earlier in the day. It is important that ski technique minimises wind drag while using high sustained horizontal ground reaction forces to make smooth turns. While gravity does most work on the athlete to increase their velocity, it appears the athlete can use ground reaction forces to increase velocity by making use of changes in slope and engaging ski edges early in the turn while the athlete's centre of mass and ski trajectory are diverging.

Future work will attempt to define both an athlete and course specific optimum race strategy and associated optimum turn technique. There are also tentative plans to use an improved version of the system with instrumented skis to analyse forerunners on the FIS world cup race circuit for the purpose of reducing knee injuries and to provide an enhanced experience to the television audience. In alpine ski racing forerunners ski the course before the first athlete to set ski tracks through the gates and check the safety of the course.

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