



Development of a real-time performance measurement and feedback system for alpine skiers

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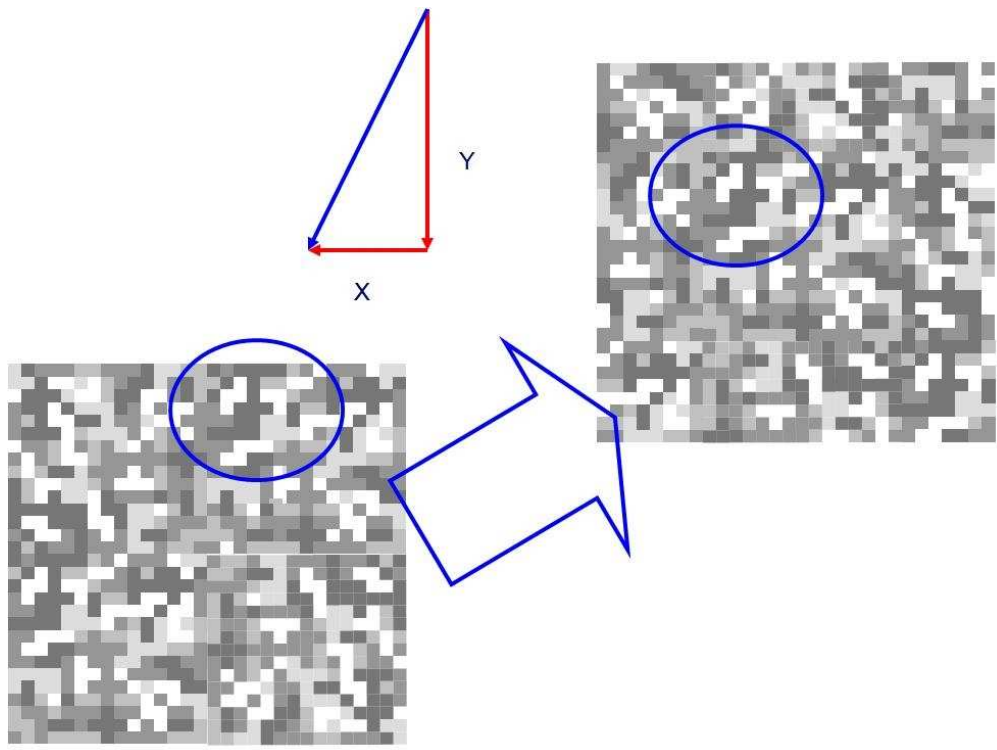


Figure 1. Two successive images taken with an optical navigation sensor with one of the common patterns circled.
259x194mm (96 x 96 DPI)

review



Figure 2. vLink shuttles mounted on skis. Set to measure inside edge of outside ski.
104x69mm (240 x 240 DPI)

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Figure 3. vLink remote with ear buds for real-time audible feedback.
104x96mm (240 x 240 DPI)



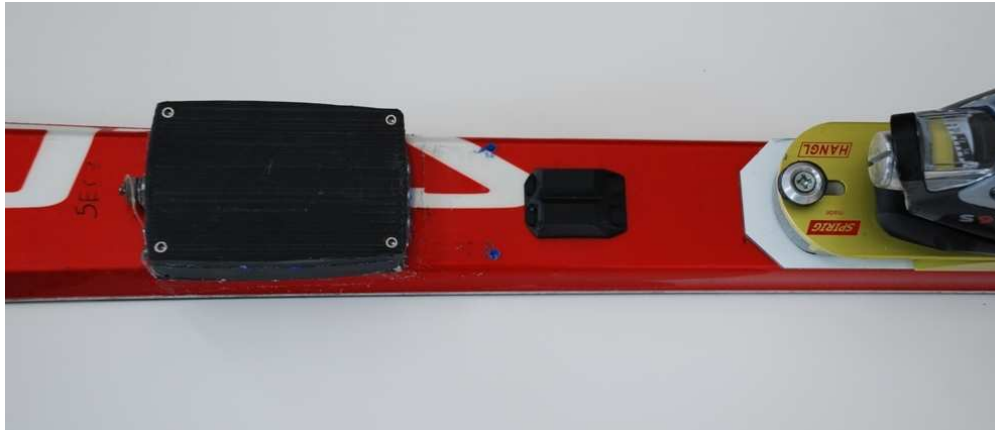


Figure 4. Early vLink prototype with sensors mounted on top of a ski and windows in ski to allow sensors visibility of snow.
83x35mm (300 x 300 DPI)

Peer Review

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Figure 5. Early vLink prototype with sensors mounted on the tail of a ski.
125x96mm (200 x 200 DPI)

Review

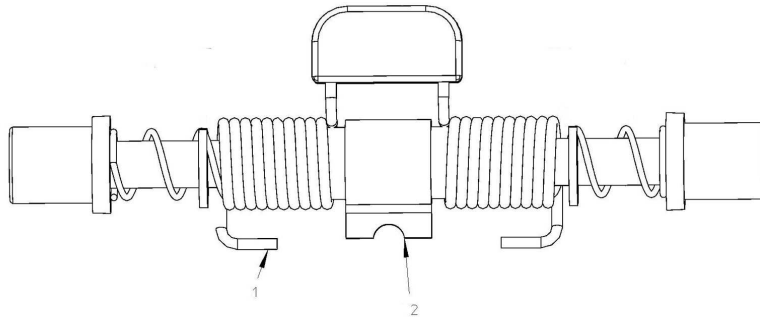


Figure 6. vLink suspension with uni-directional torsion spring [1] engaged friction damper [2].
83x41mm (600 x 600 DPI)

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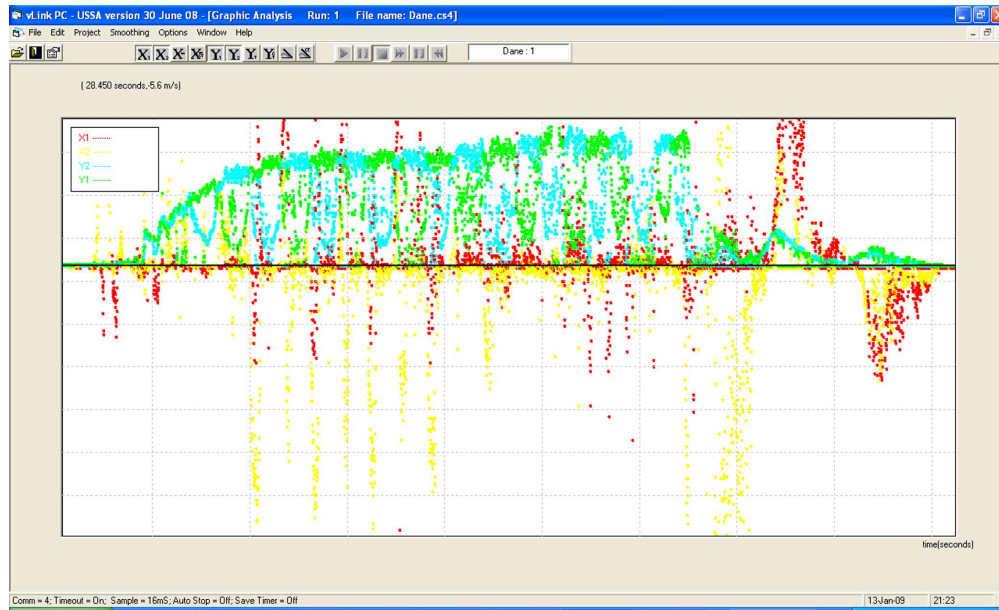


Figure 7. Raw vLink Data. X axis is time in seconds. Y axis is speed (m/s) for the blue and green points which are forward speed from left and right shuttles respectively. For the red and yellow points, which are lateral displacement from left and right shuttles respectively, the Y axis is distance in millimeters, with positive values being displacement to the right and negative values being displacement to the left.
177x107mm (300 x 300 DPI)

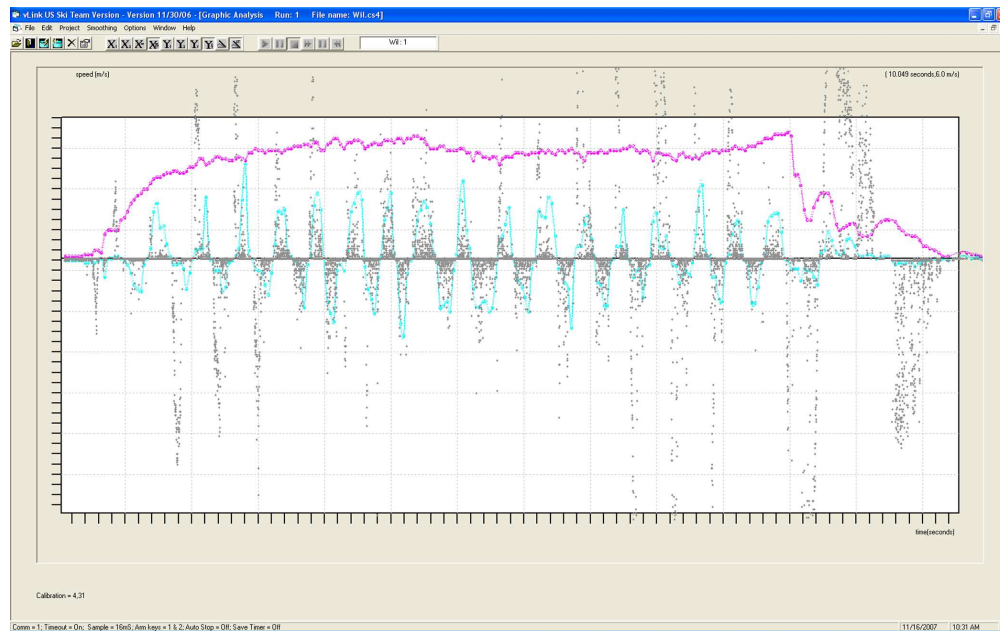


Figure 8. vLink data processed and fitted with Catmull Rom Splines. The X axis is time in seconds. The Y axis is speed in m/s for the magenta spline data, which represents the forward speed, derived from the forward speed of the shuttle that is in contact with the snow. The gray points are lateral displacement in millimeters. The cyan represents the approximate edge angle (in degrees) which is derived from the difference between the forward speed measured by the right shuttle minus that measured by the left shuttle.
177x110mm (300 x 300 DPI)

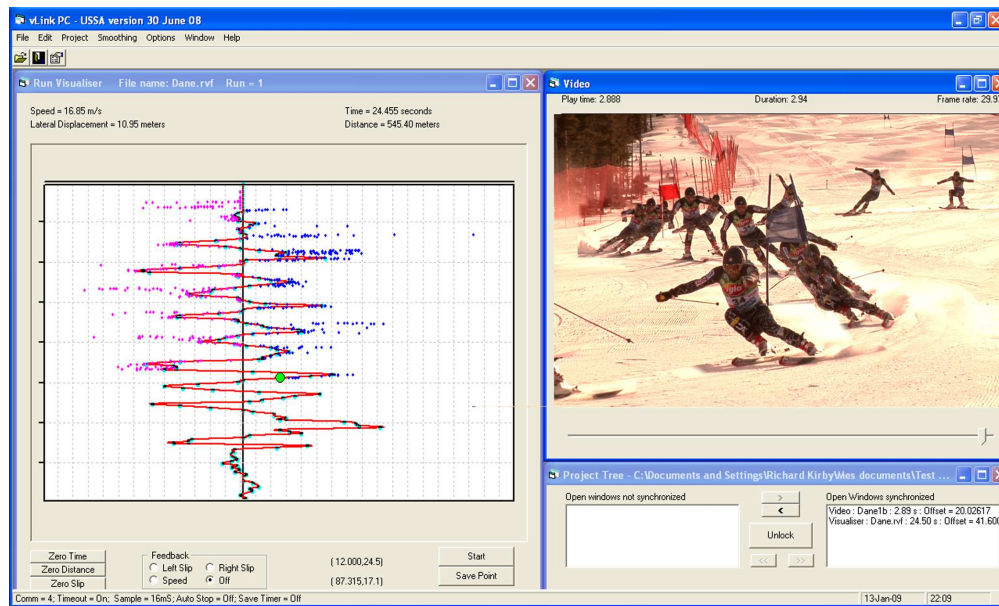
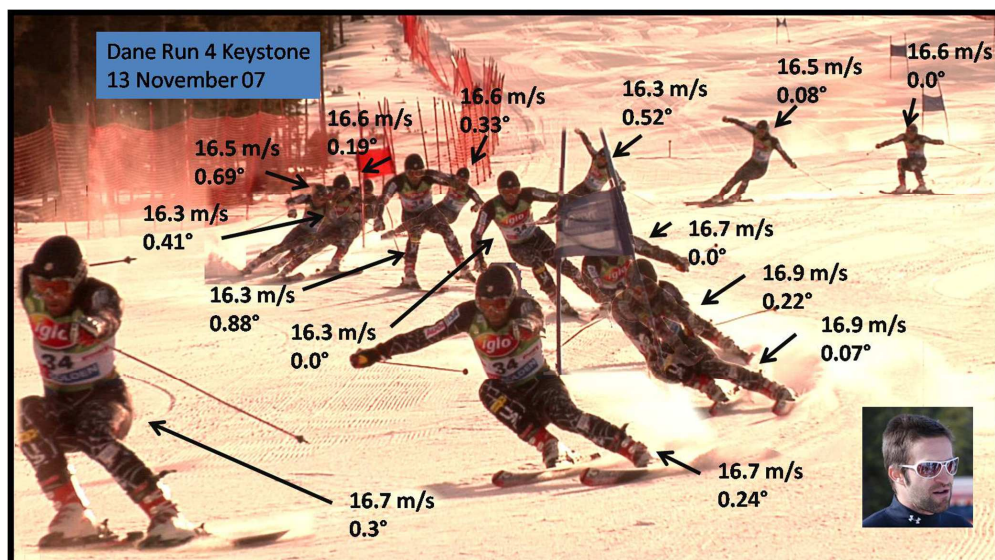


Figure 9. vLink data synchronized with a strobe video. In the graph the Y axis is time and in increases in the downward direction. For the red spline the X axis of the graph represents the approximate ski edge angle. The Magenta points are lateral displacement to the skier's right in millimeters and the blue points are lateral displacement to the skier's left, also in millimeters.
177x106mm (300 x 300 DPI)



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Figure 10. Photomontage of a US National Team skier running Giant Slalom gates. Each skier image contains a vector of the skier's speed in m/s and the angle between the skier's direction and the direction his skis are pointed.
177x98mm (300 x 300 DPI)

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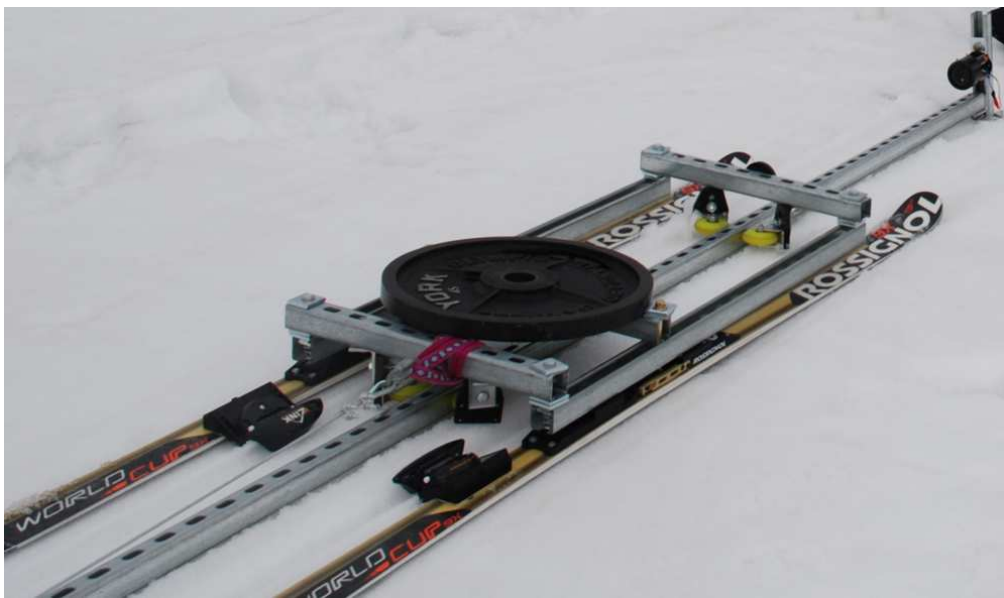


Figure 11. Validation test apparatus consisting of a sled running along a monorail.
83x49mm (300 x 300 DPI)

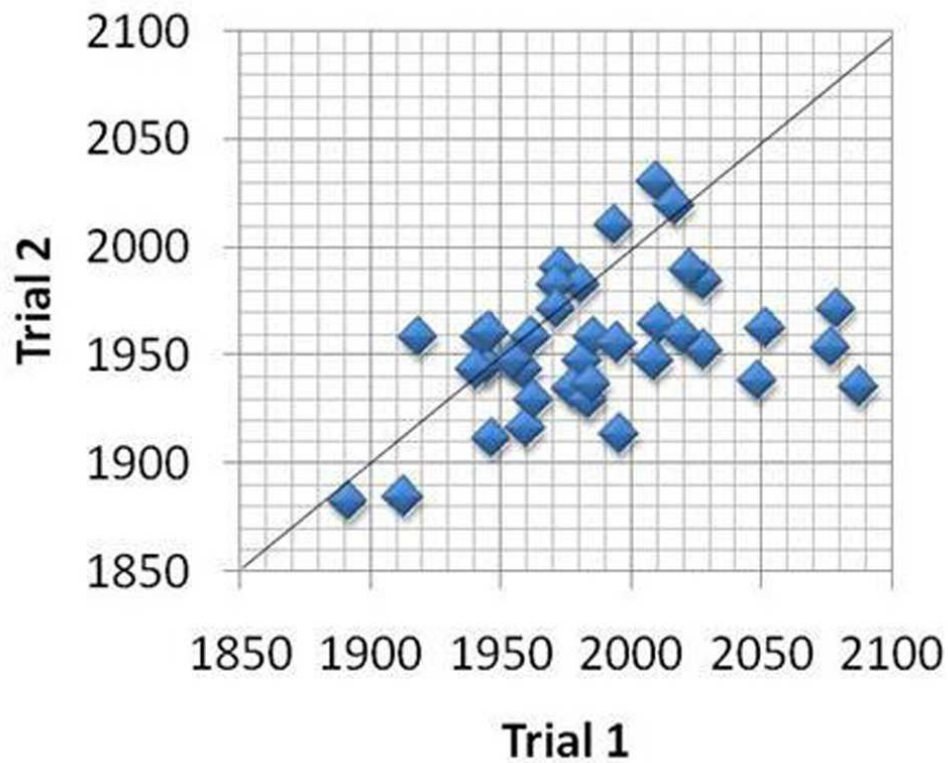


Figure 12. Results of validation test. X axis is distance in millimeters measured by vLink sensor on the left ski and the Y axis is the distance in millimeters measured by the vLink sensor on the right ski.

83x72mm (300 x 300 DPI)

Development of a real-time performance measurement and feedback system for alpine skiers

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Short Text for TOC

With the difference between places in Alpine ski racing coming down to a hundredth of a second, teams are looking to new high-tech methods to train Alpine racers. This paper explores the development of a real-time feedback system for training alpine ski racers

Figures for TOC

Figures 2 and 10

1. Introduction

Feedback has been shown to be important for all aspects of motor behavior [1] and is our brain's link to the body and to the environment. Müller states "Numerous investigations in the area of motor learning and technical training have indicated in concert that suitable feedback systems can significantly contribute to shortening acquisition time according to the principle of objectively supplementing rapid and immediate information" [2].

To date, sport scientists have used video analysis of alpine ski racers as the primary tool for providing athletes with feedback related to technique and tactics. However, many racers and coaches perceive the delay between performance and video feedback (often many hours) as detrimental to the effectiveness of video as a feedback tool.

More rapid acquisition of the correct movement patterns in alpine skiers could be obtained if skiers were to receive real-time feedback on aspects of their technique that they are trying to improve.

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3 One of the characteristics of a cleanly carved turn, often considered the ideal turn
4 both by racers and recreational skiers, is that the ski does not experience any lateral
5 displacement, or slip. For racers, lateral displacement produces braking forces and
6 while braking is sometimes required, the best racers are able to minimize the amount
7 of braking force due to lateral displacement. For recreational skiers, a cleanly carved
8 turn provides the most control and the most thrills as the skis' edges bite deeply into
9 the snow allowing quick, high-*g* turns.
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14 This paper describes the development of the vLink racing computer, a system which
15 measures the forward and lateral displacement of alpine skis and converts the lateral
16 displacement into real-time audible feedback. In addition, the results of a study of the
17 effectiveness of using real-time audible feedback by young alpine ski racers are
18 presented.
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26 **2. The Carved Turn**

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28 A carved turn is a turn where every point on the edge of the ski passes through the
29 same point on the snow. It is performed by putting the ski on edge through a
30 combination of ankle and knee angulations without pivoting the ski around the
31 vertical (normal to the ski) axis. As the ski is placed on edge by the skier, the tip and
32 the tail of the ski, which are substantially wider than the waist of the ski on a modern
33 carving ski, make contact with the snow. The weight of the skier causes the waist of
34 the ski to be pushed against the snow, but since a ski is much stiffer side to side than
35 top to bottom, the ski bends into an arc top to bottom. When bent into an arc with no
36 torsional load around the axis normal to the ski, the entire length of the ski's edge
37 rides in the groove initiated by the tip of the ski.
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42 In a carved turn, the radius of the turn is determined by the shape of the ski's side-cut
43 (the hourglass shape of the ski's edges) and the angle the ski's edges make with the
44 surface of the snow. A ski's side-cut is usually marked on the ski in terms of a radius
45 in meters. This ski radius refers to the radius of the circle that would be formed if one
46 extended the side-cut of the ski into a full circle. A ski made for rapid turns, a slalom
47 ski, may have a 14m side-cut and one made for a speed event, like downhill, may
48 have a 45m side-cut. The radius of the turn that the skier is capable of making, while
49 keeping the ski carving, is a combination of the ski's side-cut and the angle that the
50 ski makes with the snow. A large side-cut ski (small ski radius) or large edge angle
51 will create a turn with a smaller radius.
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56 Racers consider a carved turn to be the ideal racing turn because there is no braking
57 effect. Recreational skiers that desire to perfect their technique also prefer the
58 cleanly carved turn in that it provides the most control and highest *g*-forces possible
59 in turning skis.
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3 Carved turns, however, are considered by many to be more complex to execute than
4 the more standard slipped or drifted turn. This is because in a carved turn the skis
5 must be put on edge before the skier leans into the turn. Once the skis are put on
6 edge it takes a finite amount of time before the skis bend into an arc and start to
7 change direction. Timing the inward lean and change of lower body angles to exactly
8 coincide with the increasing centrifugal force requires very subtle and complex
9 movement patterns. For most skiers, it is far easier to initiate the turn by pivoting the
10 ski around the axis normal to the plane of the ski and skidding the skis until the skis'
11 direction changes due to the friction forces on the skis from the snow's surface. It is
12 these friction forces that turn a ski in a standard slipped or drifted turn that cause the
13 significant reduction in speed that racers are trying to avoid.

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19 What makes executing a perfect carved turn even more challenging is that it is
20 extremely difficult for a skier to detect small amounts of lateral displacement. Often a
21 skier will initiate a carved turn with a small amount of drift and then lock the skis'
22 edges into a true carved turn. This small amount of drift may be measured in
23 millimeters and occur in one tenth of a second, making it impossible to measure
24 through previous means.
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30 31 **3. The Objectives driving the development of the vLink racing computer**

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33 An effective real-time training tool for alpine skiers would need to be able to measure
34 lateral displacement of each ski with respect to the snow and convert the measured
35 lateral displacement into real-time feedback such that the skier is made aware that
36 the ski edge is not tracking in a clean arc.
37

38
39 Since skis are almost always on edge and accomplished skiers use both the inside
40 and outside edges of both skis to carve, the ideal training tool should be capable of
41 taking measurements from both skis.
42

43
44 Additionally, the system must not affect the performance of the skis and must be
45 removable for races as electronic measurement systems are not allowed on skis
46 during a race.
47

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49 Lastly, the feedback mechanism must provide accurate and timely feedback on the
50 amount and timing of lateral displacement, but minimize distraction to the skier.
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54 55 **4. Sensor Technology Selection**

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57 The accurate measurement of ski speed and displacement has been attempted using
58 a number of different methods over the past 30 years. These methods include
59 mechanical wheels [3], laser interferometers [4], radar, accelerometers,
60 magnetometers, gyroscopes and GPS [5].

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3 Accurate measurement of ski speed and displacement, however, has eluded
4 designers up until recently for the following reasons:
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- 7 • Skis are constantly changing planar orientation relative to the snow.
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- 10 • Snow comes in a multitude of forms, from ice, to breakable crust, to ultra-light
11 powder.
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- 13
- 14 • Skis are in a very rugged environment with shock forces measured as high as
15 1000 *g*, large temperature extremes and rapid temperature changes (e.g.
16 going from a waxing room at 20 °C to snow at -20 °C.)
- 17
- 18
- 19 • Snow turns to water in warmer areas of a run (at lower altitudes and in the
20 sun) and refreezes at the top of the lift at higher elevations and in the shade,
21 freezing most mechanical systems.
- 22
- 23
- 24
- 25 • Skiers move fast, over 50 m/s for competitive downhill skiers
- 26
- 27
- 28 • The time difference between top skiers can be as small as 1/100th of a second
29 which can be easily lost or gained with a few more or less millimeters slippage,
30 thus a useful system would have to be accurate down to the millimeter level.
- 31
- 32
- 33 • Turns can be as short as 1 second, requiring data collection in the 100 Hz
34 range to accurately characterize all elements of the turn.
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38 In the late 1990's Hewlett-Packard Company developed a new type of optical sensor
39 that was designed to replace mechanical ball mice. This new type of sensor took
40 high speed sequential images of a surface and processed them in an Optical
41 Navigation Engine, which detects patterns in the images, identifies common patterns
42 between two successive images, and determines a shift in those patterns, resulting in
43 an accurately measured X and Y displacement (Figure 1).
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47 Optical Navigation Technology (ONT) revolutionized the computer mouse market
48 almost overnight by replacing older style mechanical ball mice with non-contact
49 optical sensor mice which are not sensitive to the build-up of dirt.

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51
52 ONT sensors showed promise in solving the issues related to using other sensor
53 technologies, specifically:
54

- 55 • ONT sensors can be made less sensitive to planar orientation than other
56 technologies by correctly designing the optical system to have a sufficiently
57 large depth of field.
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- ONT sensors can image a wide range of surface types without mechanical interaction; which allows them to be used in any snow condition.
- ONT sensors, which are silicon chips, are inherently rugged and can survive the shock and vibration that skis are exposed to with a proper suspension system.
- ONT sensors don't have mechanical parts and if properly enclosed are not effected by moisture that may refreeze.
- ONT sensors can be made to operate at relatively high speed with correct optical design.
- Off-the-shelf ONT sensors have a resolution of 0.05 mm compared to the best DGPS systems that have a resolution of 10 cm and more affordable GPS systems with a resolution of 1m.
- ONT sensors are capable of data collection rates as high as 6500 Hz which compares to 20Hz for high end DGPS and 1 Hz for more affordable GPS systems.

5. The vLink racing Computer – system overview

The vLink racing computer consists of two articulated “shuttles” (Figure 2) mounted on the inside edge of each ski. These shuttles follow the surface of the snow using a compact unidirectional damped suspension system and each shuttle contains an ONT chip which contains a CMOS photo sensor array and an Optical Navigation Engine, in addition there is a microcontroller, a 2.4 GHz transceiver, a power supply, and either a single AA or two AAA batteries for power. Each shuttle weighs a mere 132 grams.

The shuttle wirelessly transmits forward speed and lateral displacement to a receiver (Figure 3) that the athlete wears. When set to provide lateral displacement feedback, the receiver converts lateral displacement into a series of beeps. Each beep indicates a certain amount of lateral displacement depending on how sensitive the user has configured the remote to be. At the highest sensitivity setting, each beep signifies 0.5 mm of lateral displacement.

A second kind of feedback is also available that takes the forward speed and converts the speed into a tone with a frequency which is proportional to the speed. The tone changes with acceleration or deceleration. This allows athletes to determine precisely what movement patterns cause an increase or decrease in speed.

6. Design Challenges

a. Speed

Commercially available optical mouse sensors are designed for hand movement speeds (typically 1 to 2 m/s) and to tracking displacement on relatively smooth surfaces (desktops). Competitive skiers regularly exceed 50 m/s and snow is very coarse compared to the surface of a desk or mouse pad.

The first major engineering challenge was to increase the speed of an optical mouse sensor to allow it to function at ski speeds. Designing an entirely new sensor was prohibitively expensive as well as impractical due to patent protection of much of the optical mouse sensor technology. Thus, the design team started with an existing mouse sensor and made modifications that would increase the speed by a factor of about twelve. This was accomplished by redesigning both the imaging system and the illumination system of standard optical mouse sensor.

In theory, the frame size and the frame rate of an optical mouse sensor determine how fast an optical mouse sensor will function. Optical mouse sensors normally need an overlap between consecutive images of two thirds in order to detect the speed. If the frame size (the size of the surface being imaged) is 1.8 mm square, then the frame can only shift up to $1.8 \text{ mm} / 3 = 0.6 \text{ mm}$ between images. If the frame rate is 6500 Hz then the maximum measureable speed would be 3.9 m/s which is an extremely high performance sensor used in gaming.

Increasing the frame size to 18 mm and redesigning both the imaging and illumination systems to match provided a theoretical tenfold improvement in maximum speed.

Redesigning the illumination system was the most challenging part of increasing the speed. The design team needed to keep the power consumption low, which meant using a single LED as an illumination source (the single LED uses more power than all the other components combined), but it was necessary to illuminate a surface area that was 200 times larger than that normally imaged by an optical mouse sensor.

In addition, the design team needed to increase the depth of field of the illumination (which comes in at an oblique angle) to match that of the optics and needed to eliminate the dark spot in the middle of the illumination cone characteristic to LEDs, which is caused by the cathode and reflective cup. This dark spot confuses the Optical Navigation Engine, because it doesn't move while the rest of the patterns does.

The illumination system uses a single LED and a collimation lens which has four distinct quadrants. The quadrants break the illumination cone that comes from the

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3 LED into four independent beams and slightly overlaps these beams to create evenly
4 distributed intensity with a collimated beam over the entire imaging surface.
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7 While the redesigned optics theoretically increased the mouse sensor speed to 39
8 m/s, the consistent patterns created by the rich texture of snow and the evenness of
9 the illumination system allow actual speed measurements up to 50 m/s under many
10 conditions.
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12 13 14 15 **b. Suspension and mounting**

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17 Skis experience extreme shock and vibration. The ski company, Rossignol,
18 measured these vibrations by placing accelerometers each centimeter along the
19 surface of a pair of World Cup downhill skis. They measured shock loads from 9 *g*
20 under the ski binding to as high as 1000 *g* at the tip and tail of the ski during a high
21 speed run made by an elite skier [6].
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25 Additionally, skis are constantly changing angular orientation relative to the surface of
26 the snow. An elite skier will go from a 65 degree edge angle on one side to a 65
27 degree edge angle on the other side in under a second.
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29
30 To get accurate measurements using ONT, it was necessary to develop a mounting
31 and suspension system that keeps at least one shuttle within imaging distance and
32 orientation of the snow surface, while surviving the extremely harsh environment that
33 elite skiers subject their skis to.
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35
36 Initially the measurement system was incorporated into the body of the ski (Figure 4),
37 by specially modifying skis with windows. This was impractical as the modification
38 changed the bending characteristics of the skis as well as the snow particles thrown
39 in the air by the skis obscured the sensors.
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42
43 The second attempt (Figure 5) involved installing the system on the tail of the ski.
44 This posed a different set of problems including the much higher *g*-forces at the tail of
45 the ski, which made it nearly impossible to keep the sensors a constant distance
46 away from the snow, as well as interference with how the ski turned (the shape of the
47 tail of the ski has a major impact on how the ski release the edge in exiting a turn).
48

49
50 The configuration that solved the problems involved putting sensors in an outrigger
51 arrangement to the side of the skis just behind the rear binding (Figure 2). The boot
52 and rear binding provide good protection for the vLink “shuttle” and being to the side
53 of the ski prevents snow in the air from interfering with the imaging.
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57 Keeping the vLink on the surface of the snow, however, posed a problem because
58 we were dealing with vibration in the 9 *g* range. Initial tests were done with a spring
59 loaded system, but the shock loads caused the shuttle to swing violently from one
60 limit stop to the other when the vLink was on the edge of the ski that was elevated

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3 above the snow. These violent impacts on each turn quickly turned our early
4 prototypes into a pile of shattered components. The next step in the evolution of the
5 suspension system involved adding a damping system, which solved the shock
6 problem, but when enough damping was added to allow the vLink shuttle to survive
7 the shock loads, the vLink shuttle wouldn't return to the snow surface fast enough to
8 accurately collect data.
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12 A novel damping system design was developing using a friction damper, similar to
13 that found in notebook computer hinges, combined with a torsion spring. As the
14 vLink shuttle starts to retract, the torsion spring clamps down on an axel shaft, which
15 engages the friction damper. As soon as the shuttle starts to descend, the torsion
16 spring releases its grip on the axel shaft, disengaging the friction damper and
17 allowing a rapid un-damped return (Figure 6)
18

19
20
21 Attachment to the ski needed to be simple and non-invasive as racers are very
22 particular about their skis and competition rules change frequently. Screws were
23 initially attempted, but world cup athletes refused to allow screws to be put into their
24 skis. The design team evaluated different types of adhesives, eventually leading to
25 the use of VHB (Very High Bond) a 3M adhesive with 0.69 MPa of tensile strength,
26 which is a high-tech version of double sided sticky tape.
27

28
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30 The VHB had several benefits:

- 31
32
- 33 • Vary rapid (less than 5 minutes per pair of skis), tool free installation.
 - 34 • Removable without leaving a trace on the ski, and
 - 35 • In a hard fall, the tape bond would break before anything else, acting as a
36 protection mechanism for the vLink and the skier
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43 44 **c. Condensation** 45

46 On a sunny, but cold day, the sun warms the body of a vLink shuttle and
47 consequently the air inside. When a warm vLink shuttle is put on cold snow, the
48 glass window through which imaging occurs, contacts the snow and cools, much
49 faster than the plastic of the rest of the shuttle body. This creates a situation similar
50 to that of a humid bathroom with a cool mirror. The warm air on the inside of the
51 shuttle comes in contact with the snow cooled glass of the window and the air in the
52 vicinity of the window drops below the dew point. Any moisture in the air near the
53 window on the inside of the vLink shuttle then condenses out on the inside of the
54 window, impeding accurate imaging.
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58
59 The design team's initial efforts to solve the problem involved purging the air from
60 inside the vLink shuttles and refilling with dry nitrogen that had less than 3% RH
(relative humidity). The vLink shuttles where then hermetically sealed using a solvent

1
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3 bond and tested by pulling as close to a full vacuum as our vacuum pump was
4 capable of. The quality of the seal was measured by measuring the differential
5 between the vacuum being held by each vLink shuttle and the vacuum in a reference
6 cylinder that was brought to the same level of vacuum at the same time as the vLink
7 shuttle. .
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11 To the design team's surprise, even with dry nitrogen at 3% RH, condensation still
12 occurred. It was theorized that small quantities of water were retained in the PCB
13 and plastic parts and over time the water vapor in these components equalized with
14 the dry nitrogen.
15

16
17 This problem was eventually resolved by adding silica gel packets inside each of the
18 vLink shuttles. When combined with a dry nitrogen purge, shuttles with no damage
19 to their hermetic solvent bond have been in consistent use for several years without
20 experiencing condensation.
21
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23 24 25 26 **d. Audible Feedback**

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28 The feedback was developed in conjunction with the athletes, coaches, the sports
29 science team, and the athletic director of the US Ski Team. The USST has specific
30 requirements for the audible feedback which included:
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- 32
33 • The delay between the event that caused the feedback and the feedback had
34 to be short enough that the athlete perceived the feedback as coinciding
35 exactly with the event.
36
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- 38 • The feedback had to provide an intuitive measure of the quantity of slip so the
39 athlete could tell the difference between low levels of slip and high levels of
40 slip.
41
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- 43 • The feedback had to be adjustable for snow conditions and for the level of the
44 athlete.
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- 47 • The feedback had to be simple enough to virtually eliminate the athlete's
48 learning curve.
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54 Skiers and coaches typically divide a turn into phases. Commonly these phases
55 include: transition (skis are flat on the snow crossing from one set of edges to the
56 opposite set of edges), initiation (edging starts), fall line (skis are pointed straight
57 down the hill), maximum pressure (highest centrifugal force in turn) and exit (skis
58 coming down off the edges).
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3 Skier errors can be divided into two main groups: technique and tactical. Drifting the
4 skis to initiate a turn would be considered a technique error and starting a turn too
5 early or too late would be considered a tactical error. Tactical errors can appear to
6 be technique errors. For example, if a skier initiates a turn too late, they may have to
7 slip to get the skis redirected prior to the turn exit.
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11 Often technique and tactical errors are associated with a certain phase of the turn.
12 As in the previous example, tactical issues with the timing of turn initiation could show
13 up later at the maximum pressure phase. A slalom turn is the quickest of the turns in
14 ski racing and each turn typically takes 1 second. These constraints drove the
15 design team to select a minimum frequency of 8 Hz for the feedback. Higher
16 frequencies were considered, but with less than one eighth of a second to give
17 feedback, there is not enough time to give multiple beeps to indicate slippage
18 magnitude.
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23 Once the frequency of the feedback was chosen it drove a number of other
24 decisions, including transmission rates for the transceivers, clock speed for the
25 processors, and how much of the time critical code would have to be written in
26 assembler for speed.
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30 In order to minimize the learning curve, we tried several different types of sounds and
31 sound patterns for the feedback. These were tested on groups of athletes and
32 coaches. We settled on the simplest of sounds, a short beep or “blip” like a Geiger
33 counter, and the magnitude of the lateral displacement was proportional to the
34 number of ticks heard.
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38 At the most sensitive level, the athlete hears a Geiger counter like beep for every
39 0.50 mm of lateral displacement. Since this level of carving performance is limited to
40 a small number of the world’s best skiers in perfect snow conditions, a user
41 controllable adjustment was added to allow a matching of the feedback threshold to
42 the skill level of the skier and the quality of the snow surface. Each threshold level
43 allows a certain rate of slippage before giving feedback. The difference between
44 levels is a rate of 0.01 m/s of lateral displacement. Elite athletes use the vLink with
45 the threshold set between 0.03 m/s and 0.05 m/s.
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49 We also found that the feedback was more intuitive if lateral displacement to the left
50 came in the left ear and lateral displacement to the right came in the right ear. This
51 permitted the athlete to internalize the feedback at a subconscious level more readily.
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58 **e. Analysis for Coaches and Sports Scientists**

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3 While the real-time feedback was very practical for the skiers; coaches and sports
4 scientists wanted hard data for more detailed study and analysis.
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7 The typical configuration for the vLink shuttles is to mount one on the inside edge of
8 each ski. This is because in a turn, the inside edge of the outside ski is down and the
9 outside edge of the inside ski is down. Thus in any given turn one vLink shuttle is
10 against the snow, collecting accurate data and the other vLink shuttle is in the air,
11 collecting inaccurate data and measuring snow spray, instead of sideways slip. The
12 challenge in analyzing the data is to determine which vLink shuttle is against the
13 snow and which vLink shuttle is in the air. The raw data (Figure 7) consists of
14 positive and negative slip from each ski and forward speed of each ski, but without
15 knowing which way the skier is turning, one can't delineate true speed or true slip.
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20 The vLink shuttle, which is in the air, "sees" a much larger area of the snow surface
21 than the vLink shuttle which is against the surface of the snow. This is much like
22 looking at the ground below an airplane from altitude vs. just before landing or take-
23 off. The closer one is to the moving ground, the smaller the portion of the ground
24 one sees and the faster it appears to be moving. This is the same with the vLink
25 shuttles, the vLink shuttle that is against the snow surface sees a much higher (and
26 correct because this is the way the optics were designed and calibrated) speed
27 compared to the vLink shuttle in the air. By comparing the forward speed coming
28 from the two shuttles and determining which shuttle has the higher speed; one knows
29 which way the skier is turning. For example, in a right turn, the skier's left ski has the
30 inside edge down and the left vLink shows the higher speed. Many skier's actually
31 call this a left footed turn because the outside ski usually provides more of the turning
32 force. By plotting the difference between the right and the left speed, one gets a
33 cyclical waveform which indicates turn direction with positive values (right shuttle
34 down) being left turns and negative values (left shuttle down) being right turns. While
35 not perfectly accurate, the coaches call this the edge angle, because it is a pretty
36 good indication of the angle that the inner ski makes with the snow.
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44 Once the turn direction is determined it is relatively easy to find true speed and true
45 slippage. Both the true speed and the true slippage come from the lateral and
46 longitudinal displacement of the shuttle which is against the snow. To reduce the
47 jaggedness caused by the discrete digital values that the sensors output, Catmull-
48 Rom splines were fitted to the derived data for edge angle and forward speed
49 (Figure 8).
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53 Once the data was in readable form, coaches wanted it synchronized with video, their
54 main tool. This posed two challenges, first finding a common point in time between
55 the data and the video and second, how ensuring that the video camera and the
56 vLink clocks are running at the same speed.
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59 In video, it is relatively easy to see the point in the transition phase, where the skis
60 are flat on the snow. This is also very easy to see in the data, as it is the point where
the edge angle crosses the time axis. By picking two transitions in the video and the

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3 associated two transitions in the data, the video and data can be synchronized at
4 those two points and the time scale of the video camera and the vLink data can be
5 adjusted to match.
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8 This was further improved (Figure 9) by turning the chart 90° so that the time axis
9 points straight down. In this configuration, the location on the graph represents pretty
10 closely the location on the slope of the skier, because the edge angle lines up pretty
11 closely with the skier's location in the turn. Although technically not accurate, it made
12 it much easier for skiers and coaches to orient the data.
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16 The final and most abstract iteration and currently the easiest to use and understand
17 is the strobe image containing a vector of the skier's velocity (Figure 10). The vector
18 has magnitude (the skier's speed) and direction which is the angle between the
19 skier's direction of displacement and the direction that their skis are pointed. This
20 method of looking at the data allows a very quick analysis of the skier's performance
21 and an explanation (slip, body position, or line) of why speed increased or
22 decreased.
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28 **7. Validation Testing**

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30 In order to use the vLink for research purposes, it was important to determine how
31 accurate and repeatable the vLink data is [7].
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34 Initial tests were carried out on a CNC milling machine. The vLink shuttles were
35 attached to the frame of the milling machine and a textured surface with optical
36 characteristics that are similar to snow was attached to the moving table. The table
37 was then moved back and forth at a precision of 0.005 mm while the vLink shuttles
38 collected data for 5.00 meters of displacement. The mean distance measured was
39 5.00 meters (this is because we used this test to calibrate the vLinks), the standard
40 deviation was 8mm and the typical error was 0.22%. This gave the design team a
41 baseline accuracy and a calibration factor to convert the internal mouse sensor
42 measurement system (counts) into a physical measurement.
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47 Setting up a repeatability test on snow was challenging because after each pass of
48 the vLink, the snow changes slightly. In an effort to try to minimize the effect of snow
49 changes, the design team built a sled with skis as runners and the sled followed a
50 monorail for approximately 2 meters (Figure 11).
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53 The team then collected data from the left shuttle and from the right shuttle
54 independently and plotted left data against right data (Figure 12).
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57 The typical error between the left and right shuttles was 1.57%. Assuming the mill
58 test accurately describes the error margin of the vLink (0.22%) the remaining error
59 (1.57% - 0.22%) comes from the instability of the snow.
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8. Field Trials with Competitive Skiers

a. Method

Twelve racers participating in summer race camps at Mt Hood, Oregon USA were randomly selected to participate in a user test of the vLink racing computer system [7,8]. Selected racers had 5 to 15 years of racing experience with 11 of the racers between the age of 13 and 18 years old. One 43 year old master ski racer also participated. The average age of the racers was 18.9 years old and the group consisted of 5 girls and 7 boys.

Each racer went through a series of familiarization drills to learn how to use the vLink racing computer and to become accustomed to the feedback. Racers were then asked to train for two hours in gates using the system. Racers filled out a survey after their training and were interviewed for subjective comments. Where possible, the racer's coach was also interviewed for subjective comments.

b. Results

Results from the questionnaire are summarized in Table 1. These results showed that 83% of subjects stated that real-time audible feedback of their lateral displacement definitely helped them to better understand their carving skills. In addition, 50% of subjects stated that the real-time feedback definitely helped them improve their carving skills on the first day they used the system.

c. Discussion

The perceived benefits of real-time feedback were clearly demonstrated with 100% of subjects stating that real-time feedback had definitely or probably helped them better understand their carving skills and 83% of subjects stating that the real-time feedback definitely or probably helped them improve their carving skills after only one two-hour session.

While we were not able to evaluate if performance actually improved, we interviewed several of the coaches who believed that they saw improvements in their athletes after the two-hour test. A more in-depth and longer term study that measures actual performance improvements would be a logical next step.

Several comments made by racers during the follow-up interviews help to explain the results. One racer stated that using the real-time feedback system was like "watching a video of myself while I was skiing". This racer felt he was getting the same feedback that he normally gets watching video, but while he was skiing,

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3 allowing him to make immediate corrections to his technique and have immediate
4 feedback that identifies if the results were what he was looking to achieve.
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7 Another racer stated that “I’ve been racing for 10 years and I didn’t know I slipped
8 that badly at the initiation of my turn.” This particular racer had been getting
9 feedback from her coach concerning her drifted turn initiation, but thought she had it
10 under control. In this case the real-time feedback was a validation that her coach’s
11 feedback was correct and she still needed work on her turn initiation.
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14 While the intent of the study was to determine if real-time feedback could help skiers
15 improve technique, one skier stated that the real-time feedback “really helped me
16 understand the issues I have with the timing of my turns”. This skier was initiating
17 her turns too early and was forced to drift out to get around the gate. While she was
18 aware of this tactical issue, the real-time feedback made it clear to her in each gate
19 what she was doing and how much it was costing her.
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23 Several skiers made comments similar to “the audio feedback was distracting at first”.
24 Many racers are highly tuned to certain things (e.g. where the pressure is on their
25 feet) and a new form of feedback is difficult to assimilate. It appeared that skiers that
26 were more familiar with computer or video games were better at adapting to the
27 feedback. This comment also highlighted the importance of the familiarization
28 process. The familiarization process was intended to get the racers accustomed to
29 the feedback without all the difficulties associated with running gates. A longer, more
30 in-depth and more controlled familiarization process prior to allowing skiers to train in
31 gates may significantly improve the benefits of the feedback.
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Table 1 Subject responses following the use of a real-time optical navigation system attached to the skis during training

Did having the device attached to your skis affect your skiing?	Frequency (%)
1. Definitely	0
2. Probably	0
3. Not sure	0
4. Probably not	0
5. Definitely not	100
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Did the real time feedback help you better understand your carving skills?	Frequency (%)
1. Definitely	83
2. Probably	17
3. Not sure	0
4. Probably not	0
5. Definitely not	0
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Did the real time feedback help you improve your carving skills?	Frequency (%)
1. Definitely	50
2. Probably	33
3. Not sure	17

4. Probably not	0
5. Definitely not	0

How often would you like to use real time feedback in training (9 responses)?	Frequency (%)
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1. > 70% of the time	11
2. 30% to 70% of the time	88
3. < 30% of the time	11

How satisfied were you using real time feedback for training?	Frequency (%)
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1. Very satisfied	58
2. Somewhat satisfied	33
3. Neither satisfied nor dissatisfied	9
4. Somewhat dissatisfied	0
5. Very dissatisfied	0
