Development of Fusion Motion Capture for Optimisation of Performance in Alpine Ski Racing

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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 (with less than 20 FIS[1] points) skiing through a complete training giant slalom racecourse were analysed.

FMC consists of multiple light weight sensors attached to the athlete including inertial measurement units (IMUs), pressure sensitive insoles and a global position system (GPS) receiver. 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. FMC fuses the signals from the IMUs and GPS without the need for the post filtering, usually applied to motion capture data, and therefore, maintains maximum bandwidth. The FMC results were stable and relatively independent of motion type and duration unlike other inertial systems available in 2005, when the research was initiated.

Analysis of data collected from an athlete skiing giant slalom 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. The results also 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'.

Race performance was determined 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.

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. Data driven animations and colour coded force vector diagrams were developed to enhance athlete feedback. Inline skating data was also analysed.

[1] 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.

To Emily, Reuben, and Douglas who are more precious than sunshine

Preface

The preface tells a story about a research journey. Along the road 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. After the success in these awards the Foundation for Research Science and Technology made a short professional video which also provides and interesting introduction to the thesis. The videos and poster from the competition are available on the accompanying CD (**Appendices\MacDiarmid 2008\Stage 2 Gold_Science.mpg**) and the video entry is also available on YouTube at the following address:

www.youtube.com/BrodieMAD

The project was originally titled 'The Optimisation of Athlete Movements in Alpine Ski Racing' but was changed to reflect the shift in focus of the research to the development of Fusion Motion Capture. At the start there were many obstacles to overcome. There was no funding, a suitable motion capture system was not available, ski racing was not a high priority in New Zealand, and the nearest ski area was several hours drive away. It soon became apparent that motion capture of giant slalom racing in the harsh alpine environment was not an easy proposition. Several times, contrary to the weather forecast, conditions were favourable. If all the hidden obstacles had been known in advance then a different path might have been chosen, but then ignorance was bliss.

One by one the obstacles fell, but like the heads of the serpent Hydra from Greek mythology more keep appearing. Fortunately, most of Hydra's heads eventually represented the possibility of novel contributions to the body of knowledge and so the mantra was adopted, 'every cloud has a silver lining (and a publication)'.

The research for this PhD resulted in several peer-reviewed publications in journals, books and conferences. It also generated a lot of mainstream media interest, including TV appearances, radio interviews and articles in magazines, newspapers and on the internet.

There is a saying: "May you live in interesting times." It has been and still is an interesting journey.

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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.

Glossary

AP	Anterior Posterior axis of the human body or segment, pointing forwards and generally parallel to the ground.
ASIS	Anterior Superior Iliac Spine, bony landmarks on the front of the sacrum
Bias	1. GPS clock bias or error, both satellite and receiver, because of the unstable receiver clock bias four satellites instead of three are required to fix receiver location in three dimensions. 2. IMU accelerometer, magnetometer or gyroscope low frequency error.
C7	Posterior bony landmark, 7^{th} cervical vertebra, close to the neck joint centre
Carrier-frequency	GPS data and the signal used to measure relative velocity between satellites and receivers.
CI	Confidence interval, usually 95%
CoM	Centre of Mass, the single point in space that represents the mean location an athlete's distributed mass. A force acting though the centre of mass of a body causes no torque or rotation of that body.
CoP	Centre of Pressure, two meanings. 1. The weighted mean location of pressure measurements taken with separate measurement cells that are part of a pressure sensitive insole. 2. An imaginary point between the modelled ski and snow surfaces. If the multiple ground reaction forces acting on different parts of the ski were approximated by a single force, then that combined force would act through the CoP.
DOP	Dilution of precision, 50% of GPS measurements fall within the stated DOP usually in metres. It is different from absolute accuracy.
Differential GPS	Use of a fixed base station to reduce GPS roving receiver errors
Drift	The rate of change of GPS clock bias, because of clock drift four satellites instead of three are required to fix GPS receiver velocity.
ECEF	Earth Centred Earth Fixed coordinate system in which GPS operates. The origin is the Earth's centre. The Z-axis refers to a north-pointing vector through the geographic poles of the earth and the X-axis intersects the Greenwich meridian (where longitude = 0°).
EMG	Electromyography, a measurement of muscle activity.
FMC	Fusion Motion Capture, a prototype wearable motion capture system that combines multiple data streams developed in this thesis.
GPS	Global Positioning System, consists of multiple satellites orbiting the earth and receivers on Earth's surface
GRF	Ground Reaction Forces, forces between the athlete's skis and the snow surfaces
IMU	Inertial Measurement Unit, a motion tracking sensor, in this thesis the IMUs contain accelerometers, gyroscopes and magnetometers.

Inverse dynamic	Analysis when differentiation of positional data is used to obtain rates and accelerations.
IPAQ	A portable handheld computer used as a data logger in this thesis
Kinematic analysis	Analysis of visual parameters such as location or limb angles
Kinetic analysis	Analysis of accelerations, forces, rates and torques, which cannot be determined from a single video frame
MATLAB	A technical computing language used in this thesis to develop fusion motion capture algorithms, to develop data visualisations and analyse the skiing data.
MEMS	Micro-Electro-Mechanical-Sensors, very small electromechanical devices such as sensors and actuators with integrated electronics
MID	Message Identification number in binary communication protocol
MT9B	A type of IMU sensor from XSens Technology
ML	Medio Lateral axis of the human body or segment, generally parallel to the ground and pointing laterally.
PSIS	Posterior Superior Iliac Spine, a bony landmark on the rear of the sacrum
PS	Pubic symphisis, a bony landmark on the front of the sacrum
PCMCIA	Communication slot used to connect the GPS to the IPAQ
Pseudo-range	GPS time of flight data used to measure relative distance between satellites and receivers.
RMS	Root Mean Square, used in this thesis to determine noise in a signal
VMA	Video Motion Analysis
XBus	A communication hub to which multiple IMUs can be attached

Symbols

Bold font represents a vector or matrix quantity and normal or *italic* font represents a scalar value. Subscripts often denote the source or owner of the parameter.

A	Acceleration
A_c	Cross sectional area normal to the relative wind velocity
bo	IMU sensor bias
bT	IMU sensor temperature bias
C_d	Wind drag coefficient
CF	Carrier Frequency
c	Speed of light constant used internally by the SiRF2 GPS chip (299,792,458ms^{-1}), (SiRF Technology Inc, 2005)
E	Estimated error in a measurement
F	GPS signal frequency (1575420000 Hz) used by the SiRF2 GPS chip (SiRF Technology Inc, 2005)
F	Force, a subscript if present denotes the type of force
F_N	Normal force, applied perpendicularly to the ski base
g	Gravity
Go	IMU sensor gain correction
GRF	Ground Reaction Forces
GT	IMU sensor temperature gain compensation
H, h	Earths magnetic vector (in the GLOBAL and local reference systems)
HGRF	Horizontal ground reaction forces
I	1. Identity Matrix. 2. An Inertial Tensor describing the rotational inertia of a body segment.
$K_{Friction}$	Lumped inline skating bearing friction coefficient
K_{Drag}	Lumped wind drag coefficient
m	Mass
PR	Pseudo Range
Q	Quaternion representation of orientation consists of four elements Q0 to Q3, it describes orientation in terms of a rotation of cos(θ/2) about a vector **U**sin(θ/2). More information is provided in Chapter 4.1.1
R	A Rotation matrix (3 by 3) that describes three degree of freedom orientations relative to a global reference system. Each element is a cosine of one of nine angles between the axes of the reference and local body system.
$\mathbf{R}_{\mathbf{LG}}$	A rotation from the local sensor to the global reference system as denoted by the order of the subscripts
Re	Reynolds number, a dimensionless quantity that describes the characteristics of the airflow about the skier as he descends the snow slope
S	Calibrated IMU data
T	Torque or moment
T	Temperature
To	Temperature offset

U	1. Raw binary IMU data. 2. A unit vector describing the axis of rotation used in defining quaternions
V, V, Vel	Velocity
X, Y, Z	Global axes, Z is always vertical and X generally points in the direction of travel and Y floats. Sometimes however X points towards magnetic north.
x, y ,z	Local axes of a body segment, y points along the limb caudally, z is mediolateral and x floats
$\times$	Cross product of two three element vectors
α	Angular acceleration
ε	Residual errors
θ	Angle of rotation
ρ	Density of air
σ	Standard deviation
μ, μ_{F}, μ_{V}	Snow/ski friction or resistance coefficients, static and velocity dependent
ν	Kinematic viscosity of air
ω	Angular velocity
$\perp$	Normal to a surface or perpendicular
$\|\mathbf{F}\|$	Magnitude of a force vector