

Acquisition systems for in situ monitoring of athletes and equipment in curling and snowboarding

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Declaration

I declare that this thesis has been composed by myself and is all my own work except where otherwise stated.

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Abstract

This thesis covers work conducted to develop robust sensing systems which quantify the behavior of sporting equipment in its real environment. The data collected provides an understanding of how the athlete and the equipment are performing. It has allowed further analysis into specific competitive sports, improving training methods, providing equipment performance analysis and advanced equipment selection techniques. The work has focused on snowboarding and curling, both sports are conducted in a cold, harsh environment. Literature and research into previous work on these sports is presented.

This thesis presents a study of the mechanical behavior of snowboards and show how this can be used to enhance training techniques. Procedures for quantifying physical characteristics of a snowboard are examined. A custom built laboratory rig is used to test snowboards under controlled, repeatable conditions. Results from static and dynamic on-slope tests are presented, with reference to technical literature. Correlation between qualitative rider assessment and quantitative laboratory data is shown. The design and iteration of sensing arrangements for on-slope analysis capable are shown. Dynamic testing was performed using custom wireless and hard-wired acquisition systems. The data from static and dynamic testing are correlated with snowboarder performance and its application to current training techniques is discussed.

Systems developed for snowboards were transferred to curling to develop an instrumented curling brush (*sweep ergometer*). The ergometer measured the forces and accelerations involved in sweeping. The results gathered are analysed to present statistical analysis, velocities and distances swept providing users with an individual sweeper profile. The data is the first of its kind in the world of curling, allowing repeatable accurate data for sweeping at Olympic standard. Analysis of force and velocity parameters has contributed to GB Olympic team selection prior to the Turin

Winter Olympics 2006. The MK3 ergometer will continue to be used for team selection before major tournaments and for tactical selection of sweepers during a game. Use of the sweep ergometer has led to improved training adopted by the British Curling team. The novel training regime incorporated data from the sweep ergometer to focus on an individuals' consistency and the amount of energy an individual exerts whilst sweeping. Increasing energy exerted allows greater control of the curling stone as the path and distance the stoner travels can be changer to a larger extent. Systems developed for this thesis provide rapid quantitative feedback that can be used to enhance sporting performance.

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Chapter 1 Introduction

Sporting performance continually pushes both athletes and equipment to its limits, sometimes beyond, in attempts to win. It is inherent in the nature of competition that a broad spectrum of approaches from sports psychology, coaching, dietary studies and scientific analyses are now adopted by top athletes as they strive to be the best in their chosen discipline. Several governments including the Australian and United Kingdom have set up organisations to aid sporting achievement. They provide resources, services and facilities to enable athletes to pursue and achieve excellence in sport while also furthering their educational and vocational skills and other aspects of their personal development. Investments are made by these organisations in the aim to achieve results; technology is often seen as one of the major opportunities during this investment process. These bodies have invested in technologies and techniques similar to those described in this thesis to improve training and coaching technique.

This thesis covers work conducted into developing systems which provide quantitative data, allowing further analysis into competitive sports, improving training techniques and aiding equipment selection. The work was conducted on two competitive sports: snowboarding and curling.

1.1 Snowboarding and Curling History

As different as they may initially appear, they share several similarities, they are now both Olympic sports and competition is fierce. Curling was included in the programme as a demonstration sport in the winter Olympics of 1924 (Figure 1-1) and in 1998 received full Olympic status. The first Olympic snowboard competition also took place at the 1998 Nagano Winter Olympics and has since grown to include 3 Olympic

snowboard events: half pipe, parallel giant slalom and snowboard cross [http:www.olympic.org]. Both sports are physically demanding on the athlete and they are heavily reliant on the technical equipment used. As with all truly competitive sports, equipment used has witnessed dramatic changes during the last 20 years through adoption of the latest materials, this is especially true for snowboarding (Figure 1-1). Another similarity is that equipment used in both sports experience similar conditions. Both curling brushes and snowboards run on a layer of water created by frictional forces between equipment and ice or snow [Penner, 2001. Lind, Saunders 1996]. It is the increased scientific focus on sports equipment to gain greater comprehension of equipment and athlete performance during ‘real’ use that this thesis covers. This thesis describes the systems that have been designed, tested and redesigned to analyse both sports, it provides novel results and datasets for both sports. Quantitative data has been correlated with training techniques to further improve coaching capability and athlete performance.

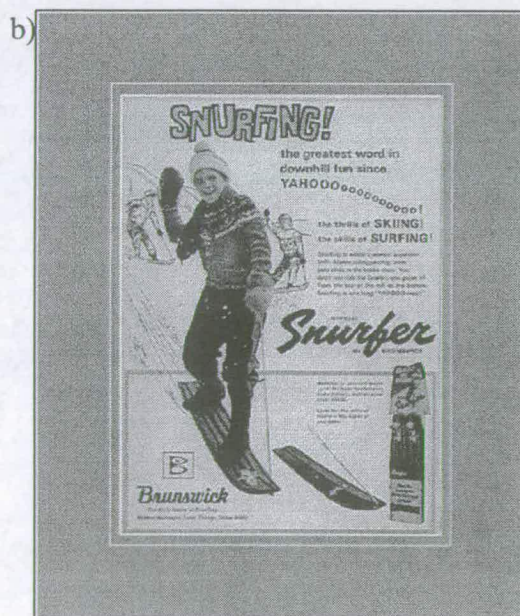


Figure 1-1 Early versions of two sports: a) Curling- Chamonix 1924 Winter Olympics, The British Team. (<http://www.olympic.org/uk/sports>) b) A 1960's advertisement for the first form of snowboard or *Snurfer* (<http://www.toyadz.com/toyadz/snurfer/largesnurfer.html>)

1.3 Coaching Technique

Professional coaches are required to improve the performance of their athletes through all legal means. A coach must continually observe, provide feedback, confirming positive achievements and suggest changes to their technique. Figure 1-2 shows a simplified coaching process model. This model is fundamental to the delivery of any performance coaching project. Other than the use of timing devices such as stop watches, traditional coaching methods relied mainly on the coaches' ability to provide qualitative analysis. Using modern techniques coaches supplement their qualitative observations with quantitative results, providing additional value to the second stage of the coaching process model. Work conducted during this thesis provides quantitative information for coaches, allowing additional data on which to assess and feedback to the athlete.

In reality, this model is too simplistic and further work has since been completed to account for the different forms of quantitative data currently available to coaches [Drawer, 2004]. This thesis presents remote acquisition systems which allow the coach to provide direct feedback during an exercise or activity. The method shown in Fig 1-3 improves on the overall of progression of more traditional coaching techniques (fig 1-2) as feedback can be given during practise. Figure 1-3 illustrates process driven steps taken when providing performance related information to enhance the coaching process. Coaches are provided with the data to deliver quantitative information between stages 1 and 2, 2 and 2b and into stage 3. The majority of the data collected by the GB curling team was used to provide post analysis and feedback of directed practise (stage 3). Once sufficient comprehension of average was achieved real time feedback was given when using the wireless sweep ergometer.

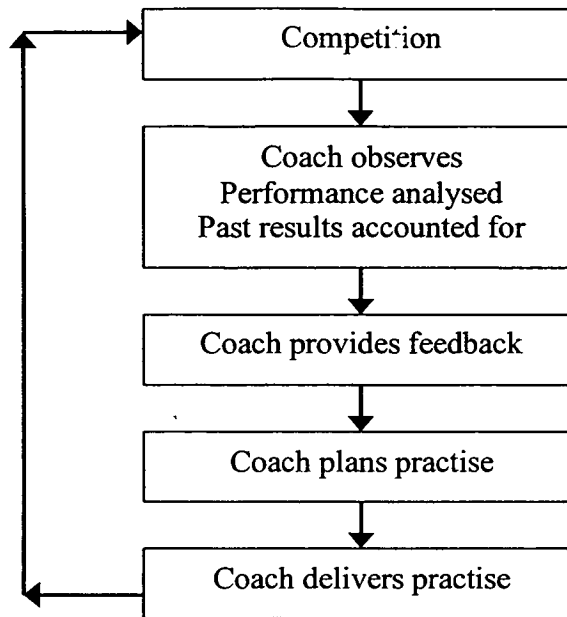


Figure 1-2 A coaching process model (Franks et al, 1983).

As is the case in many sports, performance cannot be accurately analysed only through use of the naked eye. Technology adds extra value to the coaching process. Video-based analysis is one of the simplest forms of augmented feedback that can be used to gain basic understanding of the kinematics of an athlete [Anderson, Collins, 2004]. Events can be reviewed multiple times and individual movements of an athlete can be scrutinised using this process. High speed video-based motion analyses are now widely used not only by professional coaches and top athletes. These systems are commercially available and are for example widely adopted by amateur golfers.

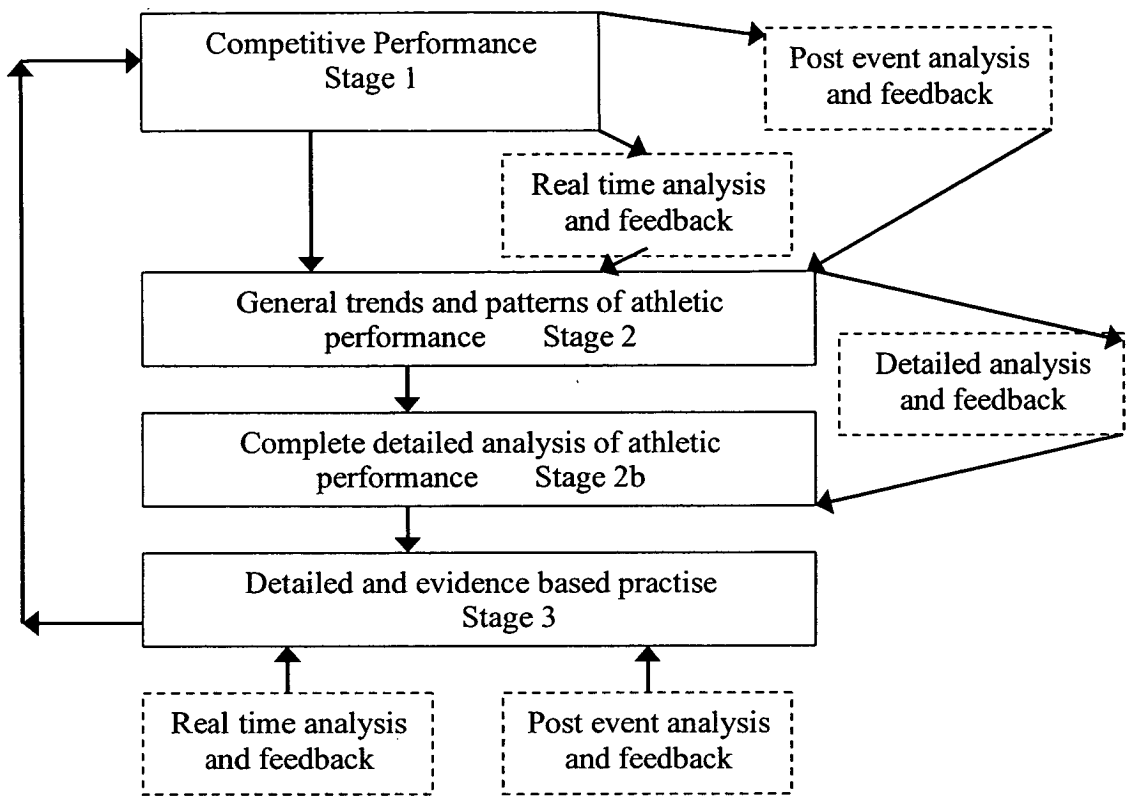


Figure 1-3 The provision of athlete performance data through coaching technology (Drawer 2004).

1.3 Scope of Thesis

Monitoring techniques not only provide coaches with normally unobservable athlete performance information, but are used to provide valuable information about the athletic equipment used. This quantified information provides the platform for design evolution of sporting equipment. Figure 1-4 depicts a simplistic representation of the types of studies used within the field of Sports Engineering. Studies are represented by black boxes. The relevance of the study to coaches is represented by the area in the blue oval; relevance for Manufacturers is represented by a green oval, the area in which overlap occurs shows that the studies are relevant to both manufacturers and coaches. The red

dashed section depicts the core area in which work was conducted for this thesis. This thesis covers both laboratory based experimentation and real environment testing which are relevant to both coach and manufacturer. The information gathered for curling has been used to initially understand sweeping technique, improve individuals technique and as a fitness indicator.

Monitoring Techniques

Techniques used for 'real' environment studies are as applicable to equipment monitoring as they are for an athlete study. For example, the previously mentioned video analysis techniques are used to analyse the equipment in order to make improvements. Examples of this are ice hockey and tennis where ice hockey stick and tennis ball performance are analysed using high speed video [Moreno, et al 2004, Goodwill, 2004].

Advanced equipment measurement techniques can replace the athlete with a robot to ensure that as many variables as possible are monitored or controlled. For example in testing golf clubs and balls, an electro-mechanical machine named the 'Iron Byron' is used by the United States Golf Association to test golf clubs and golf balls for conformity to standards. Iron Byron can be adjusted to repeat the same swing ten thousand times before equipment deteriorates, which is useful for comparing the relative

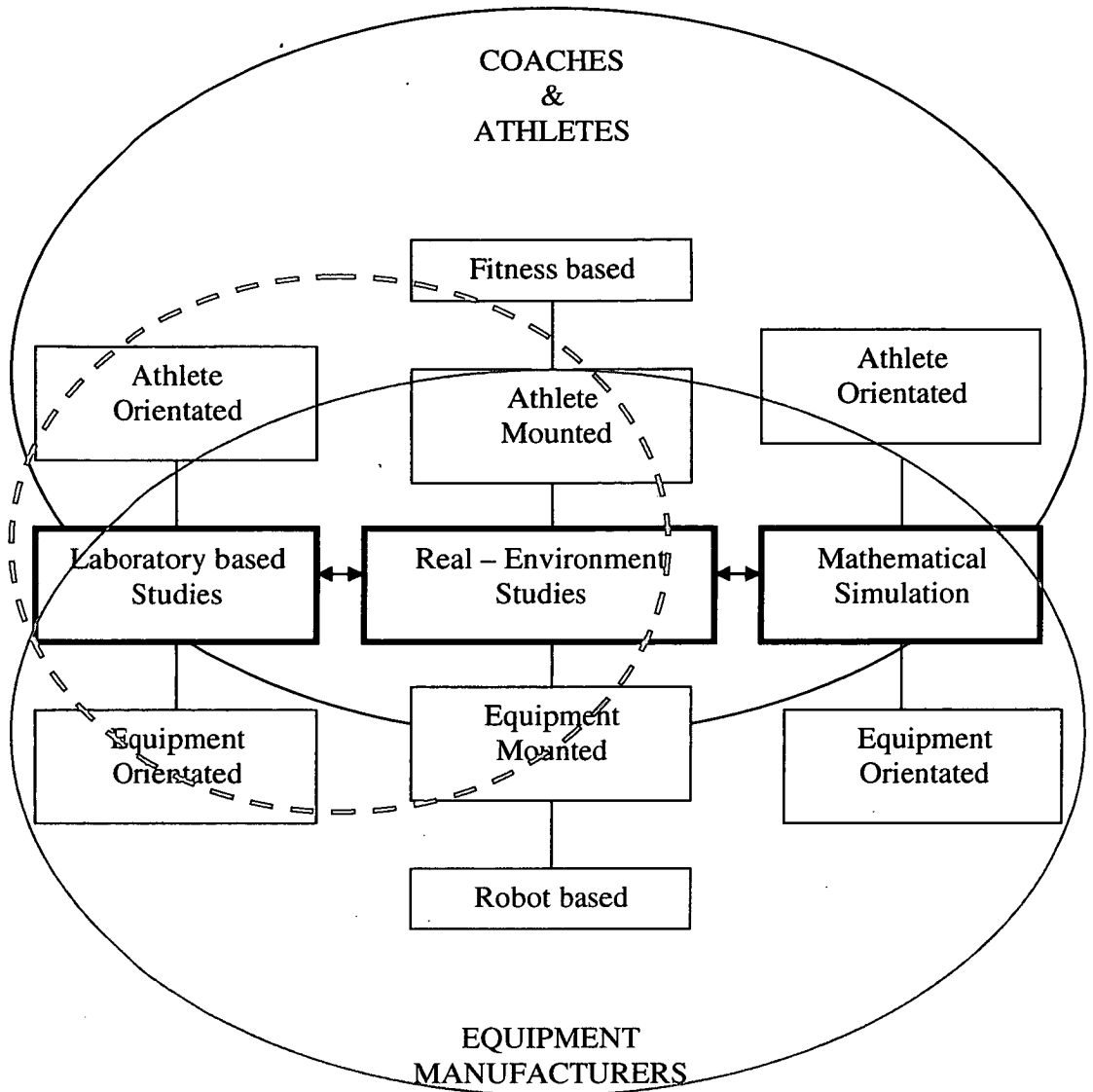


Figure 1-4. Graphical representation of Sports Engineering studies and associated relevance to both coaches and manufacturers. The work conducted for this thesis is represented by the area denoted by the red hatched line.

properties of clubs and balls. Copies of the robot are used by individual manufacturers such as True-Temper and Wilson Sports (Figure 1-4). Nike Sports Corp currently claim

to have produced the World's most advanced driver using this machine combined with advanced finite-element (FE) modelling techniques. Replacing athletes with robots allows laboratory style techniques to be performed in the real environment and can provide comparison between data collected from an athlete and that from a robot. Such tests have been performed in skiing [Yonegawa et al, 2002] using robots to replicate human movements on a real ski slope.

Competitive sports are subject to numerous variables, including: equipment, athlete and external conditions. To reduce these variables different types of experimentation are adopted.

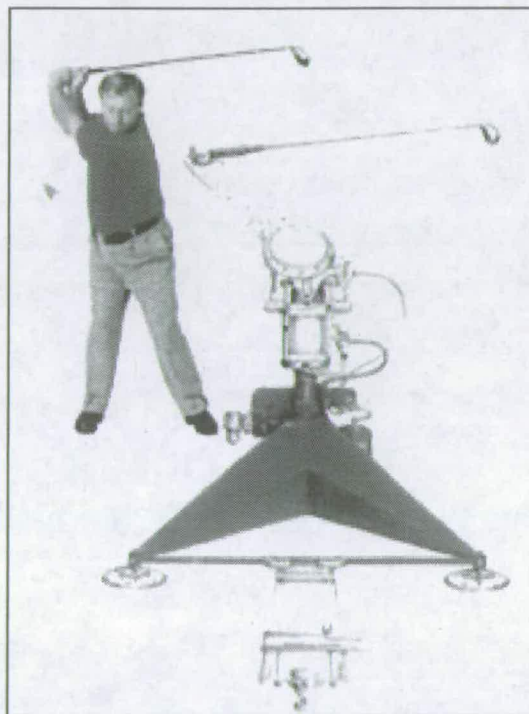


Figure 1-5 The 'Iron Byron' the electro-mechanical machine used by the United States Golf Association to test golf clubs and golf balls for conformity to standards (photo Golf labs, San Diego)

Only when certain variables have been understood can real-time experimentation be conducted. Whether it be laboratory synthesising of a sport, or mathematical monitoring,

testing in this manner provides basic information necessary to gain a more complete understanding of the full system. The laboratory approach, prior to real-environment study has been adopted for work with snowboards.

Real Environment Testing

For a true representation of the entire system the athlete and equipment must be tested in a real environment, ideally an environment representative of competition, as this is where the athlete wants to excel. Sport psychology suggests that in order to make athletes perform well when being tested, the measuring equipment has to look and feel as similar to the normal implements as possible. If possible the athletes should not be aware of what is being tested in order for them not to be biased during the test. This poses numerous problems as the equipment used to gain data must perform under exactly the same conditions as the athlete, be non-invasive and record the large number of variables a sports person or equipment is subject to, in order to provide information of significance. With the advent of low cost, low mass sensing equipment, the capability [Glaser, 2005] for athletes to use systems will increase further, and the real expertise will be in coordinating the technical experts and the coaches to provide systems of true value.

To gain real time feedback and remove lengthy post-processing, coaches use telemetry systems. Today, telemetry systems are becoming increasingly available, but accurate systems are still very expensive. The capability for real time data acquisition reduces the time-lag for coaches to be able to provide valuable feedback during a training session. During this thesis a low cost telemetry system was developed to provide real time data.

Sports engineering is a growing subject area. Sports manufacturers have relatively large R & D budgets [Chou, 2004] and are early adopters for novel materials. The adoption is often in a trial and error fashion due to the cost implications of modelling these complex

structures. This mix of material adoption coupled with trial and error manufacturing will continue to require substantial technical work to fully comprehend and improve the complex equipment arising. People will continually strive to gain better understanding of their sport; the equipment and systems used, and ultimately what the required attributes to win are.

Low cost monitoring systems capable of storing significant amounts of quality data will become widely available, acting as catalysts to equipment improvement. The low cost telemetry systems developed for this thesis are an example of this. Equipment will advance until it reaches the point where governing sporting bodies restrict the use of certain technologies. It is now true that in professional competition in tennis, baseball and golf, commercially available equipment is banned as it is perceived to perform too well.

Chapter 2 Snowboard Instrumentation and Analysis

Presented in this section are the analytical techniques and results obtained from static and dynamic testing of snowboards. Factors that influence snowboard performance are described with reference to literature on snowboards and skis. The materials used to produce snowboards and modern construction techniques are introduced.

Mechanical properties are measured using repeatable laboratory testing. It is possible to identify and compare the physical characteristics (e.g stiffness) of snowboards. In situ data is presented, with design and development stages of the acquisition systems used. The acquisition systems developed provide novel in situ data sets to improve both equipment and snowboarding technique. In situ dynamic data and static results have been compared to qualitative snowboarder feedback in the aim to quantify the 'feel' of a snowboard, exploring its potential to enhance equipment selection processes. Snowboarder ability has been correlated against in-situ data. This information is compared against current training techniques adopted by governing snowboard teaching organisations. Discussion of measurement techniques and capability to improve snowboard design and training techniques is presented.

2.1 Background

Snowboarding is one of the world's fastest growing sports and there are now numerous companies world wide producing snowboards for an estimated market of 3.6 million snowboarders [Head Sports 2004]. Snowboards have experienced a rapid development since the mid 70's when the sport was first invented. Today, the shapes and construction of snowboards have stabilised, following numerous evolutionary stages since the original *snurfer* (Figure 1-1b). This development has until recently been conducted through trial and error alone. To continue the progression of snowboard design,

manufacturers must look at acquisition techniques and adopt a scientific approach linked to qualitative input to achieve further advances.

2.1.1 Categories of Snowboard

Snowboards come in numerous shapes and sizes, specific to the rider and the discipline for which they are designed. The main disciplines are:

- Race
- Freestyle
- Freeride
- Freestyle/Freeride
- Beginner

The shape, size and geometry of a snowboard is usually dictated by the discipline that board falls into.

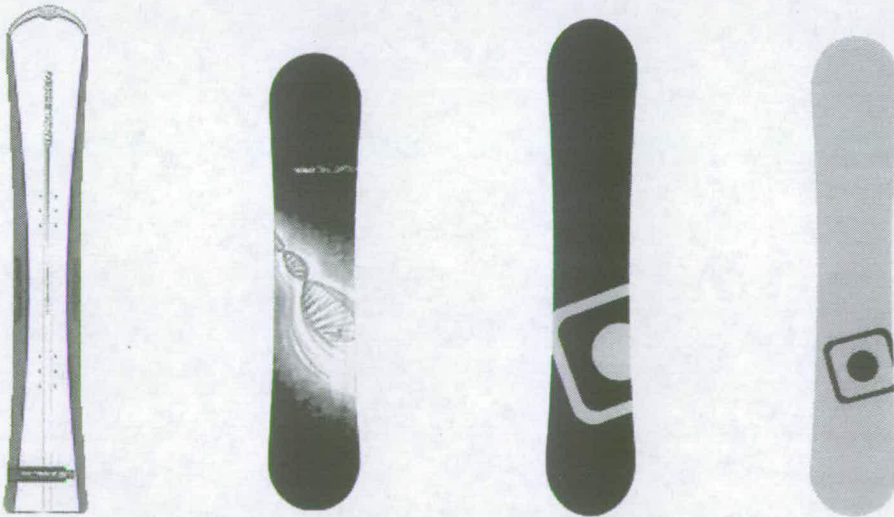


Figure 2-1 Examples of the different categories of snowboard available today (From left to right; Race, Freestyle, Freeride, Freeride/Freestyle)

2.1.2 Snowboard geometry

Geometric terminology for snowboards can be seen in Figures 2-2 and 2-3. Nomenclature used for calculations is shown in Figure 2-3 and has been adapted from the ski standard [ASTM 1998]. The fore and aft bodies each originate from the central point of the forward and rear binding inserts respectively. The waist width is defined as the narrowest section of the snowboard and often corresponds to the central point between the bindings. The forward control point (FCP) and aft control point (ACP) are the two points where an unloaded snowboard touches, when laid on a flat surface.

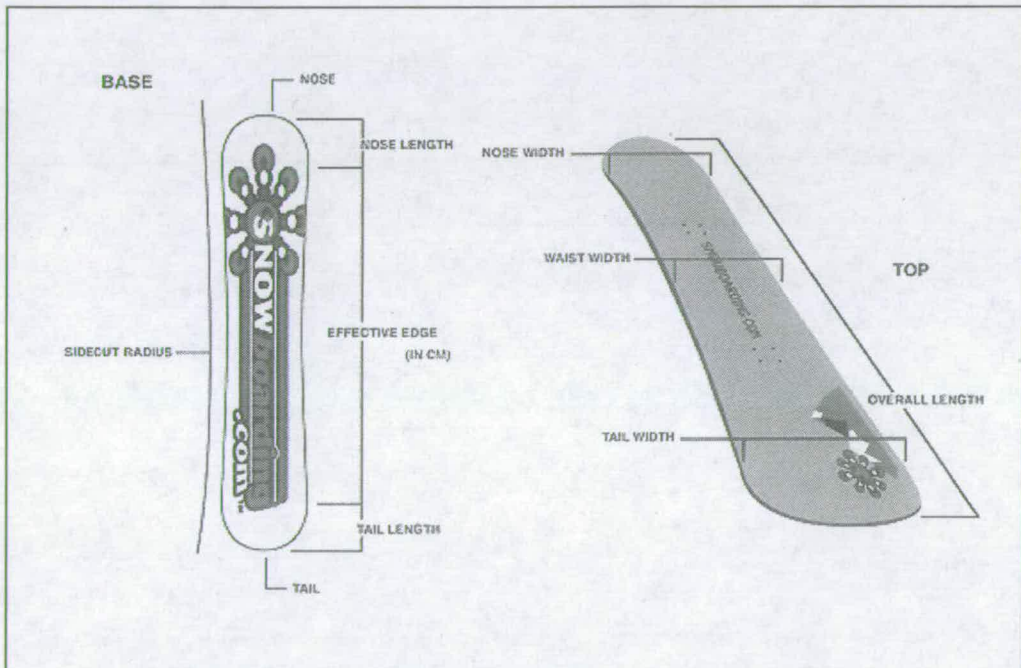


Figure 2-2 Base and top of a snowboard showing nomenclature (courtesy of snowboarding.com)

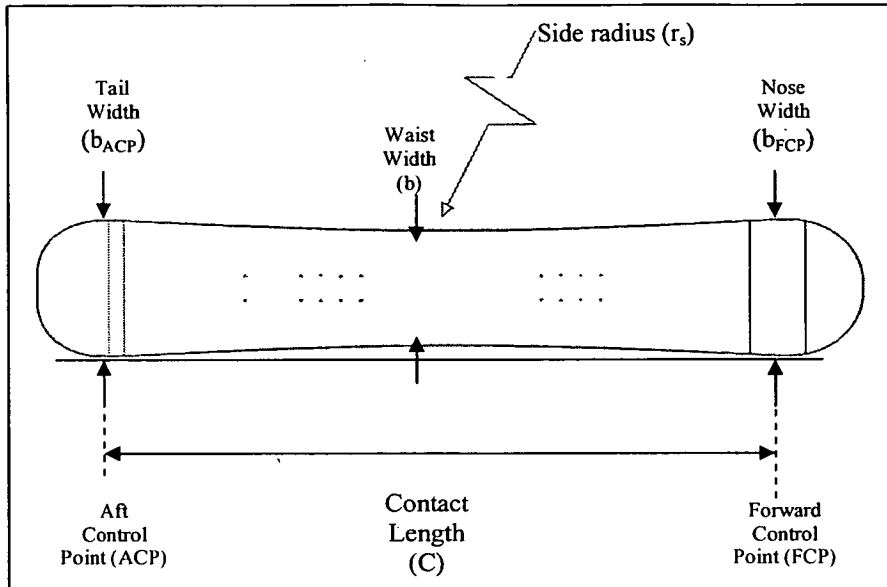


Figure 2-3 Snowboard dimensions and nomenclature adapted for ASTM testing

The nose and tail widths are the widest points of the snowboard at nose and tail respectively. These often, but not always, correspond to the ACP and FCP.

2.1.3 Snowboard Construction

Snowboards are manufactured by pressing layers of component materials together under pressure and temperature for a specific time period. Epoxy adhesives are used to bond layers. Snowboard constructions (see Figure 2-4) may be classified into three types:

1) True Cap: A true cap construction wraps the top laminated layer down to the edges on the sides of the board. This construction produces a lighter snowboard than the sandwich construction, and is preferred amongst freestyle snowboarders.

2) Half Cap: The half cap is a combination of the true cap and sidewall types of constructions. Half Cap construction offers the advantages of both constructions and is usually only found on high end snowboards.

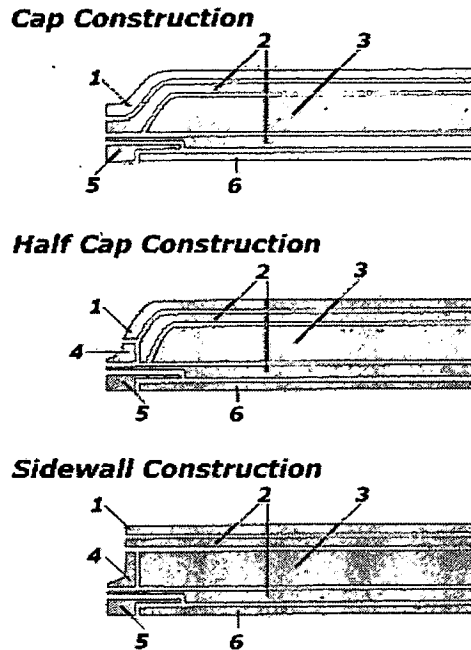


Figure 2-4 Cross-sections of snowboard constructions - A snowboard comprises of a polyethylene topsheet (1), fiber glass layer (2), core (3), sidewall (4), hardened steel edge (5) and Base (6)

3) Sidewall or Sandwich: In sandwich construction a strip of material is used along the sides of the snowboard, sandwiched between the topsheet and the edges. Sandwich construction allows the rider to apply more pressure to an edge during turns.

2.1.4 Materials

A snowboard comprises of a polyethylene topsheet (1), fiber glass layer (2), core (3), sidewall (4), hardened steel edge (5) and Base (6) (see Figure 2-4) bonded together using epoxy adhesive. Table 2-1 presents average physical material properties of those used in snowboard construction.

2.1.4.1 Core materials

As with skis the snowboard's core is commonly made of laminated wood [Lind & Saunders 1996]. Aspen and poplar are generally the main woods used for cores. The materials used in the core contribute to vibration damping, and therefore the dynamic stability of a snowboard. Wood provides good vibration damping, stiffness and structural stability. Some companies replace this with foam, which is light, but foam cored snowboards often rapidly lose their structural stability. Other companies use a metal alloy core manufactured in the shape of honeycomb. This makes for extreme lightness without sacrificing strength. However, this also lacks the damping qualities of a full wood core. The core may be a mix of different woods for different characteristics. Balsa and cork may be used for lightness in areas that do not require much structural strength. Birch, beech, and abachi may be used to reinforce specific areas for added strength.

2.1.4.2 Fiberglass Layer

The snowboard's core is also sandwiched on the top and bottom by at least two layers of fiberglass. The fiberglass adds stiffness and strength to the board. The fiberglass laminate may be either biaxial (fibers running the length of the board and more fibers 90 degrees perpendicular to it), triax (fibers running the length of the board with 45 degree fibers running across it), or quadax (a hybrid of the biax and triax). Some snowboards also add carbon and aramid (kevlar) stringers for even more strength.

2.1.4.3 Base Materials

A snowboard's base material, being the part most in contact with the snow, is very important. Base material is polyethylene (P-Tex), and is the same material used on skis. The preparation of this base material defines its qualities.

Extruded: The P-Tex is cut from a large extruded sheet. A low maintenance base, it is the least expensive and easy to repair. Extruded bases do not hold much wax, and are slower sliding than other base types.

Sintered: P-Tex base material is ground to powder then reformed with pressure and heat, and cut to shape. A sintered base is very porous and absorbs wax well. Sintered bases slide faster than extruded bases, but are more expensive, and harder to repair.

Graphite: Sintered bases may have graphite added to the mix. Graphite bases hold a lot of wax and are extremely fast as they dissipate static charges between the base and snow. High-end racing boards have graphite bases for maximum sliding speed. Additives may also include gallium, or indium.

P-Tex bases must be waxed for maximum sliding speed. A properly waxed snowboard glides more easily and also gets minor protection from friction with the snow.

Material	Density gcm-3	Tensile Modulus GNm-2	Tensile strength GNm-2
Carbon (graphite)	1.66	228 -379	2.21-3.10
Aramid (Kevlar)	1.44	68.9-172	2.76
Polyethelyne	0.97	117-172	2.62-2.96
Fibreglass	2.50	89.6	3.45-4.55
Hardened Steel	7.85	207.0	2.00

**Table 2-1 Physical properties of materials used in snowboard construction
(compiled with reference to Lind and Sanders (1996))**

2.1.5 Snowboard Selection Criteria

When choosing a suitable snowboard the size of the board chosen is dependant on the rider, their ability and the snow conditions in which it is intended to be used. Snowboarders control the direction of a snowboard by applying different moments to the board by moving their mass relative to the board. The centre of gravity in relation to the centre point of the snowboard defines the direction of the snowboard. The centres of gravity for humans differ due to different body size and shapes. For the average person in a snowboarding stance it is usually located in the pelvic area where the heaviest bone is. Figure 2-5 highlights the position where the centre of gravity acts, x denotes the distance from the centre of the board longitudinally and y is the distance from the centre of the board in the transverse direction. It is the moment arms; mgx and mgy that a rider

will exert on a snowboard. Taller / heavier people require longer boards due to their capability to produce larger moments than a shorter lighter rider as the forces for a heavier rider are greater and the moment arm is greater for a taller person.

People with larger feet require a wider snowboard to allow the angle between the edge of a board and snow to be maximised without the toe or heel of the boot contacting the snow during turning manoeuvres. Manufacturers provide specific models of snowboards in a range of sizes to cater for individuals' differing dimensions. It is standard for snowboard companies to document critical measurements for overall length and widths in their brochures.

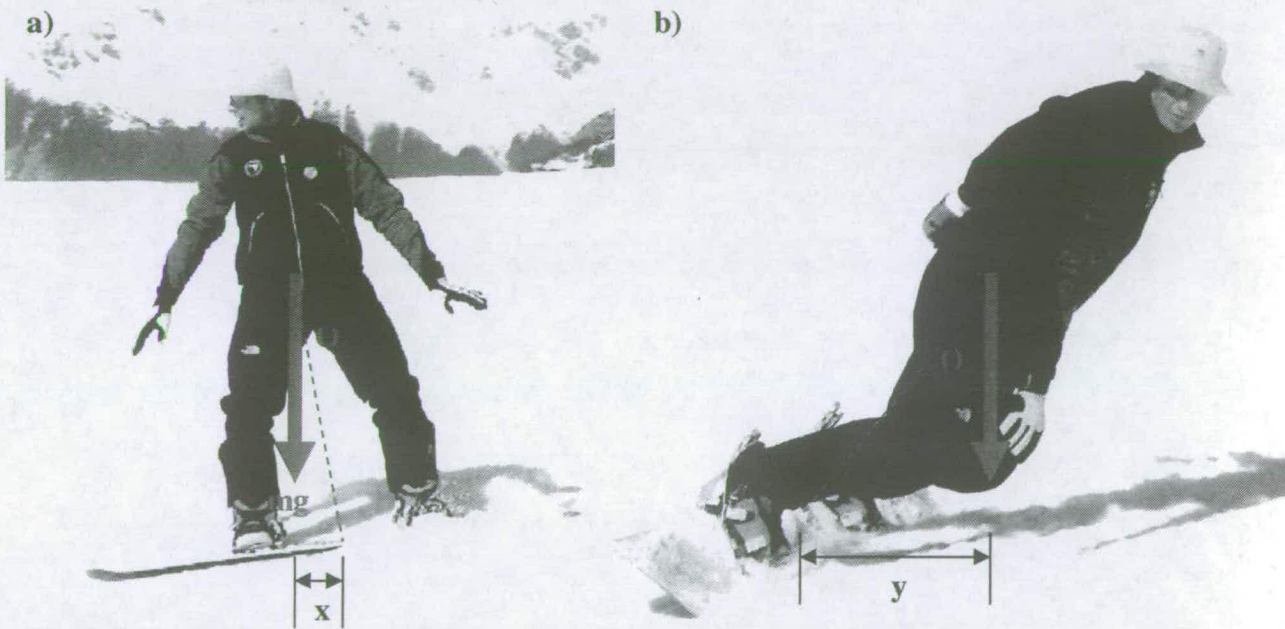


Figure 2-5 A snowboarder controls the direction of the snowboard by adjusting body position relative to the centre of the board. The centre of gravity acting a) longitudinally at moment arm x , b) transversely with moment arm y .

The stiffness of a board is dependant on the discipline the board is designed for and chosen according to the mass and ability of the rider. (Definitions of snowboard stiffness are described in section 2.7 of this chapter). Race boards are extremely stiff as they are deigned to travel at higher velocities than other categories of snowboard. In contrast, snowboards designed for the beginner are generally much softer as the rider is not capable of making accurate body movements to provide the positioning of forces required to flex the snowboard. A softer snowboard has greater manoeuvrability than its stiffer counterpart and thus a softer board is more forgiving to incorrect body movements. The mass of the rider determines the stiffness of the board required, snowboarders with greater mass require a snowboard with greater stiffness to prevent excessive deflection or even failure of the snowboard during use. Stiffness is not quantified in manufacturer's documentation.

Boards designed specifically for deep powder snow are longer with greater surface area than those used "on piste". With a greater surface area the pressure applied by the base of the snowboard on the snow is reduced and the snowboard penetrates the snow to a shallower depth. Freestyle snowboarders typically use shorter boards than other snowboarders, as the shorter board length reduces the weight and moment of inertia. This reduced weight makes it easier to spin and maneuver.

The way in which a snowboard acts in situ, or the "feel" of the board is a quantity that little is known about. Two snowboards of similar dimensions may "feel" totally different when ridden. Work has been conducted to analyse signals gathered from snowboards in-situ to improve understanding of this.

When choosing a board it is advisable and normal to consult published reports of how the board performs and how it feels when ridden. These tests are conducted by

professional snowboarders and although informative are entirely qualitative with reports like “This board is cosmic! Nice and solid riding pretty much anything” and “Every now and then you get a board on your feet and it feels perfect, this is one of those boards” [Kemp, 2000]. Snowboard manufacturers also hold test days where people can try out their snowboards free of charge. This can help to decide between a range of boards from one manufacturer, but not between manufacturers or for the complete beginner. Quantitative on-slope data could be used to form an important part of this decision.

There are many variables that must be considered when selecting a suitable snowboard. Elite athletes will choose a snowboard that suits their chosen snowboarding discipline, previous experience and their physical dimensions. Snowboard choice is usually restricted to one manufacturer dependant on sponsorship arrangements. A selection of snowboards will be chosen from the sponsors’ range and tested on snow. Elite riders will replace their board on a regular basis as the chamber of the board and related feel will change over time. Physical dimensions are documented but static quantities such as stiffness are not. All snowboarders could benefit from this, making the task of choosing a board more scientific, and allowing them to know which of the boards available best suit them. Manufacturers could definitely benefit from these results, allowing them to clearly identify how well the board works, and from this fine-tune the shape and construction to achieve a better final product.

2.1.6 Literature Review

As a snowboard may be considered similar to a short, wide ski in many ways, literature published on skis is relevant to this thesis. As skiing is a 2500 year old sport [Glennie et al 1997], significantly more research has been conducted with more information available in this field which must be acknowledged. Despite its great public success, papers published on this subject matter are still limited. This is however changing as more sports engineers look to improve techniques, equipment [Bianchini, Spangler, 2004, Reichel, 2004] and limit injuries sustained. Research on both sports is discussed here simultaneously.

A comprehensive summary of the material properties of skis and snow, testing procedures and studies on skis is available in the 'Physics of Skiing' [Lind & Saunders 1996]. This body of work covers the equivalent ski construction and mechanical properties for skis, reference is made to snowboards but the study focuses on skis. The original ASTM procedures which are adapted to analyse snowboards are covered in this text.

2.1.6.1 Mechanical Properties

Significant research on the mechanics of skis and skiing has concentrated on the measurement and characterisation of the mechanical properties of skis [Lind et al 1996] and the measurement of forces involved in ski manoeuvres [Nordt & Springer 1999b, Alison et al 1999]. These are not focused on the "feel" or the design and construction of the ski, but give valuable information for methods of testing. The information on turning shape and body positions are, however, only relevant to skiers. Body position and muscle groups used when snowboarding differ considerably from that of skiing.

2.1.6.2 Ski Design

These mechanical tests have been enhanced by using finite element analysis for static testing based around simple models for a ski's construction [Nordt et al 1999] to provide results that focus on the design of the ski. These simple models are based around basic laminate structures. These tests have proved fairly accurate with accuracies of 10% between theoretical and test values [Deak et al 1975]. There have also been similar static tests for snowboards, modelled as simple composite beams [Mangasarian et al 2000] that are found again to be within 10% accuracy. Clearly the errors arising in these tests are due to an overly simplistic model being used. Because of the increasing complexity of construction for both skis and snowboards, it is becoming more difficult to model them using finite element analysis. At present, skis are very sophisticated heterogeneous structures, which may be made of more than twelve different homogeneous or composite materials [Clerc et al 1989]. Fibres used in construction can be uni, bi or tri directional weaves which exhibit different mechanical properties dependant on direction. These methods of static testing were important to this project as methods that are now "standard" on skis were used in the static analysis. The test methods along with full descriptions surrounding the properties of skis are available in the 'physics of skiing' [Lind et al 1996].

2.1.6.3 Quantifying 'Feel'

Until recently limited publications on the 'feel' and in-situ environment have been performed. [Darques et al 2004] goes some way toward examining the correlation between mechanical properties and qualitative feedback for both skis and snowboards. This study used laboratory testing to determine geometry, bending stiffness, torsional stiffness and damping factor for skis, the equivalent procedure used during this thesis to quantify snowboards. Comparison of these results with on-slope test card scores validated the method for a specific type of ski that of the giant slalom ski. Work in this

study used the similar techniques and showed correlation between qualitative and quantitative skier feedback though work did not extrapolate to snowboards. This work replicates work conducted by the author using ISO standards opposed to that of ASTM testing. There is little examination of real-environment quantitative data, which is not captured although the focus is that of product performance. Understanding the link and the dynamic properties simultaneously could provide a platform for accelerated progression of ski design.

2.1.6.4 Injury

As with skiing, several papers relate to injuries sustained during participation in snowboarding. Injury patterns show snowboarders are at higher risk of sustaining ankle and wrist injuries than alpine skiers, who are more prone to damaging the knee [Johnston et al 2005]. Quantitative data that provides information on the forces to which a snowboarder is subjected to in the 'real' environment would allow greater comprehension of forces involved during injury and equipment could be designed to reduce risk of injury.

2.1.6.5 Geometry

Geometry plays a major role in the performance and feel of a snowboard. One ski study has been focused on purely historical ski geometry [Fricke 1999]. This concentrates on the mechanical properties of skis produced between 1975 and 1996 and focused on the statistical changes of flexural rigidity, mass and moment of inertia over the years. It was discovered that the changes were fairly small from year to year, and ski design has changed rapidly with the birth of parabolic-carving skis in recent years. Advances in materials used in ski construction provided increased torsional stiffness allowing the top

and tail of a ski to be wider, and allowing creation of current snowboard designs. These materials are the same as used for snowboard construction (see section 2.4) and therefore relevant in looking at the shape and its effects on a snowboard's mechanical properties. Equivalent historical shape studies have not been conducted on snowboards, but in contrast their overall shape has changed little in recent years. In the early models there was a great variation in shape but recently the shapes have been more consistent from year to year. It may be assumed that a similar pattern is evident in manufacturers' documented shapes and sizes and the associated qualitative reports.

2.1.6.6 Vibration Analysis

There has been vibration analysis testing of both skis and snowboards [Piziali, Mote, 1972, Devaux, Trompette, 1980, Bianchini, & Spangler, 2004]. [Buffington et al 2001], document the first three bending modes shapes and frequencies; dependant on snowboard average around 2, 17 and 44 Hz with the first two torsional modes around 20 and 55Hz respectively. Strong correlation between modeling and experimental laboratory results were found. The research has been aimed mainly at the design of skis or snowboards and the majority of this has been carried out in the laboratory. But, with recent developments in electronics, in situ testing has begun and is becoming more advanced. Initial tests were aimed around single elements of skiing or snowboarding, such as a turn, but are now more advanced. During this project in situ testing was conducted for a whole snowboard run, allowing greater understanding of all frequencies present when riding, this is an advancement as little study has been conducted in this area.

Data collection techniques and equipment have improved dramatically over recent years allowing use of smaller devices and faster data collection rates. When measuring dynamic systems the sampling frequency denotes the maximum frequencies which can

be observed from the data. Previous studies have been limited to data collection at around 100Hz [Buffington et al 2001], only allowing nyquist frequencies of 50Hz to be observed. Greater sampling speeds allow higher frequencies and their related vibrational modes to be observed.

Although most studies are not trying to correlate the “feel” of the snowboard to any quantitative measure, many do mention the “feel” of the ski or board. Papers published in the late 1970’s and 1980’s describe it as far from being determined, whereas the more recent papers are more optimistic about a correlation. They do however emphasise that for increased performance of both skis and snowboards the correlation between quantitative and qualitative results is necessary. Some papers [Fricke (1999), Gulland, (1999)] deal with the damping of vibrations having a positive effect on the “feel” or performance of the board, and have discovered that test riders did not always prefer the most damped board, but one with critical damping, with around 75% of vibrations still remaining. Damping is any effect, either deliberately engendered or inherent to a system, that tends to reduce the amplitude of oscillations. This means that boards with different damping, and therefore vibration patterns, will feel different, and those with natural damping (as opposed to forced damping by an external source such as piezo ceramic dampers) that is close to this “critical” damping should feel better.

There have also been studies describing specific forces on skis and snowboards during use [Lind, Saunders (1996), Clerc et al, 1989, Gulland, (1999)]. These look at computer aided design and the forces between the ski and the sliding surface. They were not especially relevant to this project but gave ideas and figures of the forces on a ski / board as it is used.

2.1.6.7 Qualitative Snowboard Testing

The qualitative testing for snowboarding and skiing has been documented in magazine articles and publications for some years. The largest snowboard test publications in Britain are produced by Snowboard UK [Gibbins, Doherty 2000] and Snowboard Document [Spearing, 2000]. These tests are well regarded by the industry and give valuable information on physical dimensions along with reports on the “feel” and “ride” of the individual boards. The largest British publication of qualitative reports on skis and snowboards was approached as a route to publish quantitative findings on the same products. However the potential for unfavourable findings resulted in them declining due to previous manufacturer sponsorship arrangements.

2.1.7 Snowboard training techniques

An individual’s snowboarding performance is based more on qualitative than quantitative information. It is reliant on visually assessing and therefore is subjective. The analysis here is conducted using British Association for Ski and Snowboard Instructors (BASI) techniques. BASI training techniques look at the rider’s position as they make certain manoeuvres. The majority of snowboarder’s problems can be related to the basic stance adopted and the way in which the riders move their bodies in relation to manoeuvres they are performing.

Correlating these to the data collected allows training techniques to be adapted. Current methods only use video analysis to analyse techniques. It is difficult to get a time base for this analysis as it is often filmed using low speed film. With the sensing techniques described in this thesis, time between manoeuvres and the forces applied to the snowboard can be analysed. Strong correlations between technique and force transmitted have been discovered.

2.2 Method

2.2.1 Laboratory Testing

Static testing in the laboratory has been conducted on four snowboards. The methods for conducting these tests are derived from the ASTM 1998 test methods [ASTM 1995]. A snowboard simulator was designed and built by the author to provide early test results. The second generation Ski and Snowboard Simulator (Figure 2-6) was designed and developed by Angus Wardlaw of Reactec Ltd.

The simulator was designed to be capable of testing skis and adapted by the author to snowboards. The system comprised of two clamping structures which could be rotated around their longitudinal axis. The clamps were supported by a bearing arrangement clamped to a machine bed. The positioning of these bearings and clamps could be manually altered to accommodate different skis and snowboards. Tension arms were capable of locking the rotating clamp in place or loaded with masses to provide a torsional load. This simulator was used to produce deflection results for vertical and torsional loading of the snowboard along the entire length or specific sections, such as the nose or tail of the board. Four snowboards are tested against each other to investigate stiffness characteristics.

Board	Mass	Overall length	Contact length l_c	Nose width	Waist width
			C	b_{FCP}	b
	kg	mm	mm	mm	mm
1	3.6	1655	1280	315	270
2	3.55	1640	1280	316	270
3	3.35	1640	1280	316	270
4	3.15	1525	1160	285	246

Table 2-2 Physical dimensions of test snowboards

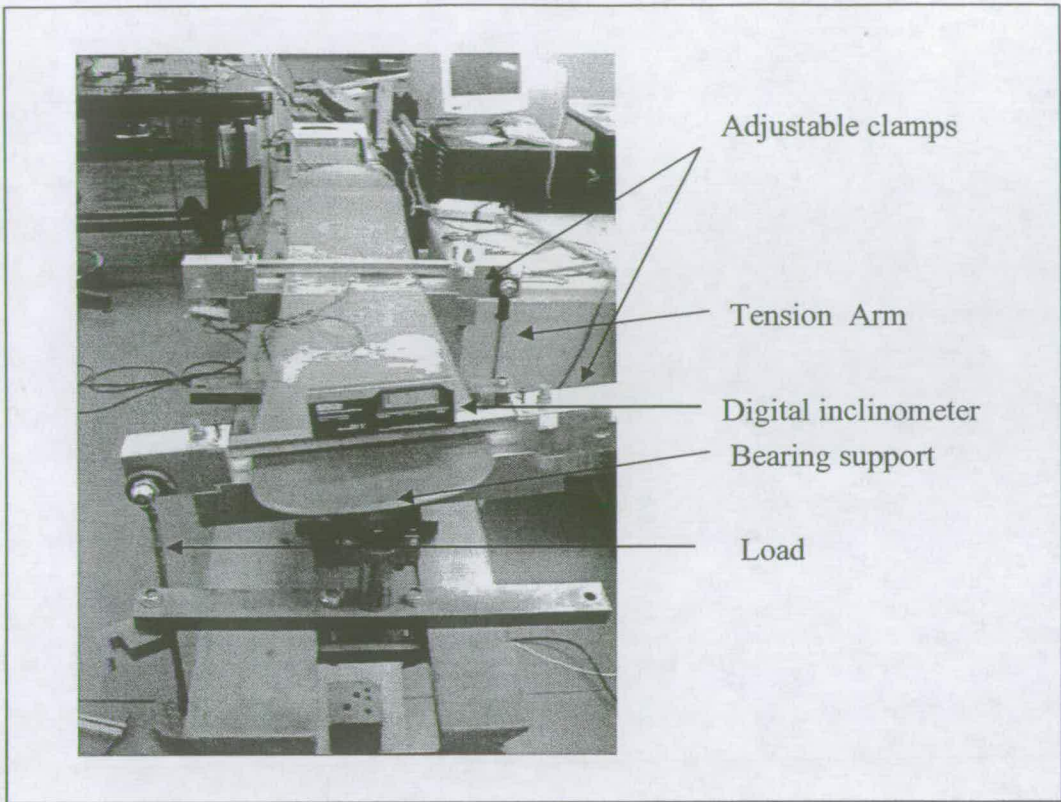


Figure 2-6 Test board 4 undergoing torsional testing on simulator rig

The overall length, contact length, waist and nose widths were recorded (Table 2-2). These provide necessary information for stiffness calculations. ASTM tests to provide information on snowboard properties are: overall stiffness, forebody stiffness, aftbody stiffness and torsional stiffness. Tests were conducted using the adjustable simulator rig (Figure 2-6).

2.2.1.1 Snowboard stiffness

The centre spring constant (i.e. stiffness) was determined by adapting ASTM guidelines [ASTM p 498-77 (1998)]. The snowboard is simply supported and statically loaded with a series of masses whilst measuring the vertical deflection at the middle poise. Figure 2-

7 shows the simply supported snowboard arrangement. Bending stiffness (B) is proportional to the product of the modulus (E) of elasticity and the second moment of area (I);

i.e. $B = E \cdot I$ [2-1]

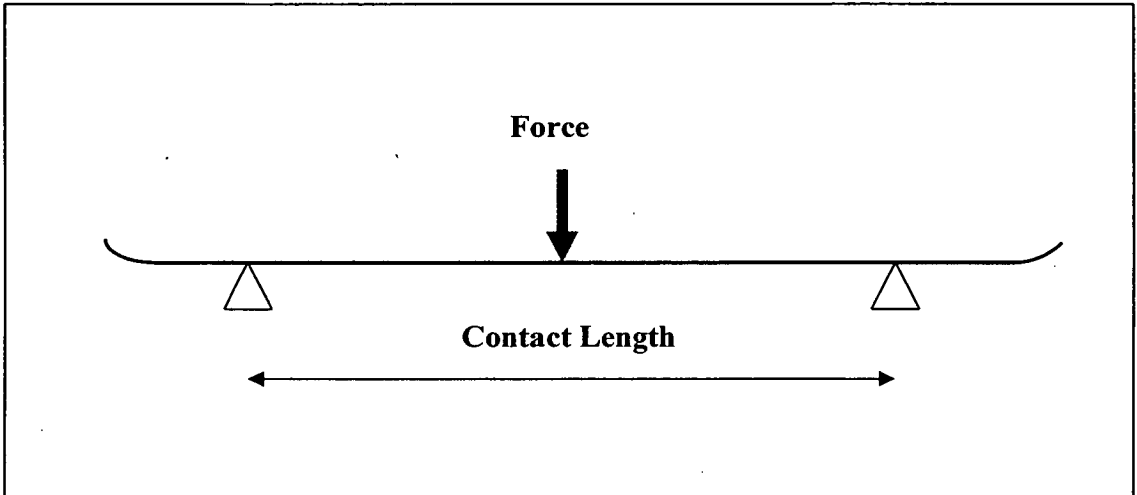


Figure 2-7 Simply supported snowboard used to determine overall snowboard stiffness (based on [ASTM 498-77 (1998)]).

The overall stiffness of the snowboard is calculated using the following equation:

Overall stiffness; $S = \frac{F}{d} = \frac{48B}{C^3}$ [2-2]

Where: S = overall stiffness N/mm, F = applied force N, d = vertical deflection at the centre mm, B = bending stiffness $N \text{ mm}^2$ and C = contact length mm.

2.2.1.2 Forebody and aftbody stiffness

Forebody stiffness and aftbody stiffness are calculated using equation [2-2] where C becomes C_F and C_A , the length from the centre of the binding inserts to the widest point at the front and back respectively. Tests are conducted independently and forces F_{FCP} and F_{ACP} are applied at the FCP and ACP (Figure 2-8).

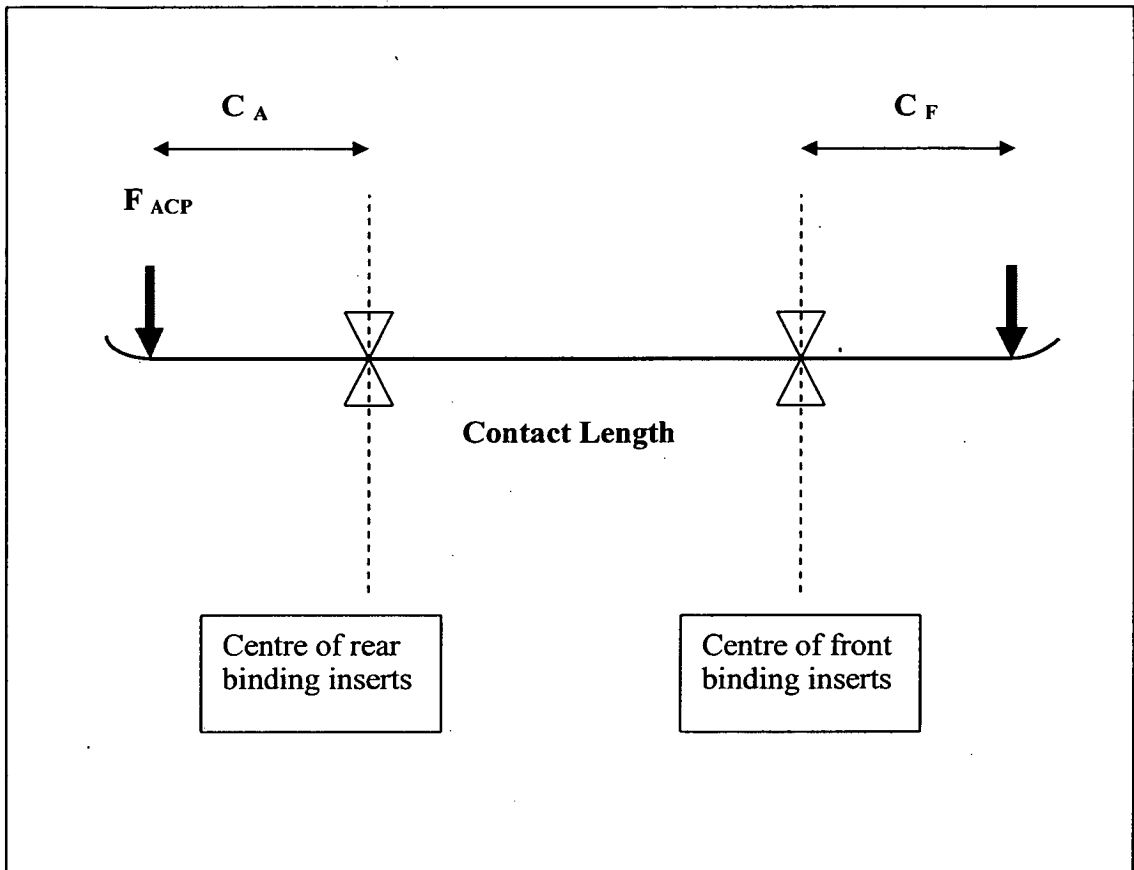


Figure 2-8 Determining Forebody and aftbody stiffness

2.2.1.3 Torsional stiffness

Snowboards require high torsional rigidity so that they do not twist whilst on an edge. Torsional stiffness may be measured by clamping the snowboard in the centre and measuring the ratio of torque to the angle of twist. The simulator was used to perform these tests (Figure 2-6)

Torsional stiffness is calculated using [2-3].

$$\frac{T}{\theta} = \frac{2G}{L} \quad [2-3]$$

Where: T = torque Nm, θ = angle of twist rad, G = shear modulus Nm^2/rad and L = distance between clamps m.

2.2.2 In situ testing

Initially the dynamic testing was going to be done purely on snow as this is real in-situ testing for the boards, but due to a lack of snow during the on-snow test period the dynamic testing had to be conducted on both snow and dry mat. The aim of the dynamic testing was to record the vibrations of each board and compare them. A 'vibration footprint' for each board was the intended goal.

Tests were conducted on an artificial "dendex" dry-slope. This reduces the complexity of the system as an artificial slope has consistent properties in comparison with snow, which makes comparisons between board properties and rider performance simpler. There are differences in the way in which a snowboard reacts with the slope and riding technique compared to on snow. This difference is neglected in this study.

2.2.2.1 Qualitative in situ testing

The four boards that were tested in the static tests were ridden on-slope (artificial and snow) by four hand picked riders deemed capable by a qualified instructor. Each rider gave a qualitative assessment of the boards based on their perception of 'Feel'. This was graded from 1 to 10 (10 being excellent) and then stiffness estimated using stiff, medium and soft ratings. The findings were averaged and summarised in Table 2-3.

Board	Feel	Overall stiffness	Torsional stiffness
1	7	medium / stiff	medium
2	8	medium	soft
3	5	soft	stiff
4	6	soft	medium

Table 2-3 Qualitative average results correlated from the four test riders

2.2.2.2 Quantitative on-slope testing

Several methods for data acquisition and sensor arrangement have been trialled on these and other test snowboards. This section covers equipment design, techniques used and experiments conducted.

Initial real environment tests were conducted to obtain a quantitative measurement for the feel of a snowboard. Three snowboards were supplied by Option Snowboards inc. for this test. The boards were all similar in length and geometry, the major difference between them was that of construction due to different materials used in their lamination. As it is imperative that the system used to monitor an athlete training must not impede performance several systems were trialled. As the snowboarding environment is harsh, developing a suitable and accurate monitoring system proved difficult. Temperature experience on-slope can often fluctuate between 10°C and -20 °C during a week testing. The lower temperatures reduce power capabilities of batteries and in several instances extra heating systems were used to prevent the batteries and

equipment from freezing. The equipment must be suitably protected against water damage and shock loading.

2.2.3 Sensor Arrangement

A non-invasive sensor is required that will measure the deformation of a snowboard during dynamic operating condition, without altering the response of the board. A consistent signal output is required in a low temperature environment (i.e. -20 °C to 20°C). Several arrangements and different sensing options were trialled.

The first sensors trialled on a snowboard were strain gauges in a half bridge arrangement in an attempt to measure both longitudinal strain (bending) and understand major frequencies experienced in on-slope testing. Strain gauges had been used on the central section of a ski by [Gardiner et al, 1974] to measure bending, torsional and sideflex vibration. Skiing on hard snow at moderate speeds showed increased frequencies with torsional response of 85Hz and sideflex responses between 50-55Hz over those on soft snow.

Piezo based sensors were trialled and used for the majority of tests (see section 2.10.3)

2.2.3.1 Strain Gauges

Initial trials were conducted using a single half-bridge strain gauge arrangement in both the laboratory and on-slope. However, it was decided that a strain gauge arrangement covering the entire snowboard would require the rider to carry excessive amounts of equipment possibly affecting the rider's technique. To ensure that a strain gauge monitoring system does not suffer from thermal drift and noise requires a dummy gauge and the amplification circuit to be as close to the sensors as possible, difficult if the rider is to carry equipment in a backpack. A system such as this would highlight major

frequencies, but would be extremely difficult to provide accurate strain measurement. Lead wire effects induced large thermal drift on the system and results recorded using strain gauges were dismissed for snowboard results. Strain gauges were later used with a curling sweep ergometer and lead effects overcome (see Chapter 3).

2.2.3.2 Lead-Wire Effects

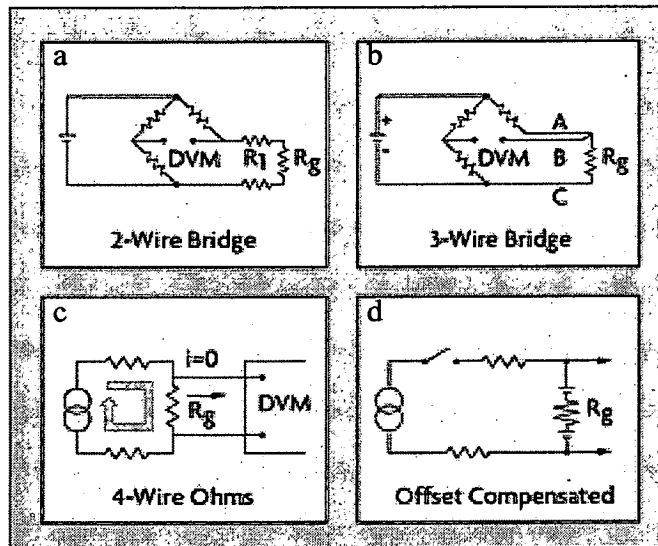


Figure 2-9 Alternative lead wire configurations (courtesy of National Instruments)

Strain gauges are often mounted at a distance from amplification circuits and data logging equipment. This was the case for snowboard tests as the rider would carry amplification circuits and logger in a backpack to prevent damage. This required a long lead length (1.5m) and increased the possibility of errors due to temperature variations and lead-wire resistance changes. In a two-wire installation as used for snowboards and curling equipment (Figure 2-9a), the two leads are in series with the strain-gauge element, and any change in the lead-wire resistance (R_1) will be indistinguishable from changes in the resistance of the strain gauge (R_g).

To correct for lead-wire effects, an additional, third lead can be introduced to the top arm of the bridge, as shown in Figure 2-9b. In this configuration, wire C acts as a sense lead with no current flowing in it, and wires A and B are in opposite legs of the bridge. This is the minimum acceptable method of wiring strain gauges to a bridge to cancel at least part of the effect of extension wire errors. Theoretically, if the lead wires to the sensor have the same nominal resistance, the same temperature coefficient, and are maintained at the same temperature, full compensation is obtained. In reality, wires are manufactured to a tolerance of about 10%, and three-wire installation does not completely eliminate two-wire errors, but it does reduce them by an order of magnitude. If further improvement is desired, four-wire and offset-compensated installations (Figures 2-8c and 2-8d) should be considered.

In two-wire installations, the error introduced by lead-wire resistance is a function of the resistance ratio $R1/Rg$. The lead error is usually not significant if the lead-wire resistance ($R1$) is small in comparison to the gauge resistance (Rg), but if the lead-wire resistance exceeds 0.1% of the nominal gauge resistance, this source of error becomes significant. For the sweep ergometer the lead-wire lengths were minimised by locating the amplification circuit in the bottom of the handle 5cm away from the gauges and gauge resistance was significantly larger than the lead wires used.

2.2.3.3 Piezo sensors

The piezoelectric polyvinylidene fluoride (PVDF) sensor is suitable for measuring under these environmental constraints. Laminated DT series Elements (LDT1 – 028K/L with factory fitted lead wires and riveted connections) from Measurement Specialties Incorporated (MSI) were selected to retrofit a non-invasive sensor array for in situ testing.

Piezo film sensors bonded with superglue and sealed with water-resistant silicon were used during the experimentation for this project. One difference between most tests carried out previously and those conducted for this project is that the sensors are positioned solely along the edge of the top-sheet of the snowboard as opposed to the grid formation adopted for these project tests. It is claimed [Bianchini Spangler, 2004] that the vibrations toward the centre of the snowboard have little effect but there is little evidence to back this up. This would be a feasible pattern for skis due to the small width, but as snowboards are substantially and increasingly wider, the vibrations have been tested in a grid format for this project, to give information from all sections of the board.

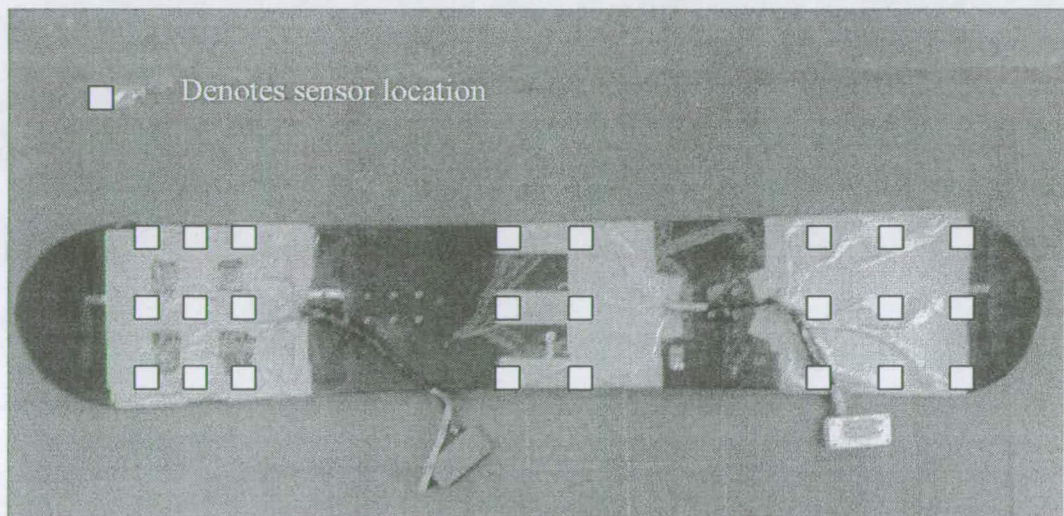


Figure 2-10 Sensored snowboard with PVDF arrangement used in initial testing

Data was gathered by applying PVDF sensors in a grid pattern across the top sheet of the snowboard. Initially three equally spaced grid formations were used; 3x3 on the nose of the board, 2x3 on in the centre and 3x3 at the tail (Figure 2-10) to capture data from

across the snowboard allowing analysis of the entire structure whilst in situ. Three sensors were positioned on the FCP equally across the snowboard. and the following grid was inline 8cm closer to the centre, with the final grid a further 8cm. The same procedure was repeated on the ACP. The centre 3x2 grid was spaced 8cm apart centred around the mid point of the board.

Logging systems capable of simultaneously logging the 27 channels were unavailable for tests due to financial constraints. For the grid sensor configuration each grid was recorded independently using a Pico ADC 11 (see section 2-11).

Tests to assess riders' performance and ability were conducted with a simplified four sensor grid pattern around the leading foot (Figure 2-11). The sensors were bonded with superglue and waterproofed with silicone sealant as for the previous grid pattern.

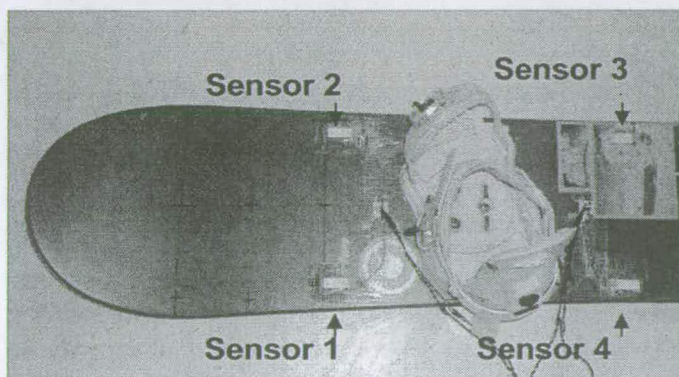


Figure 2-11 Simplified PVDF sensor arrangement

2.2.4 Acquisition of data

Sampling limited bandwidth signals with equally spaced sampling frequency f_s must be greater than twice of the maximum frequency f_{max} , in order to have the signal uniquely reconstructed without aliasing.

$$f_s > 2f_{max} \quad [2-4]$$

The frequency f_s is the Nyquist sampling rate. Half of this value, f_{max} , is sometimes called the Nyquist frequency [Horowitz 2001]. Nyquist established that for periodic signals, no information would be lost if the sample rate is at least twice as fast as the signal of interest. The data recorded during in situ testing would be decomposed into a sum of sines and cosines of different frequencies using a Fast Fourier transform. Therefore the Nyquist sampling theory can be used up to a maximum frequency to sample a periodic function without loss of information.

Three models of analogue to digital converter (ADC) are used during the course of this work; the *Pico* ADC-11/10, a custom built PIC based ADC circuit and a *Biomedical Monitoring Systems Ltd.* 4-channel device.

2.2.4.1 Pico

The Pico ADC – 11/10 is a compact ADC that interfaces with a laptop via a D-type connector and connects to sensors via a custom built terminal block. It is capable of multiplexing 11 channels with 10-bit resolution with a maximum sampling rate for a single channel of 10kHz. This maximum sampling rate reduces in proportion to the number of channels being used at any one time. The input voltage range for the ADC - 11/10 is from 0V to 2.5V. To be able to record reading of a negative voltage the system

requires the addition of a voltage offset circuit and the associated additional power source. The ADC11/10 was used in in-situ testing without supplementary power supply and was therefore only capable of recording positive voltages.

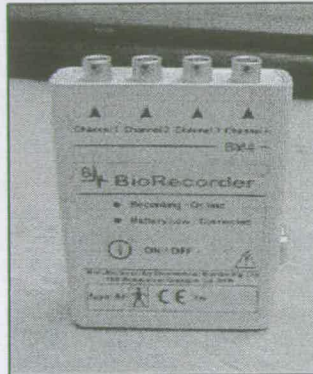


Figure 2-12 The Biomedical recorder used for ADC conversion during in-situ testing.

2.2.4.2 Low cost telemetry system

A low cost RF telemetry system was developed and trialled to gather in situ data. The system was designed to perform the analogue to digital conversion using a microchip PIC16C71 [Microchip, 1997]. The 16C71 is a high-power, low cost CMOS programmable 8-bit microcontroller with inbuilt analogue to digital conversion. The 16C family of microchips employ advance RISC architecture. A circuit was designed and constructed (figure 2-13) to utilise the inbuilt ADC to provide sampling of 4 channels between a voltage range of 0V and 5V, each at 200 Hz. As with the previous Pico system, used directly in conjunction with PVDF sensors only allows positive voltage to be recorded.

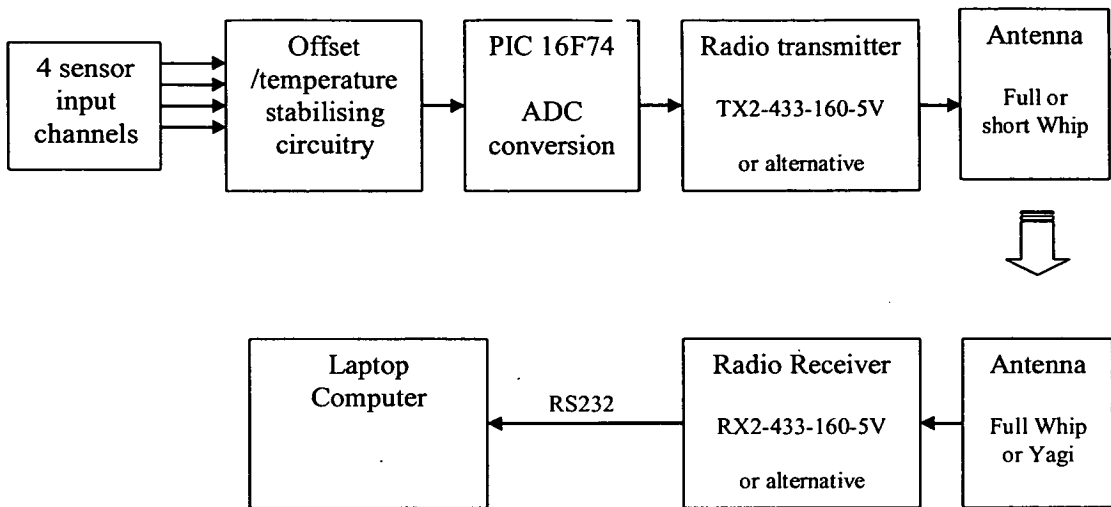


Figure 2-13 Schematic of telemetry system used

Radiometrix transmitters and receivers were used in conjunction with a microchip PIC16C71 programmed to perform the ADC. As the PIC was using 4ADC channels, the sampling rate was 250 Hz to allow frequencies up to around 70Hz to be captured. Figure 2-13 shows a schematic of the telemetry system.

The PIC was programmed using a combination of hex and C code compiled in Mplab 5.0 (see Appendix A for code). The system was housed in shielded boxes and attached to the front binding of the snowboard (Figure 2-14)

Half whip, full whip and Yagi antenna arrangements for transmission and receiving data were trialled in an attempt to increase the usable distance of the system and reduce noise. The optimum arrangement was found to be a full whip antenna on the snowboarder and Yagi antenna on the receiver.

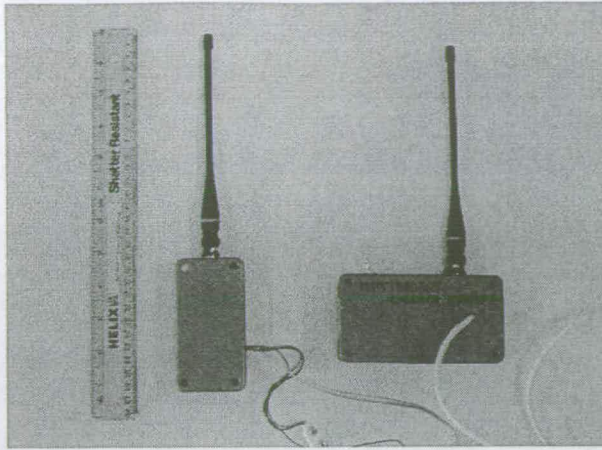


Figure 2- 14 Low cost telemetry system with whip antenna, used to collect in situ data from snowboards.

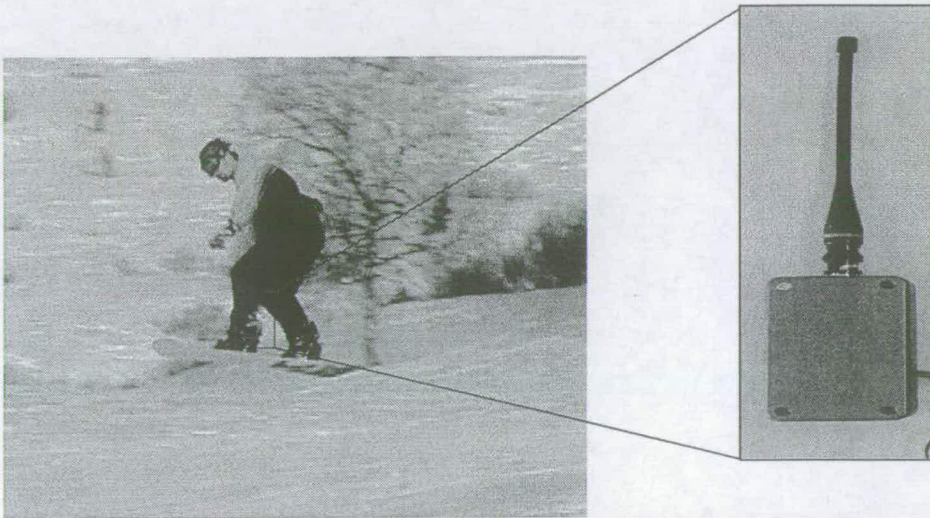


Figure 2-15 Telemetry system in use on a snowboard



Figure 2-16 Receiving telemetry data from a snowboard

The telemetry system has advantages over the Pico system as little equipment was carried by the rider, however, the system had several faults. The system was prone to picking up large levels of noise due to multiple path distortion on the open band frequency; this phenomenon was exaggerated on snow due to its reflective properties. The system would only work on a line of sight basis which only allows data to be gathered when the snowboarder is turning in one direction. Alternative systems of greater accuracy were sought which required the rider to carry minimal extra mass.

2.2.4.3 Biomedical Monitoring

The Biomedical Monitoring Systems Ltd. 4-channel device (Figure 2-11) was later used with the simplified 4 sensor PVDF grid pattern due to its small size ($75 \times 56 \times 18\text{mm}$) and low mass (100g including battery). The device could be used without the need for other large electronic equipment (i.e. laptop computer) so there was no requirement for the test subject to carry a rucksack. During tests it was placed in the snowboarder's pocket,

providing minimal influence to snowboarding technique. It was hard wired and produced results with greater accuracy than the telemetry system.

The device was capable of a maximum sampling speed of 4 kHz, to simultaneously record 4 channels the device would multiplex the signals and the maximum sampling rate of 1 kHz per channel was used. The device has inbuilt amplifiers and voltage offsets on each channel which can be set independently. This feature allows a full signal to be recorded and an appropriate gain set to maximise the signal/noise ratio. Data captured is transferred to an internal 64MB smart digital card and post processed using BioMed software. Output from the sensors was recorded using the Biomedical Monitoring Systems data logger at a sampling frequency of 1 kHz per channel with 12 bit resolution.

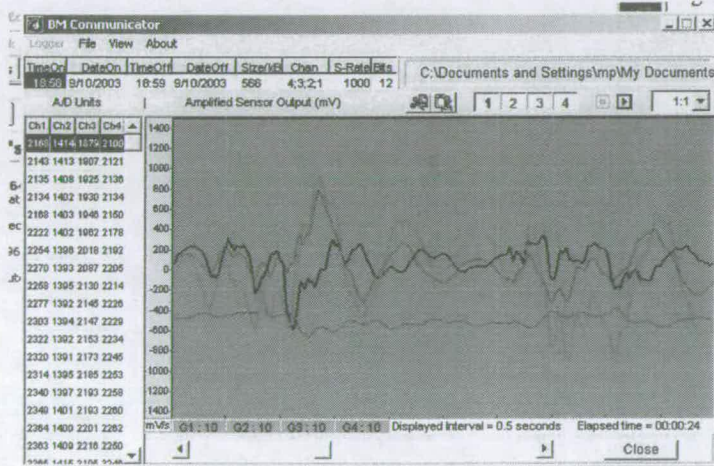


Figure 2- 17 Raw data displayed on the BioMed software

2.2.5 Standardised test Procedure

A specific course of eight snowboard race gates placed in line down the slope at 5m intervals was used to maintain continuity when recording in situ data to be calibrated against rider ability. Tests were conducted on Hillend Dry Ski slope in Edinburgh.

To remove variables in situ tests were conducted with a single snowboard for training experimentation. Four riders of similar build and differing standards: ranging from beginner to advanced were tested. The four riders will be called, beginner, intermediate, advanced and Jimmy. Jimmy received training during testing to advance his riding level from beginner towards intermediate standard.

Figure 2-18 shows representative results obtained from testing in accordance with the standardised procedure.

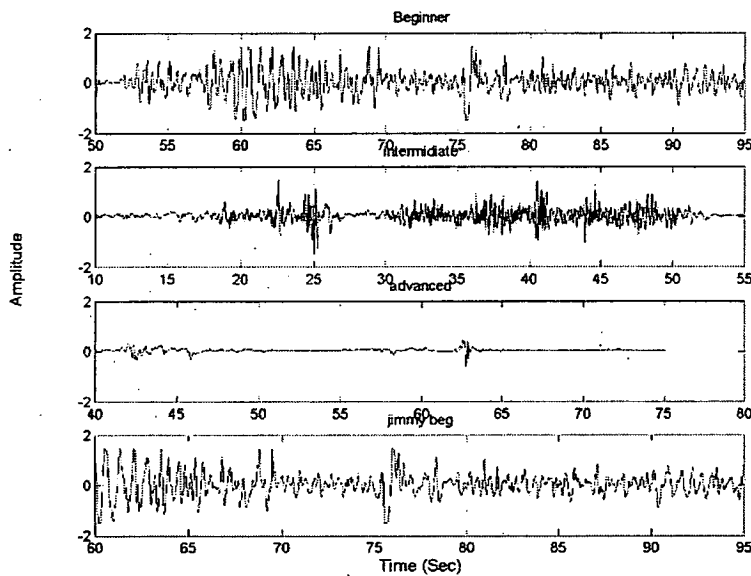


Figure 2-18 Raw data from sensor three for four riders of differing ability for the duration of two turns.

2.3 Results

Dimensions and mass play an integral part in the performance of a snowboard and are necessary for calculating board properties (see table 2-1), Results for overall stiffness can be seen in Table 2-4.

Board	Overall	Front	Rear	Front	Rear
	S	S_f	S_r	G	G
	(N/mm)	(N/mm)	(N/mm)	Nm^2 / rad	Nm^2 / rad
1	2.8	2.9	3.4	49.2	55.0
2	2.7	2.6	3.7	59.4	70.6
3	2.6	2.6	3.4	67.2	94.1
4	2.6	2.9	3.5	41.0	44.0

Table 2-4 Stiffness properties of the snowboards

Overall snowboard stiffness varies from 2.6 to 2.8 N/mm². Snowboard 1 has highest overall stiffness whilst snowboard 3 has the greatest torsional stiffness.

The fast Fourier transforms clearly show that the major frequencies present are below 100Hz. Frequency components are evident up to 200Hz, but due to the minimal levels of vibrations above 100Hz analysis of these have been excluded from this thesis. The following Figures 2-19 to 2-23 show the fast Fourier transforms for riders of different ability when riding the standardised test course.

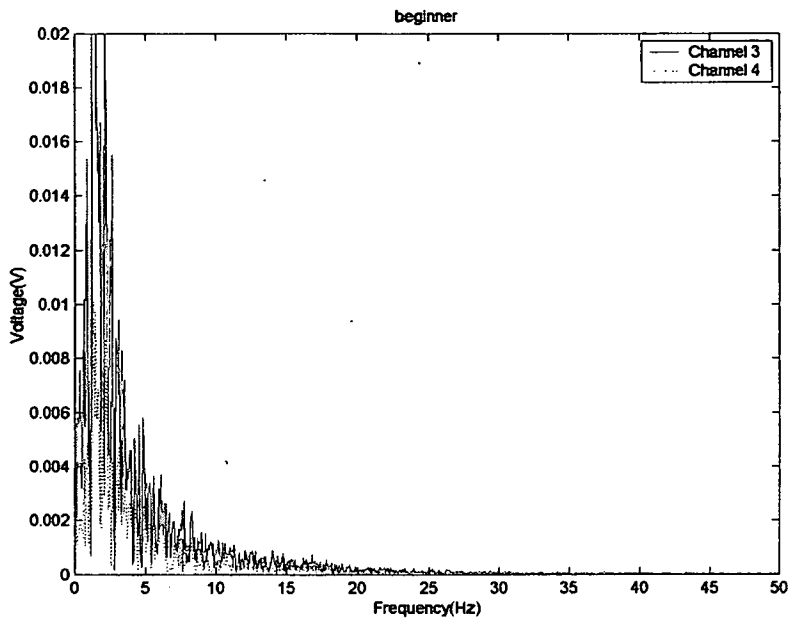


Figure 2-19 FFT of beginner snowboarder during 2 turns

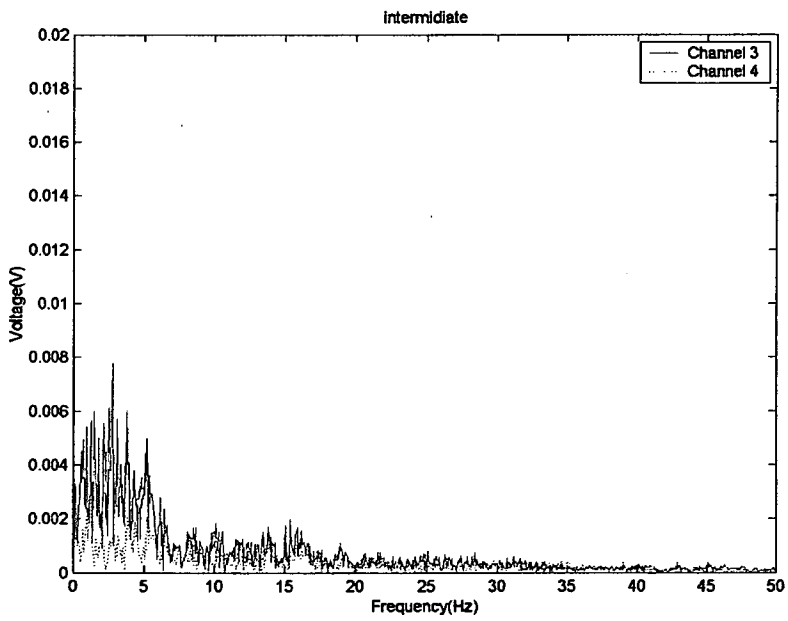


Figure 2-20 FFT of intermediate snowboarder during 2 turns

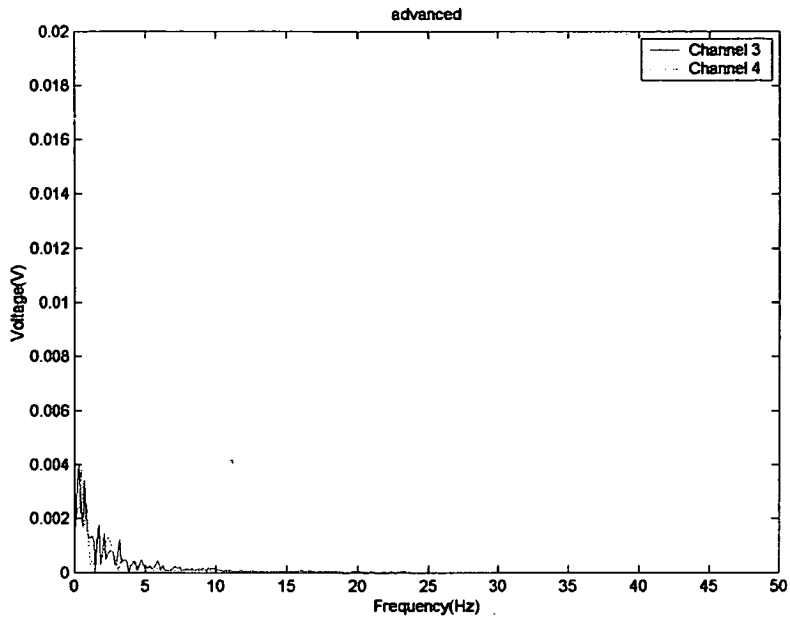


Figure 2-21 FFT of advanced snowboarder for during 2 turns

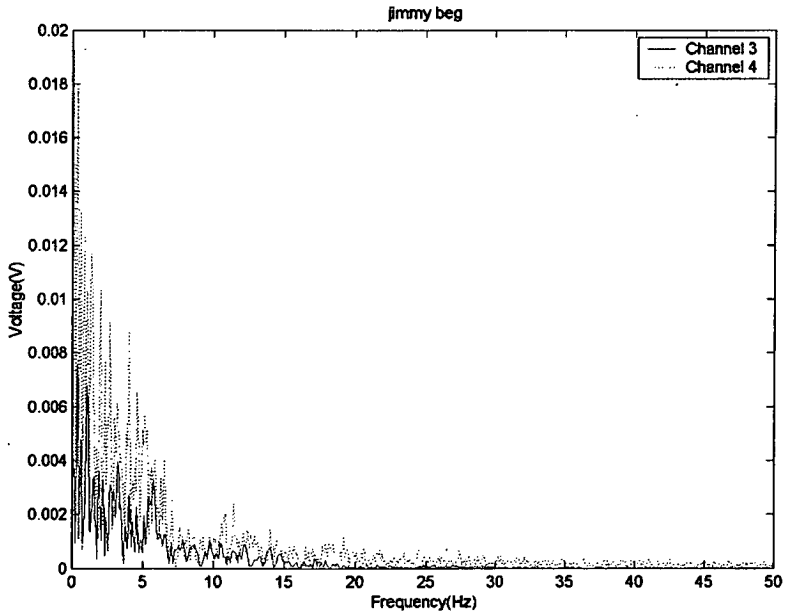


Figure 2-22 FFT of Jimmy at beginner level

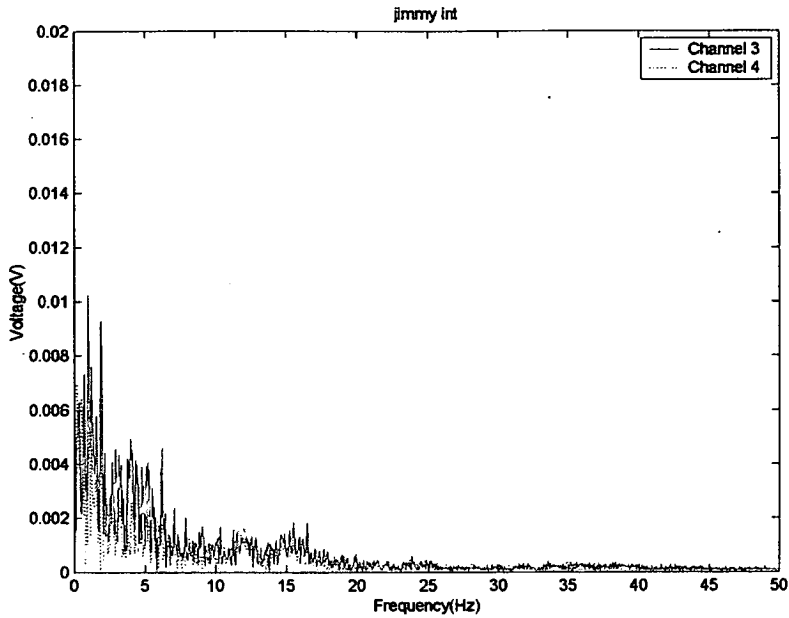


Figure 2-23 FFT of Jimmy at intermediate level

2.3.1 "Pedalling"

A technique also promoted is that of "pedaling", where the rider pushes the feet as if pushing a pedal independently to twist the board. This aids initiation and ending of a turn. This is extremely difficult to see on video analysis, monitoring the forces around the foot allows quantitative analysis of this technique that was previously unavailable. Examples of good and poor techniques are shown in Figures 2-24 and 2-25, therefore showing how quantitative data can be used to improve technique.

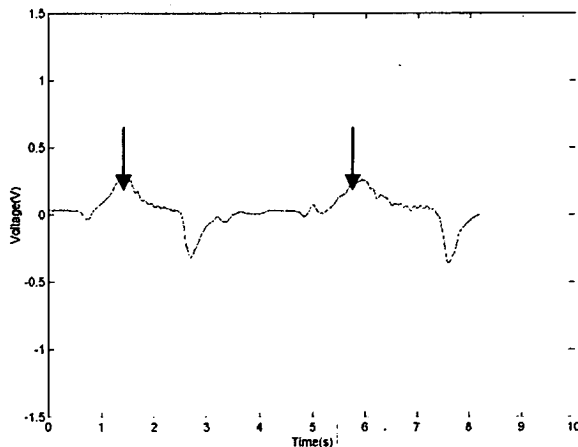


Figure 2-24 Examples of good pedaling technique (arrows indicate maximum points of twist.)

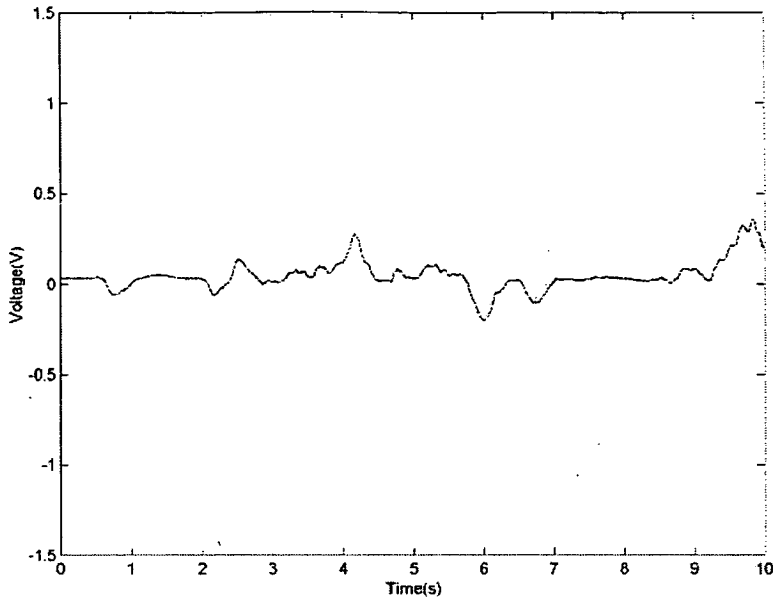


Figure 2-25 Example of poor pedaling

2.4 Discussion

The trends in qualitative results from riders about the 'feel' of a board (Table 2-2) showed direct correlation with the findings of the static testing results (Table 2-3). The riders used to test the boards were experienced and had been exposed to riding different types of snowboard, and were therefore capable of analysing the subtle differences between boards. This correlation between static tests and rider analysis is what has progressed the majority of snowboard design and manufacture to date.

At an early stage of learning to ride a snowboard obvious improvements can be made by using video analysis. Body position is key to improving performance. This can be viewed accurately by looking at individual frames in sequence. Once up to intermediate

standard snowboarders find it difficult to improve, much smaller changes are required to improve technique. Video analysis is the current method for tuning technique.

Figure 2-19 shows the raw data from a sensor being ridden by beginner, intermediate, advanced and Jimmy (at early learning stage). It can be seen that voltage, which is proportional to rate of change of strain, is high with beginners as they cannot apply forces in a controlled manner. Looking at Figures 2-19 and 2-21, it is evident that this relatively high voltage has low frequency content. This is believed to be caused by correction of body position to retain balance. Once a rider becomes more advanced the high voltage levels are reduced and higher frequencies are observed, Figure 2-20.

To assess this data trend, Jimmy, a non-snowboarder received tuition. Beginner stages produced Figure 2-21 with high voltages at low frequency. As he advanced the voltages were reduced and higher frequency content observed, Figure 2-22.

A skilled sportsperson should be able to apply large forces in a smooth manner. The pedalling data (Figures 2-22 and 2-23) show the difference observed with smooth application of strong forces and uneven weak forces being applied. This controlled application of forces is what top level snowboarders have to achieve. Monitoring of forces allows the application of these forces to be observed, something unavailable until now. Data collected during testing is proof that previous testing techniques have been unable to capture frequencies in excess of 40Hz.

Data captured from the instrumented snowboard provides some information useful to coaching. Frequencies show that there are

2.5 Conclusion

Snowboards have been tested in the laboratory, providing values for flex, torsional stiffness. Agreement was found between the mechanical properties of the boards measured in the lab and a qualitative assessment of on-slope performance.

A system has been developed to collect dynamic data from snowboarders on-slope. It is:

- compact in size
- capable of sampling at a rate of 4kHz/sec
- of variable amplification to allow optimal signal/noise ratio.
- uses PVDF sensors to measure rate of change of strain

Data from on-slope testing shows we can:

- differentiate between riders of different competence levels (beginner, intermediate and expert)
- track improvements in rider performance.
- measure forces the rider transmits to the board

This system can be used in training snow-boarders and is likely to be particularly useful in training elite riders.

Higher data acquisition rates allow the frequencies prevalent during riding on an artificial slope to be measured. It is evident that more advanced riders stimulate higher frequencies in the snowboard; limitations of the artificial surface and size of slope are believed to prevent higher frequencies from being evident. It may be possible to excite frequencies well in excess of 100Hz during fast riding on snow. Testing the system on snow will produce further complexities as the surface conditions vary substantially.

Chapter 3 Curling

This chapter provides a background to the sport of curling, supported by referenced literature. An introduction to the physics of sweeping and factors which influence sweeping are presented. Previously the forces and acceleration involved in sweeping were unknown. A sensed curling brush known as a sweep ergometer has been developed to quantify sweeping for improved knowledge and technique in the sport. Detailed technical specification of the sweep ergometer and the stages of the development, supported by associated reasoning, are presented.

1.1 Introduction to curling

The Winter Olympic sport of curling is the only target-based sport where a projectile can have its trajectory corrected once it has left a player's hand or delivery device. This is done by sweeping the ice in front of an approaching stone (Figure 3-1) and modifying the coefficient of friction at the sliding interface. The sweeping techniques and the athlete's fitness can provide the crucial difference between winning and losing a game of curling at both club and Olympic levels. Despite its importance, there has been no quantitative measurement of sweeping technique. Instead, sweeping techniques have developed over centuries of curling in a qualitative and anecdotal manner. The author has developed a sweep ergometer, which for the first time enables curling athletes and coaching staff to measure the acceleration and forces applied to the ice while sweeping, providing an important advancement in the sport.

Curling is played on ice by two teams of four; each team delivering eight ~18.6 kg stones alternately. Stones are delivered with both a translational velocity ($\sim 2 \text{ ms}^{-1}$) and rotational velocity ($\sim 1.5 \text{ rad s}^{-1}$) and slide ~28 m to the target area known as the *house* (Figure 3-2a). The rotational velocity component results in the stone having a curved trajectory, which is used to avoid stones that have been played previously [Harrington,

1924]. The dynamics of curling stones has been the subject of several papers [Shegelski et al, 1996, Denny 1998, Penner, 2001, Jensen et al 2004, Marmo and Blackford 2004]. Points are scored by the team whose stone(s) lie closest to the centre of the target area at the other end of the ice rink once all eight stones have been delivered. Curling is both a highly technical and tactical game [Mcmillan, 1999].



Figure 3-1 Rhona Martin of the Olympic Gold Medal Team 2002 training with the MK1 ergometer , Mike Hay is pushing a stone along the ice at standard play velocity whilst the player must sweep consistently for a 25 second period. Sweeping is performed to clean the ice and extend the length the stone travels, this happens because the coefficient of friction is reduced by the heating effect of the brush.

Once the stone is released, one or more players from the same team track it down the ice, sweeping in front of the stone. Sweeping produces frictional heat between the nylon brush head and the ice and brings the temperature of the ice closer to its melting point and thereby reduces the coefficient of friction [Marmo et al 2006].The frictional heat produced increases with the downward force applied and with the sweeping velocity [Marmo et al 2006]. Sweeping is used to increase the distance a stone travels and reduce

the amount a stone deflects laterally or 'curls'. Once sweeping of a section of ice is completed the frictional heat is conducted away from the ice surface and it returns to the bulk temperature of the ice rink. To maximise the effect of sweeping, curlers must sweep as close to the on-coming stone as possible without coming in to contact with it [Marmo et al, 2006].

There are two extremes in sweeping technique: low force with high frequency and high force with low frequency. The majority of curlers assessed using the ergometer fall between these extremes. The forces applied and techniques used in sweeping have not been analysed previously in a quantitative manner. We have developed a sweep ergometer to measure the forces and velocities applied by curlers while sweeping. The design of the sweep ergometer is presented here, as are the initial test results.

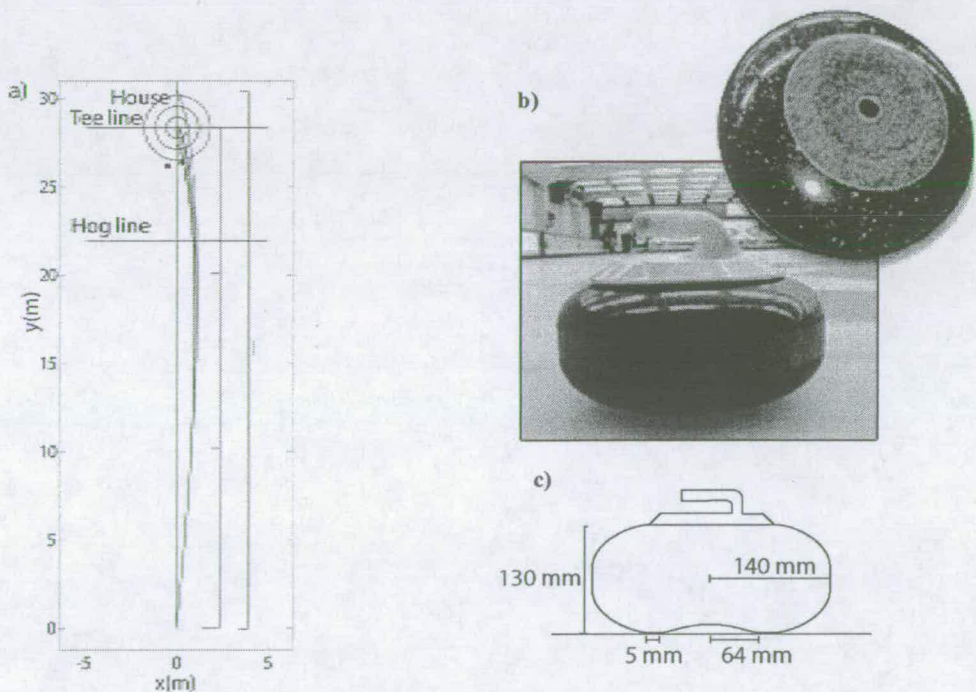


Figure 3-2 a) diagram of a curling lane with path marked for curved trajectories. b) Granite curling stone c) Line drawing of curling stone showing height, stone radius, running band radius and running band width.

1.2 Quantitative measures used by British curling team

The Great British (GB) Curling team like many of today's professional athletes have been using quantitative techniques (see below) in order to increase understanding and ultimately performance. In addition to quantitative methods and fitness training the GB team have been utilising custom equipment to measure performance whilst training.

The GB curling team use microwave based speed guns to measure the speed at which curlers push off, to send a stone down the rink. Training sessions and competitive games are filmed using high speed video to analyse technique of individuals and the accuracy of curling strategies implemented. Custom computer programs have been developed which post-process this video analysis, providing statistical analysis of stone positions during play. A large data set has been collected over a six year period, as increasing the size of the data set increases the statistical accuracy.

Sweeping is a major part of the game, and is by far the most physically demanding aspect. Prior to the work covered in this thesis, there was no quantitative method of producing sweeping data. The development of the sweep ergometer provided the team with additional data to be used in training and selection processes.

3.3 Development of Sweep ergometer

The development of the sweep ergometer through its design and three development stages are presented here, as are the test results. For ease the different brush designs are referred to as MK1, MK2 and MK3 respectively

Figure 3-3). MK1 and MK2 ergometers were used for training, while the MK3 was used for Olympic team selection.

1.3.1 Rationale

The sweep ergometer originated when the Scottish Institute for Sport (SIS) approached Dave Saunders at the University of Edinburgh Sport and Exercise Department. Mr Saunders contacted Dr Jane Blackford of the Centre for Materials Science and Engineering (CMSE). The SIS requested that the British curling coach, Mr Hay, quantify his players' sweeping technique in order to improve selection techniques.

A project was designed by Dr Jane Blackford, and Mr Johan Malm (an undergraduate student) began work on producing a sweep Ergometer in 2000. It was agreed with Mike Hay, and David Saunders, sport physiologist, what the most important variables to be measured by the first generation sweep Ergometer should be. It was unanimously decided that stroke length, stroke velocity, vertical and horizontal forces must be gathered by the ergometer. Initially a lab-based device was considered, as it was thought that it would be easier to design an accurate system than with a true rink-based version. However to complement the training and selection procedures, the system would have to provide accurate analysis in a real environment, so it was clear that a rink-based system was the answer.

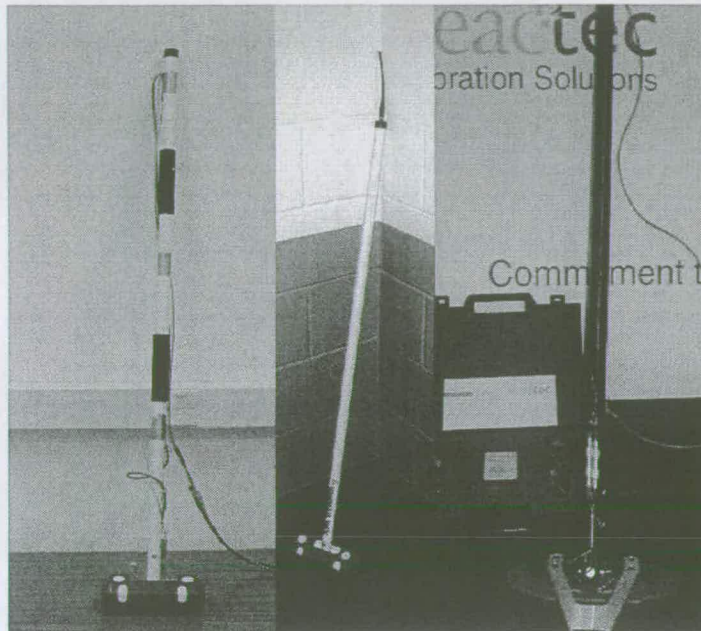


Figure 3-3 The three versions of the sweep ergometer, MK1, MK2 and MK3 from left to right. MK1 is a hardwired adapted *Hammer Classic* brush, MK2 a wireless *Hammer Classic* and MK3 a hardwired adapted *Performance* brush. Each brush monitors vertical and horizontal forces, and acceleration.

Mr Malm developed the MK1 brush and conducted initial tests. Subsequent testing was conducted by other members of CMSE including the author. The MK2 wireless iteration was designed by the author. The MK3 was designed and built by Reactec with the author taking technical lead.

3.3.2 Brush design and evolution

It is crucial that the 'sweep ergometer' remain as close to a standard curling brush as possible to ensure results show a true representation of techniques used whilst sweeping with a standard brush. Athletes rely heavily on lightweight equipment to achieve their desired performance; increasing the mass disadvantages the athlete. Instrumented equipment must also look and feel the same as the athlete's standard equipment, otherwise athletes tend to be distracted and the whole sweeping process *looks and feels* different.

The popular Hammer Classic curling brush was initially used for the basis of the MK1 sweep ergometer. The final MK3 version used the latest Performance brush produced by *Andre Ferland*. The Hammer Classic was widely used in competition, and has sufficient space within the head of the brush to incorporate sensors and associated electronics. The Performance brush has recently been adopted in competition curling, but lacked the space of the classic to implement sensors and associated electronics. The MK3 brush utilised space in the handle and adapted brackets to house the sensors and electronics.

The MK1 sweep ergometer was a hard-wired version device, the MK2 version was wireless. The MK3 brush was smaller and required a more advanced electronic data storage system. As it was more practical the design returned to the hard-wired version, ensuring accuracy through elimination of noise.

3.4 The MK1 Ergometer

To monitor forces applied to the brush head, the standard plastic axle was replaced by a machined steel axle and bearing arrangement (Figure 3-4). The inclusion of a steel axle, instrumentation and associated batteries increased the mass of the Hammer Classic brush from 0.91kg to 1.16kg. A needle-bearing was used for the coupling and it is assumed that negligible energy was lost to friction. The machined axle was designed specifically to transmit the applied force, yet deform sufficiently that resistance strain gauges could measure strain within their 4% strain range.

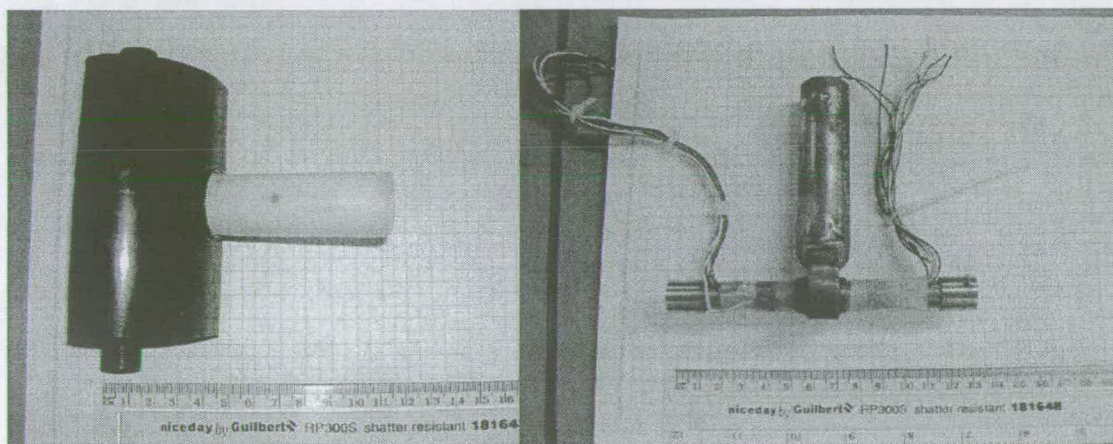


Figure 3-4 Original plastic brush axle (left) which was replaced with the machined steel (right) to allow strain to be measured.

The dimensions and strain induced in the adapted axle were calculated by representing the axle as a simply supported beam with end supports 100 mm apart and a load at mid-span. Theoretical maximum loads were calculated for a 100kg curler. The maximum

vertical force V occurs when the entire mass of the curler is transferred vertically down the brush handle onto the brush head and is 1000N (Figure 3-6).

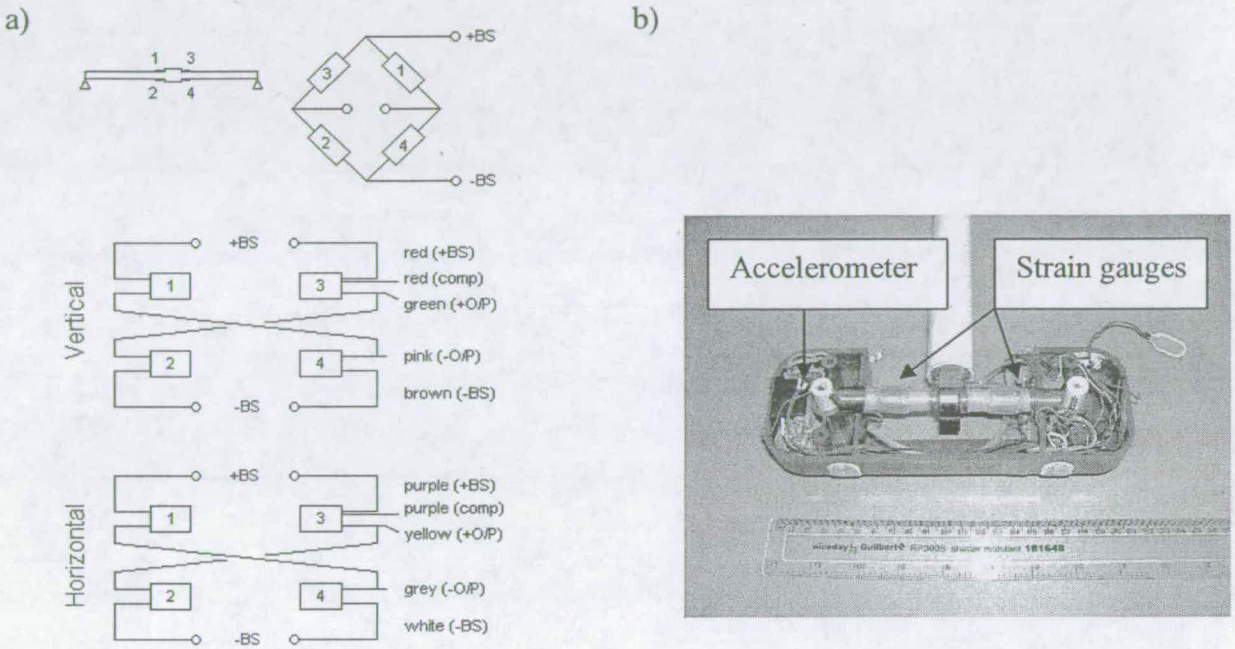


Figure 3-5 a) Strain gauges were bonded in both the vertical and horizontal planes in order to measure the force components normal to these two planes. The diagram shows where the strain gauges were positioned, how they were connected using a Full Wheatstone bridge arrangement and their colour coding. b) The internals of the brush head with replacement steel axle, strain gauges and accelerometer shown for MK1 and MK2 *Hammer Classic* sweep ergometers.

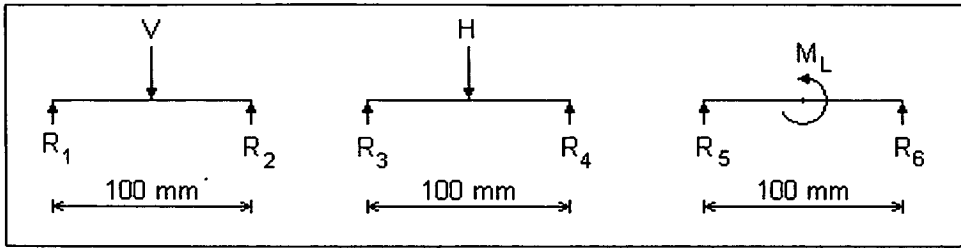


Figure 3-6 Freebody diagrams representing the loaded brush axle

The maximum horizontal force H occurs when the angle between the brush handle and ice is a minimum (when the brush head is furthest from the player). From observation this angle is $\sim 66^\circ$ so that the maximum horizontal force resolved from 1000N acting down the brush handle is $\sim 400\text{N}$. Resolving moments for a simple supported beam model gives the maximum vertical moment M_v , and horizontal moments M_H :

$$M_v = \frac{Vl}{2}, \quad [3.1]$$

$$M_H = \frac{Hl}{2} \quad [3.2]$$

where l is the length of the beam so for the 100mm axle the maximum vertical and horizontal moments are 50Nm and 20Nm respectively.

Two pairs of strain-gauges were used to measure the vertical forces applied to the axles (Figure 3-5) and a further two pairs of strain-gauges measure horizontal forces. Strain-gauges were bonded to the degreased steel shaft using superglue and later waterproofed using heat shrink wrap and low corrosion silicon sealant. Two full Wheatstone bridge wiring arrangements allowed vertical and horizontal forces to be measured independently without effect from torsional loading (Figure 3-5). It was estimated a

maximum ~0.1mm deflection at the mid-point of the steel axle was the up deformation limit for this strain-gauge arrangement. Bending moment theory was used to determine the radius for the axle that would deflect 0.1 mm under the maximum load (1000N). The deflection from the neutral axis y_{max} of a simply supported beam is given by:

$$y_{max} = \frac{Ll^3}{48EI} \quad [3-3]$$

where L is the load, l is the length of the beam, E is Young's Modulus (200 GPa for mild steel) and I is the second moment of area. Given that the second moment of area for a cylinder orthogonal to its central axis is:

$$I = \frac{\pi r^4}{4} \quad [3-4]$$

It follows that:

$$r = \left(\frac{Ll^3}{12\pi E y_{max}} \right)^{1/4} \quad [3-5]$$

An axle with a radius of 6mm would therefore deflect the required 0.1mm under a load of 1000N. A Kistler, Hampshire, United Kingdom, force plate was used to calibrate the output of the strain gauges (Figure 3-7). Due to the mechanical and strain gauge arrangement of the brush axle, side loading on the brush would not affect the vertical and horizontal results. Figure 3-5 a) shows strain gauge positions, along with the colour coding used for wiring.

Table 3-1 shows the strain calculations for the brush axle at different loads. The strain due to bending moment has not been included because its effect is cancelled in the wheat-stone bridge (see chapter 2).

Strain calculations

V (N)	H (N)	M _{tot} (Nm)	d (mm)	I (m ⁴)	Strain	microstrain	
1000	400	26.9	12	1.0 x10 ⁻⁹	7.9E-04	794	Maximum strain
500	200	13.5	12	1.0 x10 ⁻⁹	4.0E-04	397	Typical strain
505	200	13.6	12	1.0 x10 ⁻⁹	4.0E-04	400	Typical +5 N
510	200	13.7	12	1.0 x10 ⁻⁹	4.0E-04	404	Typical +10 N

V is the vertical force

H is the horizontal force.⁻⁹

d is the diameter of the shaft.

1000 N is approximately the weight of a 100 kg person.

The 5 N increments depict the corresponding increase in microstrain.

Table 3-1 Strain calculations for the brush axle when loaded with 1000, 500, 505 and 510N respectively.

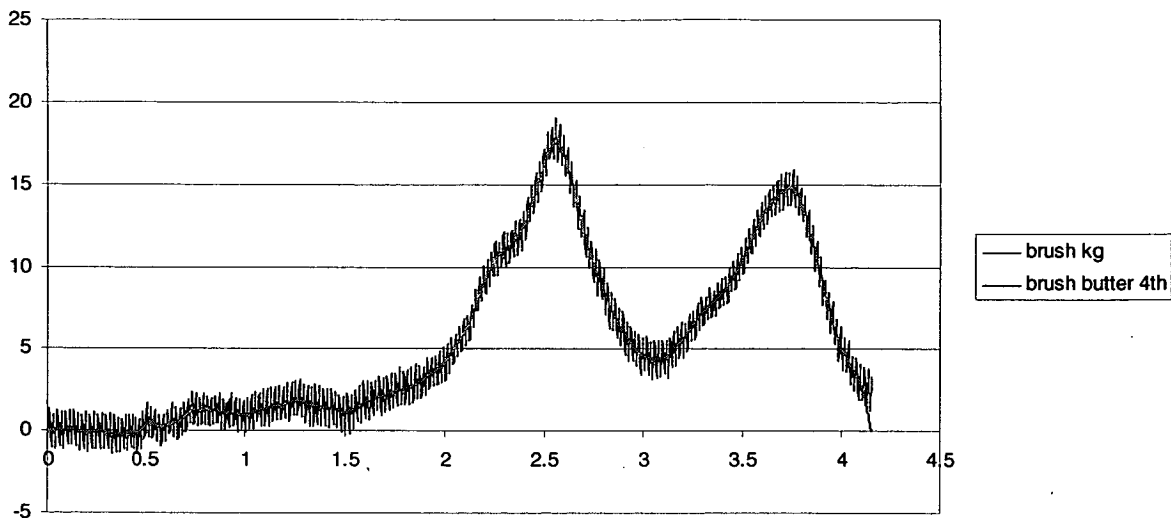


Figure 3-7 Graph showing results for strain gauge calibration against output of a commercially available piezo force plate.

The strain gauges were bonded to the degreased steel shaft using superglue and later waterproofed using heat shrink wrap and low corrosion silicon sealant. The strain gauge arrangement on the steel axle weighed 321g. Acceleration was measured using a +/- 25g Crossbow CXL25LP3-R 3 axis accelerometer which is ideally suited due to its internal temperature compensation amplifier and small size. A schematic for the MK1 brush can be seen in Figure 3-8.

Figure

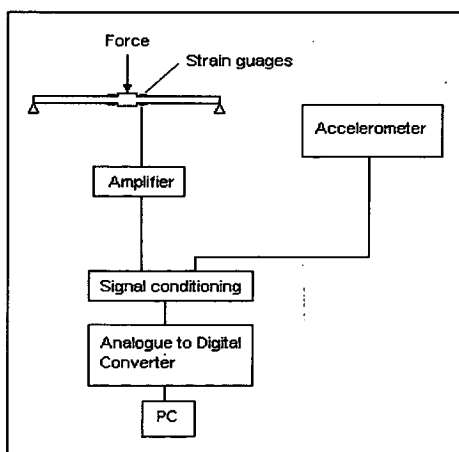


Figure 3-8 Schematic of Sweep Ergometer MK1

1.4.1 Analogue to Digital conversion ADC

A Pico technology ADC-11/12 provided analogue to digital conversion (see chapter 2); with 12-Bit, 10 KHz sampling at an accuracy of $\pm 0.5\%$. With the ADC powered by the laptop, the system was capable of being used without mains supply or excessive battery requirements. An off the shelf strain gauge amp PCB was populated with electronic components to perform strain gauge amplification and voltage off set to provide optimal input for the ADC (Figure 3-9). (RS Stock no: 435-692). The amplification circuit used two PP3 batteries to provide -9v, 0v and +9v supply. The gain of these amplification circuits was set to 47. Although a little cumbersome the system was suitable for use and performed well in a rink (Figure 3-1).

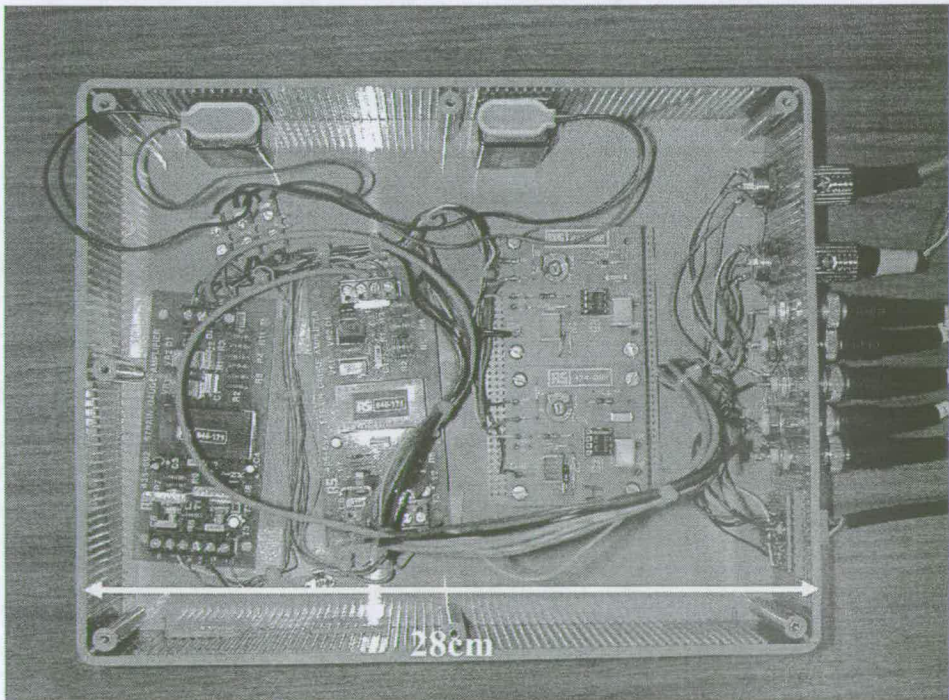


Figure 3-9 RS components amplification circuitry, providing a gain of 47 for the vertical and horizontal full bridge strain gauge arrangements.

The ADC 11 connected via parallel port to a laptop and recorded data into Microsoft Excel using visual basic macros. The ADC buffered data to the laptop, once a data set recording had been taken it would post-process the results. Post-processing applied a Butterworth filter to reduce noise and calibration factors. Numerical integration was used to calculate velocities from the sampled acceleration data in excel, producing velocity data had an error +/- 6 %, and double integrating gave displacement.

Integration was performed using the finite difference equation;

$$\dot{x} = \frac{1}{2}(\ddot{x}_+ + \ddot{x}_0) \times \Delta t \quad [3-6]$$

Where \ddot{x}_0 and \ddot{x}_+ are consecutive acceleration values, with Δt of 0.004s, giving velocity \dot{x} .

The variation of velocity, vertical and horizontal forces with time were then displayed graphically. Sample results for a 25 second period, showing vertical force (V), horizontal force (H) and velocity (v) can be seen in Figure 3-10. These results clearly show the sweeper applying initial force, then upon adjustment, applying even forces for the duration of the test.

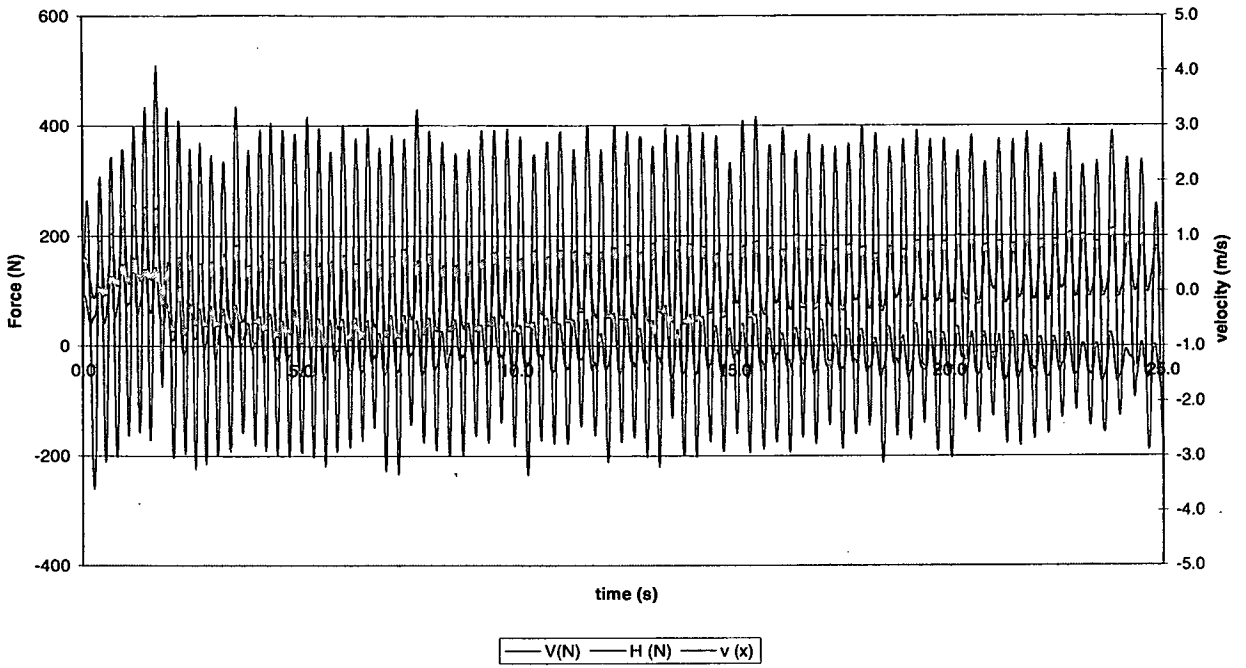


Figure 3-10 Sample data from the MK1 sweep ergometer showing vertical force V, horizontal force H and acceleration v.

3.5 MK2 Ergometer

Initially the MK1 brush was connected to the computer via a 5m shielded cable. This length of cable was prone to picking up electronic noise. Improvements were made by reducing the cable length, however the eventual length led to the amplification circuits, ADC and laptop having to be carried alongside the brusher on the ice (Figure 3-1). This hindered the sweeper's performance and led to the potential of an expensive accident. There was a clear need to implement an alternative and a wireless system was subsequently developed.

1.5.1 Wireless system

The MK2 brush was designed with a RF wireless system to transmit data that negated the need for a connecting cable.

Figure shows a schematic of the MK2 Brush. Radiometrix open band 418 and 433MHz transmitter receivers were used for data communication. These transmitters and receivers were chosen based on their 25m range, minimal power requirements, small size and low cost. This change required the ADC and strain gauge amplification circuits to be incorporated into the brush head. This reduction in size was achieved by designing a miniature amplification circuit using a custom built surface mount board. The circuit was based around a Burr Brown INA 115 ADC chip, which provided gain of 100 with adjustable offset (Figure 3-12). To maximise space available in the brush head the circuit was duplicated on both sides of double sided surface mount board, which allowed an amplifier for each full bridge arrangement. The Radiometrix transmitters and receivers were used in conjunction with a microchip PIC16F74 (Figure 3-13) programmed to perform the ADC. As the PIC16F74 has only 4 dedicated AD conversion inputs, the vertical axis reading from the accelerometer was no longer recorded. Previous results had shown the sweep ergometer rarely leaves the ice surface

and therefore accelerations in the vertical axis can generally be ignored. If a player were to lift the brush off the ice surface it would be visually apparent, and detectable on the vertical force reading. As the PIC was using 4ADC channels, the sampling rate was 250 Hz allowing frequencies up to around 70Hz to be captured [Marmo et al 2006]. The PIC was programmed using a combination of hex and C code compiled in Mplab 5.0, see appendices for code.

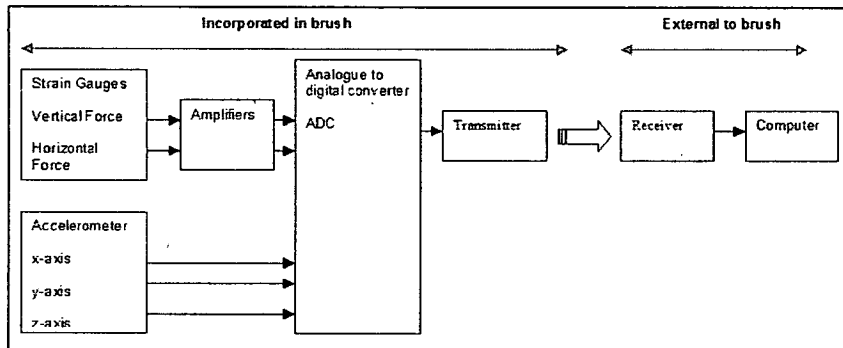


Figure 3-11 Schematic of MK 2 Sweep Ergometer

Another improvement to the MK2 brush was achieved by changing the accelerometer to a +/- 10g accelerometer. Previous results from the ergometer never exceeded 7g in use; a 10g accelerometer was used to provide a safety margin. This further improved signal to noise ratio of the accelerometer signal thereby improving data captured.

Power requirements were supplied by a single PP3 Duracell Powercell via separate surface mount power regulation board. This supplied +/- 5V, ground and 8V for the INA amplifier circuits, PIC, radiometrix transmitter and accelerometer respectively. The PP3 battery supplied sufficient power to run the system for over 1 hour in the cold conditions of the ice rink. The receiving side of the transmission system used a small circuit with the Radiometrics receiver connected to an RS232 serial port connector. The laptop computer connected ran Microsoft Windows 95 and was used to collect data with HP Vee Software (Figure 3-14).

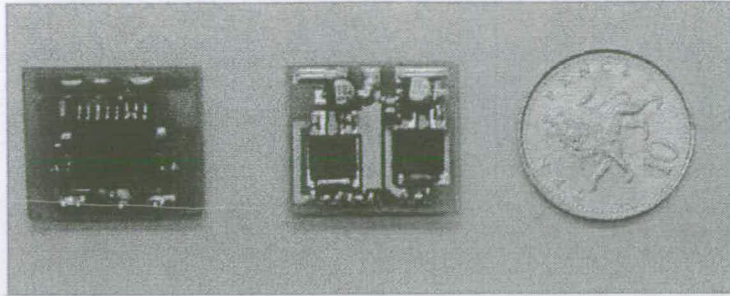


Figure 3-12 INA amplification and power circuit amplify strain gauge signal from the brush axle.

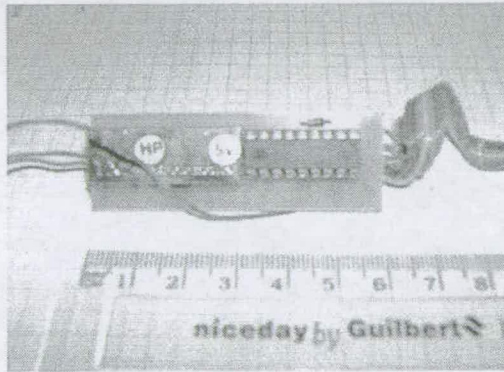


Figure 3-13 ADC circuitries with transmitter, concealed in the handle of the brush

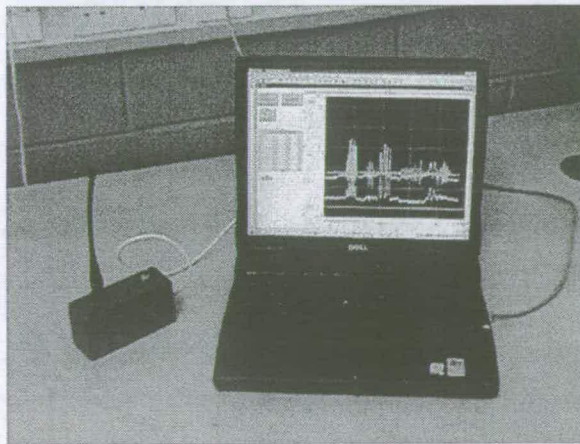


Figure 3-14 Receiver and Laptop displaying forces and accelerations in real time using Hp Vee software

1.5.2 Data representation

The system used HP Vee to provide near real time graphical representations of vertical and horizontal, force and acceleration. Slight fluctuations in real time representation were observed, this was due to the computer periodically running internal applications which affected processor use. It would therefore not be accurate to describe the system as a true real-time representation, although fluctuations would be less than 0.1sec.

The near real time graphical display system enabled coaches to see changes in the force applied whilst a player swept and provided the opportunity for corrective feedback. Once a session had been completed the program would send the information to the original Excel post-processing program and the data post processes in the manner as explained in section 3.4.1.

3.6 MK3 Ergometer

The MK3 system was designed to replace the previous versions and consisted of two major components: the Sweep Ergometer and custom computer software. The MK3 system was based around the Performance brush produced by *Andre Ferland* (Figure 3-15).

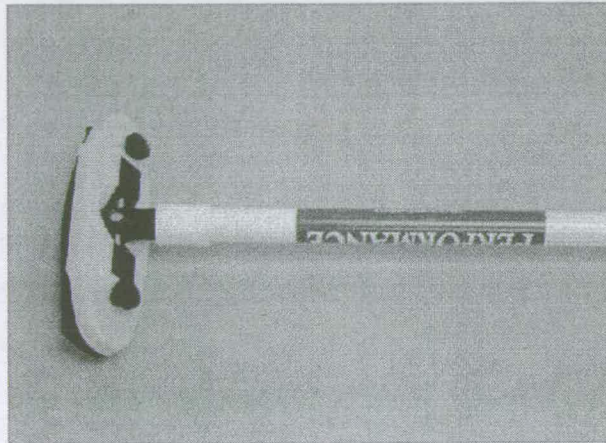


Figure 3-15 An un-adapted *Performance* brush

Since the handle is attached via an articulated joint, the Performance brush adapts itself to any sweeping style. This articulating handle pivots around 2-axes and allows a perpendicular movement in front of the stone; therefore, the second sweeper can sweep much closer to the stone (Figure 3-16). Previously with the hammer brush sweepers had to sweep perpendicular to the head of the brush as it only pivots in a single axis. At 1.7kg the performance brush is heavier than the Hammer Classic at 1kg. The oval head shape of the Performance brush head has a smaller surface area (0.0084 m^2) than the Hammer at 0.0014 m^2 , consequently, for a given force the pressure applied on the ice is greater.

The performance brush lacks the internal space in the head previously used to incorporate sensors and electronics for the MK1 and MK2 ergometer. The previous spindle could not be incorporated within the brush so the sensing had to be incorporated around the brush head. This change in brush selection required a full redesign of the sensing system.

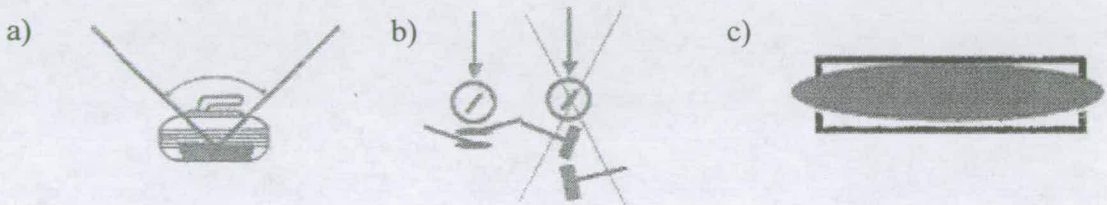


Figure 3-16 Diagrams illustrating the capabilities of the Performance brush a) the stone can be swept from any angle, b) the second sweeper can sweep closer to the stone; c) the Oval head provides a longer 'sweep'. (<http://www.performancebrush.com>)

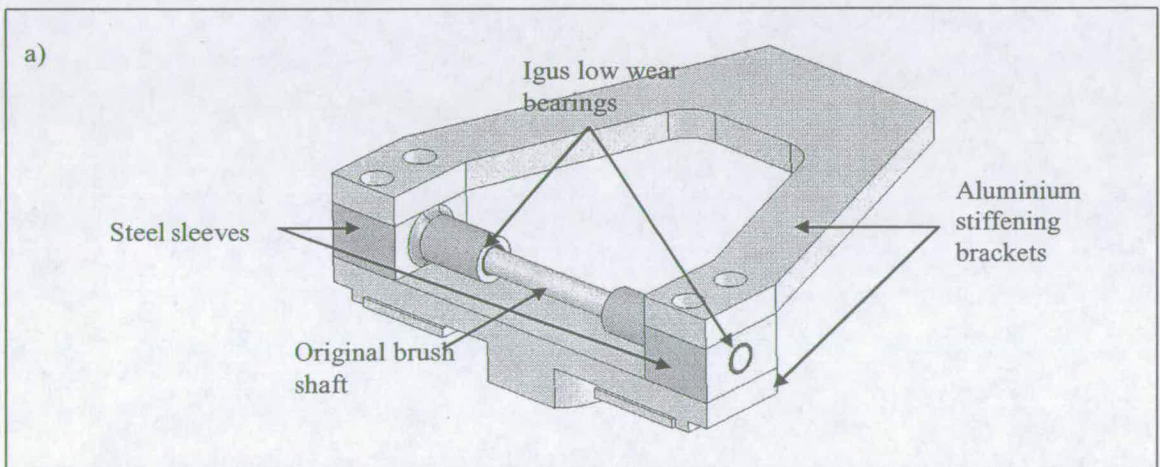
1.6.1 Design considerations

The emphasis for the MK3 system was accuracy, repeatability and reliability. The MK3 brush was commissioned not only to use in training, but as a selection tool for new team members.

For these reasons the MK3 brush returned to being a hard-wired system, using knowledge learnt from design flaws from both MK2 and MK1 systems. MK3 was designed to meet all analysis requirements for sweeper performance. With a wired system sensitivity could be ensured and it was envisaged software problems associated with the MK2 telemetry system could be overcome. As the logging system used was small (75×56×18mm) with a mass of 100g, it was easily placed in a pocket or clip on the players belt during testing.

1.6.2 Instrumentation

To overcome lack of instrumentation space the two plastic sleeves holding the axle were replaced with steel sleeves, on which the strain gauges were mounted. Two aluminum brackets were incorporated to provide sufficient stiffness to allow deflection of the steel sleeves and accurate monitoring of strain in both vertical and horizontal positions (Figure 3-17a). These brackets also provided extra space for the accelerometer, whilst amplification circuits utilized space in the hollow fiberglass handle. Solidworks basic finite element (FE) package was used to determine that sufficient strains would be observed in the steel sections (Figure 3-17b).



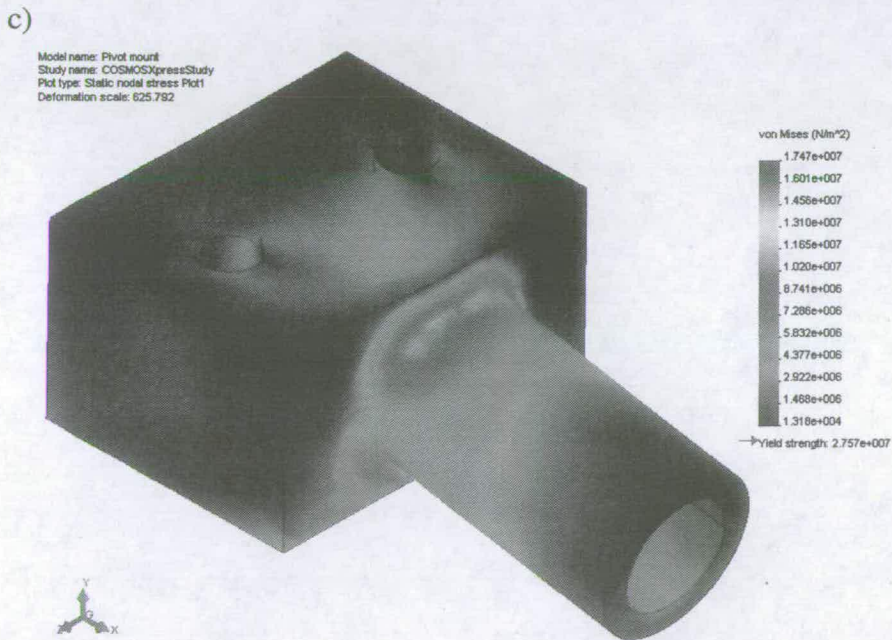
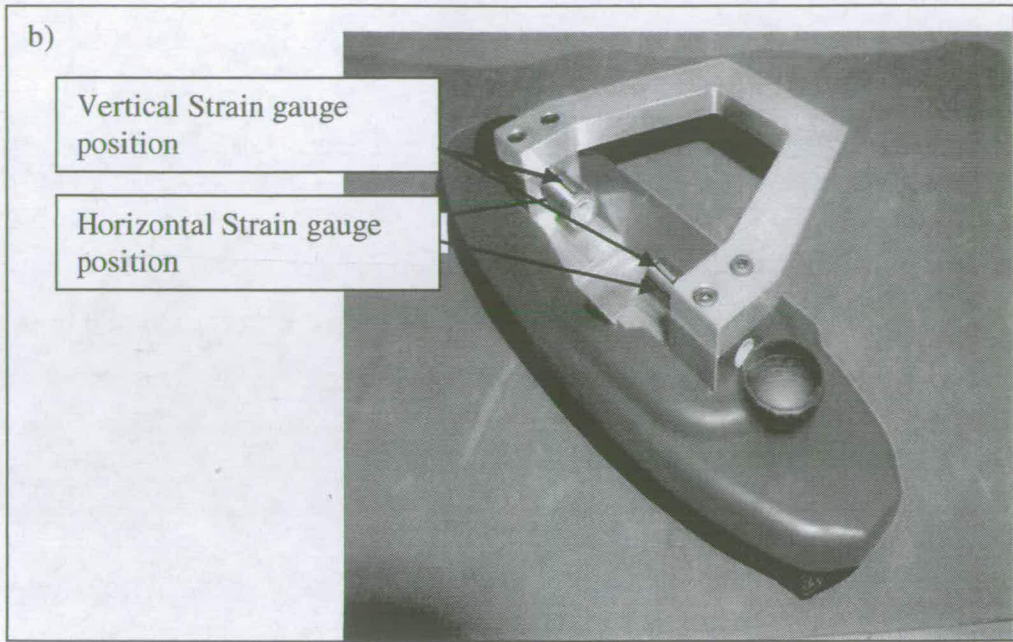


Figure 3-17 a) CAD assembly showing steel and aluminum components. b) Adapted performance brush head, showing locations for vertical and horizontal strain gauges. The Igus bearings can be seen inserted into the steel sleeves. c) Von Mises stress calculations of supports using FE analysis.

The aluminum brackets were designed to give full movement for the bearing joint but remain stiff enough that the first mode would exceed any acceleration likely to be produced by a curler. During design mass remained a major consideration, any additional weight added to the head would adversely affect sweeper performance. The metal replacement sections added 250g to the system. A CAD drawing of the assembly and photograph of the brush head can be seen in Figure 3-17.

The ergometer itself consists of several sensors: 3-axis accelerometer +/- 10g Crossbow accelerometer, horizontal strain gauge and vertical strain gauge. The accelerometer is a crossbow CXL04LF3 as it has a sensitivity of 500mV/g, with a good frequency response up to 100Hz and 10mg RMS noise. Strain gauges and amplifiers were provided, installed and calibrated by Pi Research Ltd (see Appendix C) to the same specifications as that used to monitor F1 cars. The amplification circuit provided gain of 100 with temperature stability over +/- 10 °C .The amplifier was powered by 2 pp3 batteries. Lead wires used careful balancing to prevent temperature effects (see Chapter 2)

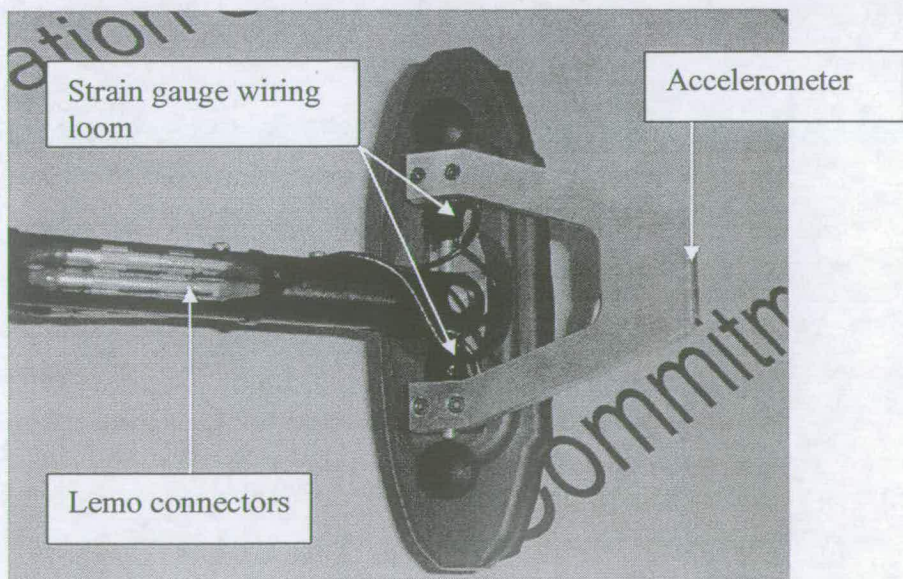


Figure 3-18 Fully assembled brush head. Lemo connectors were used to allow maintenance if required.

1.6.3 ADC and data storage

The information from the sensors was recorded to a 256MB Smart Digital card by a Biomedical Monitoring ADC. This card can be removed from the ADC and placed into a card reader attached to a laptop for easy processing. The system had capacity to store 250 tests before it was necessary to remove the card. The data logger is an eight channel version of the Biomedical Monitoring logger system used for the final snowboard test system (see Chapter 2, for wiring arrangement see Appendix C). The Biomedical Monitoring data acquisition device is based on a 12-bit ADC (Analogue to Digital Converter). This gives an accuracy, on a -5V to 5V range, of 2.4mV. Coupled with the Crossbow CXL04LF3 accelerometer the ADC error is $1.2 \times 10^{-3} \text{ ms}^{-2}$, thus a total error of $\sim 11 \times 10^{-3} \text{ ms}^{-2}$. This error is well within the required accuracy for the task. The Biomedical logger provides a flexible platform as it can be programmed to provide different gains, offsets, amplifications and sampling rates for each channel. Sampling rates for each channel were set at 500Hz. Power requirements were provided to the strain gauge amplifiers by a PP3 battery stored in the handle of the brush. The thermocouple and accelerometer derive their power from the AA battery in the Data logger.

1.6.4 Calibration

A simple calibration device was designed to allow periodic calibration by the British Curling team (Figure 3-19). The device comprised of a rubber seal and hanging block to allow masses to be placed on the handle providing a force similar to that a curler would provide. This is done by applying weights to the brush in increments of 2 kg. A custom written calibration program asks the team to place the brush on one of two orientations and load the system up to 30kg. For horizontal force calibration component the resolved horizontal component was used as the brush cannot be loaded perpendicularly.

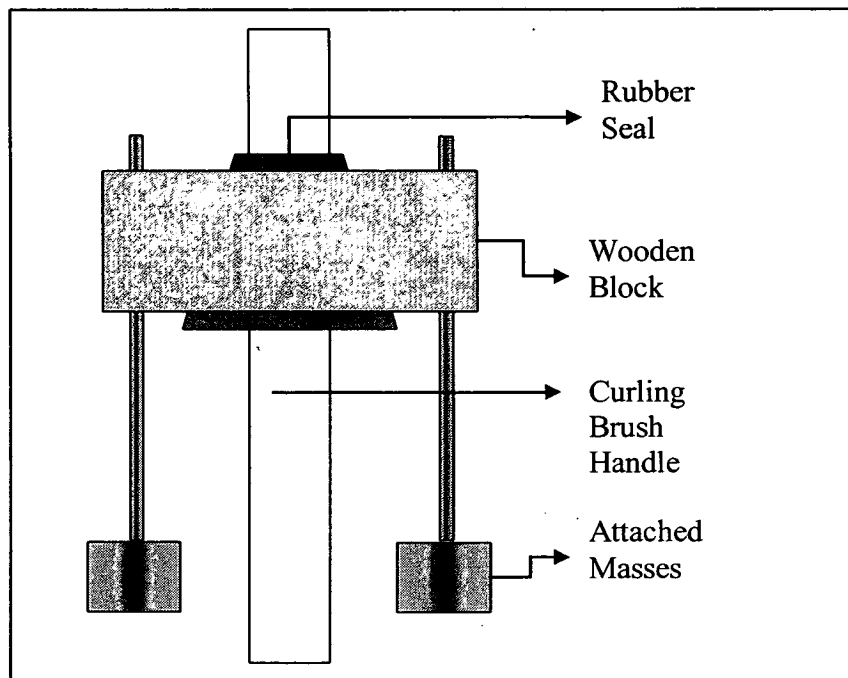


Figure 3-19 Schematic of simple calibration device provided for the team

1.6.5 Analysis Software

The software for the MK 3 ergometer is a custom built, stand alone programme which processes data collected by the Sweep Ergometer on any Windows operating system. The software was designed by the author and Charles Keepax of Reactec Ltd, to analyse the data to produce meaningful results which are easily understood by both coaches and athletes (Figure 3-20). A help file was incorporated and a manual written to aid any issues the team may have in using the software.

The sweep ergometer software was developed by Charles Keepax using the language C++. C++ is an object-oriented programming language and is used as standard in most major software developments. Microsoft Foundation Classes (MFC) were utilised to facilitate rapid development. MFC classes permit the use of Windows Application Programming Interface, this allows the software to run on a Windows operating system. The MFC framework provides two formats of linked architecture; hidden document architecture and visible view architecture. The document classes automatically save raw data to disk and load processed data into memory. The sweep ergometer software was built around a single view file.

As the data was initially stored on Smart Digital (SD) card, the format of the data had to be converted into another format when loading data to the ergometer software. During this conversion calculations were performed to produce the mean, standard deviation, RMS, minimum, maximum, integration, and Fourier transforms.

The software produces "Sweeper Profile" (Figure 3-20). The sweeper profile consists of several graphical and numerical displays of the calibrated sensor data. The sweeper profile displays the variables show in Table3-2.

Vertical / Horizontal Force (N)
Force vs. Time Graph RMS Value Average Minimum Force with Standard Deviation Average Maximum Force with Standard Deviation Peak Frequency
Vertical/ horizontal Displacement (cm)
Displacement vs. Time Graph RMS Value Average Minimum Displacement with Standard Deviation Average Maximum Displacement with Standard Deviation Peak Frequency
Vertical / Horizontal Velocity (m/s)
Velocity vs. Time Graph RMS Value Average Minimum Velocity with Standard Deviation Average Maximum Velocity with Standard Deviation Peak Frequency
Acceleration (m/s²)
Frequency Spectrum (0 – 100Hz range) for each axis

Table 3-2 The variables produced by the sweeper profile

The software loads data from a trial and displays the variables in numerical and graphical form (Figure 3-20). Results of a test are displayed on screen, and the software allowed coaches to input important additional information about each trial such as; Athletes Name, Trial Number, Date, Location and ice conditions. A notes section allowed special events observed during the test to be recorded. The results could then be be saved as a sweeper profile file or exported as a comma separated variables (CSV) file for further analysis using other windows based software.

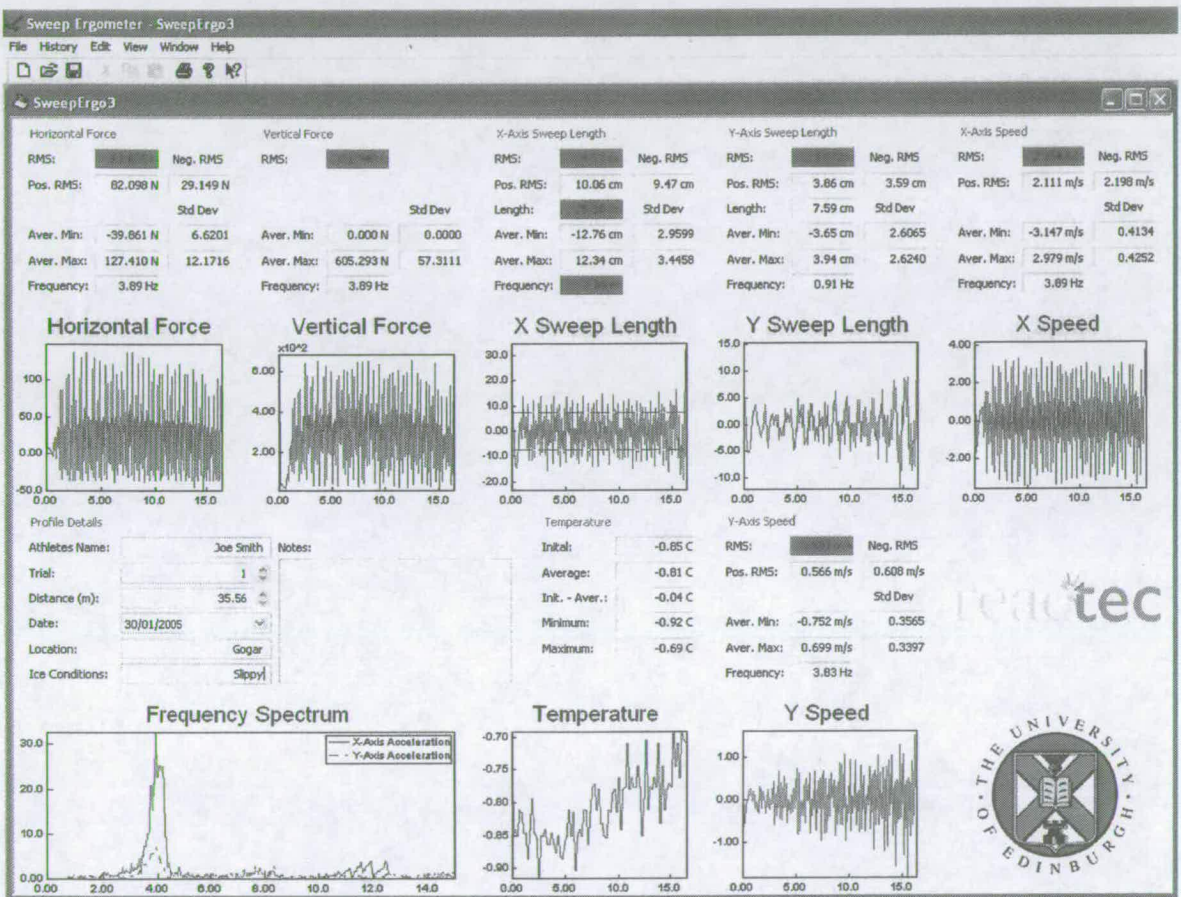


Figure 3-20 Screen shot of the Sweep Ergometer software

The software was programmed to print this information as a sweeper profile (Figure 3-21). This allows individuals to keep a hard copy of their tests.

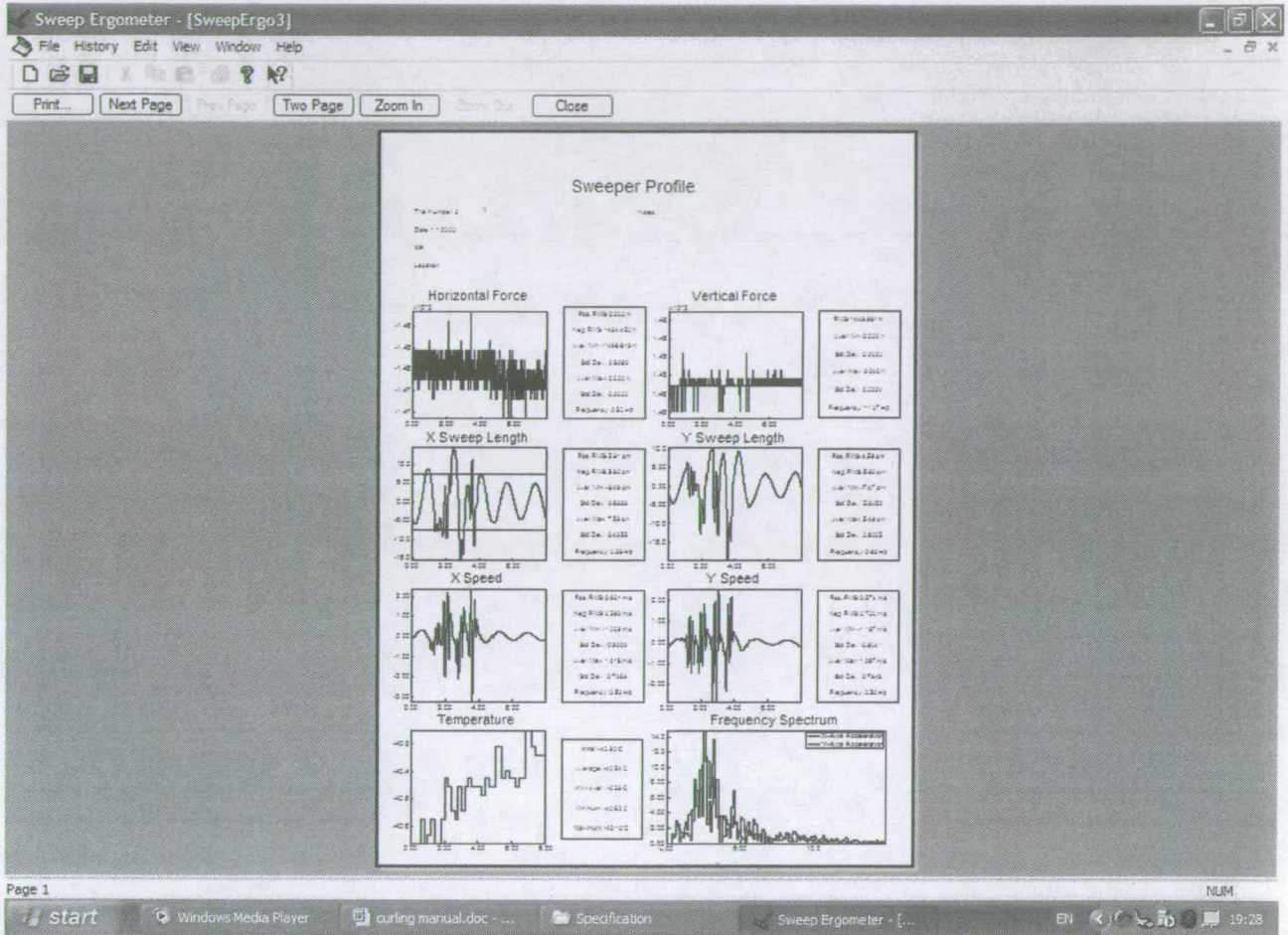


Figure 4 An example sweeper profile printout

1.7 Discussion

The MK2 and MK3 ergometers each produced data of greater accuracy than their predecessor. The MK1 suffered from slight thermal drift ($\pm 5\%$) due to lead wires and the amplification circuit. These effects were reduced by allowing the brush and amplifier temperatures to stabilise in a curling rink for half an hour, this often delayed testing and reduced valuable 'ice' time.

The MK2 improved usability for both the athletes and coaches, and incorporated improved hardware. Without wires attached the ergometer swept like a normal brush which athletes preferred over the MK1 version. The risk of damaging a laptop during testing was greatly reduced as they did not have to be carried on the ice by the coach and could remain at the side of the rink. Data could be seen in near real time by the coach, which allowed rapid assessment of an entire team without delays for processing, sweepers would simply hand the ergometer to the next player and the coach would be ready. As the system produced the post-processed results in the same format as the MK1, further more detailed analysis could be performed. Improvements in accuracy were achieved by changing the accelerometer and strain gauge amplification circuits. An accelerometer with a smaller range was used: results from the MK1 brush provided maximum values of $\pm 7g$ so the accelerometer was reduced from a $\pm 25g$ to a $\pm 10g$ accelerometer. This improved the signal to noise ratio and therefore the accuracy of critical acceleration, velocity and distance results. The INA 115 amplification circuit had improved temperature stability and accuracy; this improved the accuracy of the force results. The MK1 and MK2 brushes were designed on low budgets ($<£1000$) to be used as a training instrument and both performed this task well.

The MK3 brush was designed to be incorporated into the Olympic selection process for the GB team. The MK3 brush was required to produce the best results possible on a

development budget of £25,000. The Performance Brush used to build the MK3 ergometer is the current brush used by the GB team, but changing the brush from the previous MK2 required a new design. All equipment used in the production of the MK3 sweep ergometer was of the highest level available during the two month development program. The final MK3 brush produced reliable low error results consistently providing the GB team with a performance instrument.

1.8 Conclusion

Three versions of a sweep ergometer have been designed, tested and built. The ergometers have proved an invaluable resource to curling athletes and their coaching staff. All sweep ergometers measured the vertical and horizontal forces and acceleration in two axes and provided the first quantitative analysis of sweeping in the sport of curling. Software has been designed and produced which analyses the raw data and produces calibrated meaningful results which can easily be understood by coaches and athletes. Analysis of force and velocity parameters have contributed to GB Olympic team selection prior to the Turin Winter Olympics 2006. The MK3 ergometer will continue to be used for team selection before major tournaments and for tactical selection of sweepers during a game. Results and analysis of data produced by the three ergometers is presented in chapter 4.

This novel data has immediate implications for the design of curling brushes. Knowing the maximum forces exerted by both men and women allows custom lightweight brushes to be designed to these specific forces. The force requirements and ultimate strength of individual components can be modelled and surplus material removed.

Chapter 4 Dynamics of Sweeping in the Sport of Curling

There was a need for quantitative sweeping data to get an understanding of the dynamics involved in curling. Prior to the work described in this thesis there has been no quantitative data for sweeping and curlers have had to theorise about the effects based on personal experience and observation. A sweep ergometer has been developed to perform the first quantitative analysis of sweeping dynamics (see Chapter 3). The sweep ergometer is a curling brush equipped with a series of strain gauges and an accelerometer that measures the forces and velocities applied by curlers. This chapter details qualitative results recorded using the sweep ergometer along with the thermal effects of sweeping. Both Olympians and novice curlers were tested; the results from the MK1, MK2 and MK3 ergometers are described.

4.1 Standardised test procedure

A repeatable test was designed with input from the British Team coaches, where each player had to sweep the full length of the rink in front of a stone being pushed by the coach at a similar velocity to that which a stone would travel during regular play (Figure 4-1). The final standardised test required curlers to sweep for 25 seconds with maximum physical exertion. Players were instructed to brush as hard and fast as possible. This exercise was repeated three times by each player with a two minute recovery interval between each exercise. The two minute interval between each sweeping exercise is representative of the break period during a formal match. During this two minute interval most players recovered and began with the same frequency (Fig. 4-2). This test would allow player characterisation and fitness levels to be determined. When assessing a curling team this test was conducted by five elite sweepers (one player acts as team reserve). Numerous tests were conducted with different players and rinks.

4.2 Thermal effects of sweeping

Work conducted by Brett Marmo is included in this section; significant collaborative work has been conducted on thermal effects of sweeping. This section provides a summary of the thermal effects of sweeping and derivation of calculations used by the author to produce data on individual curlers. Appendix 0 provides a full text on thermal factors within the sport.

Curlers sweep the ice vigorously ahead of the progressing curling stone in order to adjust the trajectory of the stone. Stones that move along swept paths decelerate more slowly and curve less. The ice is swept vigorously to increase the distance over which the stone moves or to tactically avoid or impact stones already played. Low velocity sweeping is occasionally conducted to clean the ice in front of the stone, ensuring no foreign particles are in the stone's path which may affect the trajectory. Vigorous sweeping increases the temperature of the ice. The change in temperature and related variation in the coefficient of friction of ice are dependent on the velocity that curlers sweep, the downward force they apply and the pattern that is swept. Sweeping is a highly physical component of the sport.

Ice friction is the central process in the sport of curling. Ice is commonly regarded as an extremely slippery material because it has a coefficient of friction an order of magnitude lower than other crystalline solids. Friction on ice depends on a number of parameters including the velocity, thermal properties and surface roughness of the sliding object and on the morphology and temperature of the ice.

The mechanisms that operate when a material slides across ice are complex. Several interdependent mechanisms have been identified, though different mechanisms tend to dominate under different conditions. At velocities greater than $\sim 0.01 \text{ ms}^{-1}$ and temperatures above $-10 \text{ }^\circ\text{C}$ frictional heating is sufficiently high to melt the ice surface

and provide a lubricating film of liquid water [Bowden 1939, Bowden 1950, Evans et al 1976, Marmo et al 2006b]. At velocities less than $\sim 0.01 \text{ ms}^{-1}$ frictional heating is not sufficiently high to lubricate the ice-slider interface and frictional sliding proceeds via the deformation of asperities and surface fractures [Barnes 1971, Rist 1997, Montagnat 2003]. Thus at low sliding velocity, the coefficient of friction is controlled by the creep rate of ice [Barnes et al (1971)], adhesion by sintering leading to asperity growth [Tushima, 1977] or a combination of both processes [Kennedy et al, 2000].

Lubricated sliding due to frictional heating is the dominant friction mechanism for most of the velocity and temperature ranges in curling and other winter sports involving sliding on ice or snow. The thickness and behavior of the fluid films that form at the sliding interface control the friction of curling stones on ice. For a given load, the frictional heating and the thickness of the fluid film increase with velocity, resulting in a non-linear reduction of friction with velocity ($\mu \propto v^{-1/2}$) [Evans et al, 1976, Stiffler 1984]. It is this inverse and non-linear relationship that is responsible for the curved trajectory of curling stones [Marmo et al 2004].

Friction on ice is strongly dependent on temperature. As ice approaches its melting point less thermal energy is required to melt its surface. Thus, for a given load and velocity more lubricating melt is produced at higher temperature T so μ varies inversely with T . The presence and thickness of the fluid film is also dependent on the thermal properties of the slider. As the thermal diffusivity of the slider increases more frictional heat is transported away from the sliding interface and is not available for ice melting so the thickness of the fluid film is reduced and friction increased [Akkok et al, 1987]. The thermal history of both the slider and ice are important. The longer that a sliding event occurs the more heat is accumulated by the system. In the case of sweeping on ice the thermal history can be complex and strongly affect the coefficient of friction.

Friction is dependent on the surface roughness of both the ice and slider. A proportion of the lubricating fluid penetrates into the 'valleys' between surface asperities thereby

reducing the effective thickness of the fluid film. As the sum surface roughness of the ice and its counter-facing surface increases the effective thickness of the fluid film reduces and μ increases

The frictional heat Q generated by rubbing is equivalent to the work done over a finite time Δt :

$$Q = Fv\Delta t \quad [4-1]$$

Where v is the sliding velocity and F is frictional force. As;

$$F = \mu N \quad [4-2]$$

Where, μ is the coefficient of friction between the surfaces and N if the force normal to the surface.

$$v \Delta t = d \quad [4-3]$$

Where d is the distance in metres.

$$Q = \mu Nd \quad [4-4]$$

Where Q is the frictional heat in Joules. Equation 4-4 allows the calculation of frictional heat from data gathered using the sweep ergometer (see section 4.4).

4.3 MK1 and MK2 results

As the sensing equipment from MK1 and MK2 brushes produced the same data, the results have been amalgamated in this section. All results shown are from the standardised test procedure.

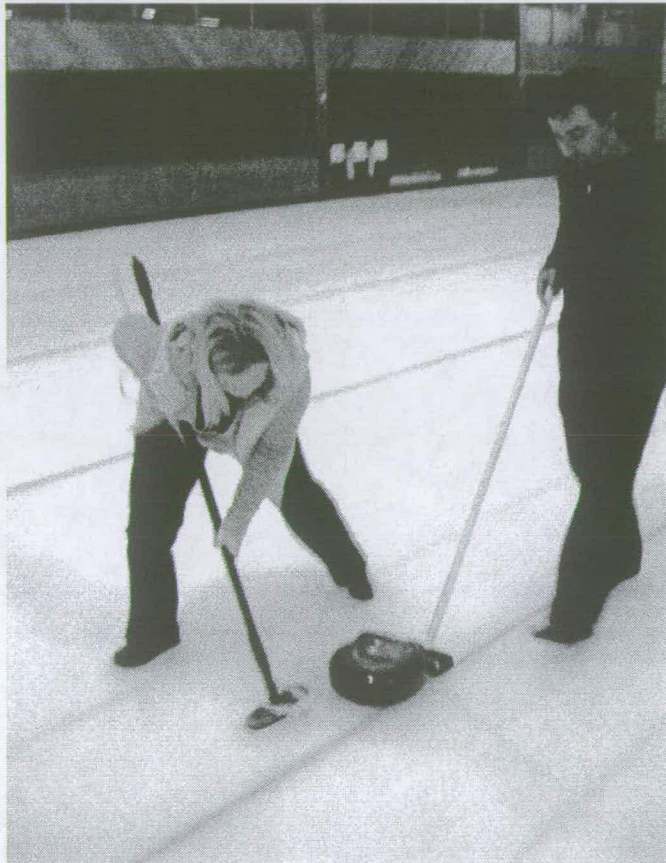


Figure 4-1 The current Scottish team captain, Kelly Wood, undergoing the standardised test procedure with the MK3 brush.

The results in this section were obtained from the Womens 2002 Olympic gold medal winning team.

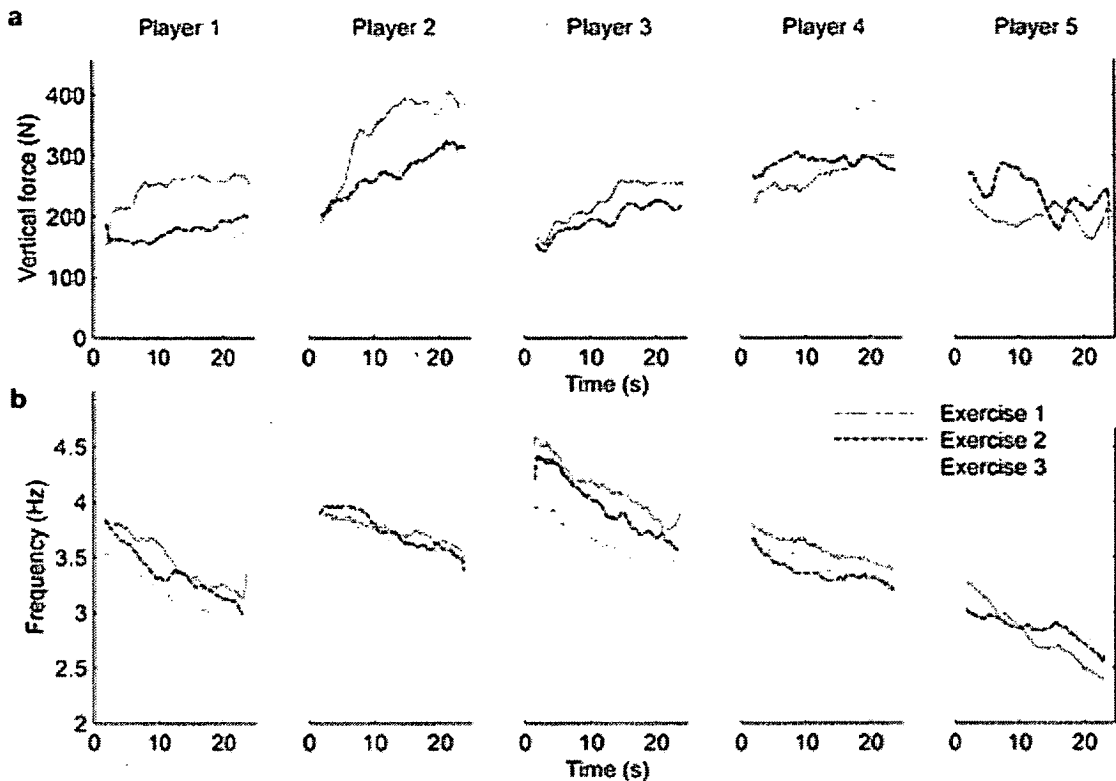


Figure 4-2 Sweep ergometer output from training exercises for 5 elite curlers. Each player completed three exercises where they swept with maximum effort for 25 seconds. There was a two-minute recovery time between each exercise. a) Variation of the peak vertical force over the duration of each exercise. The peak vertical force was the maximum force applied during each stroke. b) Variation of stroke frequency with time over the course of each exercise. The reduction of stroke frequency with time is due to player fatigue.

During sweeping the peak vertical force is the maximum downward force applied by the curler during each stroke; these forces vary from 130N to 400N. In general each player began by not pushing down as hard as they could and then increased their downward force over the course of each exercise (Figure 4-2). In one case (Player 4, Exercise 3, Figure 4.2a) the player increased the downward force dramatically after some persuasive encouragement of the head coach. The gradual increase in vertical force may be due to

the player saving some energy for later in the exercise. In this case, a coach could make sure that players are applying the maximum effort during training with the sweep ergometer.

Generally the vertical force diminished with successive exercises due to player fatigue, which is most notable for Players 1 and 3 (Figure 4.2). Player 2 applied the greatest downward force during the first exercise and then dropped to a lower but more consistent level. Player 5 was the most erratic with the vertical force changing sporadically throughout each exercise (Figure 4.2a). This is an example of poor sweeping as it would prove problematic to the team skip who chooses when and when not to sweep. The inconsistency of Player 5 would make it difficult for the skip to judge when and for how long the player should be sweeping.

The stroke frequency shown in Figure 4.2b was calculated as the inverse of time between velocity peaks. The stroke frequency for all five players decayed over the course of each exercise due to player fatigue. It was found most players swept in the region of 4Hz (Figure 4.2). The maximum frequency observed was 4.85 Hz by player 3, and the minimum 2.4 Hz by player 5 (Figure 4.2). The steepness of this decay gives a good indication of player fitness. Most players also show a marked decrease in stroke frequency over successive exercises (Figure 4.2b, Players 1, 3, 4). Player 2 provides an example of a highly fit player with a relatively shallow decay in frequency over each exercise followed by strong recovery and consistent frequency in successive exercises (Figure 4.2b).

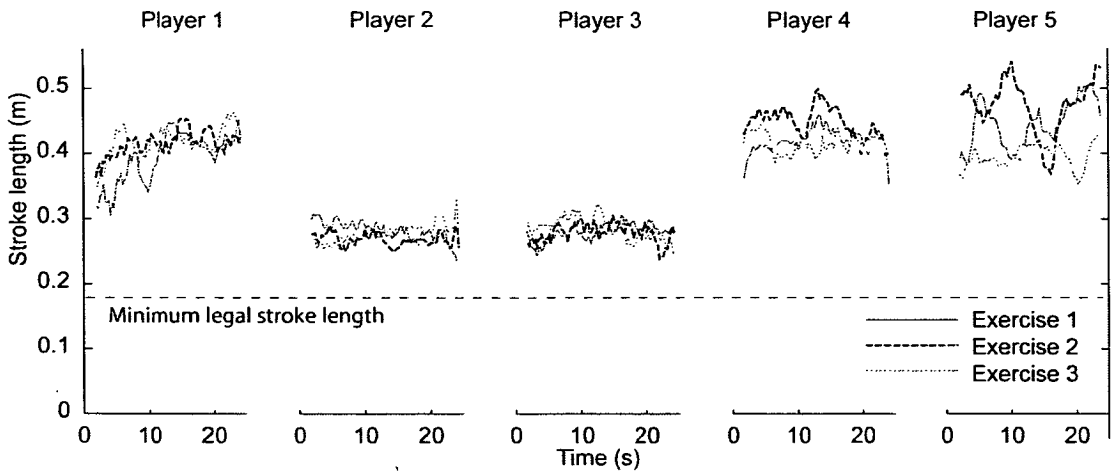


Figure 4-3. Stroke length during training exercises for 5 elite curlers. The stroke length is determined by the double integration of acceleration output from the sweep ergometer. The rules of the sport specify that each stroke must commence and terminate outside the width of the running surface of the approaching curling stone. This distance is 0.14 - 0.18 m depending on the specification of the curling stone and is represented on the figure as a dashed line (0.18 m).

A curling stone runs on a band 13.5 cm in diameter (see section 3 Figure 3-2) and players are required by the laws of the sport to sweep across the entire width of the running surface [McMillan, 1999]. The distance of each stroke was calculated by the double integration of acceleration data from the sweep ergometer (Figure 4-3). This is to prevent the players from intentionally 'dumping' ice debris in front of one side of an approaching stone to radically alter its trajectory. Players 1, 4 and 5 swept approximately twice the required distance and thus wasted valuable energy (Fig. 4-3). Players 2 and 3 swept a consistent distance of approximately 30 cm. Coaching staff can monitor the stroke length of players with the sweep ergometer and correct their style to make their sweeping form more efficient.

4.4 MK3 results

The MK3 brush provided significantly more information than the MK1 and MK2, due to the increased accuracy and software complexity (see chapter 3). Results shown in this section were taken during selection for the 2006 Winter Olympics. The British curling coaches used quantitative measures to assess the top ten male and ten female curlers in the UK. The standardised test was used as part of the process to select the best 5 individuals for each team. As each player and the coaches repeated the test three times, what is believed to be the single largest data set for curlers was recorded. Some of the same athletes were measured for the women's results that were included in Figure 4-2 and Figure 4-3 from previous Ergometer brushes.

As the data sets are so large the majority of results can be found in appendices E through to J. Selections of results that are characteristic of the data set are presented here. The average force and frequency values for both men and women are shown in Figure 4-4, Figure 4-5 and Table 4-1. Men sweep at higher frequency and with higher force than women and thereby transmit greater energy to the ice. The average male maximum vertical force is 497N, whilst the females' maximum is 320N with frequencies of 3.43Hz and 3.29Hz respectively. As the force applied is an oscillation signal and the maximum force is only observed for a brief instance during the stroke, root mean square values (RMS) show a representative value for the force applied throughout the stroke. The RMS for males is 251.5N and 168.6N for females. The difference between the RMS and Maximum is representative of the range of forces a sweep applies (Figure 4-4, 4-5). These higher forces and frequencies allow the stone to travel further if other factors remain consistent.

Graph Showing Mens Vertical Force

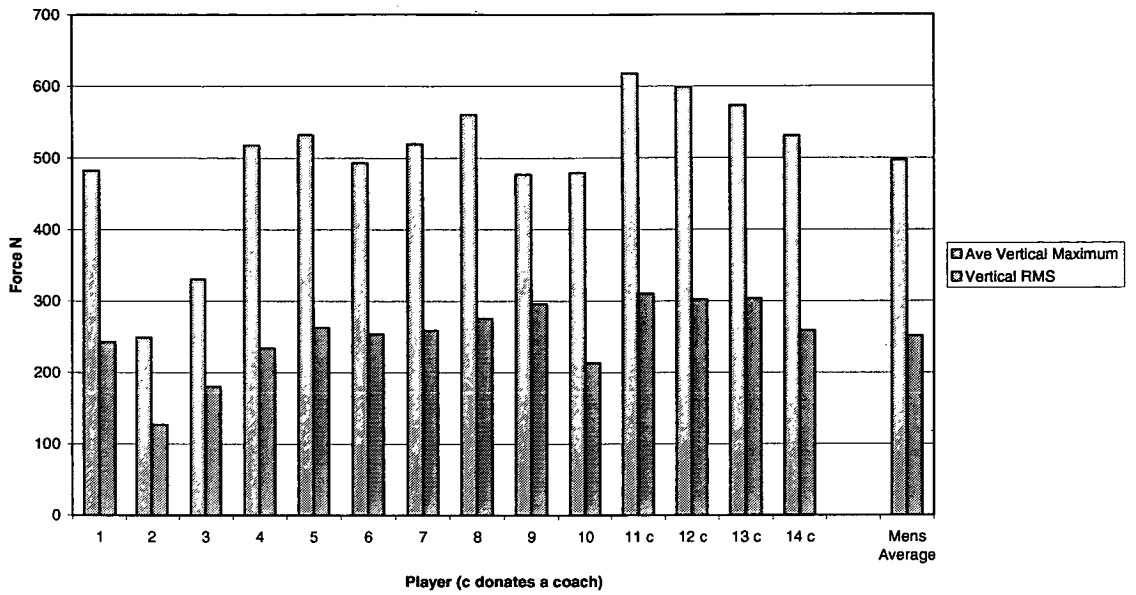


Figure 4-4 Men's vertical forces including coaches

Graph Showing Vertical Forces

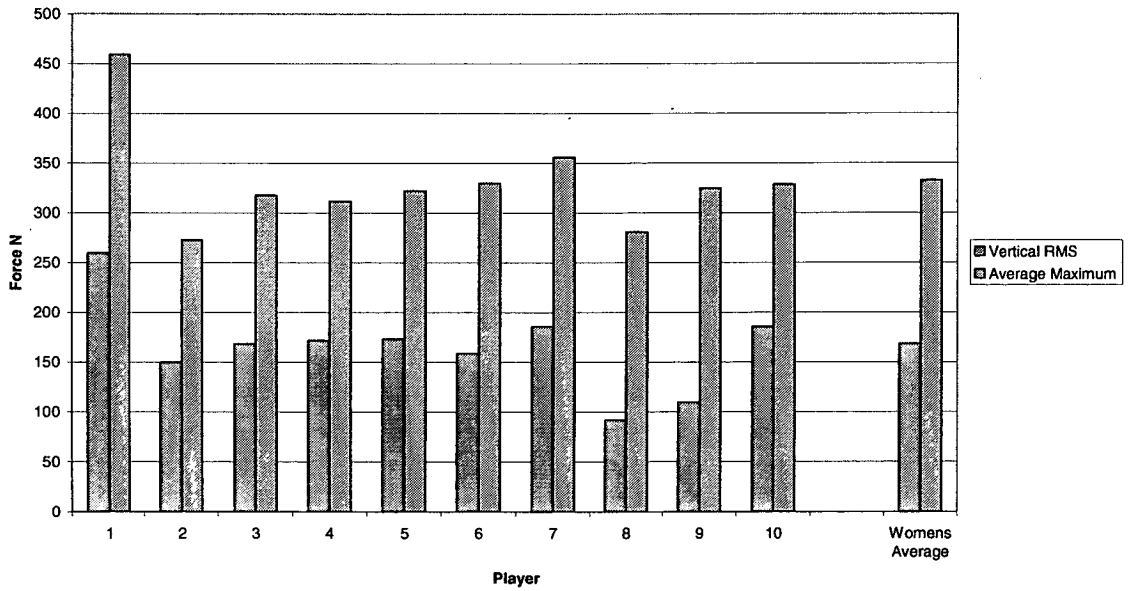


Figure 4-5 Women's vertical force

	Vertical Force RMS (N)	Vertical Force Average (N)	Horizontal Force Average Max (N)	Horizontal Force Average Min (N)	Frequency (Hz)
Male Average	251.5	497.3	9.9	-85.21	3.43
Female Average	168.6	332.7	8.12	-51.5	3.29

Table 4-1 Average Force and frequency values for both men and women

If distance swept is observed (Figure 4-6, Figure 4-7) again it can be seen that the men are sweeping a greater distance on average than their female counterparts in both axes (i.e inline with brushing and perpendicular to brushing).

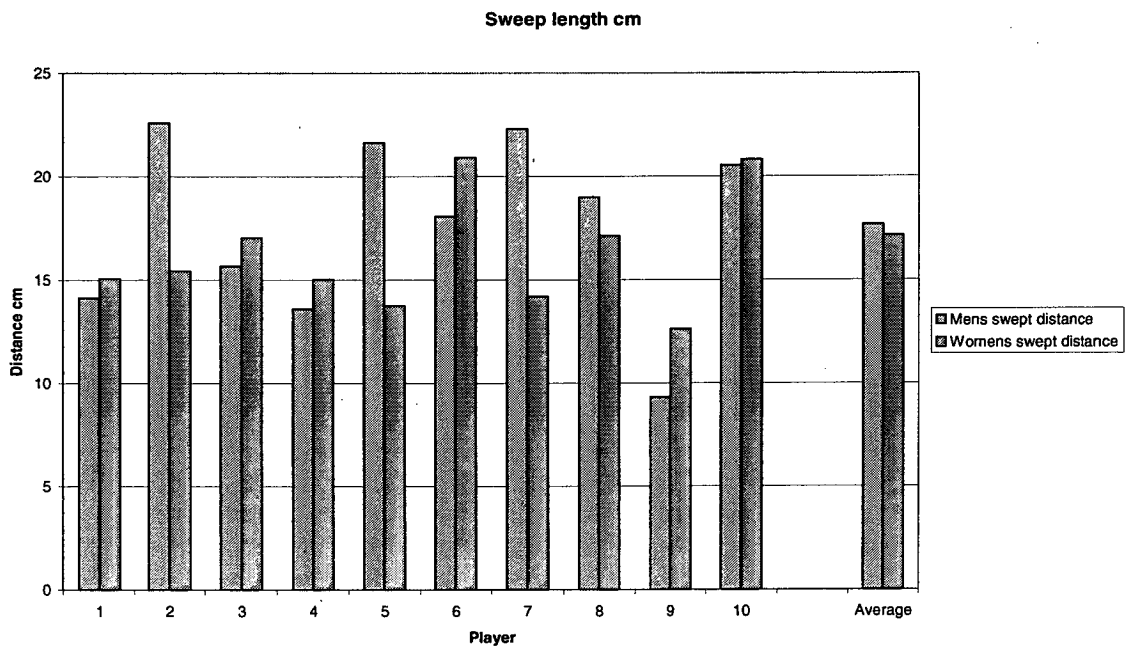


Figure 4-6 Swept length in-line with brushing motion for all 10 male and female players

Many sweepers do not sweep perpendicularly to the stone which is why distances vary dramatically amongst sweepers. The sum of the distances swept is representative of the overall swept distance. The men have a greater overall swept distance than the females.

This greater distance is not an advantage, the sweeper must sweep the entire 13.5cm width of the running surface, distances greater than this are inefficient as the stone will not travel on the ice to which force has been applied. It is therefore the females who are more efficient in this discipline.

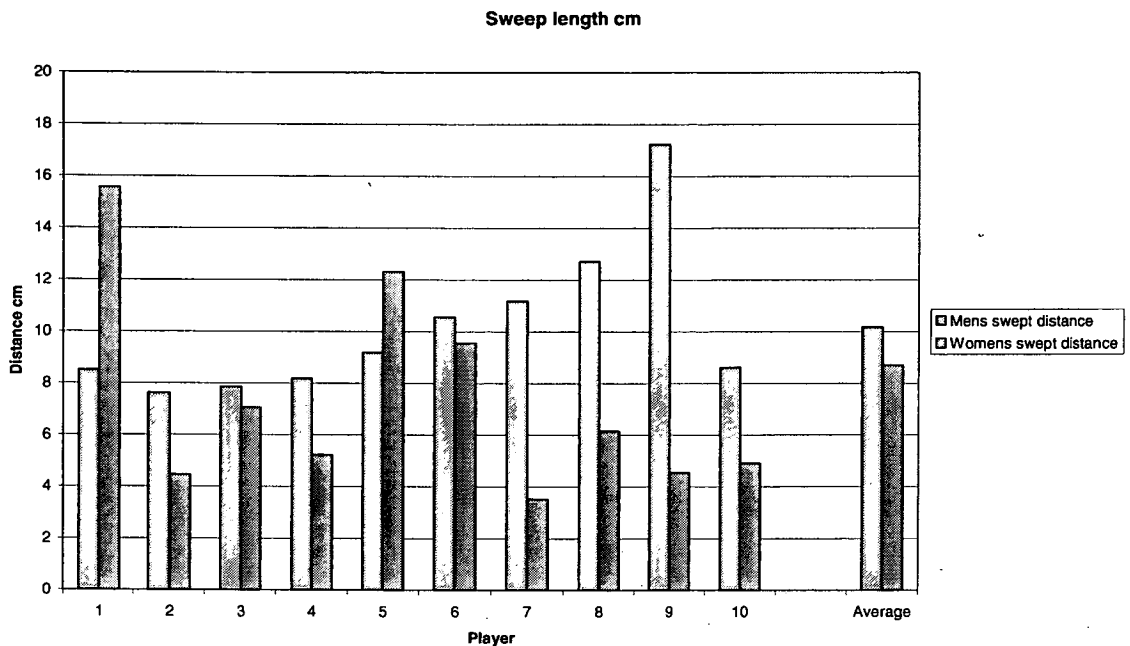


Figure 4-7 Swept length perpendicular to brushing motion for all 10 male and female players

If one sweeper swept a greater distance from the stone than another whilst sweeping in exactly the same manner, the stone with the closest sweeper would travel farthest, as the stone would benefit from a greater temperature of the ice on which it is travelling. This emphasises the number of areas a sweeper must focus on to allow optimal performance.

As the change in ice temperature is dependant on frictional heat produced which in turn is dependant on the force and velocity the brush head experiences: using equation [4-4] where d = the sum of swept lengths in the x and y directions (Figures 4-6, 4-7), and N = RMS vertical force (Table 4-1), using a coefficient of friction μ of 0.1 for nylon and ice the frictional heat can be calculated. Figure 4-8 shows the individual and average

frictional heat produced for both male and female players. As males sweep with greater velocity and higher force they generally transmit greater energy and the ice experiences a greater temperature increase. The average frictional heating for the men was 6.5 Joules and 4.4 Joules for the women.

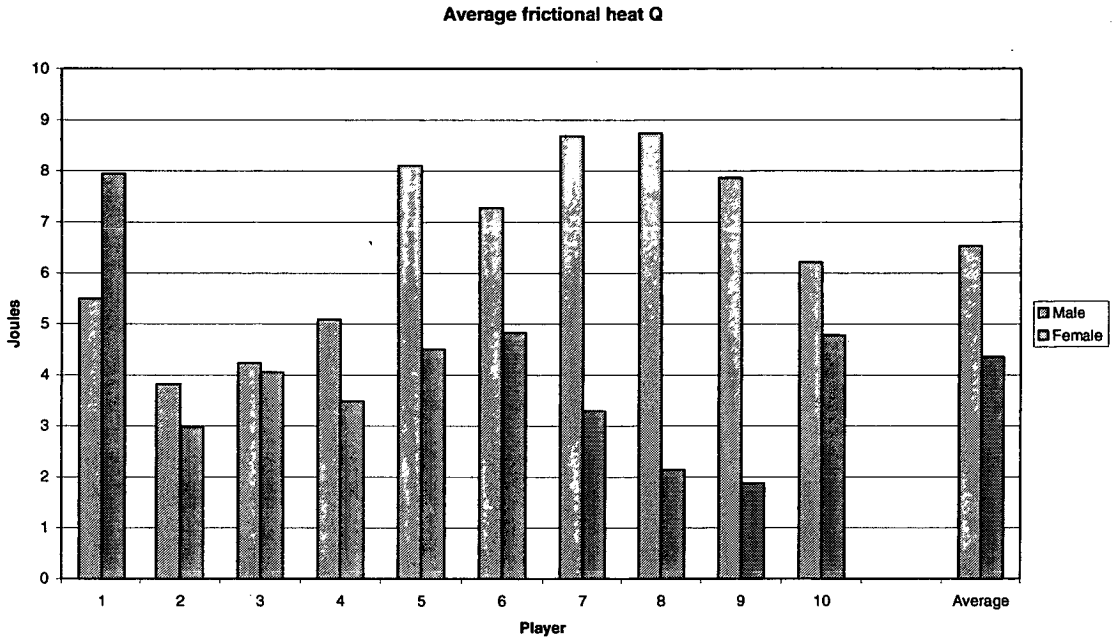


Figure 4-8 Average frictional heat produced during sweeping for men and women

4.4.1 Training

Different sweeping styles can be identified using the sweep ergometer. From section 4.3, player 3 provides an example of a high velocity (frequency) stroke with little downward force compared to Player 2 who has a high force, lower velocity style. The analysis of force and frequency decay will enable the tactical selection of sweepers during a game, i.e. players with high force and/or velocity but fatigue over the duration of a game can be utilised to a greater extent at the beginning of a game or 'saved' to perform at the end of a game. When more than one sweeper is used the player closest to the stone has the

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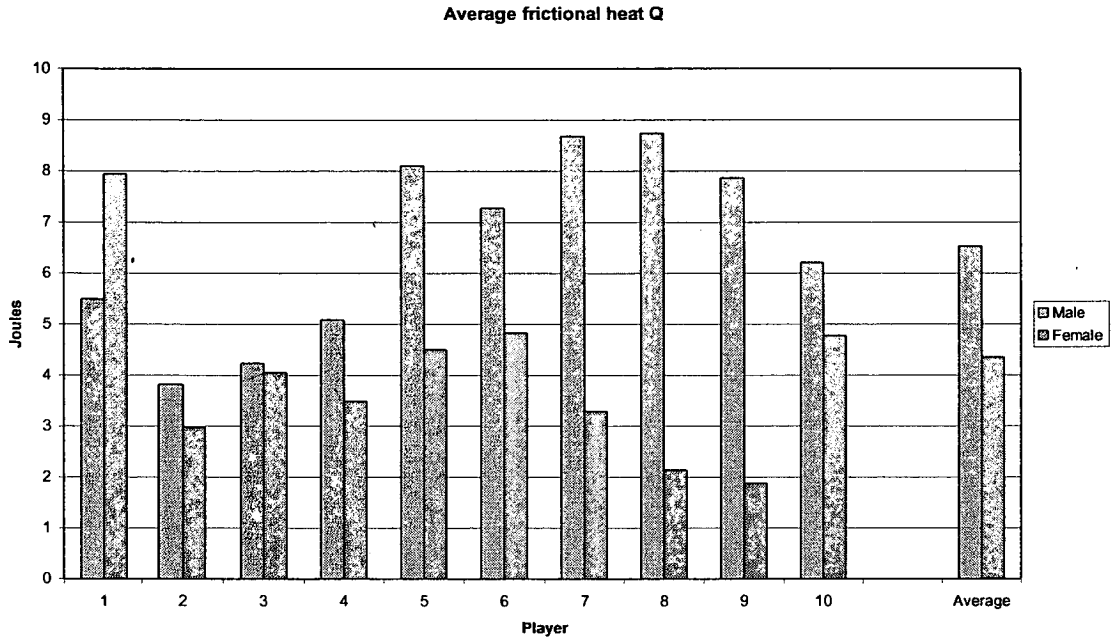


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greatest effect. In this case, the stronger sweeper can be identified using the sweep ergometer and placed next to the approaching stone.

Players must understand their own profile and take individual aspects of their sweep in order to improve its effectiveness. Initially consistency is the desired approach, allowing the skip to 'call' with more accuracy. Following this the player must improve physical technique and ability to increase both force and frequency. This will allow them to increase the range of variation in both distance and position that they can leave a stone by sweeping. They must then look at the relationship between their brush and the stone.

The data from these results was used for selection and the MK3 ergometer has been used in the periodic monitoring and further training of the British Olympic squads. Force applied, velocity and consistency were the major factors used by the coaching team to assess players.

4.5 Conclusions

Several successful tests were performed with different players and on a variety of curling rinks. Results based on the sweeping performance of five curlers show that the efficiency of their sweeping technique and fitness can be easily identified using the graphical output from the sweep ergometer. The decay in frequency over the course of a single sweeping exercise is a strong indicator of a player's fitness. Likewise, the decay in the mean frequency over successive exercises is indicative of recovery rate and fitness. Player strength and technique can also be identified from the force history and appropriate adjustments made during training. Analysis of force and velocity parameters will contribute to team selection before major tournaments and the tactical selection of sweepers during a game.

The MK3 ergometer was used to assess the entire GB curling team and used as part of the Olympic Selection Process. Individual sweeper profiles were gathered and figures for elite curling average collated. It was shown that men exert more work while sweeping via both higher velocities and forces, which leads to higher frictional heating of the ice surface. The male players can therefore adjust the stones trajectory to a greater extent than that of the females.

The aim of this section is to highlight aspects of this research that may, and are currently being continued. In-situ analysis of snowboards supported with static analysis has provided a platform for further systems. Systems which provide data in a more appropriate format for athletes and coaches alike would increase the value gained from the system. The third iteration of the sweep ergometer (MK3) now provides reliable data which is extremely valuable to athletes and coaches alike. The accuracy of data produced has the potential to be combined with other devices to further improve training techniques, and similarly to the study of ice friction in the academic field.

5.2 Snowboard Instrumentation and Analysis

In situ data from snowboards was captured as a standard CSV file and post processed by the author. Custom software similar to that used for the MK3 sweep ergometer would allow coaches to see relevant data without the requirement for complex processing. If a program were to be developed an iterative process should be developed which can automatically detect errors in riding technique. This would require the input of athletes and coaches to develop and refine a specific algorithm. The system would then automatically inform coaches of errors on technique. Individual algorithms would be required for the different snowboard disciplines and manoeuvres. This system is best implemented on elite riders who have to concentrate on small differences in order to continuously improve.

The final hardware used in in situ snowboard analysis would benefit from additional work. Collection of data from PVDF sensors could be improved upon by combining accelerometers and strain gauges to allow simple force calibration, and provide extra data of the snowboards global movement. Returning to a telemetry system on a

restricted or secure frequency would allow data to be monitored and recorded in real time, alongside standard video data. Both coach and athlete could then review the results at the end of a run when information about the run is still fresh in the mind of the athlete. Reducing the feedback time allows faster more effective input into training.

A system which can give feedback of timing and forces applied relative to body position would potentially be of huge benefit to top level athletes. Combining high speed video analysis with knowledge of applied forces would allow a rider to improve the efficiency of manoeuvres and experiment with different techniques.

Understanding how individual riders apply forces and how vibration patterns affect the 'feel' of a snowboard allows improvement in the design of snowboards. With sufficient in-situ data it is likely that matching an optimal board to snow conditions for a specific rider could be understood by using this system. Snowboard manufacturers could utilise a similar system to that used in this study and continue correlating this to qualitative feedback from test riders. Combining this information with advanced dynamic modelling programs such as LS DYNA, would allow designers to design the snowboard on computer and understand the static properties and likely 'feel' prior to pressing a board on the production line.

5.2 In situ curling analysis

On going work the Centre for Materials Science has used the data produced by the sweep ergometer to further investigate ice friction. Specifically, mathematical models have been developed for the curved trajectory of a stone [Marmo, Blackford 2004] and the thermal influences of sweeping [Marmo et al 2006]. The data collected using the MK3 ergometer has been inputted into these models to verify and refine the algorithms. Recent trials from the MK3 ergometer have been modelled to produce time based digital

images of heat traces of the sweeping motion by Doctor Brett Marmo (Figure 6-1). In order to refine these thermal models additional data on ice surface and thermal traces will be required. Combining sweep ergometer trials with thermal imaging cameras of high resolution could provide useful data to refine calculations.

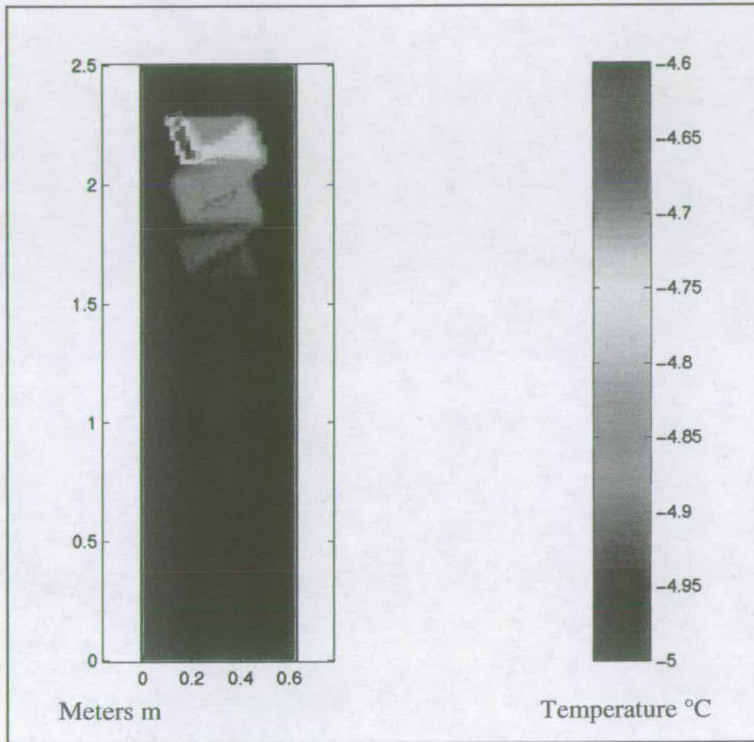


Figure 6-1 Thermal model traces of sweeping (courtesy of Dr Brett Marmo)

The forces and frequencies play a large part and can be used to train or grade an individual player, but for a picture of sweeping effectiveness these thermal videos allow clear depiction of the effectiveness of sweeping and the surface heat of the ice experienced by the stone. The videos provide an extremely clear indication to the athletes themselves as to what the ergometer means to them, individual figures and facts are hard to comprehend even when compared to an average value. A video image from

gathered data allows athletes to comprehend what is happening when they sweep with little explanation. A specific improvement for the software would be to automatically produce video files when uploading data. Coaches and athletes alike would gain considerably from this advancement.

To develop a fuller understanding of sweeping in the sport of curling additional equipment would be necessary to provide missing information the sweep ergometer does not monitor. Combining the work with the sweep ergometer and a machine which accurately delivers stones (Figure 6-2) would allow direct comparison and effectiveness of different sweeping techniques. As the relationship between sweeping and the distance a stone travels is non-linear with many variables work continues on this topic

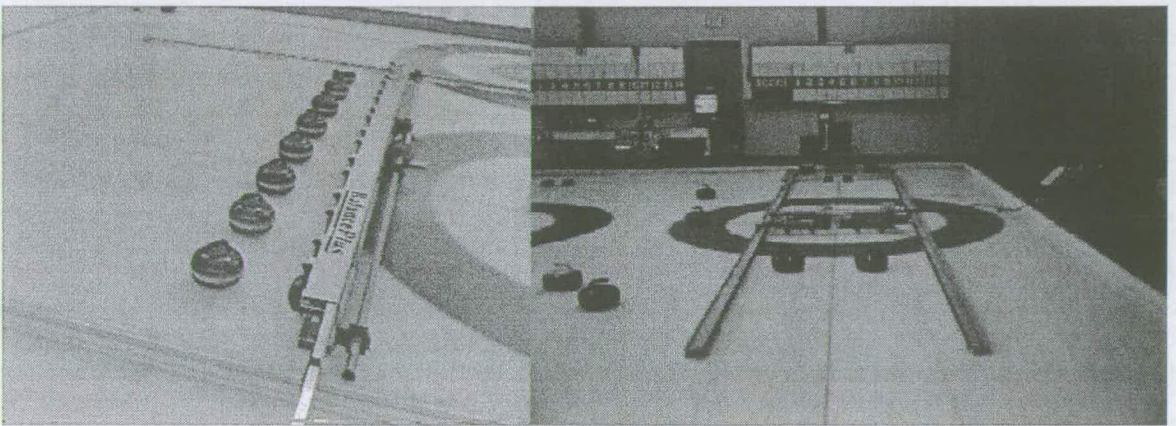


Figure 6-2 An automated stone throwing machine capable of throwing multiple stones with specified velocity and handle (images courtesy of Scottish Institute for Sport).

The sweep ergometer can show the consistency of players and their general sweeping characteristics which enables coaches to work on differences in individuals' technique, thus improving performance. As sweeping at different point along the stones trajectory can have dramatic effects, once a player has improved their own consistency they should then work with one of these machines. Using the same handle and velocity on the same

line, the sweeper can understand how much they can affect a stone. Repeat trials on the same line will lead to changing ice conditions as sections will have pebble removed. Coaches can develop games which show how sweeping at different point change the direction and end position of the stone.

Chapter 6 Conclusions

1. *Quantitative snowboard measurements*: procedures are established for quantifying physical characteristics and conducting in situ analysis of snowboards. Laboratory measurements provide accurate values for longitudinal, forebody, aftbody and torsional stiffness. In situ testing provides signal analysis from snowboards and allows observation of snowboard and snow interaction.
2. *Qualitative vs. Qualitative Snowboard data*: agreement between measured mechanical properties of the snowboards and subjective rider assessment has been shown. The qualitative difference may be explained by measured differences in torsional and longitudinal stiffness. In general it was observed that elite snowboarders preferred snowboards with greater longitudinal stiffness due to reduced levels of vibration when travelling at high velocities and lower torsional stiffness which allow for easier turn initiation.
3. *In situ snowboard data as a training tool*; the relationship between rider ability and in situ data is explored. Data from in situ testing of instrumented snowboard has been shown frequency analysis to differentiate between riders of different competence levels (i.e. beginner, intermediate and expert). Tracking improvements in rider performance and forces the rider transmits to the board has been demonstrated. This system can be used in conjunction with video analysis when training snow-boarders and is expected to be particularly useful in training elite riders.
4. *Dynamic curling analysis*; the ability to obtain accurate and detailed force and acceleration measurement with a sweep ergometer is clearly shown. Design reasoning and development stages have been documented. Results have been

presented in a format which can easily be understood by coaches and athletes. Elite curlers sweep in the frequency range of 3 to 3.5 Hz with maximum vertical forces of between 300 to 600N for male athletes, and 250 to 450N for female athletes.

5. *The sweep ergometer as a training tool:* the sweep ergometer has provided quantitative analysis for curlers of varying standard including the Great British Curling team. The system has proved highly successful and has been adopted as a training tool for the British Curling team. The ergometer is now incorporated into the player selection process for British Olympic Curling teams.

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Appendix A

Programming code used for the PIC16C71 to perform A/D conversation and transmit the data. Developed by the author.

```
#include <friday.h>
#fuses HS, NOPROTECT, NOWDT
Watch Dog Timer */
#use standard_io(B) /* Set pins of port B to be I/O or O/P as required
every time before use */
#use RS232(baud=2400, BITS=8, xmit=PIN_B6, rcv=PIN_B7) /* Set baud rate, transmit and receive pins
on port C bits 6&7 */
int in_Ch0 = 0; /* Declare 5 integer Variables (8 bit) for storing samples */
int in_Ch1 = 0;
int in_Ch2 = 0;
int in_Ch3 = 0;
main()
{
    setup_port_a( ALL_ANALOG ); /* port A can have up to 4 analogue inputs - all used here */
    setup_adc( ADC_CLOCK_INTERNAL ); /* Use internal (4MHz/4 = 1 MHz) clock - assumes 4 MHz
crystal */
    while (TRUE) { /* This construct will make it loop for ever */
        output_high(PIN_B4); /* Oscilloscope trace goes to 5V at this instant */
        set_adc_channel(0);
        delay_us(50); /* When switching channels delay of 50 us to allow analogue MUX
etc. to settle */
        in_Ch0 = Read_ADC();
        printf("%u\n", in_Ch0); /* O/P sample as RS232 on PIN_C6 at 4800 baud */
        set_adc_channel(1); /* Repeat for Channel 1 etc. */
        delay_us(50);
        in_Ch1 = Read_ADC();
        printf("%u\n", in_Ch1);
        set_adc_channel(2);
        delay_us(50);
        in_Ch2 = Read_ADC();
        printf("%u\n", in_Ch2);
        set_adc_channel(3);
        delay_us(50);
        in_Ch3 = Read_ADC();
        printf("%u\n", in_Ch3); /* Output a space to delimit these 5 samples from the next 5 */
        output_low(PIN_B4); /* Oscilloscope trace goes to 0V at this instant */
        delay_ms(20); /* Sample rate of 50 samples/sec. Rest of loop time ignored. */
        /* Adjust with oscilloscope on PIN_B4 for 20 ms loop */
    }
}
```

Appendix B

Fast Fourier Transform (FFT) algorithm is commonly used to compute discrete data. The FFT's conducted for data presented in this text used the following MATLAB coding to perform this operation;

```
function output = do_fft(input)
% DO_FFT Perform an FFT on the input data and returns frequency spectrum
%
% OUTPUT = DO_FFT(INPUT) INPUT should be a N,M matrix where rows
% represent samples. Column 1 should give the time index (in Seconds)
% and Column 2 should give the sample.
%
% NOTE: The more irregular the sampling frequency the less accurate
% this function will be. Ideally a constant sampling frequency
% should be used.

[num_samps y] = size(input);
output = zeros(num_samps,y);

% Calculate sampling frequency in Hz
total_time = input(num_samps,1)-input(1,1);
samp_freq = 1/(total_time/num_samps)

% Label frequency axis
half_samps = num_samps/2;
half_floor = floor(half_samps);
half_ceil = ceil(half_samps);
if (floor(half_floor)==half_ceil) % Check if number of samples is even
    % Even
    output(1:half_floor,1) = (-half_floor:-1)';
    output(half_ceil+1:num_samps,1) = (0:half_floor-1)';
else
    % Odd
    output(1:half_floor,1) = (-half_floor:-1)';
    output(half_ceil:num_samps,1) = (0:half_floor)';
end
output(:,1) = samp_freq*(output(:,1)/num_samps);

% Perform FFT
for i = 2:y
    output(:,i) = fft(input(:,i),num_samps);
    output(:,i) = fftshift(output(:,i));
    output(:,i) = sqrt(output(:,i).*conj(output(:,i))) / (num_samps/2);
end
```

Appendix C

Strain gauge calibration data provided by Pi Research



Strain Gauge Calibration Sheet

Company Reactec
Description Curling Brush
Serial no. 01B-130187 //V LOAD SN 001
Date 21-01-05

Calibration Data

Excitation voltage: 12.00 V DC

Load (Kgf)	OP (V)
0	0.5481
15	0.7440
30	0.9379
45	1.1490

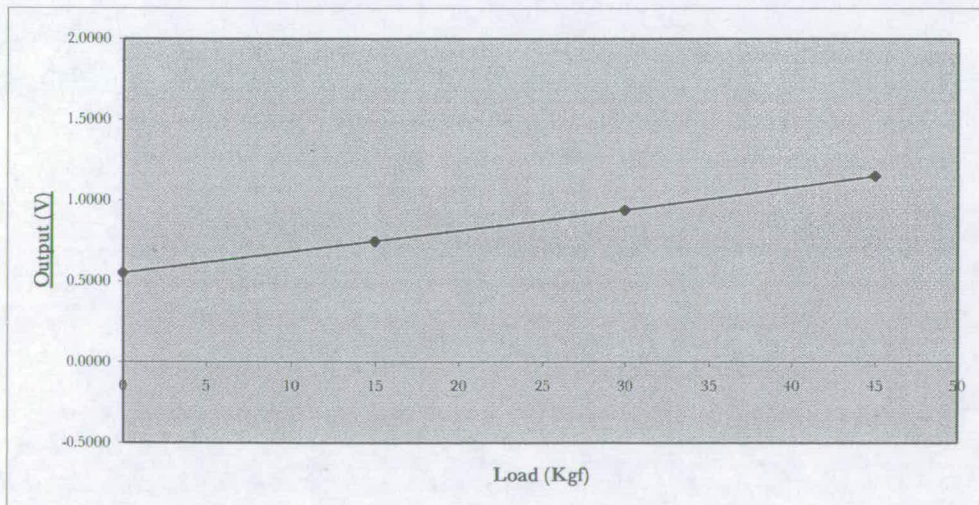
Wire legend

+12V	RED
Sig +	WHITE
GND	BLUE

Linearity = 99.981%

Gain (Kgf/V)= 75.10

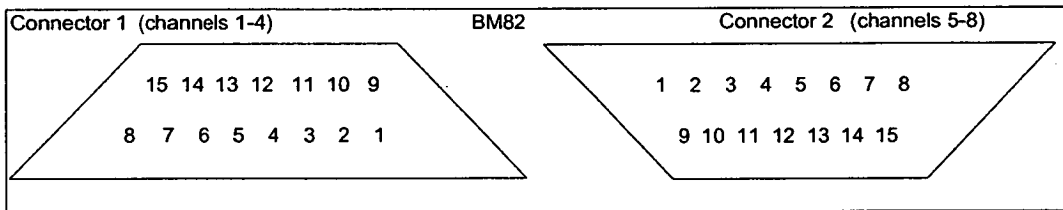
Offset (Kgf) = -40.94



Appendix D

Wiring diagram for the Biomedical Monitoring 8 channel logger used for the MK3 ergometer.

Pin	Connector 1			Connector 2		
	Gain-Offs			No gain-Offs		
1	Gauge1	Channel 1 +Signal		Extra In	Channel 8 +Signal	
2	Gauge1	Channel 1 +Power(5V)			Channel 8 +Power(5V)	
3	Gauge2	Channel 2 +Signal		X-bow Z	Channel 7 +Signal	
4	Gauge2	Channel 2 +Power(5V)			Channel 7 +Power(5V)	
5	Extra In	Channel 3 +Power(5V)			Channel 6 +Power(5V)	
6	Extra In	Channel 3 + Signal		X-bow Y	Channel 6 +Signal	
7	Thermo	Channel 4 +Power(5V)		X-bow (+)	Channel 5 +Power(5V)	
8	Thermo	Channel 4 +Signal		X-bow X	Channel 5 +Signal	
9	Gauge1	Channel 1 -Signal				
10	Gauge2	Channel 2 -Signal				
11	Gauge1	Ground (0 V)		X-bow (-)	Ground (0 V)	
12	Gauge2	Ground (0 V)			Ground (0 V)	
13	Thermo	Ground (0 V)			Ground (0 V)	
14	Extra In	Channel 3 -Signal				
15	Thermo	Channel 4 -Signal				



Wiring layout for the Biomedical Monitoring Logger used for the MK3 curling brush.

Appendix E

Vertical forces recoded for the British male and female curling team

Male athletes		Vertical Force(N)					
<i>Athlete</i>	<i>RMS</i>	<i>Average Min</i>	<i>Aver. Min Std. Dev.</i>	<i>Average Max</i>	<i>Aver. Max Std. Dev.</i>	<i>Frequency Hz</i>	
1	242.92	0.55	10.22	482.33	82.39	4.24	
2	126.61	-3.56	9.11	248.90	41.05	3.61	
3	180.10	19.79	15.31	330.88	54.00	4.71	
4	233.74	32.27	19.36	517.96	42.46	3.01	
5	263.16	7.21	8.54	532.09	43.55	4.34	
6	254.21	10.72	24.75	493.04	76.14	3.26	
7	259.33	-31.51	86.46	519.48	103.56	3.63	
8	275.75	4.86	14.60	560.16	69.68	2.43	
9	296.50	125.98	30.66	476.87	78.92	3.46	
10	213.29	4.89	10.56	479.19	71.59	2.15	
Average	234.56	17.12	22.96	464.09	66.33	3.48	

Female athletes		Vertical Force(N)					
<i>Athlete</i>	<i>RMS</i>	<i>Average Min</i>	<i>Aver. Min Std. Dev.</i>	<i>Average Max</i>	<i>Aver. Max Std. Dev.</i>	<i>Frequency Hz</i>	
1	259.61	4.92	16.91	459.28	42.33	2.28	
2	149.66	15.99	9.49	272.72	25.47	3.28	
3	168.34	-17.54	4.18	317.81	34.68	4.19	
4	172.03	11.19	12.10	311.70	37.33	2.16	
5	172.99	-3.87	8.75	322.19	47.32	3.72	
6	158.68	-7.99	4.93	329.60	45.17	3.59	
7	186.12	39.26	21.32	355.72	66.02	2.59	
8	91.98	2.35	10.03	280.91	59.04	2.83	
9	109.65	-5.18	26.23	324.63	65.30	3.70	
10	185.81	25.70	18.58	328.42	36.17	3.00	
Average	168.55	5.57	12.92	332.72	43.48	3.31	

Horizontal forces recorded for the British male and female curling team

Male athletes		Horizontal Force (N)							
<i>Athlete</i>	<i>RMS</i>	<i>Pos. RMS</i>	<i>Neg. RMS</i>	<i>Average Min</i>	<i>Aver. Min Std. Dev.</i>	<i>Average Max</i>	<i>Aver. Max Std. Dev.</i>	<i>Frequency Hz</i>	
1	35.57	35.07	36.43	-56.47	20.67	51.81	9.14	4.24	
2	40.90	39.26	43.20	-68.41	12.23	60.89	6.24	3.61	
3	46.28	38.35	55.41	-84.04	17.14	57.76	7.06	4.71	
4	38.63	28.18	57.11	-82.11	15.45	52.08	5.35	3.01	
5	51.44	42.30	61.35	-98.08	13.21	62.85	4.74	4.34	
6	38.36	32.81	47.36	-71.54	15.47	52.17	5.62	3.26	
7	118.90	38.06	174.26	-122.83	217.43	59.38	28.85	3.63	
8	53.49	39.01	69.56	-115.59	23.41	67.56	10.47	2.43	
9	37.07	18.94	40.36	-65.03	17.37	10.89	14.11	3.46	
10	42.92	30.89	62.05	-90.57	25.32	53.12	7.56	2.15	
Average	50.36	34.29	64.71	-85.47	37.77	52.85	9.91	3.48	

Female athletes		Horizontal Force (N)							
<i>Athlete</i>	<i>RMS</i>	<i>Pos. RMS</i>	<i>Neg. RMS</i>	<i>Average Min</i>	<i>Aver. Min Std. Dev.</i>	<i>Average Max</i>	<i>Aver. Max Std. Dev.</i>	<i>Frequency Hz</i>	
1	44.58	30.15	54.66	-81.77	8.73	41.46	12.96	2.28	
2	25.50	24.73	26.61	-41.23	10.97	36.97	5.44	3.28	
3	31.07	32.07	29.20	-45.14	13.05	44.15	8.66	4.19	
4	34.13	28.94	39.61	-59.42	10.68	42.27	4.77	2.16	
5	32.07	24.16	40.98	-61.81	13.03	37.20	5.91	3.72	
6	32.26	32.15	32.43	-50.44	19.71	49.91	9.65	3.59	
7	25.97	25.68	26.30	-42.53	21.42	40.98	10.04	2.59	
8	24.42	22.73	33.12	-34.33	30.04	30.79	14.27	2.85	
9	36.61	22.99	75.01	-61.62	23.13	40.71	14.85	3.72	
10	29.84	29.50	30.33	-45.34	10.70	42.75	2.92	3.00	
Average	35.31	27.61	42.94	-51.54	22.30	41.79	8.12	3.33	

Appendix G

Swept velocities in the x direction (in line with major sweeping motion) recorded for the British male and female curling team

Male athletes		X-Axis Velocity m/s						
Athlete	RMS	Pos. RMS	Neg. RMS	Average Min	Aver. Min Std. Dev.	Average Max	Aver. Max Std. Dev.	Frequency
1	1.46	1.43	1.50	-2.17	0.48	2.02	0.46	4.24
2	2.05	2.09	2.01	-2.79	0.36	2.95	0.36	3.61
3	1.72	1.79	1.65	-2.39	0.38	2.71	0.45	4.71
4	1.17	1.14	1.19	-1.90	0.73	1.91	0.76	3.01
5	2.02	1.97	2.08	-2.93	0.25	2.80	0.39	4.34
6	1.50	1.52	1.48	-2.11	0.65	2.20	0.71	3.26
7	1.93	1.96	1.91	-2.72	0.71	2.80	0.74	3.57
8	1.88	1.95	1.82	-2.57	0.48	2.75	0.51	2.43
9	0.76	0.75	0.77	-1.00	0.52	0.95	0.50	3.46
10	1.64	1.61	1.67	-2.46	1.06	2.38	1.07	2.15
Average	1.61	1.62	1.61	-2.30	0.56	2.35	0.59	3.48

Female athletes		X-Axis Velocity m/s						
Athlete	RMS	Pos. RMS	Neg. RMS	Average Min	Aver. Min Std. Dev.	Average Max	Aver. Max Std. Dev.	Frequency
1	1.41	1.47	1.35	-1.92	0.46	2.05	0.50	2.28
2	1.30	1.32	1.28	-1.81	0.33	1.90	0.31	3.28
3	1.55	1.54	1.55	-2.31	0.43	2.23	0.43	4.19
4	1.36	1.40	1.33	-1.91	0.25	1.97	0.21	2.16
5	1.21	1.21	1.21	-1.76	0.47	1.77	0.52	3.72
6	1.75	1.75	1.74	-2.46	0.59	2.53	0.59	3.59
7	1.11	1.09	1.13	-1.71	0.82	1.67	0.80	2.59
8	1.13	1.15	1.11	-1.52	1.24	1.59	1.28	2.83
9	1.03	1.04	1.01	-1.56	0.99	1.70	1.07	3.70
10	1.65	1.67	1.62	-2.41	0.21	2.42	0.31	3.00
Average	1.39	1.41	1.38	-2.00	0.54	2.03	0.54	3.29

Appendix H

Distance swept in the x direction (in line with sweeping) recorded for the British male and female curling team

Male athletes		X-Axis Displacement (cm)						
<i>Athlete</i>	<i>RMS</i>	<i>Pos. RMS</i>	<i>Neg. RMS</i>	<i>Sweep Length</i>	<i>Average Min</i>	<i>Aver. Min Std. Dev.</i>	<i>Average Max</i>	<i>Aver. Max Std. Dev.</i>
1	5.35	5.24	5.46	14.14	-7.20	2.11	6.94	1.84
2	8.11	8.09	8.14	22.59	-11.38	2.13	11.22	2.07
3	6.33	6.27	6.39	15.66	-7.74	2.62	7.92	2.78
4	4.41	4.47	4.36	13.59	-6.65	2.10	6.93	2.48
5	8.15	8.03	8.26	21.63	-10.76	2.48	10.87	2.48
6	6.33	6.41	6.25	18.07	-8.81	2.61	9.25	2.07
7	7.92	8.01	7.84	22.30	-11.07	2.39	11.23	2.41
8	6.74	6.77	6.71	18.99	-9.47	2.17	9.52	2.01
9	4.27	4.25	4.29	9.32	-4.48	3.01	4.83	2.99
10	7.23	7.04	7.42	20.54	-10.16	3.72	10.38	3.79
Average	6.48	6.46	6.51	17.68	-8.77	2.53	8.91	2.49

Female athletes		X-Axis Displacement (cm)						
<i>Athlete</i>	<i>RMS</i>	<i>Pos. RMS</i>	<i>Neg. RMS</i>	<i>Sweep Length</i>	<i>Average Min</i>	<i>Aver. Min Std. Dev.</i>	<i>Average Max</i>	<i>Aver. Max Std. Dev.</i>
1	6.24	6.39	6.09	15.06	-7.38	3.20	7.68	3.17
2	5.55	5.61	5.50	15.43	-7.71	1.35	7.72	1.57
3	6.67	6.44	6.91	17.03	-8.82	3.38	8.21	3.16
4	5.42	5.39	5.45	15.03	-7.51	1.23	7.53	1.30
5	4.81	4.77	4.85	13.74	-6.78	1.64	6.97	1.90
6	7.53	7.36	7.71	20.91	-10.57	2.81	10.34	2.57
7	4.67	4.73	4.61	14.19	-7.05	2.95	7.13	3.02
8	5.27	5.32	5.23	17.13	-8.63	5.30	8.50	5.01
9	3.78	3.76	3.80	12.61	-6.40	3.16	6.21	3.01
10	7.39	7.37	7.42	20.82	-10.39	1.52	10.43	1.52
Average	6.18	6.18	6.19	17.14	-8.59	2.40	8.55	2.43

Appendix I

Swept velocities in the y direction (perpendicular to major sweeping motion) recorded for the British male and female curling team

Male athletes Y-Axis Velocity m/s									
Athlete	RMS	Pos. RMS	Neg. RMS	Average Min	Aver. Min Std. Dev.	Average Max	Aver. Max Std. Dev.	Frequency	
1	0.88	0.99	0.79	-1.12	0.31	1.43	0.42	4.18	
2	0.61	0.57	0.65	-0.90	0.36	0.77	0.27	3.61	
3	0.76	0.71	0.80	-1.17	0.52	0.95	0.42	5.04	
4	0.71	0.69	0.72	-1.03	0.56	1.01	0.55	3.01	
5	0.90	0.82	0.97	-1.40	0.33	1.13	0.34	4.28	
6	0.83	0.87	0.78	-1.04	0.49	1.18	0.62	3.26	
7	1.00	0.88	1.12	-1.61	0.59	1.20	0.49	3.63	
8	1.22	1.20	1.25	-1.71	0.31	1.81	0.39	2.43	
9	1.44	1.41	1.46	-2.04	0.62	1.96	0.61	3.46	
10	0.69	0.64	0.75	-0.99	0.64	0.78	0.50	2.15	
Average	0.90	0.88	0.93	-1.30	0.47	1.22	0.46	3.50	

Female athletes Y-Axis Velocity m/s									
Athlete	RMS	Pos. RMS	Neg. RMS	Average Min	Aver. Min Std. Dev.	Average Max	Aver. Max Std. Dev.	Frequency	
1	1.44	1.51	1.36	-1.92	0.49	2.12	0.53	2.28	
2	0.35	0.37	0.33	-0.43	0.18	0.49	0.21	3.28	
3	0.62	0.64	0.61	-0.94	0.27	0.91	0.30	4.19	
4	0.43	0.45	0.41	-0.54	0.31	0.56	0.32	2.16	
5	1.07	1.07	1.08	-1.48	0.57	1.52	0.61	3.72	
6	0.84	0.92	0.76	-1.04	0.46	1.25	0.50	3.59	
7	0.20	0.21	0.19	-0.23	0.16	0.27	0.21	2.59	
8	0.35	0.36	0.34	-0.44	0.37	0.50	0.43	2.80	
9	0.33	0.32	0.34	-0.47	0.40	0.43	0.34	3.70	
10	0.38	0.36	0.39	-0.53	0.25	0.47	0.18	3.05	
Average	0.70	0.71	0.69	-0.95	0.37	0.98	0.38	3.27	

Appendix J

Distance swept in the y direction (perpendicular to major sweeping motion) recorded for the British male and female curling team

Male athletes		Y-Axis Displacement (cm)							
<i>Athlete</i>	<i>RMS</i>	<i>Pos. RMS</i>	<i>Neg. RMS</i>	<i>Sweep Length</i>	<i>Average Min</i>	<i>Aver. Min Std. Dev.</i>	<i>Average Max</i>	<i>Aver. Max Std. Dev.</i>	
1	3.34	3.32	3.37	8.50	-4.50	1.67	4.01	1.66	
2	3.24	3.09	3.39	7.62	-4.00	2.18	3.62	1.89	
3	3.55	3.35	3.75	7.87	-4.41	2.54	3.46	2.26	
4	2.83	2.84	2.82	8.18	-4.13	1.91	4.06	1.95	
5	3.70	3.44	3.97	9.19	-4.86	1.50	4.33	1.81	
6	3.90	3.83	3.97	10.57	-5.39	2.58	5.18	2.04	
7	4.31	4.10	4.53	11.18	-6.01	2.45	5.18	2.39	
8	5.16	5.15	5.17	12.71	-6.31	2.30	6.41	2.51	
9	6.21	6.27	6.15	17.23	-8.72	2.24	8.51	2.42	
10	3.13	3.04	3.23	8.61	-4.62	2.52	3.99	2.26	
Average	3.94	3.84	4.04	10.17	-5.29	2.19	4.87	2.12	

Female athletes		Y-Axis Displacement (cm)							
<i>Athlete</i>	<i>RMS</i>	<i>Pos. RMS</i>	<i>Neg. RMS</i>	<i>Sweep Length</i>	<i>Average Min</i>	<i>Aver. Min Std. Dev.</i>	<i>Average Max</i>	<i>Aver. Max Std. Dev.</i>	
1	5.97	5.88	6.06	15.56	-8.05	2.64	7.51	2.46	
2	2.20	2.16	2.25	4.47	-2.27	1.55	2.19	1.37	
3	2.99	2.96	3.01	7.06	-3.66	1.74	3.40	1.87	
4	2.31	2.45	2.18	5.23	-2.34	1.46	2.89	1.60	
5	4.63	4.68	4.59	12.31	-5.85	2.65	6.45	2.58	
6	3.82	3.70	3.95	9.55	-4.86	2.64	4.69	2.29	
7	1.77	1.75	1.80	3.53	-1.71	1.62	1.82	1.49	
8	2.28	2.31	2.25	6.15	-3.18	1.73	2.97	1.97	
9	1.90	1.88	1.92	4.55	-2.24	1.64	2.31	1.67	
10	2.14	2.22	2.05	4.91	-2.45	1.21	2.46	1.42	
Average	3.50	3.51	3.50	8.70	-4.35	2.02	4.35	2.03	

Appendix k Reactec Ltd

During the timeframe of this PhD the author was involved in setting up and managing of a start-up company, Reactec Ltd. Reactec was founded in July 2001 and represents the culmination of first class engineers in the fields of electronic, mechanical and software – providing smart active systems to suppress unwanted vibrations. Initially focussed at the sporting goods market Reactec have progressed to provide vibration collection, analysis and solutions for a number of Blue Chip companies. Reactec has now files three patents; advanced control of an adaptive ski, Magnetorehoological dampers and a vibration monitoring device respectively. This chapter describes the stages through which the company as grown, technology and acquisition processes developed, the awards and achievements of the company to date and examples of work conducted.

1.1 Awards and achievements

Reactec was set up to realise the commercial potential of technology developed by Pete Watson and the author whilst studying towards PhD's at the Centre for Materials Science and Engineering. Pete Watson's PhD – Engineering Smart Skis the author's similar work on snowboards.

Dr Peter Watson entered a business plan competition run by Edinburgh Technology Fund (ETF) in 2000, an in-house seed corn funding body at the university. Dr Watson secured some initial funds through this competition and established Reactec the company, it was officially registered on the 20th July 2001. The author was brought on shortly afterwards to fill the Managing Director's role and accelerate the company achievements.

Both directors came from a technical background and initially lacked the business skills required to run a company. These skills were developed through mentoring and attending business courses specifically designed for students and provided by the Scottish Institute for Enterprise.

A second business award was won in the Scottish Institute for Enterprise (SiE) 2002 Business plan competition. Reactec has won several government based grants to further its technology. These include 4 Small Company Innovation Support awards (SCIS); the first two were for the development and commercialisation for the Concept 3 adaptive smart Ski system. The final SCIS awards were for the development and market launch reactec patent pending Magnetorheological damper.

Reactec has won a DTI SMART award for the development of Reactec's Intelligent Control Unit (ICU). The ICU is a low-cost control unit, based on a DSPiC core that monitors vibrations between two points and uses active and semi- active devices to minimise vibrations transmitted. The ICU and MR dampers are currently being trialled in the semiconductor industry and academic departments to stabilise laser experiments. The author oversaw the management of all SCIS awards and the SMART award, significant technical work and input was provided to ensure success of these projects.

1.2 Business Support

Scottish Institute for Enterprise (SiE) is dedicated to creating a culture of enterprise within the Science, Engineering and Technology communities in all thirteen of Scotland's universities. Europe is currently behind the US for university co-operation with industry [Lee 2004] and several initiatives are being implemented by the European Union to improve this. SiE are now delivering enterprise education to over 8000 students and have supported 55 sustainable businesses.

SiE have provided substantial support since incorporation, some of which has been: promotion, networking, patents funds, business plan prize funds and business courses. Recently representatives from the Scottish Institute for Enterprise at the University of Edinburgh have forged entrepreneurial ties with Slovenia after attending PODIM 24, a prestigious annual event held in the city of Maribor which was attended by top government officials and the international academic community to discuss entrepreneurship, innovation and management issues. SiE made it possible for Reactec to present at this conference, elevating both company image and securing contact within the EU community. It is this level of company promotion and perspective that a new company must have in the current environment, the market is global and small companies must remember this. During this meeting the stages in which Reactec have evolved were presented [Adamson 2003].

1.3 Reactec's Technology – THE CONCEPT 3 SYSTEM

Reactec have developed a smart materials based vibration reduction system. The *Concept 3 System* incorporates three different smart materials and a microprocessor to reduce vibrations in structures. The system uses polyvinylidene fluoride (PVDF) sensors to monitor levels of vibration (see chapter 2). This information is processed by the *Intelligent Control Unit* (ICU), a small microprocessor which in turn drives a semi-active magnetorheological fluid filled device to suppress vibration. The entire system is powered with a piezoceramic parasitic power supply. Technology and techniques are described in greater detail in previous publications [Watson & Blackford 2001, Buckingham & Blackford 2004]. This technology improves the performance of products, reduces fatigue and associated maintenance costs. The work was initially conducted with skis as the specific application. Figure 5-1 shows a CAD drawing of the *Concept 3 Ski*. Figure 5-2 shows a schematic of the system.

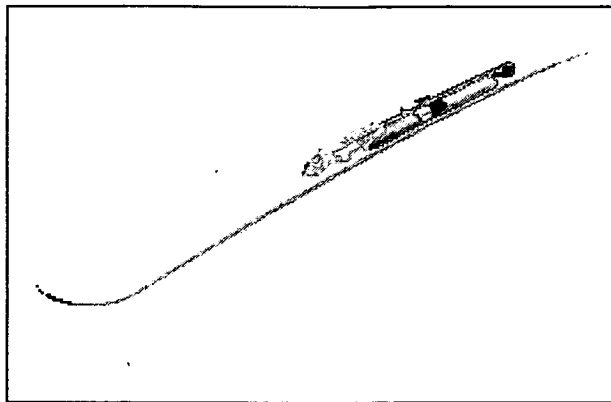


Figure 5-1 CAD drawing of the *Concept 3 Ski* (Image courtesy of Reactec)

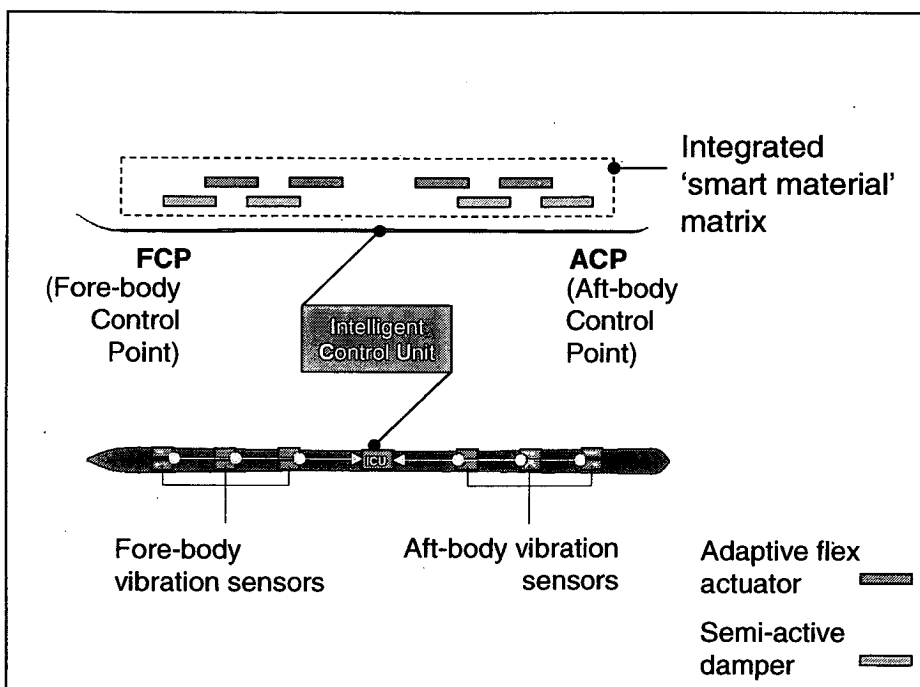


Figure 5-2 *Schematic of Concept 3 Ski* (Picture courtesy of P Watson)

The ski and snowboard market is an early adopter of technology, which is a significant brand differentiator in winter sports goods. The ski market is therefore an ideal target for the *Concept 3 System*. Skis also provide a substantial engineering challenge; the system must cope with the harsh environment skis are subjected to. Manufacturers have been seeking truly effective vibration control mechanisms for years, and the first models claiming to incorporate such technology appeared in 1995 [Glennie et al,1999]. Head and K2 are among the manufacturers that have sold skis with similar control technology. As with previous vibration control systems, the *Concept 3 System* may be adopted on the higher price models and filter down the ski range allowing increased royalties.

1.4 Intellectual property

As technology companies are based around invention, protecting the idea or Intellectual Property (IP) is of utmost importance [Megantz 2002]. Without registered rights to the idea it is easy for another company to take, and exploit the technology. There are different methods of protecting IP dependent on the technology itself. Filing a patent is the standard method for most technology based innovations. Reactec filed its first patent application, 'Improvements relating to Skis' (European Patent Application No 027880813.4) on the 12th December 2001, the second application 'Improvements in or relating to vibration control' was filed in August 2003 (International PCT/GB2004/003595), and third 'Monitoring apparatus and methods' in December 2005. All patents have been filed in Europe, the US and Japan.

1.5 *Growing the company*

Start-up companies such as Reactec need staff that are self-motivated and technically proficient. Time available to manage employees at the early stages of a company is scarce, and people who join the organisation must be capable of managing themselves or they will become a drain on resources. Reactec's staff have, to date come directly out of University. Reactec have strong relations with several academic organisations which provide excellent staff for short-term placement students. Providing the ideal opportunity to evaluate individual's capabilities and future employment with the company. Every placement student that has been part of the Reactec team has subsequently been employed.

One difficult, yet subtle issue for a technology company is that of 'technology push' vs. 'market pull' [Franklin, 2003]. Technology innovators can easily see the advantages for their own technology, but is there a market place and will the technology be accepted? Market driven technologies stand much greater chance of success than pure technological innovation. Reactec have been keen to find a balance between new designs and market driven opportunities. This is done by simultaneously running commercial contracts along side in-house Government funded technology programs. The SMART award scheme is an example of one such scheme. SMART awards are available across the UK.

To ensure that the commercial aspects of a business are covered and to increase market information, Reactec formed links with the Business Management School at the University of Edinburgh. This link provided MBA students who work along side the company, scrutinizing strategy and market awareness. This input provided excellent balance to technology lead thinking.

There is much to be gained by having strong ties with the academic institutions: staff, experience, advice, equipment. Reactec believe this relationship is highly beneficial to both parties.

1.6 Contacting and Partnering Companies

Selling to original equipment manufacturers (OEM's) can be a difficult task [Franklin 2003]; time is required to get to the relevant people in large organisations. Reactec attended trade shows in order to gain relevant contact information in the ski industry. Once contact has been made, technology demonstrations are required. This is a difficult stage if Intellectual Property has not been secured. Non-disclosure agreements would need to be signed prior to revealing any aspects of the technology.

Finding funds to support travel is a challenge that many new companies face. Sales need to be made but the associated costs can be restrictive. As most ski companies are based in Europe, Reactec's directors visited the all major ski manufacturers in a single trip. This was made feasible due to support from Scottish Enterprise through their Lothian Export Scheme.

Reactec have yet to secure the ski market for the *Concept 3 System*, several manufacturers are looking at methods of implementing the system in a cost effective manner. Other sporting goods are also ear-marked for future variations of the system.

As Reactec are a small company and need to compete in the larger global field, partner companies have been sought to strengthen Reactec's offering and extend capabilities. Reactec have now partnered with several organisations out with the University. These are all advanced vibration specialist and smart material manufacturers.

1.7 Reactec's: Solution Process

Technical difficulties have had to be overcome during commercialization of Reactec's technologies. This has led to initial products taking longer to reach the market. Reactec have replaced forecast product revenues with that of consultancy. Reactec have developed a standardised four stage process for solving clients vibration issues. The solution delivery is a customer-focused process designed to maximise the value of the solution to the client, while keeping costs to a minimum. The solution process consists of Introduction, Scoping, Requirements Analysis, and Solution Implementation. Scoping, normally lasting for one/two day(s), consists of initial testing and discussions with the client in order to outline the nature of the problem(s) in more detail, and to gain an understanding of the clients overall business needs and goals.

Requirements Analysis is the third stage of Reactec's four-stage standard solutions process. The Requirements Analysis fills the gap between the general understanding gained during initial discussions and the specific constraints of a Solution Implementation. The primary objectives of a Requirements Analysis are to streamline the solution implementation stage, to ensure that a solution meets and exceeds all technical requirements, and to ensure that a solution meets and exceeds any other requirements or constraints that the client may have.

The outcome of the Requirements Analysis is a report which includes details of the work undertaken, results from testing, technical analysis, a breakdown of the constraints and requirements, a full solution specification including initial drawings and if desired by the client, a costed and timed Solution Implementation plan.

Solution Implementation consists of fine-tuning the design, testing, carrying out any necessary modifications to the design, sourcing of materials and parts, and any other work necessary to deliver a complete solution that meets the necessary specifications.

1.8 Reactec's Vibration modeling Language VML

Reactec have developed an internal Vibration Modelling Language (VML) to allow swift and effective solution to clients when providing consultancy solutions. This section describes the background, language format and a client example completed by the author is include in this chapter.

It is necessary to get an overview of the system in question (i.e. specific machine or sub-component), the components of which it is comprised, possibly detailing the various components. On gaining understanding of the system, Reactec build up an approximate model of the system in terms of Vibration Modelling Language (VML). This model will aim to highlight various significant components and help the formulation of a logical test procedure. When depicting the problem or system in terms of VML, it clarifies points of interest and allows measurement points to be determined. Once a VML diagram has been constructed a series of standard vibration solutions can be proposed.

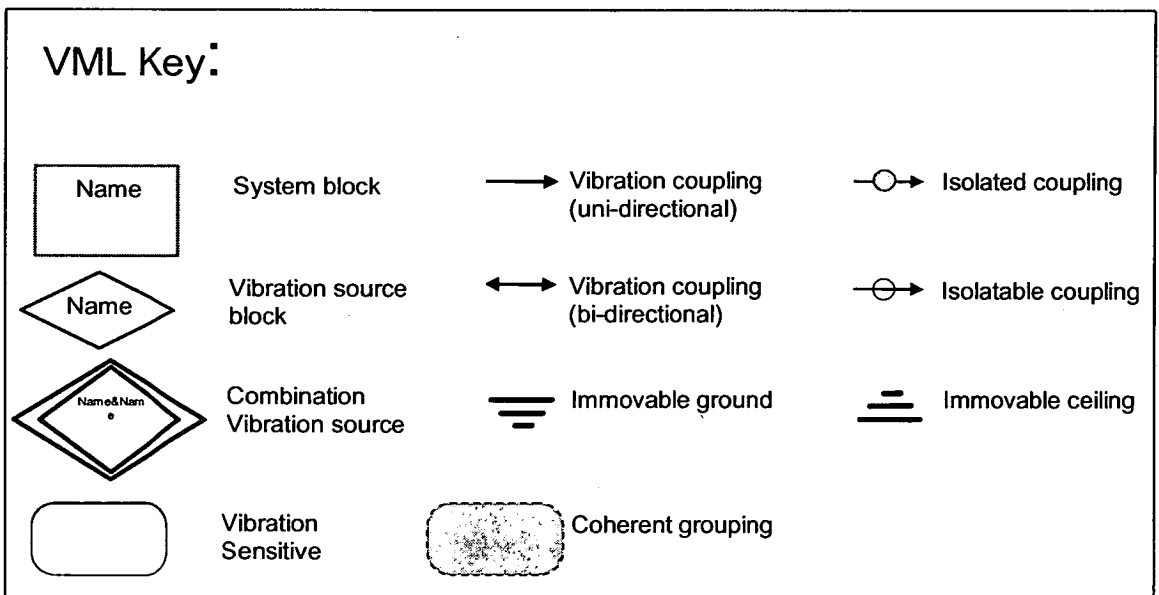


Figure 5-3 Key to Reactec's vibration modeling language

To produce a VML diagram the machine must be broken down into categories found in the key (Figure 5-3). Initially sources of vibration are determined; *Sources* are the fundamental excitation to the vibration problem, for example: an engine, pump or turbulent fluid flow. The sensitive components of the system must then be identified: the equipment or structure which has to be kept free from vibrations. (for example: a bus seat). The route or *transmission path(s)* through which the vibration move between source and sensitive must be traced. Vibrations are generally transmitted from one component to another via mechanical connections. It is useful to identify the path(s) and look at how or if it can be altered in order to reduce the transmission of vibrations to the sensitive equipment. If there is a component is rigidly fastened to an immovable object such as the ground or a larger mass which is several order of magnitude compared to the rest of the system this will be deemed a *ground*. The system must then be analysed for points where *isolation* methods are currently employed, for example, engine mounts or points where isolation is a possibility. *Coherence* is the final stage of the labeling; equipment which for whatever reason, cannot move relative to each other. Basically, isolation of such components is not an option.

Any information relating to the system and how it operates is necessary to enable a complete analysis of the system and aid the generation of any possible solutions will then be gathered. Some obvious points of interest are: Component masses, Excitations (freq, amplitudes, duty cycles, axes, and forces), Variable conditions, isolation information (spring rates, damping coefficients). Details of any previous vibration testing and solutions previously trialed will be gathered also.

Following completion of a VML diagram and collection of information, a test procedure with trial points will be formulated. Tests will be conducted and appropriate analysis with Reactec's custom vibration software will be conducted. Solutions will be tested and if successful and commercially viable, incorporated into the system.

1.9 Example of Consultancy Work

Reactec have now completed worked for several semiconductor and marine companies. The example of Reactec's work was conducted by the author for a semiconductor company ASM. ASM was founded as a European manufacturer of thermal-chemical wafer processing tools in 1968, ASM International has grown to become a leading global supplier of semiconductor equipment, serving both the Front-end, wafer processing, and Back-end, assembly and packaging, markets. Today, ASM is ranked among the top 15 semiconductor equipment manufacturers globally. Our customers include all of the world's leading semiconductor manufacturers.

The aim of this example was to reduce the vibrations on a twin headed wire-bonding machine (Figure 5-4). The wire-bonding machine is used to bridge connection from silicon chips to the external legs of the chip packaging

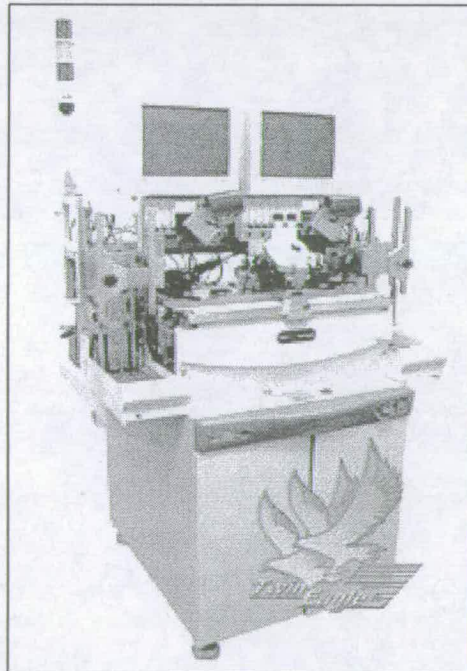


Figure 5-4 Wire bonding machine used in the semiconductor manufacturing process

The twin headed machine is capable of bonding 120 m/s for 2 mm diameter wire. It is capable of pad bonding 35 μm ultra fine pitch wire. ASM would like to increase bonding rates and reduce the vibrations transmitted from the machine. Initial analysis work has been conducted by the author to ensure confidence in potential solutions. Examples of time based frequency data taken from the casting base head (the component which supports the bonding head of the machine) during a typical bonding cycle can be in Figures 5-5, 5-6 and 5-7. These show the magnitude and frequencies present in the casting base as the right bonder runs through part of its bonding cycle. The bonding cycle is evident on these graphs.

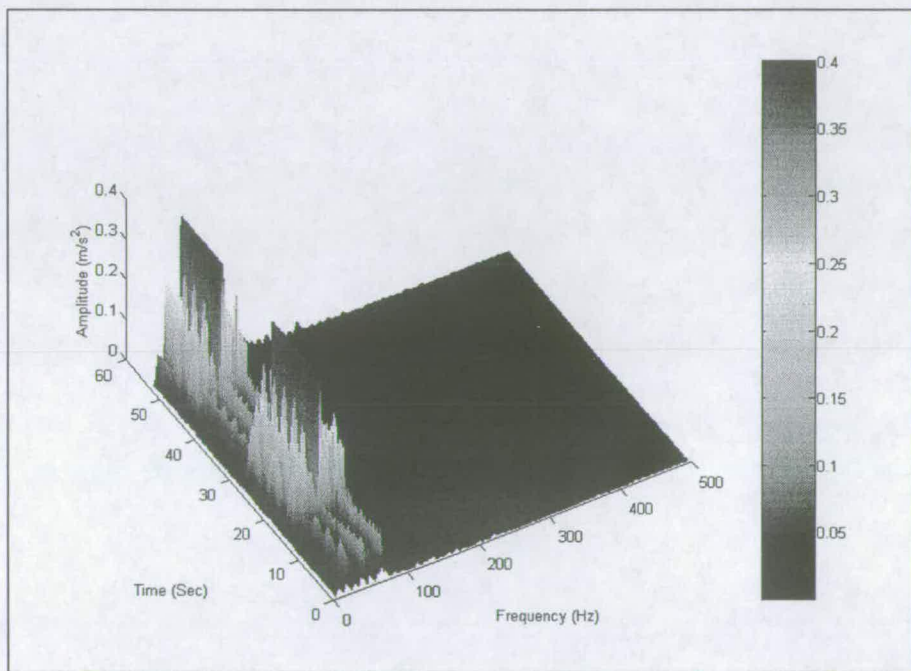


Figure 5-5 X axis vibrations produced by the wire bonder (note: peak trimmed actual peak 0.47)

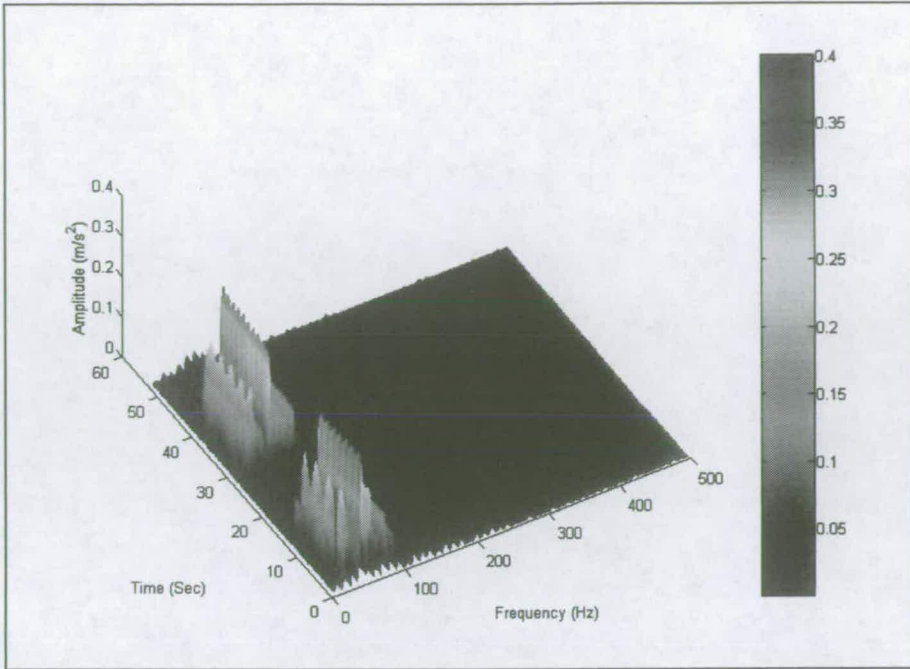


Figure 5-6 Y axis vibrations produced by the wire bonder

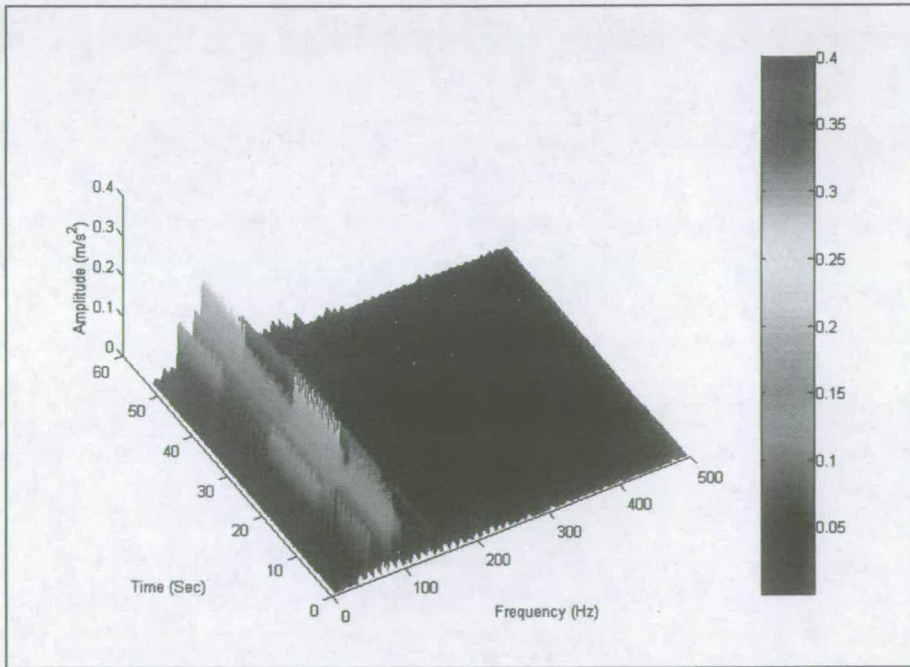


Figure 5-7 Z axis vibrations produced by the wire bonder

A VML Diagram constructed through discussion with ASM engineers. The VML diagram can be seen in Figure 5-8

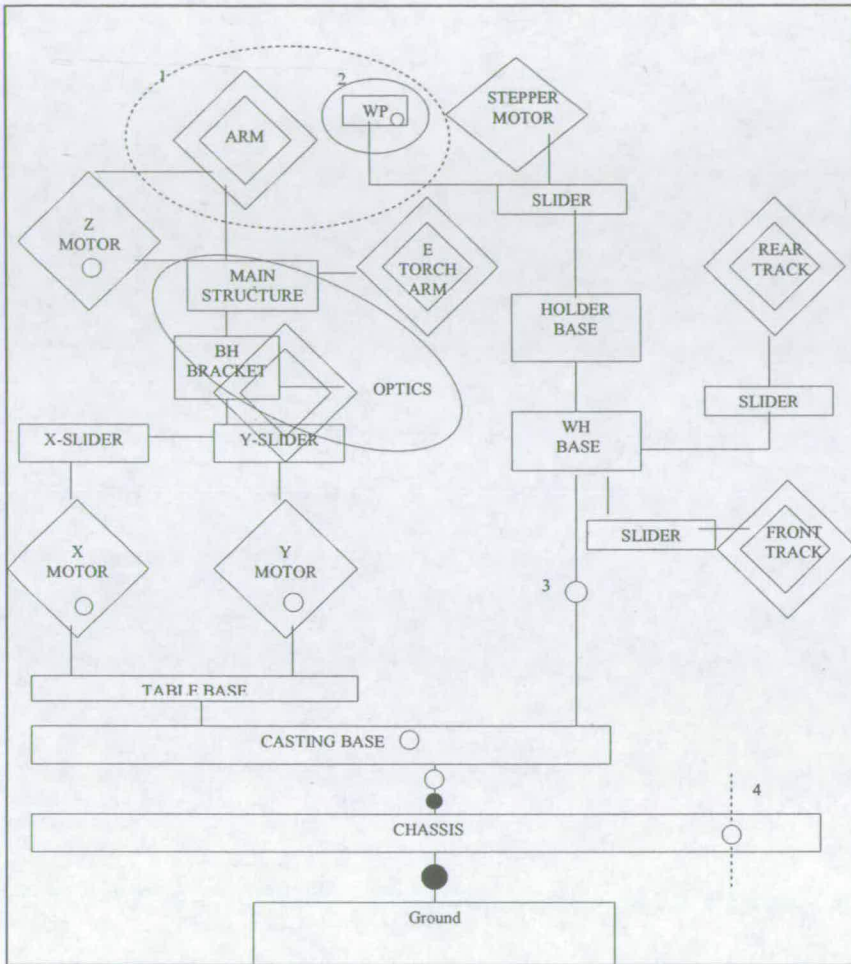


Figure 5-8 VML diagram constructed to analyse vibration on the wire binding machine

Following the production of a VML diagram and evaluating acceleration results for the 24 points across the machine, Reactec proposed installation of an active vibration suppression device. The active device chosen is produced by a partner company

Micromega dynamics and acts as an active mass tuned damper. Another Reactec Engineer is now finalizing the implementation of the devices.

1.10 Current company status

The entire *Concept 3 System* or individual parts have wider commercial scope than that of the sporting goods market. These constituent parts can be included in many devices to overcome vibration issues. They are currently being incorporated into OEM's products such as power tools and high-end audio equipment.

Reactec have now received over £500,000 of investment and grant funding and are embarking on a further funding round to develop a product based on its latest patent. Initial products are in the final stages of development prior to mass manufacturing with partner companies in the US.

1.11 Conclusions

Building a company from an academic base can provide a rewarding experience and help create jobs. Involvement with the company has allowed for increased technical equipment to support the work conducted within this text. Reactec have developed novel vibration suppression techniques, processes and devices to provide solutions in numerous markets under the management and technical direction of the author.

Appendix L Analysing snowboard mechanics

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ABSTRACT: We present a study of the mechanical behaviour of snowboards and show how this can be used to enhance training techniques. As the arrival of snowboards has been relatively recent studies covering these topics relating to snowboards are still scarce. Numerous studies have been conducted analysing construction, mechanical properties and performance of skis. We report the static mechanical testing of different snowboard constructions, conducted in laboratory tests, and dynamic data collected on-slope at data rates exceeding 1kHz. These data rates are higher than have been reported previously. The data from static and dynamic testing are correlated with snowboarder performance and its application to current training techniques is discussed.

1 INTRODUCTION

As a snowboard may be considered similar to a short, wide ski in many ways, literature published on skis is relevant to this study. As an older sport on which more research has been conducted there is significantly more information available in this field. A summary of the testing procedures and studies on skis is available in the 'Physics of Skiing' (Lind & Saunders 1996). Previous research on the mechanics of skis and skiing has concentrated on the measurement and characterisation of the mechanical properties of skis the measurement of forces involved in ski manoeuvres (Nordt & Springer 1999b). These mechanical tests have been complemented by using finite element analysis for static testing based around simple models for ski construction (Nordt & Springer 1999a, Deak et al 1975) to provide results that focus on the design of the ski. These simple models are based around basic laminate structures.

Recent snowboard specific publications (Buffington et al 2003) cover static and dynamic characteristics of snowboards. Applying procedures derived from ski analysis described .

Data collection techniques and equipment have improved dramatically over recent years, allowing use of smaller devices and faster data collection rates. Previous studies have been limited to data collection at around 100Hz (Buffington et al 2003); so that fre-

quencies up to 40Hz would be the only ones available for analysis according to Nyquist's theorem.

Presented in this paper are the laboratory results from four snowboards initially gaining quantitative mechanical data from static testing. These boards are tested on-slope to obtain results of their qualitative performance (feel). One board was equipped with sensors for dynamic on-slope testing by four riders. This information is then compared to current training techniques adopted by governing snowboard teaching organizations. Providing an insight into using measurement techniques to better understand and improve an individual's performance whilst snowboarding.

2 LABORATORY TESTS

Dimensions and mass play an integral part in the performance of a snowboard and are necessary for calculating board properties (e.g. stiffness), they are given in Table 1.

Table 1. Mass and dimensions of snowboards tested in the laboratory and qualitatively on-slope

Board	Mass	Overall length	Contact length	Nose width	Waist width
	(kg)	(mm)	(mm)	(mm)	(mm)
1	3.60	1655	1280	315	270
2	3.55	1640	1280	316	270
3	3.35	1640	1280	316	270
4	3.15	1525	1160	285	246

2.1 Static testing

Static testing in the laboratory has been conducted on four snowboards. The methods for conducting these tests are derived from the ASTM 1995 test methods (ASTM 1995). The overall length, contact length, waist and nose widths were measured. These provide necessary information for stiffness calculations and future computer modelling. There are five main ASTM tests to provide information on snowboard properties: overall stiffness, forebody stiffness, afterbody stiffness and torsional stiffness. Figure 1 shows the arrangement for stiffness measurements.

The overall stiffness of the snowboard is calculated using the following equation. (1.1)

$$S = \frac{F}{d} = \frac{48B}{C^3} \quad (1.1)$$

Where: S = overall stiffness N/mm, F = applied force N, d = vertical deflection at the centre mm, B = bending stiffness N mm² and C = contact length mm.

Torsional stiffness is calculated using equation (1.2).

$$\frac{T}{\theta} = \frac{2G}{L} \quad (1.2)$$

Where: T = torque Nm, θ = angle of twist rad, G = shear modulus Nm²/rad and L = distance between clamps m.

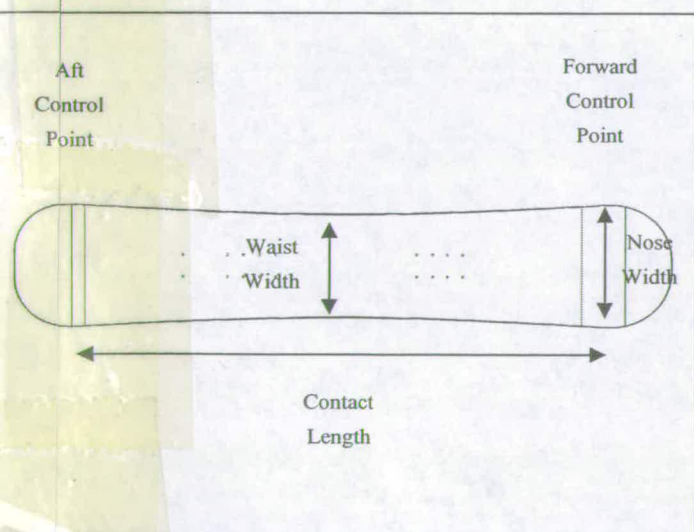


Figure 1 Snowboard geometry

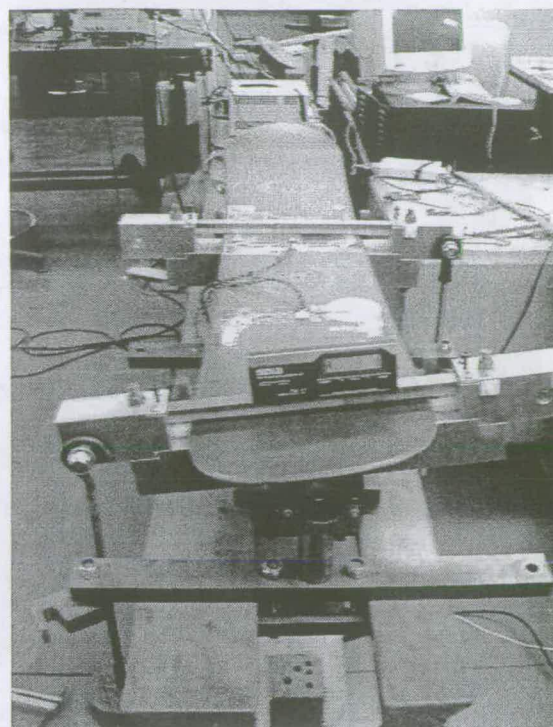


Figure 2 Ski simulator used in laboratory testing

The results from static testing are presented in Table 2.

Table 2. Stiffness properties of the snowboards

Board	Overall S (N/mm)	Front S _f (N/mm)	Rear S _r (N/mm)	Front G (Nm ² /rad)	Rear G (Nm ² /rad)
1	2.76	2.86	3.39	49.2	55.0
2	2.67	2.61	3.67	59.4	70.6
3	2.58	2.55	3.43	67.2	94.1
4	2.64	2.92	3.52	41.0	44.0

3 ON-SLOPE TESTING

Tests were conducted on an artificial "dendex" dry-slope. This reduces the complexity of the system as an artificial slope has consistent properties in comparison with snow, which makes comparisons between board properties and rider performance simpler. There are differences in the way in which a snowboard reacts with the slope and riding technique compared to on-snow. This difference is neglected in this study and will be later verified by conducting tests on snow.

3.1 Qualitative on-slope testing

The four boards that were tested in the static tests were ridden on-slope (artificial and snow) by several riders and a qualitative assessment of the boards (their feel) was made from rider perception. This was graded from 1 to 10 (10 being excellent) and

then stiffness estimated using stiff, medium and soft ratings. The findings are summarised in Table 3. Table 3 Qualitative evaluation of snowboards - rider perception from on-slope testing

Board	Feel	Overall stiffness	Torsional stiffness
1	7	medium/stiff	medium
2	8	medium	soft
3	5	soft	stiff
4	6	soft	medium

3.2 Quantitative on-slope testing

Several methods for data acquisition and sensor arrangement have been trialled, on these and other test snowboards. Dynamic tests have been conducted with a single snowboard for this study. Using four riders of differing standards: ranging from beginner to advanced. The four riders will be called, beginner, intermediate, advanced and Jimmy. Jimmy received training during testing to and advanced from beginner towards intermediate.

A 152cm Burton Snowboard (snowboard 4) was sensed with four MSI LDT10 polyvinylidene fluoride (PVDF) sensors. PVDF is a piezoelectric film sensor that gives a voltage output proportional to rate of change of strain.

These sensors were mounted around the front binding in a grid, bonded with superglue and waterproofed with silicone sealant, see Figure 3. Output from the sensors was recorded using a data logger at a sampling frequency of 1kHz per channel at 12 bit resolution, thus allowing all frequencies up to 400Hz to be recorded accurately according to Nyquist theory (Horowitz and Hill 1980). The data logger used was manufactured by *Biomedical Monitoring Systems Ltd*. It is small in size (75x56x18mm) and has a low mass (100g including battery) and relatively high data capturing rates ($\leq 4\text{kHz}$), with a 64Mb storage capacity.

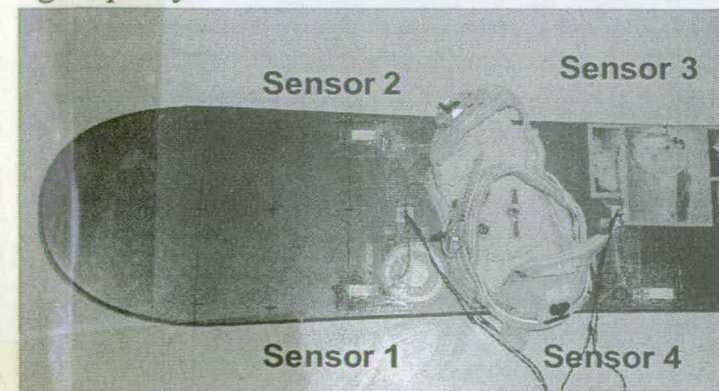


Figure 3 Sensored Snowboard

During tests it was placed in the snowboarders pocket, providing minimal influence to snowboarding technique. Data captured is transferred via a smart digital card. The amplification on each channel is variable. A gain of 10 was used for each of the channels to give optimal signal noise ratio, therefore minimising error.

3.3 Analysis of data from on-slope testing

Raw data from the sensors was examined for each rider and also processed to give a frequency spectrum. A fast Fourier transform was performed on the raw data collected, giving a frequency spectrum. A program custom written in Matlab was used for the data analysis. The fast Fourier transforms clearly show that the major frequencies present are below 100Hz. Frequency components are evident up to 200Hz, but due to the minimal levels of vibrations above 100Hz analysis of these have been excluded from this paper.

4 RESULTS

The following figures 4 through 8 show some of the results obtained from testing.

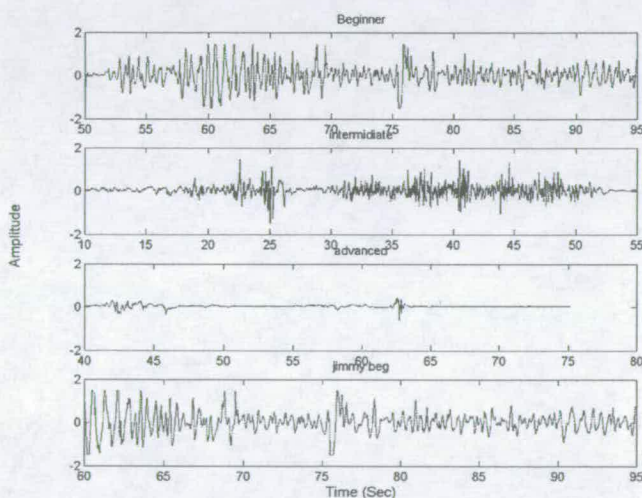


Figure 4 Raw data from sensor 3 for four riders

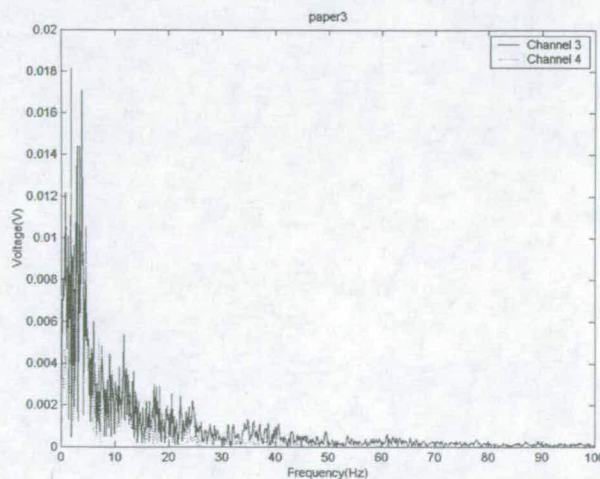


Figure 5 FFT of beginner during of 2 turns

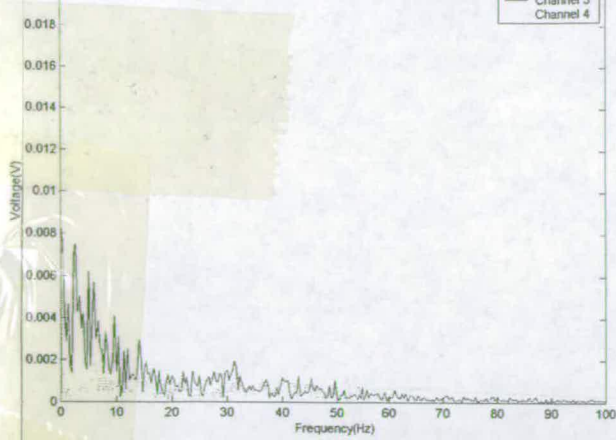


Figure 6 FFT of intermediate during of 2 turns

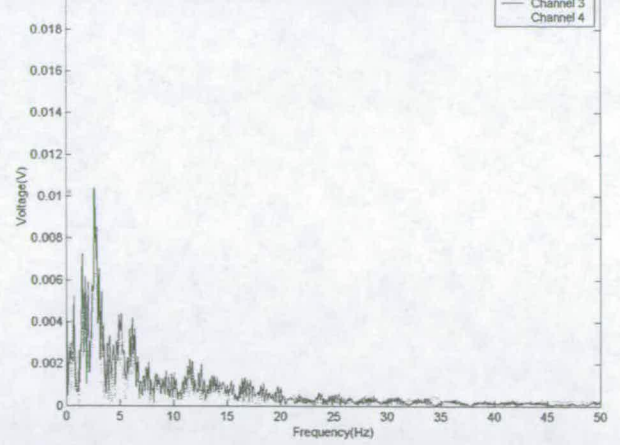


Figure 8 FFT of Jimmy at intermediate level

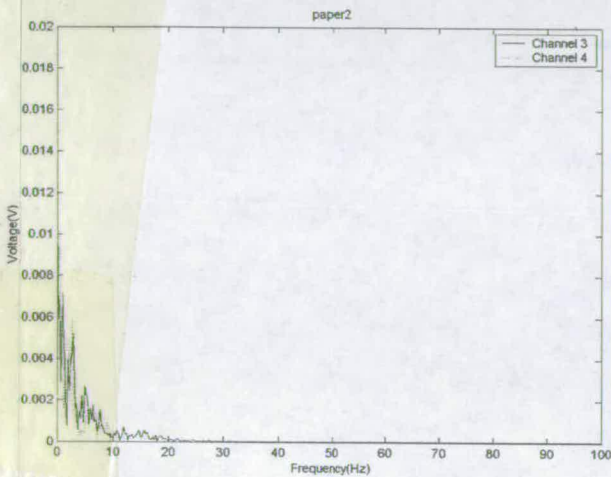


Figure 7 FFT of advanced for during 2 turns

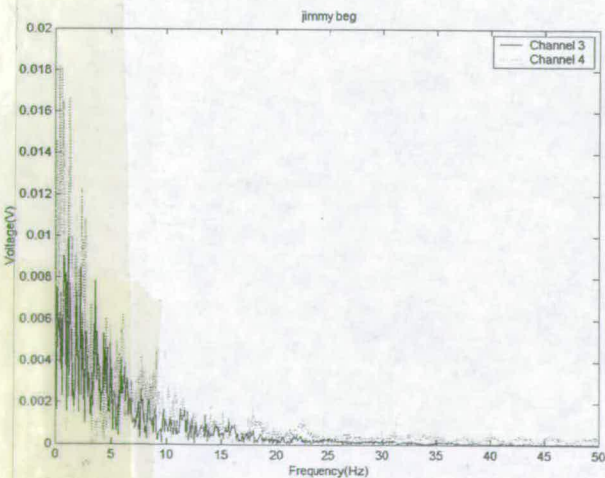


Figure 8 FFT of Jimmy at beginner level

4.1 "Pedaling"

A technique also promoted is that of "pedaling", where the rider pushes the feet as if pushing a pedal independently to twist the board. This aids initiation and ending of a turn. This is extremely difficult to see on video analysis, monitoring the forces around the foot allow quantitative analysis of this technique previously unavailable. Examples of good and poor techniques are shown in Figures 9 and 10 respectively.

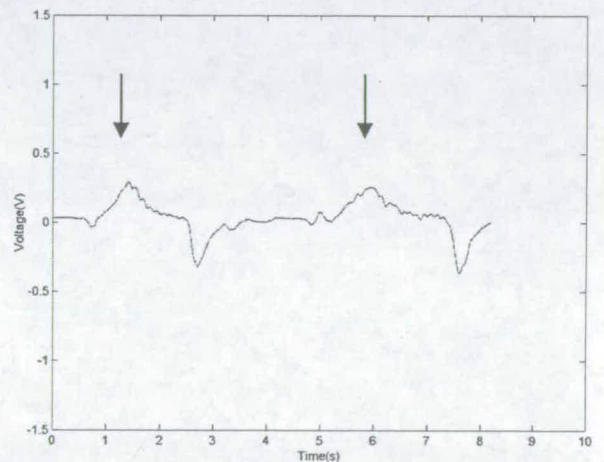


Figure 9 Examples of good pedaling technique (arrows indicate maximum points of twist.)

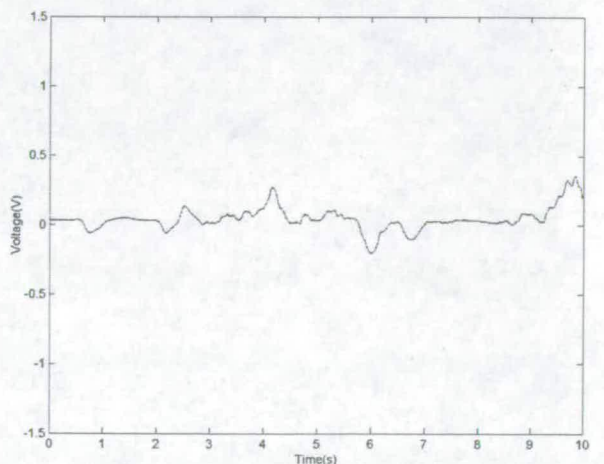


Figure 10 Example of poor pedaling

An individual's snowboarding performance is based more on qualitative than quantitative information. It is reliant on visually assessing and therefore is subjective. The analysis here is conducted using British Association for Ski and Snowboard Instructors (BASI) techniques. BASI training techniques look at the rider's position as they make certain manoeuvres. The majority of snowboarder's problems can be related to the basic stance adopted and the way in which the riders move their bodies in relation to manoeuvres they are performing.

Correlating these to the data collected allows training techniques to be adapted. Current methods only use video analysis to analyse techniques. It is difficult to get a time base for this analysis as it is often filmed using low speed film. With the sensing techniques described in this paper this time between manoeuvres and the forces applied to the snowboard can be analysed. Strong correlations between technique and force transmitted have been discovered.

6 DISCUSSION

Qualitative results from riders about the 'feel' of a board (Table 3) correlated with the findings of the static testing results (Table 2). The riders used to test the boards were experienced and had been exposed to riding different types of snowboard, and were therefore capable of analysing the subtle differences between boards. This correlation between static tests and rider analysis is what has progressed the majority of snowboard design and manufacture to date.

At an early stage of learning to ride a snowboard obvious improvements can be made by using video analysis. Body position is key to improving performance. This can be viewed accurately by looking at individual frames in sequence. Once up to intermediate standard snowboarders find it difficult to improve, much smaller changes are required to improve technique. Video analysis is the current method for tuning technique.

Figure 4 shows the raw data from a sensor being ridden by beginner, intermediate, advanced and Jimmy (at early learning stage). It can be seen that voltage, which is proportional to rate of change of strain, is high with beginners as they cannot apply forces in a controlled manner. Looking at Figures 5 and 6, it is evident that this relatively high voltage has low frequency content. This is believed to be caused by correction of body position to retain balance. Once a rider becomes more advanced the high voltage levels are reduced and higher frequencies are observed, Figure 6.

To assess this data trend, Jimmy, a non-snowboarder received tuition. Beginner stages produced Figure 7 with high voltages at low frequency. As he advanced the voltages were reduced and higher frequency content observed, Figure 8.

A skilled sportsperson should be able to apply large forces in a smooth manner. The pedalling data (Figures 9 and 10) show the difference observed with smooth application of strong forces and uneven weak forces being applied. This controlled application of forces is what top level snowboarders have to achieve. Monitoring of forces allows the application of these forces to be observed, something unavailable until now. Data collected during testing is proof that previous testing techniques have been unable to capture frequencies in excess of 40Hz.

6.1 Improvement

Higher data acquisition rates allow the frequencies prevalent during riding on an artificial slope to be measured. It is evident that more advanced riders stimulate higher frequencies in the snowboard; limitations of the artificial surface and size of slope are believed to prevent higher frequencies from being evident. It may be possible to excite frequencies well in excess of 100Hz during fast riding on snow. Testing the system on snow will produce further complexities as the surface conditions vary substantially.

6.2 Friendly software for coaches

Further work is required to provide a user-friendly system which can pick out errors in riding technique and prompt coaches to pick up on errors. A custom written program to take captured data and analyse the individual turning movement would be beneficial. This system is best implemented on elite riders who have to concentrate on small differences in order to reach optimal standard.

Collection of data from PVDF sensors could be improved upon by combining accelerometers and strain gauges to allow simple force calibration.

Understanding how riders apply forces, and understanding how vibration patterns affect the 'feel' of a snowboard allows improvement in the design of snowboards. With sufficient on-snow data it is likely that matching an optimal board to snow conditions for a specific rider could be understood by using this system.

7 CONCLUSIONS

snowboards have been tested in the laboratory, providing values for flex, torsional stiffness. Agreement was found between the mechanical properties of the boards measured in the lab and a qualitative assessment of on-slope performance.

A system has been developed to collect dynamic data from snowboarders on-slope. It is:

- compact in size
- capable of sampling at a rate of 4kHz/sec
- variable amplification to allow optimal signal/noise ratio.
- uses PVDF sensors to measure rate of change of strain

Data from on-slope testing shows we can:

- differentiate between riders of different competence levels (beginner, intermediate and expert)
- track improvements in rider performance.
- measure forces the rider transmits to the board

This system can be used in training snow-boarders and is likely to be particularly useful in training elite riders.

ACKNOWLEDGEMENTS

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Reactec – from laboratory to the slopes – commercialisation of University research

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ABSTRACT: Reactec Ltd is a spin-out company from the University of Edinburgh Centre for Materials Science and Engineering, within which there is an interdisciplinary research environment combining materials and engineering with a focus on winter sports. Founded by PhD students, the initial aim of the company was to commercialise novel vibration control systems into the sporting goods market, specifically winter sports and skis. The combination of three smart materials and a microprocessor provide semi-active damping in a structure. Foundation research taken from the PhDs, supported by additional funding from the company, allowed acceleration of the technology towards a commercial product. To build and run a successful technology business from a research base specific business skills are required. Supporting bodies such as the Scottish Institute for Enterprise provided education and training to fill the business skill gap. Proposing a novel technology to a manufacturer requires a different emphasis to that of purely academic work. In the current economic climate, companies are increasingly risk-averse. Adopting novel technologies has associated risk and this must be minimised to allow a product to advance to the market place. Initially applied to skis, the technology is now being applied to wider markets. Exploiting the technology requires a structured market focus.

1 TECHNOLOGY – THE CONCEPT 3 SYSTEM

Reactec have developed a smart materials based vibration reduction system. The *Concept 3 System* incorporates three different smart materials and a microprocessor to reduce vibrations in structures. The system uses poly(vinylidene fluoride) (PVDF) sensors to monitor levels of vibration. This information is processed by the *Intelligent Control Unit* (ICU), a small microprocessor which in turn drives a semi-active magnetorheological fluid filled device to suppress vibration. The entire system is powered with a piezoceramic parasitic power supply. Technology and techniques are described in greater detail in previous publications (Watson & Blackford 2001, Buckingham & Blackford 2004). This technology improves the performance of

products, reduces fatigue and associated maintenance costs. The work was initially conducted with skis as the specific application. Figure 1 shows a CAD drawing of the *Concept 3 Ski*. Figure 2 shows a schematic of the system.

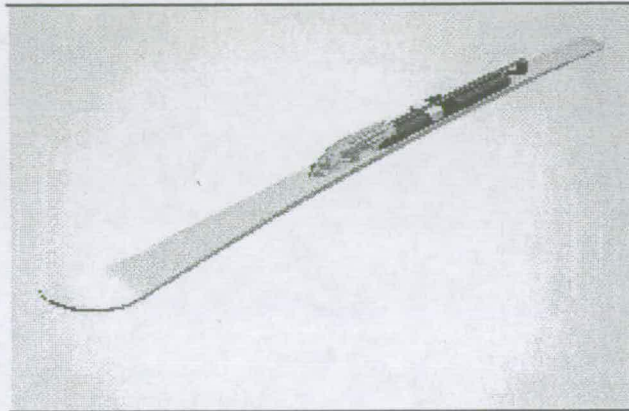


Figure 1 CAD drawing of the *Concept 3 Ski*

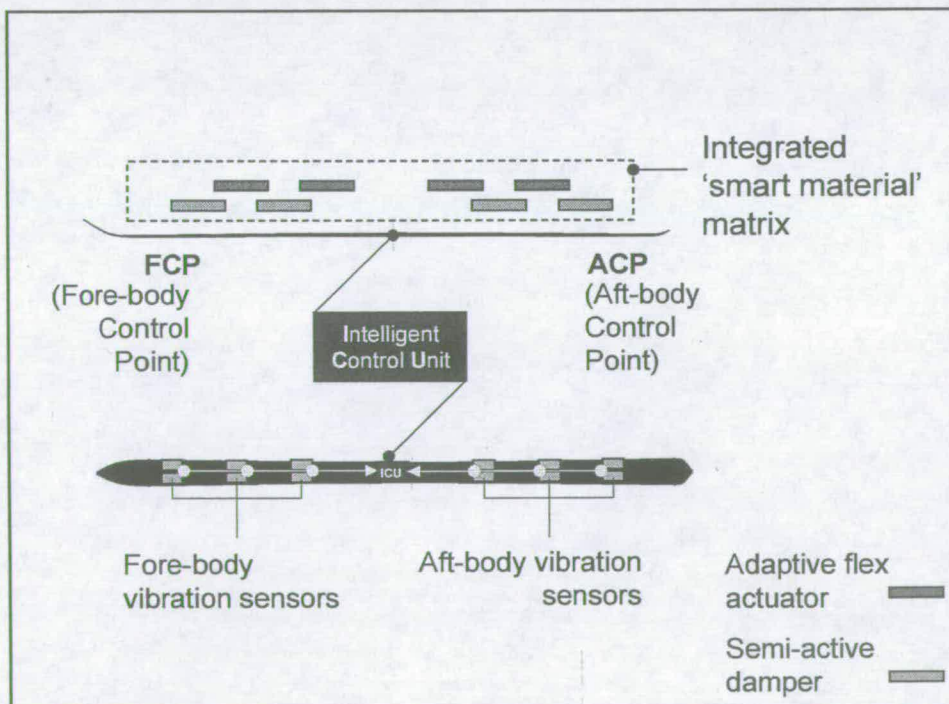


Figure 2 Schematic of *Concept 3 Ski*

The ski and snowboard market is an early adopter of technology, which is a significant brand differentiator in winter sports goods. The ski market is therefore an ideal target for the *Concept 3 System*. Skis also provide a substantial engineering challenge; the system must cope with the harsh environment skis are subjected to. Manufacturers have been seeking truly effective vibration control mechanisms for years, and the first models claiming to incorporate such technology appeared in 1995 (Glennie et al, 1999). Head and K2 are among the manufacturers that have sold skis with similar control technology. As with previous vibration control systems, the *Concept 3 System* may be adopted on the higher price models and filter down the ski range allowing increased royalties.

2 FORMING A START-UP COMPANY

Reactec was set up to realise the commercial potential of technology developed by Pete Watson and Mark-Paul Buckingham whilst studying towards PhD's at the Centre for Materials Science and Engineering. Pete Watson's PhD – Engineering Smart Skis and Mark-Paul Buckingham, working on snowboards.

Pete Watson entered a business plan competition run by Edinburgh Technology Fund (ETF) in 2000, an in-house seed corn funding body at the university. Pete secured some initial funds through this competition and established Reactec the company, it was officially registered on the 20th July 2001. Mark-Paul was brought on shortly afterwards to fill another director's role and accelerate the company achievements.

Both directors came from a technical background and lacked skills required to run a business. These skills were developed through mentoring and attending business courses specifically designed for students in our situation, provided by the Scottish Institute for Enterprise.

2.1 BUSINESS SUPPORT

Scottish Institute for Enterprise (SiE) is dedicated to creating a culture of enterprise within the Science, Engineering and Technology communities in all thirteen of Scotland's universities. Established in 2000 with funding from the Office of Science and Technology, SiE are now delivering enterprise education to over 8000 students and have supported 55 sustainable businesses.

SiE have provided substantial support since incorporation, some of which has been: promotion, networking, patents funds, business plan prize funds and business courses.

Recently representatives from the Scottish Institute for Enterprise at the University of Edinburgh have forged entrepreneurial ties with Slovenia after attending PODIM 24, a prestigious annual event held in the city of Maribor which was attended by top government officials and the international academic community to discuss entrepreneurship, innovation and management issues. SiE made it possible for Reactec to present at this conference, elevating both company image and securing contact

within the EU community. It is this level company promotion and perspective that a new company must have in the current environment, the market is global and small companies must remember this. During this meeting the stages in which Reactec have evolved were presented (Adamson 2003).

3 INTELLECTUAL PROPERTY

As technology companies are based around invention, protecting the idea or Intellectual Property (IP) is of utmost importance. Without registered rights to the idea it is easy for another company to take, and exploit the technology. There are different methods of protecting IP dependant on the technology itself. Filling a patent is the standard method for most technology based innovations. Reactec filed its first patent application, 'Improvements relating to Skis' on the 12th December 2001, the second application was filed in August 2003. Patents should be filed in all countries in which the technology is likely to be sold.

To patent an invention there must be a novel aspect which cannot be an obvious step from previous technologies and that no knowledge is available in the public domain specific to the invention. As Reactec came from an academic institution, work has to be published; therefore all patents must be filed before publishing. Even with initial patents filed it is feasible that another company may take your idea as they are aware that a start-up company will not be able to afford the legal fees to fight a court case.

IP issues must be resolved with the academic institution from which the company has been formed. Legislation varies depending on country or even internal University regulations.

4 GROWING THE COMPANY

Start-up companies such as Reactec need staff that are self-motivated and technically proficient. Time available to manage employees at the early stages of a company is scarce, and people who join the organisation must be capable of managing themselves or they will become a drain on resources. Reactec's staff have, to date come directly out of University. Reactec have strong relations with several academic organisations which provide excellent staff for short-term placement students. Providing the ideal opportunity to evaluate individuals capabilities and future employment with the company. Every placement student that has been part of the Reactec team has subsequently been employed.

One difficult, yet subtle issue for a technology company is that of 'technology push' vs 'market pull'. Technology innovators can easily see the advantages for their own technology, but is there a market place and will the technology be accepted? Market driven technologies stand much greater chance of success than pure technological innovation. Reactec have been keen to find a balance between new designs and market driven opportunities. This is done by simultaneously running commercial contracts along side in-house Government funded technology programs. The SMART award

scheme is an example of one of these such schemes. SMART awards are available across the UK .

To ensure that the commercial aspects of a business are covered and to increase market information, Reactec formed links with the the Business Management School at the University of Edinburgh. This link provided MBA students who work along side the company, scrutinizing strategy and market awareness. This input provided excellent balance to technology lead thinking.

There is much to be gained by having strong ties with the academic institutions: staff, experience, advice, equipment. Reactec believe this relationship is highly beneficial to both parties.

5 CONTACTING COMPANIES

Selling to original equipment manufacturers (OEM's) can be a difficult task; time is required to get to the relevant people in large organisations. Reactec attended trade shows in order to gain relevant contact information in the ski industry. Once contact has been made, technology demonstrations are required. This is a difficult stage if Intellectual Property has not been secured. Non-disclosure agreements would need to be signed prior to revealing any aspects of the technology.

Finding funds to support travel is a challenge that many new companies face. Sales need to be made but the associated costs can be restrictive. As most ski companies are based in Europe, Reactec's directors visited the all major ski manufacturers in a single trip. This was made feasible due to support from Scottish Enterprise through their Lothain Export Scheme.

Reactec have yet to secure the ski market for the *Concept 3 System*, several manufacturers are looking at methods of implementing the system in a cost effective manner. Other sporting goods are also ear-marked for future variations of the system.

6 CURRENT COMPANY STATUS

The entire *Concept 3 System* or individual parts have wider commercial scope than that of the sporting goods market. These constituent parts can be included in many devices to overcome vibration issues. They are currently being incorporated into OEM's products such as power tools and high-end audio equipment.

Reactec are seeking investment to rapidly expand the company. Technology companies require substantial amounts of funds in order to run, organic growth is an option but comes with the associated risk of falling behind in the market place. With investment Reactec intend to secure their own premises and elevate company status with the aim to increase the number of products which the *Concept 3 System*.

7 RECOMMENDATIONS

Building a company from an academic base can provide a rewarding experience and help create jobs. It is essential to research the available support, both on local and broader levels.

To commercialise technology in the field of sports equipment requires an explicit understanding of current technologies used. Your technology should improve the current performance of products and/or reduce the cost of manufacture. Novel technologies rarely cost less than those available, if a technology is difficult, and therefore costly to implement during manufacturing process it will not make it to market. A technology may improve current sporting equipment, but if the cost is too great it may not be adopted by the manufacturers.

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Design and use of an instrumented curling brush

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Abstract: The design and manufacture of an instrumented curling brush, sweep ergometer, has provided the first quantitative analysis of sweeping in the Olympic sport of curling. Sweeping is a method by which curlers alter the trajectory of curling stones and can provide the difference between winning and losing in a target-based sport where centimetre scale variations are vitally important. Two design phases led to the development of the wireless sweep ergometer that is able to measure an athlete's performance unencumbered. The ergometer measures the vertical and horizontal forces, and acceleration of the brush head in two axes. Graphical output can be used to analyse player technique, strength, and rate of fatigue. The ergometer provides an outstanding tool for both skill and consistency coaching and will help in team selection and match tactics.

Keywords: curling, force measurement, instrumentation, olympic training, sweeping technique

INTRODUCTION

The Winter Olympic sport of curling is the only target-based sport where a projectile can have its trajectory corrected once it has left a player's hand or delivery device. This is done by sweeping the ice in front of an approaching stone and modifying the coefficient of friction at the sliding interface. The sweeping techniques and the athlete's fitness can provide the crucial difference between winning and losing a game of curling at both club and Olympic levels. Despite its importance, there has been no quantitative measurement of sweeping technique. Instead, sweeping techniques have developed over centuries of curling in a qualitative and anecdotal manner. The authors have developed a sweep ergometer, which for the first time, enables curling athletes and coaching staff to measure the acceleration and forces applied to the ice while sweeping, an important advancement in the sport.

Curling is played on ice by two teams of four, each team delivering eight ~ 18.6 kg stones alternately. Stones are delivered with both a translational velocity (~ 2 m/s) and rotational velocity (~ 1.5 rad/s) and slide ~ 28 m to the target area known as the *house*. The rotational velocity component results in the stone having a curved trajectory, which is used to avoid stones that have been played previously [1]. The dynamics of curling stones have been the subject of several papers [2–6]. Points are scored by the team whose stone(s) lie closest to the centre of the target area at the other end of the ice rink once all eight stones have been delivered. Curling is both a highly technical and tactical game [7].

Once the stone is released, one or more players from the same team track it down the ice, sweeping in front of the stone. Sweeping produces frictional heat between the nylon brush head and the ice and brings the temperature of the ice closer to its melting point and thereby reduces the coefficient of friction [6]. The frictional heat produced increases with the downward force applied and with the sweeping velocity [8]. Sweeping is used to increase the distance a stone travels and reduce the amount a stone deflects laterally or 'curls'. Once sweeping of a

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section of ice is completed, the frictional heat is conducted away from the ice surface and it returns to the bulk temperature of the ice rink. To maximize the effect of sweeping, curlers must sweep as close to the on-coming stone as possible without coming into contact with it [8].

There are two extremes in sweeping technique: low force with high frequency (~ 100 N and ~ 5 Hz, respectively) and high force with low frequency (~ 750 N and 2 Hz). The majority of curlers assessed using the ergometer fall between these extremes. The forces applied and techniques used in sweeping have not been analysed previously in a quantitative manner. We have developed a sweep ergometer to measure the forces and velocities applied by curlers while sweeping. The design of the sweep ergometer is presented here, as are the initial test results.

2 METHODS

It is important that the 'sweep ergometer' closely resembles a standard curling brush in appearance, otherwise athletes tend to be distracted and the whole sweeping process *looks and feels* different. The popular 'Hammer Classic' curling brush was used for the basis of the sweep ergometer. At the time of testing, the Hammer Classic was widely used in competition, and has sufficient space within the head of the brush to incorporate sensors and associated electronics. Two sweep ergometers have been developed. The prototype version – mark 1 – was connected to a laptop with trailing leads (Fig. 1). This was improved by using wireless technology during the development of the mark 2 sweep ergometer, which is the focus of this article.

2.1 Brush design

To monitor forces applied to the brush head, the standard plastic axle was replaced by a machined steel axle and bearing arrangement (Fig. 2). The inclusion of steel axle, bearing arrangement, instrumentation, and power source increased the mass of the Hammer Classic brush from 0.91 to 1.16 kg. A needle-bearing was used for the coupling and it is assumed that negligible energy was lost to friction. The machined axle was designed to transmit the applied force, yet deform sufficiently so that resistance strain gauges could measure strain within their strain range up to a maximum strain of 4 per cent of the 5 mm gauge length.

To determine the dimensions of the adapted axle so that it would deform appropriately under the expected load, for the strain gauges used, calculations were made by representing the axle as a simply supported beam with end supports 100 mm

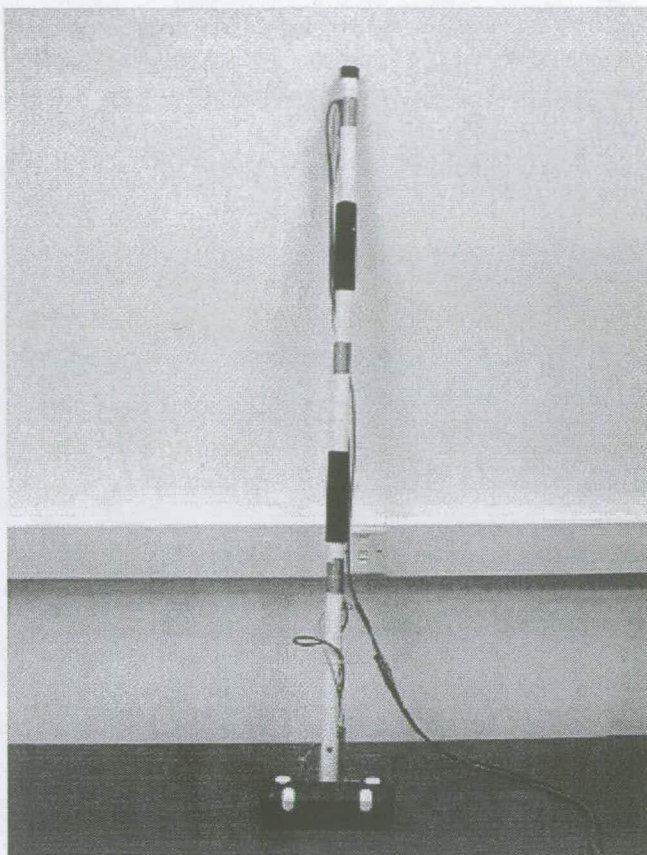


Fig. 1 The sweep ergometer was based on the popular Hammer Classic brush. The mark 1 version was hard-wired and with a lead that ran from the top of the handle to the computer

apart and a load at the mid-point. Theoretical maximum loads were calculated for a 100 kg curler. The maximum vertical force V occurs when the entire mass of the curler is transferred vertically down the brush handle onto the brush head and is 1000 N. The maximum horizontal force H occurs when the angle between the brush handle and ice is a minimum (when the brush head is furthest from the player). From observation, this angle is $\sim 66^\circ$ so that the maximum horizontal force resolved from 1000 N acting down the brush handle is ~ 400 N. Resolving moments for a simply supported beam model gives the maximum vertical moment M_V and horizontal moment M_H :

$$M_V = \frac{Vl}{2}, \quad M_H = \frac{Hl}{2}$$

where l is the length of the beam. For the 100 mm axle, the maximum vertical and horizontal moments are 50 and 20 Nm, respectively.

Two pairs of strain gauges were used to measure the vertical forces on the axle (Fig. 2) and a further two pairs to measure the horizontal forces. The strain

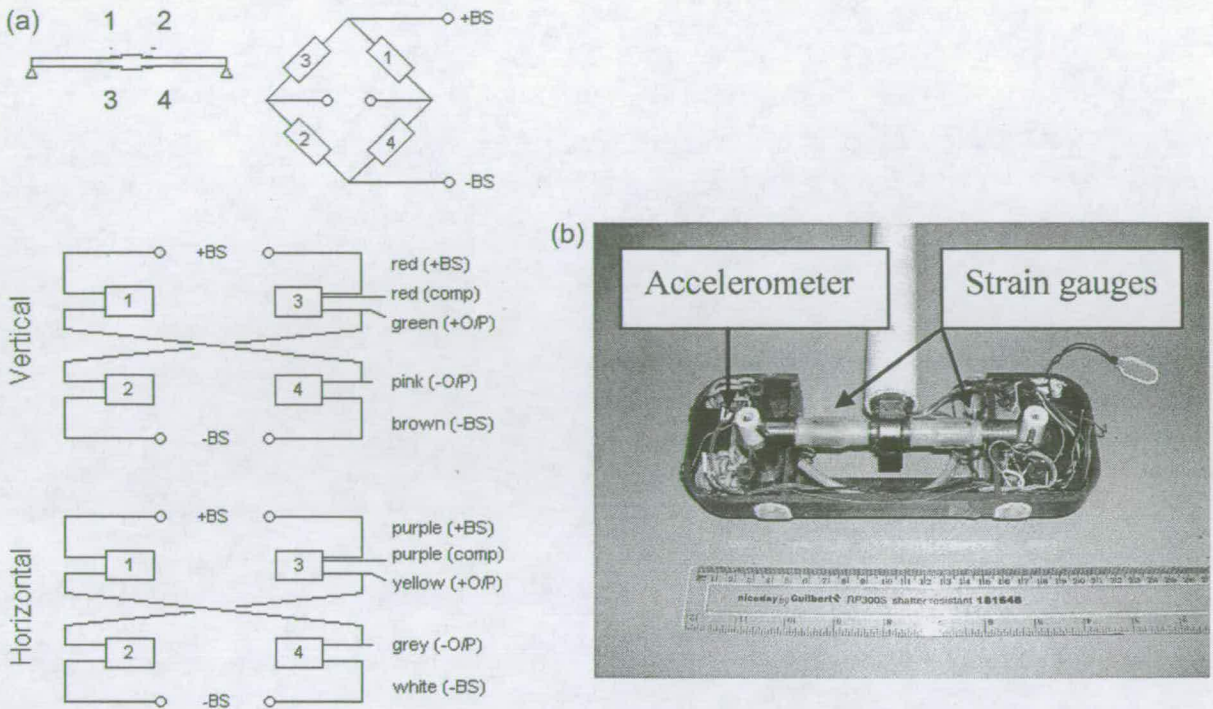


Fig. 2 (a) Strain gauges were bonded in both the vertical and horizontal planes to measure the force components normal to these two planes. The lower diagram shows where the strain gauges were positioned, how they were connected using a full Wheatstone bridge arrangement, and their colour coding. (b) The internals of the brush head with replacement steel axle, strain gauges, and accelerometer are shown

gauges were bonded to the degreased steel shaft using superglue and later waterproofed using heat shrink wrap and low corrosion silicon sealant. Two full Wheatstone bridge wiring arrangements allowed vertical and horizontal forces to be measured independently without effect from torsional loading (Fig. 2). We estimated a maximum deflection of ~0.1 mm at the mid-point of the steel axle, which corresponds to the upper deformation limit for this strain gauge-axle arrangement. This estimate was made using the following procedure: bending moment theory was used to determine the radius for the axle that would deflect 0.1 mm under the maximum load (1000 N). The deflection from the neutral axis y_{max} of a simply supported beam is given by

$$y_{max} = \frac{Ll^3}{48EI}$$

where L is the load, l the length of the beam, E Young's modulus (200 GPa for mild steel), and I the second moment of area. Given that the second moment of area for a cylinder orthogonal to its central axis is

$$I = \frac{\pi r^4}{4}$$

It follows that

$$r = \left(\frac{Ll^3}{12\pi E y_{max}} \right)^{1/4}$$

An axle with a radius of 6 mm would therefore deflect the required 0.1 mm under a load of 1000 N. The brush was loaded with known masses to calibrate the output of the strain gauges.

Acceleration was measured using a pre-calibrated ± 10 g CXL10LP3-R, Crossbow Industries, San Jose, USA, accelerometer, which was well suited because of its internal temperature compensation amplifier and small size. Preliminary results for the mark 1 brush (which used a ± 25 g accelerometer) indicated that accelerations rarely exceeded ± 7 g. The ± 10 g CXL10LP3-R accelerometer provided a relatively higher signal in the range and thereby minimized the impact of random noise. Numerical integration was used to calculate velocity v according to

$$v = \frac{1}{2}(a_{n+1} + a_n)\Delta t$$

where a_n and a_{n+1} are consecutive acceleration values and Δt is the time between acceleration

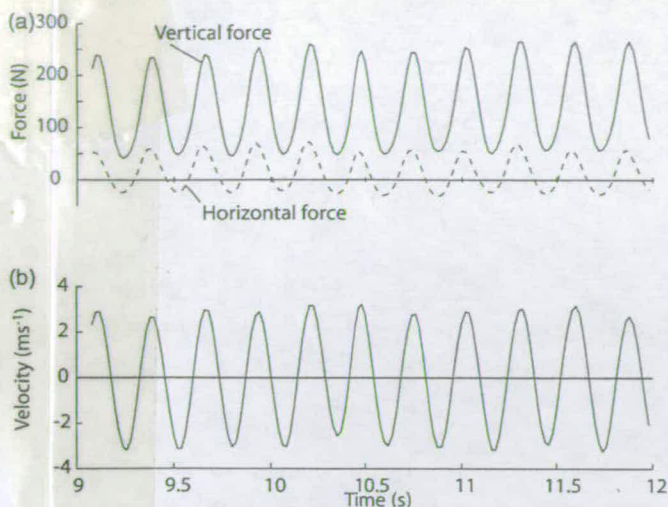


Fig. 3 Typical sample of data from the mark 1 sweep ergometer. (a) Force profile during sweeping showing both vertical and horizontal forces. (b) Velocity profile as the players sweep away from themselves (positive values) and then towards themselves (negative values)

values (0.004 s), and the initial velocity and acceleration were zero (i.e. $a_1 = 0$). Velocity calculations have a ± 6 per cent of signal uncertainty. The variation of velocity and vertical and horizontal forces with time was then displayed graphically (Fig. 3).

The mark 2 brush was designed with an RF wireless system to transmit data that negated the need for a connecting cable, making the system easier for use on the rink. Radiometrix, Middlesex, England, open band 418 and 433 MHz transmitter receivers were used for data communication. These transmitters and receivers were chosen on the basis of their 25 m range, minimal power requirements, small size, and low cost. ADC and strain gauge

amplification circuits were incorporated into the brush head (Fig 4). A reduction in size from the original amplification circuitry box measuring $200 \times 280 \times 100 \text{ mm}^3$ was achieved by the design of a miniature amplification circuit using a custom-built surface mount board measuring $25 \times 25 \times 8 \text{ mm}^3$. The circuit was based around a Burr Brown, Dallas, USA, precision instrumentation amplifier INA 115, which provided a gain of 100 with adjustable offset (Fig. 5). To maximize space available in the brush head, the circuit was duplicated on both sides of double-sided surface mount board, which allowed an amplifier for each full bridge arrangement. The Radiometrix transmitters and receivers were used in conjunction with a micro-chip PIC16F74 programmed to operate the ADC. As the PIC16F74 chip has only four dedicated AD conversion inputs, the vertical axis reading from the accelerometer was not recorded. Previous tests had shown that the sweep ergometer rarely left the ice surface and therefore accelerations in the vertical axis can generally be ignored.

Sampling limited bandwidth signals with equally spaced sampling frequency f_s must be greater than twice of the maximum frequency f_{\max} (known as the Nyquist frequency), in order to have the signal be uniquely reconstructed without aliasing [9]. As the PIC was using four ADC channels, the sampling rate was 250 Hz, allowing frequencies up to 125 Hz to be reconstructed, this is far in excess of sweeping frequencies which are usually in the region of 4 Hz, but allows fluctuations during a stroke to be captured. This high sampling rate increases the accuracy of integration of the acceleration data to produce velocity and displacement. The PIC was programmed using a combination of Hex and C code. The system would perform analogue-to-digital conversion for the PIC's AD channels 1–4 in order

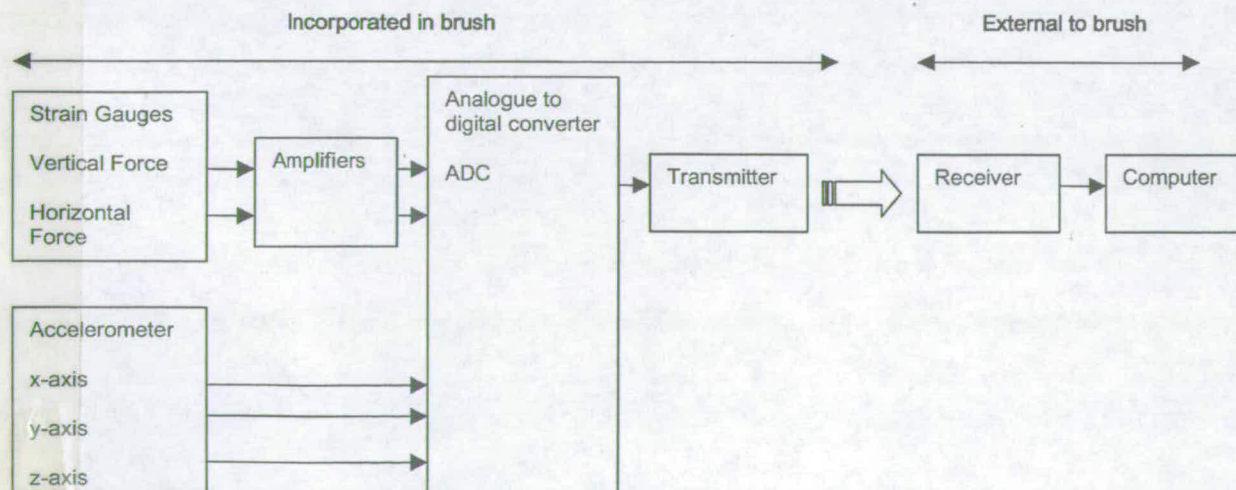


Fig. 4 Schematic representation of the system used in the mark 2 sweep ergometer

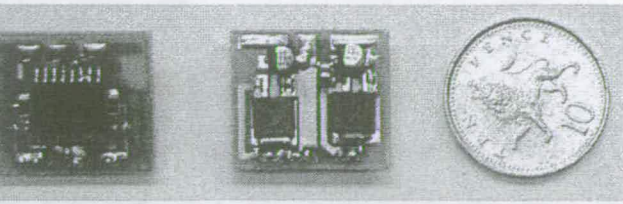


Fig. 5 INA amplification and power circuit. The circuit was miniaturized to fit within the constrictive environment in the head of the mark 2 sweep ergometer

and perform a line return and then repeat. This was sent to the Radiometrix transceiver and recorded.

Power requirements were supplied by a single alkaline-manganese dioxide PP3 Duracell, Bethel, GA, Powercell, which was selected because of its operating temperature and discharge capabilities. This supplied regulated voltages of ± 5 V, ground, and 8 V for the INA amplifier circuits, PIC, Radiometrix transmitter and accelerometer, respectively. The PP3 battery supplied sufficient power to run the system for over 1 h in the cold conditions of the rink. The receiving side of the transmission system used a small circuit with the Radiometrix transceiver connected to a serial port connector. The laptop computer connected ran Microsoft Windows and collected data with HP Vee software. HP Vee provided near-real-time graphical representations of vertical and horizontal forces and acceleration. Slight fluctuations in real-time representation were observed, which was due to Microsoft periodically running internal applications which affected processor use. These would only alter the rate of display by <0.25 s.

The graphical representation enables coaches to see changes in the force applied while a player swept and enabled the opportunity for corrective feedback. Once a session had been completed, the program would send the information to the original Excel post-processing program. Post-processing could apply calibration factors to the raw data and integrate acceleration to produce velocity and displacement.

RESULTS AND DISCUSSION

A repeatable test was designed where each player had to sweep the full length of the rink in front of a stone being pushed by the coach at a similar velocity to that which a stone would travel during regular play. Numerous tests were conducted with different players and rinks. The final standardized test required curlers to sweep for 25 s with maximum

physical exertion. This test was conducted by five elite sweepers from the same team (one player acts as team reserve). This exercise was repeated three times by each player with a 2 min recovery interval between each exercise.

In general, each player began by not pushing down as hard as possible and then increased their downward force over the course of each exercise (Fig. 6(a)). In one case (Player 4, Exercise 3, Fig. 6(a)), the player increased the downward force dramatically after some persuasive encouragement from the head coach. Generally, the vertical force diminished with successive exercises because of player fatigue, which is most notable for Players 1 and 3 (Fig. 6(a)). Player 2 applied the greatest downward force during the first exercise and then dropped to a lower but more consistent level. Player 5 was the most erratic, with the vertical force changing sporadically throughout each exercise (Fig. 6(a)). This is an example of poor sweeping technique as it would prove problematic to the team's Skip. The Skip decides when sweeping is necessary to correct a stone's trajectory. The inconsistency of Player 5 would make it difficult for the Skip to judge when and for how long the player should be sweeping.

The stroke frequency shown in Fig. 6(b) was calculated as the inverse of time between velocity peaks. The stroke frequency for all five players decayed over the course of each exercise because of player fatigue. The steepness of this decay gives a good indication of player fitness. Most players also show a marked decrease in stroke frequency over successive exercises (Fig. 6(b), Players 1, 3, 4). Player 2 provides an example of a highly fit player with a relatively shallow decay in frequency over each exercise followed by strong recovery and consistent frequency in successive exercises (Fig. 6(b)).

Different sweeping styles can be identified using the sweep ergometer. Player 3 provides an example of a high velocity (frequency) stroke with little downward force compared with Player 2 who has a high force lower velocity style. The analysis of force and frequency decay will enable the tactical selection of sweepers during a game. Players with high force and/or velocity but who fatigue rapidly can be utilized largely at the beginning of a game or 'saved' to perform at the end of a game. When more than one sweeper is used, the player closest to the stone has the greatest effect. In this case, the stronger sweeper can be identified using the sweep ergometer and placed closest to the approaching stone.

A curling stone runs on a band 13.5 cm in diameter and players are required by the laws of the sport to sweep across the entire width of the running surface [7]. This is to prevent the players from intentionally

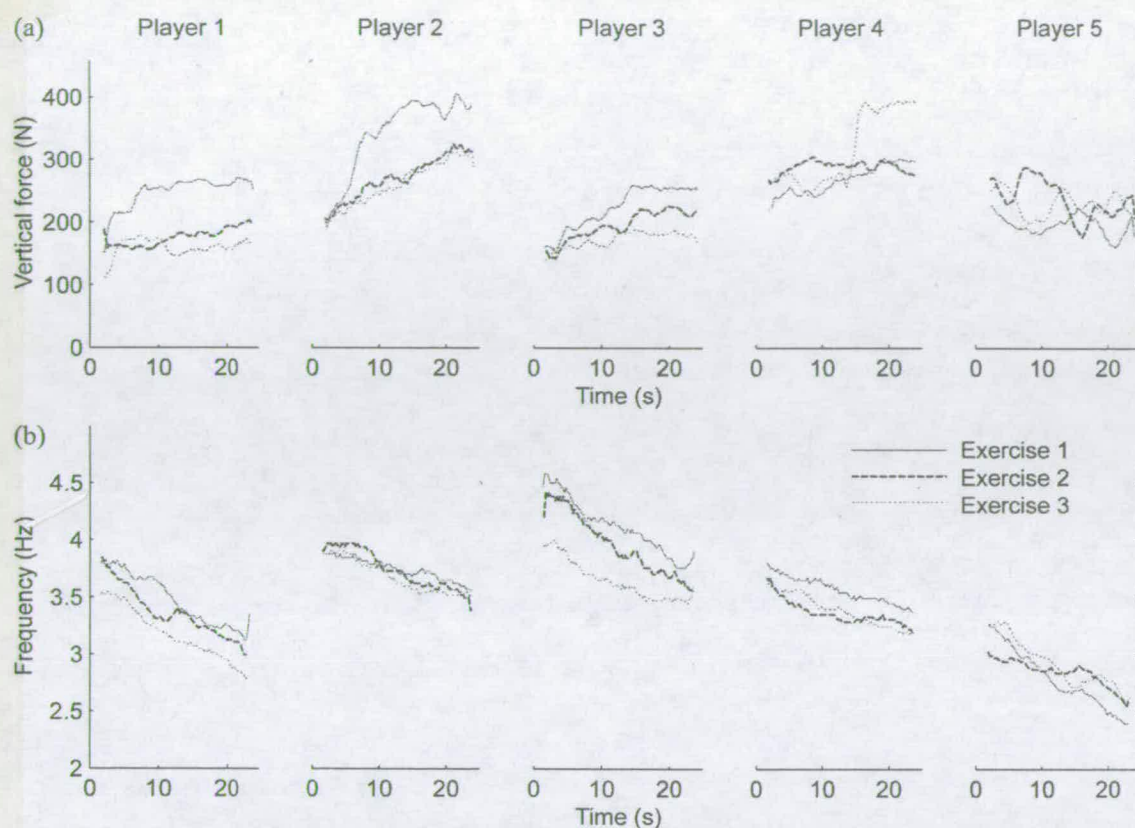


Fig. 6 Sweep ergometer output from training exercises for five elite curlers. Each player completed three exercises where they swept with maximum effort for 25 s. There was a 2 min recovery time between each exercise. (a) Variation of the peak vertical force over the duration of each exercise. The peak vertical force was the maximum force applied during each stroke. (b) Variation of stroke frequency with time over the course of each exercise. The reduction of stroke frequency with time is due to player fatigue

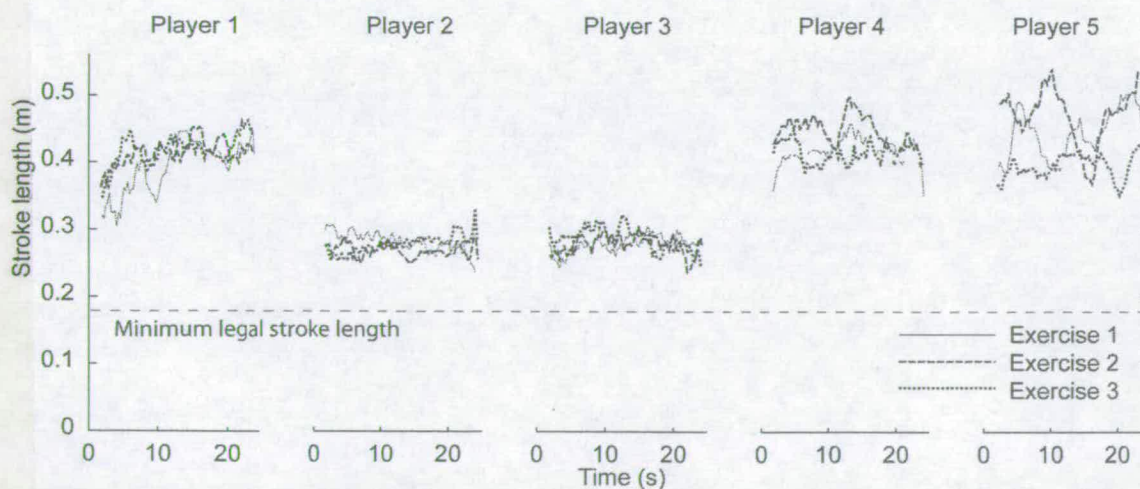


Fig. 7 Stroke length during training exercises for five elite curlers. The stroke length is determined by the double integration of acceleration output from the sweep ergometer. The rules of the sport specify that each stroke must commence and terminate outside the width of the running surface of the approaching curling stone. This distance is 0.14–0.18 m depending on the specification of the curling stone and is represented on the figure as a dashed line (0.18 m)

'umping' ice debris in front of one side of an approaching stone to radically alter its trajectory. Players 1, 4, and 5 swept approximately twice the required distance and thus waste valuable energy (Fig. 7). Players 2 and 3 swept a consistent distance approximately 30 cm. Coaching staff can monitor the stroke length of players with the sweep ergometer and correct their styles to make their sweeping form more efficient.

CONCLUSIONS

The sweep ergometer has been designed, tested, and built, which will provide an invaluable resource to curling athletes and their coaching staff. The sweep ergometer measures remotely the vertical and horizontal forces and acceleration in three axes and provides the first quantitative analysis of sweeping in the sport of curling. The wireless system did not impede performance, as it had no trailing wires and worked with minimal power in field conditions. Several successful tests were performed with different players and on a variety of curling rinks. Results based on the sweeping performance of five curlers show that the force and frequency of their sweeping technique and fitness can be easily identified using the graphical output from the sweep ergometer. The decay in frequency over the course of a single sweeping exercise or a session is a strong indicator of player fitness. Player strength and technique can also be identified from the force history and appropriate adjustments made during training. Analysis of force and velocity parameters will contribute to team selection before major tournaments and the tactical selection of sweepers during a game.

ACKNOWLEDGEMENTS

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Queries

M-P Buckingham, B A Marmo, and J R Blackford

- Q1 Please check whether "used for the basis of" is OK in the sentence "The popular . . . sweep ergometer".
- Q2 Please check the sentence "Sampling limited bandwidth . . . without aliasing" for sense.
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Analysing snowboard mechanics

MP. Buckingham & Jane R. Blackford

*School of Engineering and Electronics and Centre for Materials Science and Engineering,
University of Edinburgh*

ABSTRACT: We present a study of the mechanical behaviour of snowboards and show how this can be used to enhance training techniques. As the arrival of snowboards has been relatively recent studies covering these topics relating to snowboards are still scarce. Numerous studies have been conducted analysing construction, mechanical properties and performance of skis. We report the static mechanical testing of different snowboard constructions, conducted in laboratory tests, and dynamic data collected on-slope at data rates exceeding 1kHz. These data rates are higher than have been reported previously. The data from static and dynamic testing are correlated with snowboarder performance and its application to current training techniques is discussed.

1 INTRODUCTION

As a snowboard may be considered similar to a short, wide ski in many ways, literature published on skis is relevant to this study. As an older sport on which more research has been conducted there is significantly more information available in this field. A summary of the testing procedures and studies on skis is available in the 'Physics of Skiing' (Lind & Saunders 1996). Previous research on the mechanics of skis and skiing has concentrated on the measurement and characterisation of the mechanical properties of skis the measurement of forces involved in ski manoeuvres (Nordt & Springer 1999b). These mechanical tests have been complemented by using finite element analysis for static testing based around simple models for ski construction (Nordt & Springer 1999a, Deak et al 1975) to provide results that focus on the design of the ski. These simple models are based around basic laminate structures.

Recent snowboard specific publications (Buffington et al 2003) cover static and dynamic characteristics of snowboards. Applying procedures derived from ski analysis described .

Data collection techniques and equipment have improved dramatically over recent years, allowing use of smaller devices and faster data collection rates. Previous studies have been limited to data collection at around 100Hz (Buffington et al 2003); so that fre-

quencies up to 40Hz would be the only ones available for analysis according to Nyquist's theorem.

Presented in this paper are the laboratory results from four snowboards initially gaining quantitative mechanical data from static testing. These boards are tested on-slope to obtain results of their qualitative performance (feel). One board was equipped with sensors for dynamic on-slope testing by four riders. This information is then compared to current training techniques adopted by governing snowboard teaching organizations. Providing an insight into using measurement techniques to better understand and improve an individual's performance whilst snowboarding.

2 LABORATORY TESTS

Dimensions and mass play an integral part in the performance of a snowboard and are necessary for calculating board properties (e.g. stiffness), they are given in Table 1.

Table 1. Mass and dimensions of snowboards tested in the laboratory and qualitatively on-slope

Board	Mass	Overall length	Contact length	Nose width	Waist width
	(kg)	(mm)	(mm)	(mm)	(mm)
1	3.60	1655	1280	315	270
2	3.55	1640	1280	316	270
3	3.35	1640	1280	316	270
4	3.15	1525	1160	285	246

2.1 Static testing

Static testing in the laboratory has been conducted on four snowboards. The methods for conducting these tests are derived from the ASTM 1995 test methods (ASTM 1995). The overall length, contact length, waist and nose widths were measured. These provide necessary information for stiffness calculations and future computer modelling. There are five main ASTM tests to provide information on snowboard properties: overall stiffness, forebody stiffness, afterbody stiffness and torsional stiffness. Figure 1 shows the arrangement for stiffness measurements.

The overall stiffness of the snowboard is calculated using the following equation. (1.1)

$$S = \frac{F}{d} = \frac{48B}{C^3} \quad (1.1)$$

Where: S = overall stiffness N/mm, F = applied force N, d = vertical deflection at the centre mm, B = bending stiffness $N \text{ mm}^2$ and C = contact length mm.

Torsional stiffness is calculated using equation (1.2).

$$\frac{T}{\theta} = \frac{2G}{L} \quad (1.2)$$

Where: T = torque Nm, θ = angle of twist rad, G = shear modulus Nm^2/rad and L = distance between clamps m.

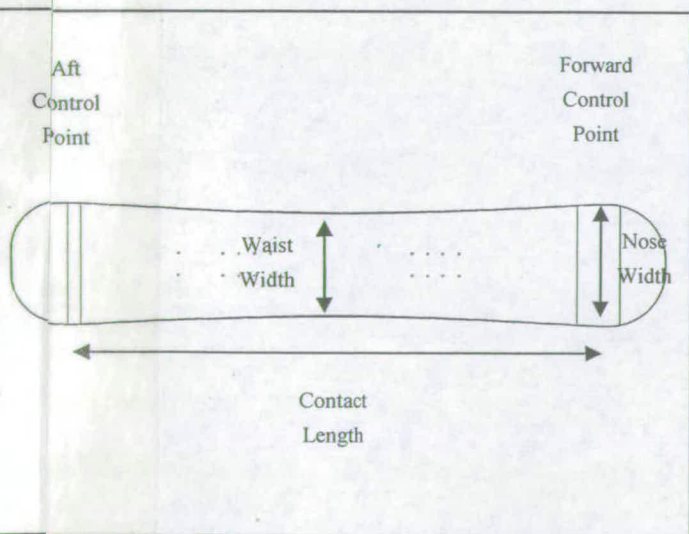


Figure 1 Snowboard geometry

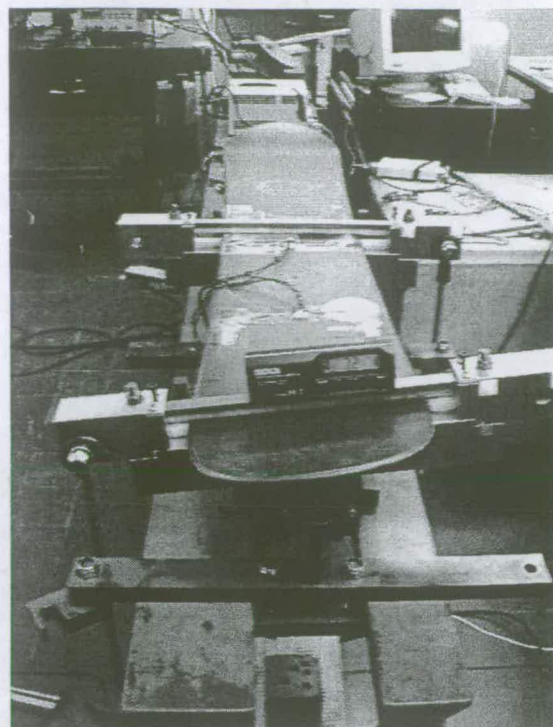


Figure 2 Ski simulator used in laboratory testing

The results from static testing are presented in Table 2.

Table 2. Stiffness properties of the snowboards

Board	Overall S (N/mm)	Front S _f (N/mm)	Rear S _r (N/mm)	Front G ₂ (Nm ² /rad)	Rear G ₂ (Nm ² /rad)
1	2.76	2.86	3.39	49.2	55.0
2	2.67	2.61	3.67	59.4	70.6
3	2.58	2.55	3.43	67.2	94.1
4	2.64	2.92	3.52	41.0	44.0

3 ON-SLOPE TESTING

Tests were conducted on an artificial "dendex" dry-slope. This reduces the complexity of the system as an artificial slope has consistent properties in comparison with snow, which makes comparisons between board properties and rider performance simpler. There are differences in the way in which a snowboard reacts with the slope and riding technique compared to on-snow. This difference is neglected in this study and will be later verified by conducting tests on snow.

3.1 Qualitative on-slope testing

The four boards that were tested in the static tests were ridden on-slope (artificial and snow) by several riders and a qualitative assessment of the boards (their feel) was made from rider perception. This was graded from 1 to 10 (10 being excellent) and

then stiffness estimated from stiff, medium and soft ratings. The findings are summarised in Table 3.

Table 3 Qualitative evaluation of snowboards - rider perception from on-slope testing

Board	Feel	Overall stiffness	Torsional stiffness
1	7	medium/stiff	medium
2	8	medium	soft
3	5	soft	stiff
4	6	soft	medium

3.2 Quantitative on-slope testing

Several methods for data acquisition and sensor arrangement have been trialled, on these and other test snowboards. Dynamic tests have been conducted with a single snowboard for this study. Using four riders of differing standards: ranging from beginner to advanced. The four riders will be called, beginner, intermediate, advanced and Jimmy. Jimmy received training during testing to and advanced from beginner towards intermediate.

A 152cm Burton Snowboard (snowboard 4) was sensed with four MSI LDT10 polyvinylidene fluoride (PVDF) sensors. PVDF is a piezoelectric film sensor that gives a voltage output proportional to rate of change of strain.

These sensors were mounted around the front binding in a grid, bonded with superglue and waterproofed with silicone sealant, see Figure 3. Output from the sensors was recorded using a data logger at a sampling frequency of 1kHz per channel at 12 bit resolution, thus allowing all frequencies up to 400Hz to be recorded accurately according to Nyquist theory (Horowitz and Hill 1980). The data logger used was manufactured by *Biomedical Monitoring Systems Ltd*. It is small in size (75x56x18mm) and has a low mass (100g including battery) and relatively high data capturing rates ($\leq 4\text{kHz}$), with a 64Mb storage capacity.

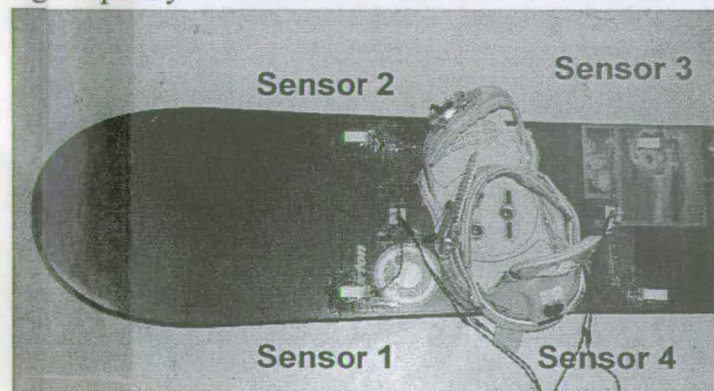


Figure 3 Sensored Snowboard

During tests it was placed in the snowboarders pocket, providing minimal influence to snowboarding technique. Data captured is transferred via a smart digital card. The amplification on each channel is variable. A gain of 10 was used for each of the channels to give optimal signal noise ratio, therefore minimising error.

3.3 Analysis of data from on-slope testing

Raw data from the sensors was examined for each rider and also processed to give a frequency spectrum. A fast Fourier transform was performed on the raw data collected, giving a frequency spectrum. A program custom written in Matlab was used for the data analysis. The fast Fourier transforms clearly show that the major frequencies present are below 100Hz. Frequency components are evident up to 200Hz, but due to the minimal levels of vibrations above 100Hz analysis of these have been excluded from this paper.

4 RESULTS

The following figures 4 through 8 show some of the results obtained from testing.

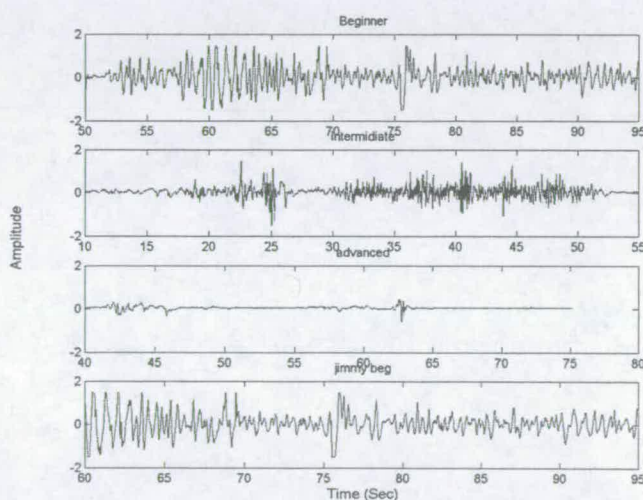


Figure 4 Raw data from sensor 3 for four riders

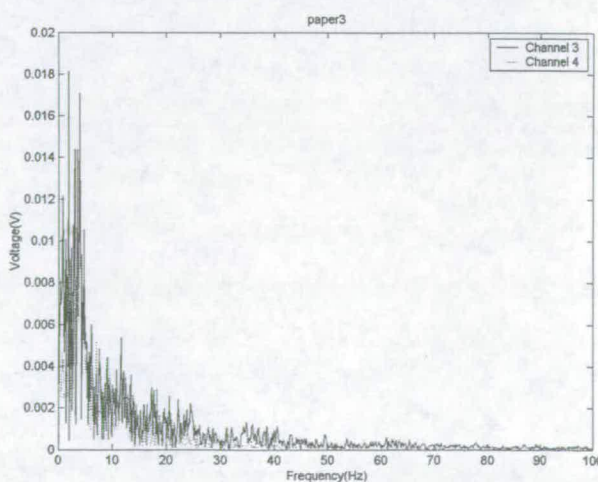


Figure 5 FFT of beginner during of 2 turns

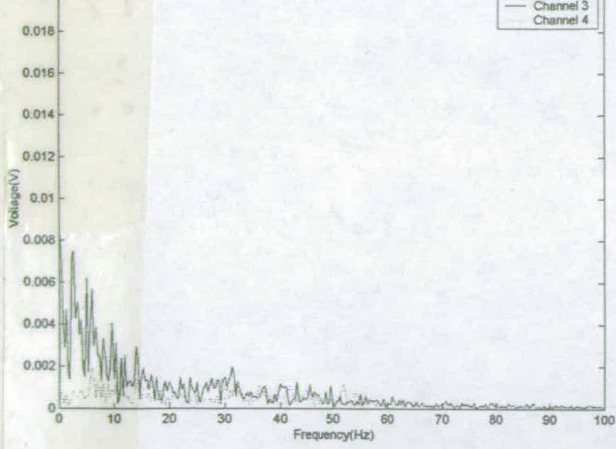


Figure 6 FFT of intermediate during of 2 turns

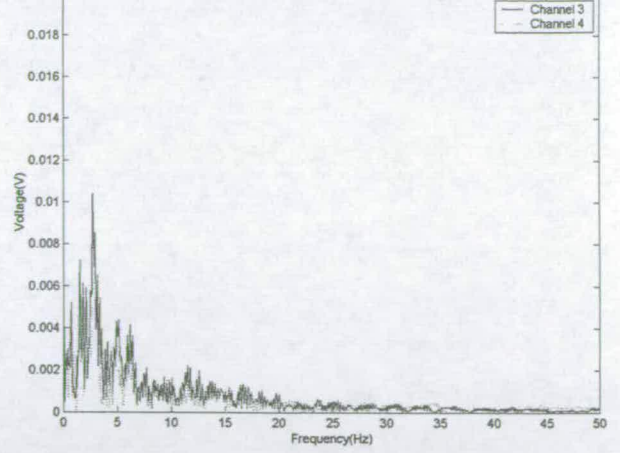


Figure 8 FFT of Jimmy at intermediate level

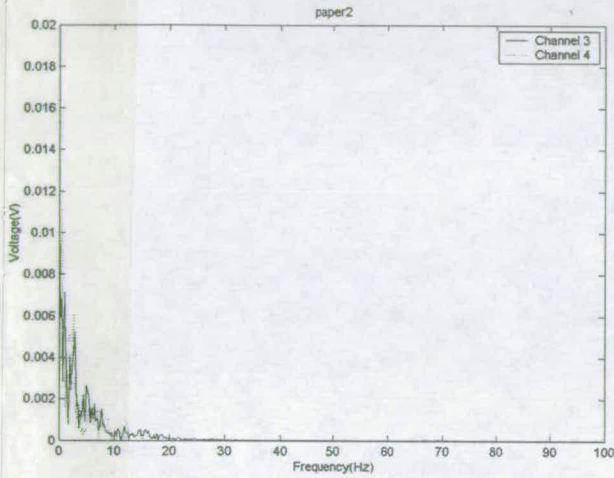


Figure 7 FFT of advanced for during 2 turns

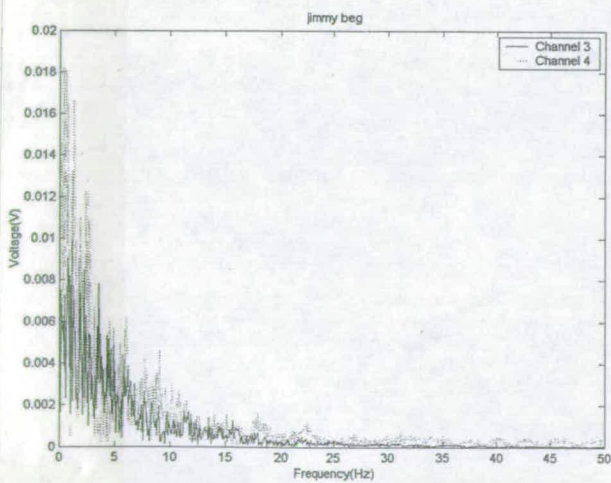


Figure 8 FFT of Jimmy at beginner level

4.1 "Pedaling"

A technique also promoted is that of "pedaling", where the rider pushes the feet as if pushing a pedal independently to twist the board. This aids initiation and ending of a turn. This is extremely difficult to see on video analysis, monitoring the forces around the foot allow quantitative analysis of this technique previously unavailable. Examples of good and poor techniques are shown in Figures 9 and 10 respectively.

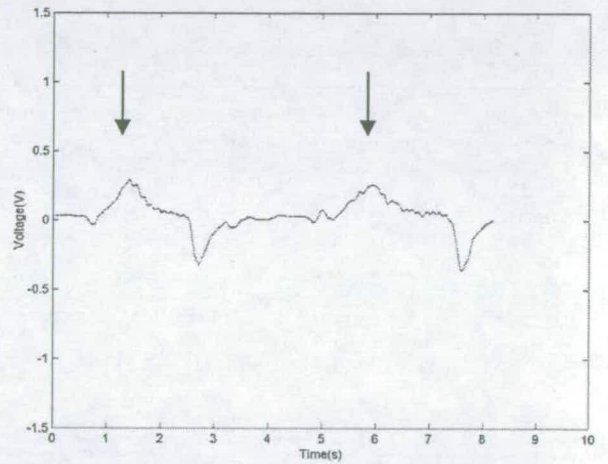


Figure 9 Examples of good pedaling technique (arrows indicate maximum points of twist.)

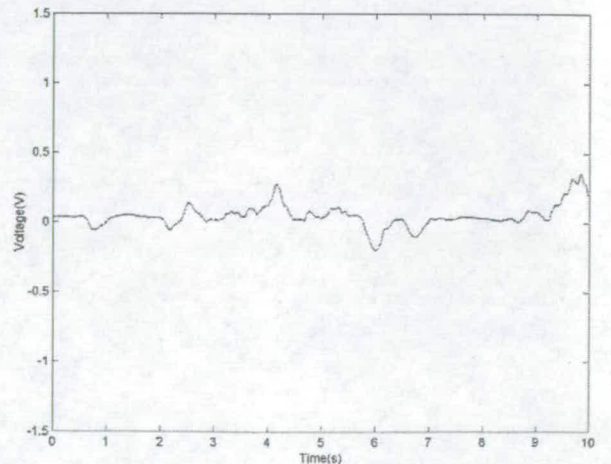


Figure 10 Example of poor pedaling

An individual's snowboarding performance is based more on qualitative than quantitative information. It is reliant on visually assessing and therefore is subjective. The analysis here is conducted using British Association for Ski and Snowboard Instructors (BASI) techniques. BASI training techniques look at the rider's position as they make certain manoeuvres. The majority of snowboarder's problems can be related to the basic stance adopted and the way in which the riders move their bodies in relation to manoeuvres they are performing.

Correlating these to the data collected allows training techniques to be adapted. Current methods only use video analysis to analyse techniques. It is difficult to get a time base for this analysis as it is often filmed using low speed film. With the sensing techniques described in this paper this time between manoeuvres and the forces applied to the snowboard can be analysed. Strong correlations between technique and force transmitted have been discovered.

6 DISCUSSION

Qualitative results from riders about the 'feel' of a board (Table 3) correlated with the findings of the static testing results (Table 2). The riders used to test the boards were experienced and had been exposed to riding different types of snowboard, and were therefore capable of analysing the subtle differences between boards. This correlation between static tests and rider analysis is what has progressed the majority of snowboard design and manufacture to date.

At an early stage of learning to ride a snowboard obvious improvements can be made by using video analysis. Body position is key to improving performance. This can be viewed accurately by looking at individual frames in sequence. Once up to intermediate standard snowboarders find it difficult to improve, much smaller changes are required to improve technique. Video analysis is the current method for tuning technique.

Figure 4 shows the raw data from a sensor being ridden by beginner, intermediate, advanced and Jimmy (at early learning stage). It can be seen that voltage, which is proportional to rate of change of strain, is high with beginners as they cannot apply forces in a controlled manner. Looking at Figures 5 and 6, it is evident that this relatively high voltage has low frequency content. This is believed to be caused by correction of body position to retain balance. Once a rider becomes more advanced the high voltage levels are reduced and higher frequencies are observed, Figure 6.

To assess this data trend, Jimmy, a non-snowboarder received tuition. Beginner stages produced Figure 7 with high voltages at low frequency. As he advanced the voltages were reduced and higher frequency content observed, Figure 8.

A skilled sportsman should be able to apply large forces in a smooth manner. The pedalling data (Figures 9 and 10) show the difference observed with smooth application of strong forces and uneven weak forces being applied. This controlled application of forces is what top level snowboarders have to achieve. Monitoring of forces allows the application of these forces to be observed, something unavailable until now. Data collected during testing is proof that previous testing techniques have been unable to capture frequencies in excess of 40Hz.

6.1 Improvement

Higher data acquisition rates allow the frequencies prevalent during riding on an artificial slope to be measured. It is evident that more advanced riders stimulate higher frequencies in the snowboard; limitations of the artificial surface and size of slope are believed to prevent higher frequencies from being evident. It may be possible to excite frequencies well in excess of 100Hz during fast riding on snow. Testing the system on snow will produce further complexities as the surface conditions vary substantially.

6.2 Friendly software for coaches

Further work is required to provide a user-friendly system which can pick out errors in riding technique and prompt coaches to pick up on errors. A custom written program to take captured data and analyse the individual turning movement would be beneficial. This system is best implemented on elite riders who have to concentrate on small differences in order to reach optimal standard.

Collection of data from PVDF sensors could be improved upon by combining accelerometers and strain gauges to allow simple force calibration.

Understanding how riders apply forces, and understanding how vibration patterns affect the 'feel' of a snowboard allows improvement in the design of snowboards. With sufficient on-snow data it is likely that matching an optimal board to snow conditions for a specific rider could be understood by using this system.

Snowboards have been tested in the laboratory, providing values for flex, torsional stiffness. Agreement was found between the mechanical properties of the boards measured in the lab and a qualitative assessment of on-slope performance.

A system has been developed to collect dynamic data from snowboarders on-slope. It is:

- compact in size
- capable of sampling at a rate of 4kHz/sec
- variable amplification to allow optimal signal/noise ratio.
- uses PVDF sensors to measure rate of change of strain

Data from on-slope testing shows we can:

- differentiate between riders of different competence levels (beginner, intermediate and expert)
- track improvements in rider performance.
- measure forces the rider transmits to the board

This system can be used in training snow-boarders and is likely to be particularly useful in training elite riders.

ACKNOWLEDGEMENTS

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Optimising Sweeping Techniques for Olympic Curlers

Brett A. Marmo, Mark-Paul Buckingham & Jane R. Blackford

Abstract. In the sport of curling players sweep the ice in the front of curling stones to increase the distance that the projectiles slide. Their vigorous sweeping raises the surface temperature of the ice thereby reducing its coefficient of friction. The change in ice temperature is dependent on the velocity that curlers sweep the ice, the downward force they apply and the pattern that is swept. The forces and velocities applied by Olympic level curlers were recorded on an instrumented brush. A numerical model was used to determine optimal sweeping pattern based on the curlers sweep force and velocity profiles.

1 Introduction

The Winter Olympic sport of curling is the only target-based sport where a projectile can have its trajectory corrected once it has left a player's hand or delivery device. This is done by sweeping the ice in front of an approaching stone to modify the coefficient of friction of ice resulting in metre scale variations of the distance the stone travels. Sweeping techniques and the athlete's fitness can provide the crucial difference between winning and losing a game of curling at both club and Olympic levels. Despite its importance, sweeping methods and equipment have developed over centuries of curling in a qualitative and anecdotal manner.

A *sweep ergometer* was developed to quantify the brush head velocities and forces achieved by Olympic level curlers (Buckingham, Marmo and Blackford 2006). Initially, the sweep ergometer was developed to monitor the fitness of athletes. However, results from the sweep ergometer also provide us with information about the dynamics of the sliding interface between the nylon brush head and the ice. A three-dimensional thermo-mechanical numerical model has been developed based on these results. The model determines the amount of heat generated by curlers and can be used to determine the optimal style of sweeping.

2 Ice Friction and Curling

In curling two teams of four players alternatively slide 19kg granite stones across 28m of ice to a target area known as the *house*. Teams score points by having the

stone(s) closest to the centre of the house. Once a stone has been released players sweep in front of the stone to modify its trajectory.

Ice friction is central to the sport. Friction on ice depends on a number of parameters including the velocity, thermal properties and surface roughness of the sliding object and on the morphology and temperature of the ice (Akkok, Ettles, and Calabrese 1987). At ice rink temperatures ($-5\text{ }^{\circ}\text{C}$) and over almost all the velocity range experienced in curling frictional heating is sufficiently high to melt the ice surface and provide a lubricating film of liquid water (Bowden and Hughes 1939; Bowden and Tabor 1950; Evans, Nye and Cheeseman 1976). Lubricated sliding is therefore the dominant friction mechanism in curling. For a given load, the frictional heating and the thickness of the fluid film increase with velocity, resulting in a non-linear reduction of friction with velocity ($\mu \propto v^{-1/2}$) (Evans et al. 1950, Stiffler 1984). It is this inverse relationship that is responsible for the curved trajectory of curling stones (Marmo and Blackford 2004).

Friction on ice is strongly dependent on temperature. As ice approaches its melting point less thermal energy is required to melt its surface. With higher temperature more lubricating melt is produced and μ decreases. Friction increases with the sum surface roughness of the counter-facing surfaces (Hutchison 1992).

Sweeping reduces μ by polishing the ice and raising its temperature. Polishing the ice of relatively smooth Olympic standard curling ice has a negligible effect on the sum roughness of the counter-facing surfaces. Raising the temperature of the ice by frictional heating via sweeping has the greatest effect on μ and is the focus of the following study.

3 Sweeping dynamics

A curling brush was equipped with a series of strain gauges and a tri-axial accelerometer to produce a sweep ergometer that measures the forces and velocity applied by curlers (Buckingham et al. 2006). A typical sweeping profile of an Olympic level male curler is shown in Fig. 1. Elite curlers sweep with a frequency $\sim 4.5\text{ Hz}$ with peak velocity of $\sim 2.5\text{ ms}^{-1}$ and a peak downward force of $\sim 450\text{ N}$ (Figs 1a & b). The peak velocity achieved by each curler is generally close to the centre of their stroke (Fig. 1c). The peak downward force does not coincide with the peak velocity (Fig. 1a & b), but occurs at the point in the stroke where the brush head is closest to the player's feet (Fig. 1d). When the brush head is closest to the player the horizontal moment arm from the curler's centre of mass is reduced to a minimum, increasing the vertical force exerted on the brush head.

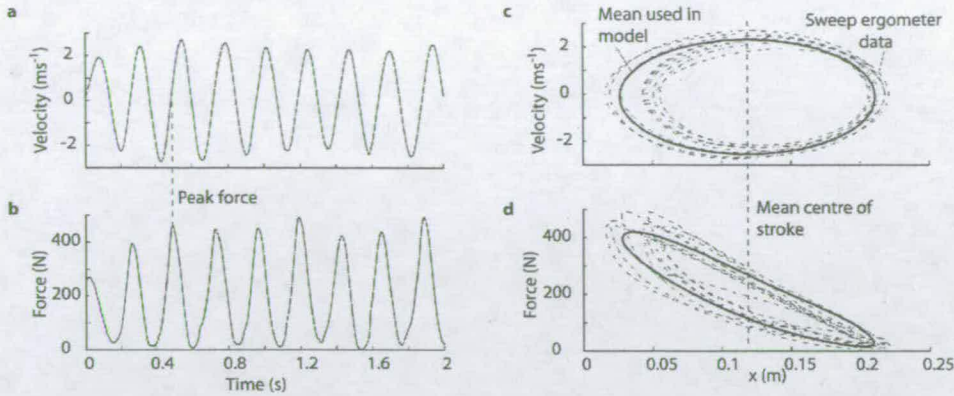


Figure 2. Velocity and force recorded from an Olympic level male curler with the sweep ergometer. a) Horizontal velocity-time history. b) Vertical force-time history. Peak velocity and force do not coincide. c) Variation of velocity with position for a curler who's centre of mass is close to the origin. d) Variation of vertical force with position. Solid line shows the mean used in the numerical model (see Fig. 4).

4 Thermal Model of Sweeping

A three-dimensional thermal model has been developed based on recorded sweeping dynamics. The model is used to determine which sweeping styles and patterns produce the greatest temperature increase in the surface temperature of ice. The model determines the heat produced by rubbing at the interface between the brush head and the ice and solves thermal conduction equations to determine how the ice temperature varies both temporally and spatially.

The model employs two 3-dimensional cubic meshes that are configured to represent the brush head and ice. The ice surface lies in the x - y plane (at $z=0$) of a right-hand Cartesian co-ordinate system where y is parallel to the sliding direction of the curling stone and z is vertical. The mesh representing the brush has its base at $z=0$ and can have any position and orientation in the x - y plane so long as it lies within the outer boundary of the ice mesh. In the x and y directions the mesh elements have equal side lengths $\Delta x = \Delta y = 0.1$ mm. Most heat flow occurs in the z -direction so elements have shorter side lengths in this direction ($\Delta z = 0.01$ mm). The mesh representing the brush is configured to represent the brush head of the popular *Performance Curling Brush*, which has side lengths of 0.22 m and 0.07 m. Elements in the ice and brush meshes are assigned the appropriate physical and thermal properties (see Table 1). The ice and brush are assumed to initially be in thermal equilibrium at -5°C and a numerical time step of $\Delta t = 0.001$ s was used. The frictional heat Q generated by rubbing is equivalent to the work done over a finite time Δt :

$$Q = Fv\Delta t \quad (1)$$

		Ice	Nylon
Thermal Conductivity	k (m kgs ⁻³ K ⁻¹)	2.2	0.35
Density	ρ (kgm ⁻³)	927	900
Specific Heat	c (J kg ⁻¹ K ⁻¹)	2090	2000
Thermal Diffusivity	κ (m ² s ⁻¹)	1.14x10 ⁻⁶	1.95x10 ⁻⁷

Table 1. Thermal and physical properties used in the numerical model.

where v is the sliding velocity and F is friction. This is discretised by re-writing Eq.1 as the heat per surface area of each mesh element, which allows the incorporation of μ and the load per unit area σ :

$$\frac{Q}{\Delta x \Delta y} = \mu \sigma v \Delta t \quad (2)$$

The coefficient of friction is dependent upon the velocity of the slider. Based on a least squares fit of velocity and force data from the sweep ergometer $\mu = 0.13 + 0.01v^{-0.5}$. Both the ice and nylon absorb heat and increase in temperature. Heat is partitioned between each material based on their relative thermal conductivity k to maintain thermal equilibrium. The model determines which elements in the ice surface are in contact with elements in the surface of the nylon brush head and their temperature increased according to:

$$\Delta T = \frac{Q}{c \rho \Delta x \Delta y \Delta z} \quad (3)$$

where c and ρ are the specific heat and density of the relevant material. Heat then conducts through each material according to the 3-dimension thermal conduction equation:

$$\frac{dT}{dt} = \kappa \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad (4)$$

where κ is the thermal conductance of the relevant material. Heat conduction also occurs across the sliding interface. For simplicity it is assumed that the counter-facing surfaces are in perfect thermal contact, no thermal energy is lost to the surrounding air and energy lost to overcome the latent heat of fusion is negligible.

5 Thermal Footprint from Sweeping

At each numerical time step the velocity and vertical forces recorded with the sweep ergometer and substituted into Eq. 2, the heat of friction calculated and allowed to conduct through the system (Eqs. 3 & 4). The model produces avi format (audio video interleave) movies showing the thermal footprint (Fig. 2) left by sweeping, which can be shown to players to augment their training program.

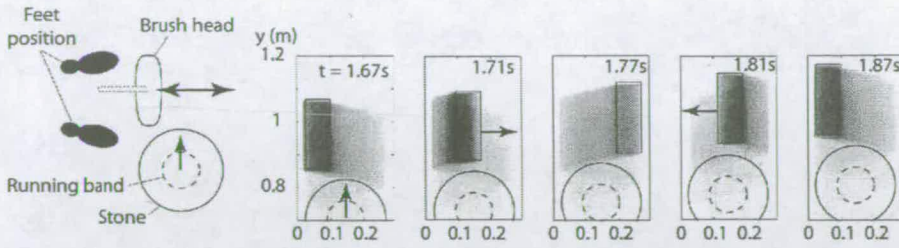
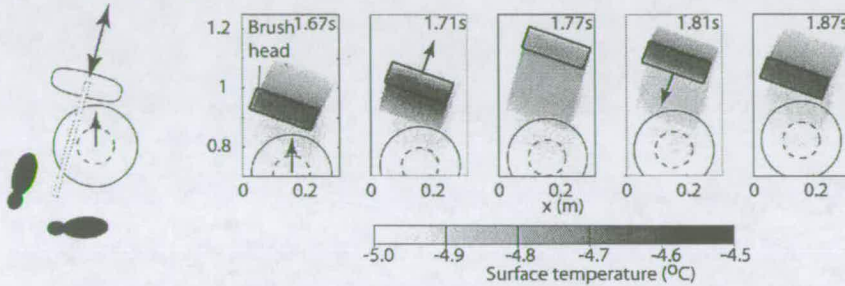
a Conventional low attack angle style

b High attack angle style


Figure 3. Thermal footprint produced by two popular sweeping styles with schematic representation feet and brush position. a) A conventional low attack angle with frames showing modeled ice surface temperature for once complete sweeping cycle. b) A high attack angle style of sweeping. Each successive stroke overlaps the previous producing elevated ice surface temperatures.

The model can also be used to determine the optimal pattern for sweeping the ice. Figure 2 shows the effect of sweeping using two popular styles. To satisfactorily compare sweeping patterns the force and velocity history needs to be more consistent than that of an actual player so a velocity-force history based on mean sweep ergometer results was used (Fig. 1c & d). Conventionally, curlers sweep across the path of the approaching curling stone with a *low attack angle* with respect to the x-axis (Fig. 2a). This style of sweeping leaves a sinusoidal thermal footprint as the curler brushes back and forth in front of the while progressively moving along the ice in front of the sliding stone (y-direction). When curlers use a conventional style the asymmetry in downward force (Fig. 1d) results in higher surface temperatures on the side of the stone that the curler sweeps from. The greatest heat is generated as the player begins to sweep away from himself (Fig 1a, frame 2). Highest temperatures occur where successive strokes overlap each other, where temperature increases of 0.5°C are produced.

A *high attack angle* style is a popular variation of the conventional style (Fig. 2b). A significant advantage of this high angle style is that brush tends to sweep over the same piece of ice several times adding heat each time to produce surface temperatures $\sim 0.2^{\circ}\text{C}$ higher than for an equivalent conventional sweeping style. Again the

maximum heat generation occurs closest to the players feet, which lies in a band directly in front of the stone. The thermal footprint is therefore less asymmetric than a conventional sweeping style.

6 Conclusion

A method of analysing the effects of sweeping in the sport of curling has been developed by integrating quantitative force and velocity measurements made with a sweep ergometer with numerical modeling of heat generation and conduction through both the ice and brush head. The model allows coaching staff to show curlers what effect their sweeping had on the ice. Different sweeping styles can be compared and an optimal style chosen. The advantage of using a high attack angle style over a conventional style has been demonstrated to be due to the over-lapping of successive strokes.

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Frictional heat generated by sweeping in curling and its effect on ice friction

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Abstract: In the sport of curling, players sweep the ice in the front of curling stones to increase the distance that the projectiles slide. Their vigorous sweeping raises the surface temperature of the ice, thereby reducing its coefficient of friction. The change in ice temperature is dependent on the velocity that curlers sweep the ice, the downward force they apply, and the pattern that is swept. The forces and velocities applied by the Olympic level curlers were recorded with an instrumented brush. Laboratory-based rubbing experiments were conducted to determine the temperature rise in ice from sweeping. A numerical model was developed on the basis of the recorded sweeping profiles and laboratory-based rubbing experiments. The model was used to compare the thermal effects of two popular sweeping styles and shows that a conventional low attack angle style is the most efficient.

Keywords: thermomechanical modelling, curling, sports engineering, frictional heating, equipment design

1 INTRODUCTION

The distance and trajectory that stones slide over ice in the Olympic sport of curling are modified by athletes who sweep vigorously in front of their stones. The act of sweeping raises the surface temperature of the ice, which reduces its coefficient of friction, resulting in metre-scale variations in the distances the stone travels. Curling is unique among target-based sports to allow 'in-flight' correction of the projectile's trajectory. The ability to significantly modify a stone's path combined with the skill to correctly judge how best to make such a correction is the key component in the sport [1].

The change in temperature and related variation in the coefficient of friction of ice [2, 3] are dependent on the velocity that curlers sweep, the downward force they apply, and the pattern that is swept. Sweeping is a highly physical component of the sport. The effectiveness of the curler's sweeping

action tends to deteriorate over the course of a match as players become fatigued, leading to a reduction in the frequency of their stroke rate [4]. It is therefore essential that the most efficient methods for sweeping ice be identified.

A three-dimensional thermomechanical numerical model has been developed to identify the most efficient sweeping style. The forces and velocities applied by an Olympic level male curler were measured using an instrumented brush, known as a sweep ergometer [4], to provide the numerical model with realistic brush head dynamics. A laboratory-based rubbing apparatus was designed and built to measure the thermal change in ice from sweeping and results were used to calibrate the numerical model. The model is used to compare the thermal response in ice of two commonly used sweeping styles and their effects on the trajectory of curling stones.

2 ICE FRICTION AND CURLING

In curling, two teams of four players alternatively slide 19 kg granite stones across 28 m of ice to a

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target area known as the house. The ice is not flat but covered by fine droplets of water that freeze to form millimetre scale protrusions known as pebbles. Teams score points by having the stone(s) closest to the centre of the house, once both teams have delivered all eight of the stones. Once a stone has been released, players are allowed to sweep in front of the stone to modify its trajectory. It is a sport that combines skill, strength, and a very high level of strategy.

Ice friction is the central process in the sport of curling. Ice is commonly regarded as an extremely slippery material because it has a coefficient of friction of an order of magnitude lower than other crystalline solids. Friction on ice depends on a number of parameters including the velocity, thermal properties, and surface roughness of the sliding object and on the morphology and temperature of the ice.

The mechanisms that operate when a material slides across ice are complex. Several interdependent mechanisms have been identified, although different mechanisms tend to dominate under different conditions. At velocities greater than ~ 0.01 m/s and temperatures above -10 °C, frictional heating is sufficiently high to melt the ice surface and provides a lubricating film of liquid water [2, 5–7]. At velocities less than ~ 0.01 m/s, frictional heating is not sufficiently high to lubricate the ice–slider interface and frictional sliding proceeds via the deformation of asperities and surface fractures [8–11]. Thus at low sliding velocity, the coefficient of friction is controlled by the creep rate of ice [8], adhesion by sintering leading to asperity growth [9, 12] or a combination of both processes [13].

Lubricated sliding due to frictional heating is the dominant friction mechanism for most of the velocity and temperature ranges in curling and other winter sports involving sliding on ice or snow. The thickness and behaviour of the fluid films that form at the sliding interface control the friction of curling stones on ice. For a given load, the frictional heating and the thickness of the fluid film increase with velocity, resulting in a non-linear reduction of friction with velocity ($\mu \propto v^{-1/2}$) [2, 14]. It is this inverse and non-linear relationship that is responsible for the curved trajectory of curling stones [1, 15, 16].

Friction on ice is strongly dependent on temperature. As the bulk temperature of ice approaches its melting point, less thermal energy is required to melt its surface. Thus, for a given load and velocity, more lubricating melt is produced at higher bulk temperature T . Given the temperature of the film is constantly at the melting point of ice (0 °C) [2], the viscosity of the water film is also constant so that μ varies inversely with T . The presence and the thickness of the fluid film are also dependent on

the thermal properties of the slider. As the thermal diffusivity of the slider increases, more frictional heat is transported away from the sliding interface and is not available for ice melting, so the thickness of the fluid film is reduced and friction increased [3]. The thermal history of both the slider and the ice is important. The longer that a sliding event occurs the more heat is accumulated by the system. In the case of sweeping on ice, the thermal history can be complex and strongly affect the coefficient of friction.

Friction is dependent on the surface roughness of both the ice and the slider. A proportion of the lubricating fluid penetrates into the 'valleys' between surface asperities, thereby reducing the effective thickness of the fluid film. As the sum surface roughness of the ice and its counter-facing surface increases, the effective thickness of the fluid film reduces and μ increases. The presence and the thickness of the fluid film are also dependent on the thermal properties of the slider. As the thermal diffusivity of the slider increases, more frictional heat is transported away from the sliding interface and is not available for ice melting, so the thickness of the fluid film is reduced and friction increases [3].

When curlers sweep in front of the sliding curling stones, they reduce the coefficient of friction for granite sliding on ice so that the stone decelerates less rapidly and can slide several metres further. Sweeping reduces μ by polishing the ice and raising its temperature. The running surfaces on the curling stones can be roughened to increase the amount that the stones curl. The surface roughness of the stone's running ($\gg 10$ μm) is several orders of magnitude larger than that of the ice (except in extreme conditions when the ice is covered in frost). The change in the surface roughness of relatively smooth Olympic standard ice by polish is negligible relative to the magnitude of the surface roughness of the counter-facing curling stone. Polishing, therefore, has little effect on μ . Raising the temperature of the ice by frictional heating via sweeping has the greatest effect on μ and is the focus of the following study.

3 MEASURING SWEEPING DYNAMICS

3.1 Monitoring an Olympic curler

A sweep ergometer has been developed to perform the first quantitative analysis of the sweeping dynamics [4]. The sweep ergometer is a curling brush equipped with a series of strain gauges and a tri-axial accelerometer that measures the forces and velocity applied by curlers [4]. A typical sweeping

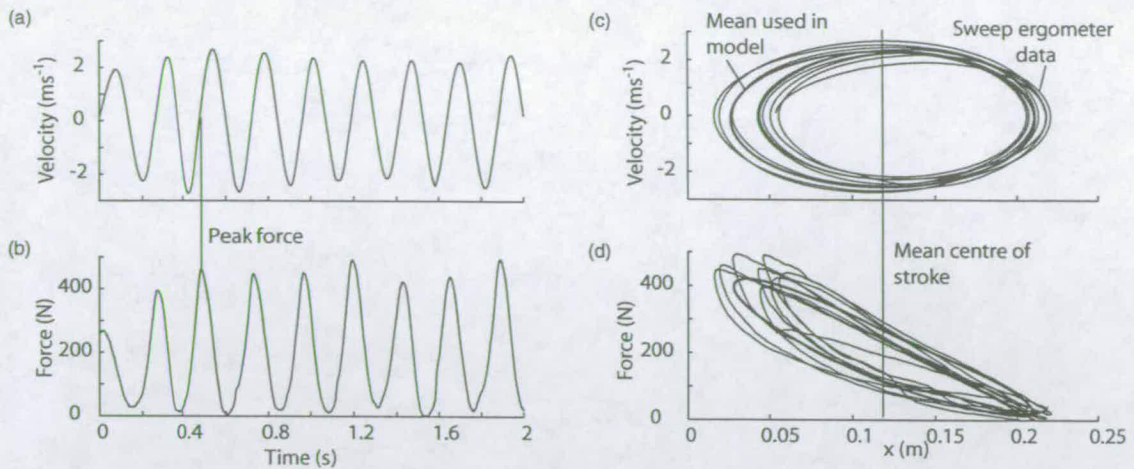


Fig. 1 Velocity and force recorded from an Olympic level male curler with the sweep ergometer. (a) Horizontal velocity–time history and (b) vertical force–time history. Peak velocity and force do not coincide. (c) Variation of velocity with position for a curler whose centre of mass is close to the origin. (d) Variation of vertical force with position. Solid line shows the mean used in the numerical model (Fig. 4)

profile of an Olympic level male curler is shown in Fig. 1. Elite curlers sweep with a frequency of ~ 4.5 Hz with a peak velocity of ~ 2.5 m/s and a peak downward force of ~ 450 N (Figs 1(a) and (b)). Given that the ergometer brush head dimensions are 0.21 m \times 0.08 m, the peak downward pressure is ~ 25 kPa.

The peak velocity achieved by each curler is generally close to the centre of their stroke (Fig. 1(c)). The peak downward force does not coincide with the peak velocity (Figs 1(a) and (b)), but occurs at the point in the stroke where the brush head is closest to the player's feet (Fig. 1(d)). When the brush head is closest to the player, the horizontal moment arm from the curler's centre of mass is reduced to a minimum, increasing the vertical force exerted on the brush head.

3.2 Measuring the temperature change produced by sweeping

A laboratory-based assembly was built to measure the temperature increase in ice due to rubbing with a standard nylon curling brush (Fig. 2) and the resulting data were used to calibrate the numerical model. The rig oscillates a nylon brush head under constant load across flat ice with an array of thermocouples embedded 2 mm below its surface. A motor-driven crank system was used to replicate the sinusoidal velocity pattern employed by curlers (Fig. 1). A 0.37 kW AC induction motor controlled with a PowerFlex700 AC inverter drive was used to power the system via a 3.33:1 gearing ratio. The crank reciprocates the body of the rig along two fixed running bars (Fig. 2) in the horizontal plane with PVC bushes

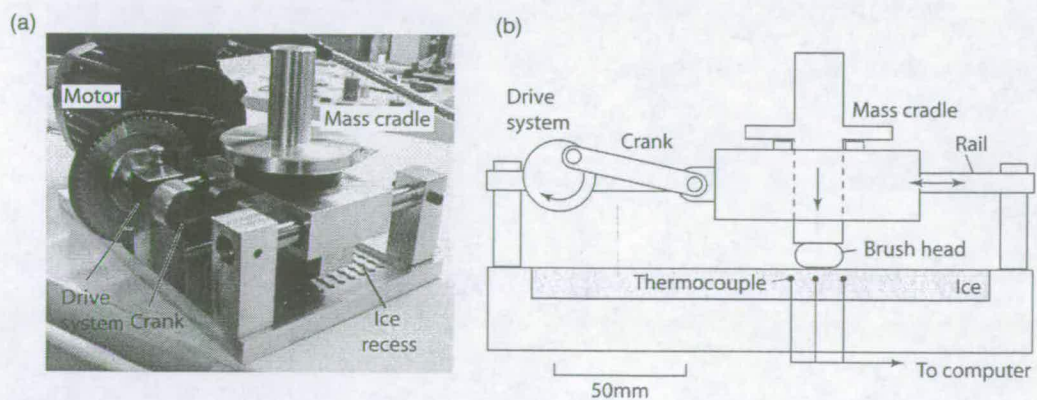


Fig. 2 Laboratory-based sweeping rig. (a) Photograph from an oblique viewpoint. Circular holes in the recess are positions where thermocouples were fixed. (b) Schematic representation of the mechanical system

to ensure smooth running. The vertical load applied by curlers fluctuates as a function of the position in its stroke (Fig. 1(d)). However, a constant load was used on the rig to keep the mechanism as simple as possible. A range of loads were applied by placing known masses on the mass cradle attached to a vertical sliding shaft with the brush head attached to its base (Fig. 2).

Brush heads were reduced to a 1:10 scale so that the force per unit area applied by curlers could be reproduced. The distance swept was likewise scaled from the curlers' average of 0.20 m (Fig. 1(c)) to 20 mm. The reduction in the distance sweep means that less work is done at the sliding interface, so less heat is produced. However, determining the effect of sweeping patterns on surface temperature was a prime goal, so the rig was designed such that the successive strokes overlapped with the same frequency as those in the sport (full-scale). The base of the assembly contained a 120 × 120 mm, 5 mm deep recess containing ice (Fig. 2). At the base of the recess, a series of 5 mm diameter holes were drilled to contain thermocouples (type K). A 50 K Ω sliding potentiometer was used to determine the distance between the ice surface and the position of the thermocouples and to record any change due to the wear of the ice surface. The signals from the thermocouples and potentiometer were then amplified and data logged using an external computer with LabView software at a rate of 100 Hz.

Figure 3 shows the change in the temperature of ice measured 2 mm below the ice surface for different sweeping frequencies and applied pressures. Each experiment began with a 10 s ramping period over which time rotational velocity of the drive system accelerated from 0 until the brush head attained the frequencies shown in Fig. 3. The greatest temperature increase in the ice is produced by a low-pressure–high-velocity (frequency) style (Fig. 3(a)). This suggests that curlers should sacrifice the amount of downward pressure they apply for greater brush head velocity.

4 MODELING THE THERMAL RESPONSE TO SWEEPING

4.1 Thermomechanical model

A three-dimensional thermal model has been developed to determine which sweeping styles and patterns produce the greatest temperature increase in the surface temperature of ice. The model determines the heat produced by rubbing at the interface between the brush head and the ice and solves thermal conduction equations to determine how the ice temperature varies both temporally and spatially.

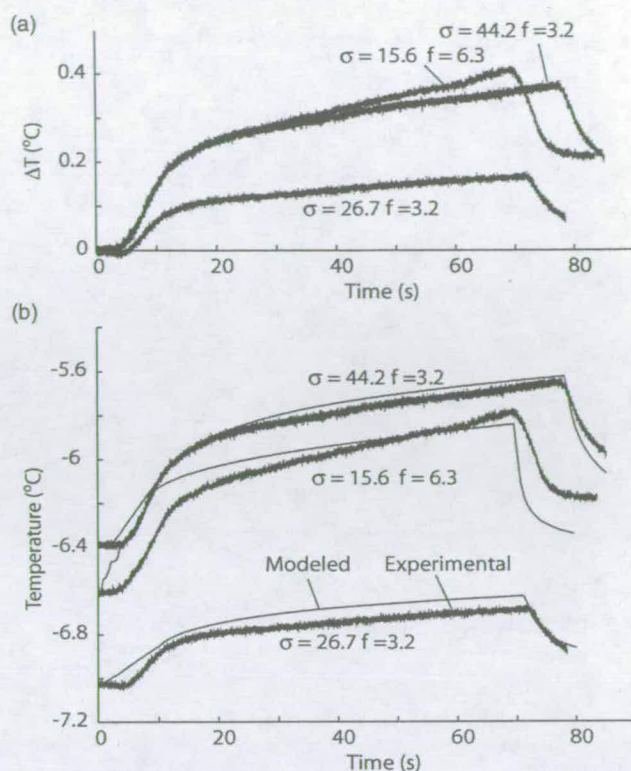


Fig. 3 Thermal profiles measured 2 mm below the surface of the ice, using laboratory-based sweeping rig. (a) Comparison of temperature change for experiments with frequency $f = 3.2$ Hz and load per unit area $\sigma = 44.2$ kPa; $f = 3.2$ Hz, $\sigma = 26.7$ kPa; and $f = 6.3$ Hz, $\sigma = 15.6$ kPa. The high-frequency–low-pressure experiment produced the greatest thermal increase. (b) Comparison of experimental data and results of calibrated model

The model employs two three-dimensional cubic meshes that are configured to represent the brush head and ice. The ice surface lies in the x - y plane (at $z = 0$) of a right-hand Cartesian coordinate system, where y is parallel to the sliding direction of the curling stone and z is vertical. The mesh representing the brush head is based at $z = 0$ and can have any position and orientation in the x - y plane so long as it lies within the outer boundary of the ice mesh. In the x and y directions, the mesh elements have equal side lengths $\Delta x = \Delta y = 0.1$ mm. Most heat flow occurs in the z -direction, so elements have shorter side lengths in this direction ($\Delta z = 0.01$ mm). The mesh representing the brush is configured to represent the brush head of the sweep ergometer, which has side lengths of 0.22 and 0.07 m. Elements in the ice and brush meshes are assigned the appropriate physical and thermal properties (Table 1). The ice and brush are assumed to be initially in thermal equilibrium at -5 °C and a numerical time step of

Table 1 Values of thermal and physical properties used in the numerical model

		Ice	Nylon
Thermal conductivity	k (m kg/s ³ /K ¹)	2.2	0.35
Density	ρ (kg/m ³)	927	900
Specific heat	c (J/kg/K)	2090	2000
Thermal diffusivity	κ (m ² /s)	1.14×10^{-6}	1.95×10^{-7}

$\Delta t = 0.001$ s was used. The frictional heat Q generated by rubbing is equivalent to the work done over a finite time Δt

$$Q = Fv\Delta t \quad (1)$$

where v is the sliding velocity and F is the friction. Equation (1) is discretized by rewriting it as the heat per area of each element in the surface of the mesh, which allows the incorporation of μ and the load per unit area σ

$$\frac{Q}{\Delta x \Delta y} = \mu \sigma v \Delta t \quad (2)$$

Both the ice and the nylon absorb heat and increase in temperature. Heat is partitioned between each material on the basis of their relative thermal conductivity k to maintain thermal equilibrium. The model determines which elements in the ice surface are in contact with elements in the surface of the nylon brush head and their temperature increases according to

$$\Delta T = \frac{Q}{c\rho\Delta x\Delta y\Delta z} \quad (3)$$

where c and ρ are the specific heat and density of the relevant material. Heat then conducts through each material according to the three-dimensional thermal conduction equation

$$\frac{dT}{dt} = \kappa \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad (4)$$

where κ is the thermal conductance of the relevant material. Heat conduction also occurs across the sliding interface. For simplicity, it is assumed that the counter-facing surfaces are in perfect thermal contact, no thermal energy is lost to the surrounding air, and energy lost to overcome the latent heat of fusion is negligible.

The velocity dependence of μ for a non-melting body sliding on ice has the form [2]

$$\mu = a + bv^{-1/2} \quad (5)$$

where a is a dimensionless parameter and b is a parameter with the dimensions m^{1/2}s^{-1/2}. The numerical model was calibrated by modifying these parameters and comparing the results to the change in ice temperature that was measured experimentally using the laboratory-based sweeping rig (Fig. 3). The model used a 10 s ramping period over which time the frequency of the brush head was increased from zero to its eventual running frequency. The ramping period was incorporated so that the model most accurately replicated the experimental methods used to measure the change in temperature. It was found that the model reproduced the experimental results best when a friction law with $a = 0.13$ and $b = 0.5$ m^{1/2}s^{-1/2} was used. The comparison of experimental and model changes in temperature 2 mm below the ice surface for different frequencies and applied pressures are shown in Fig. 3(b).

5 THERMAL EFFECTS OF SWEEPING

5.1 Thermal footprint produced by sweeping in curling

The calibrated numerical model is used to determine the optimal pattern for sweeping the ice. To satisfactorily compare the sweeping patterns, the force-velocity history needs to be more consistent than that of an actual player. A synthetic velocity-force history based on mean sweep ergometer results was used (Figs 1(c) and (d)). At each numerical time step, the synthetic velocity and vertical forces are substituted into equation (2), the heat of friction calculated, and allowed to conduct through the system (equations (3) and (4)). The heat generation and flow calculation combined with those related to the motion of the brush produce a thermal footprint on the ice with each brush stroke. The surface temperature here refers to the mean temperature in the upper 0.1 mm of the ice.

Conventionally, curlers sweep across the path of the approaching curling stone with a low attack angle with respect to the x -axis. This conventional style of sweeping leaves a sinusoidal thermal footprint as the curler brushes back and forth in front of the stone while progressively moving along the ice in front of the sliding stone (y -direction). There is an asymmetry in the downward force with respect to position in each stroke (Fig. 1(b)). When curlers use a conventional style, this asymmetry results in higher surface temperatures on the side of the stone that the curler is sweeping from. Figure 4(a) shows the results for a male player standing on the left side of the curling stone and sweeping with a low attack angle style. The greatest heat is generated as the players begin to sweep away from themselves

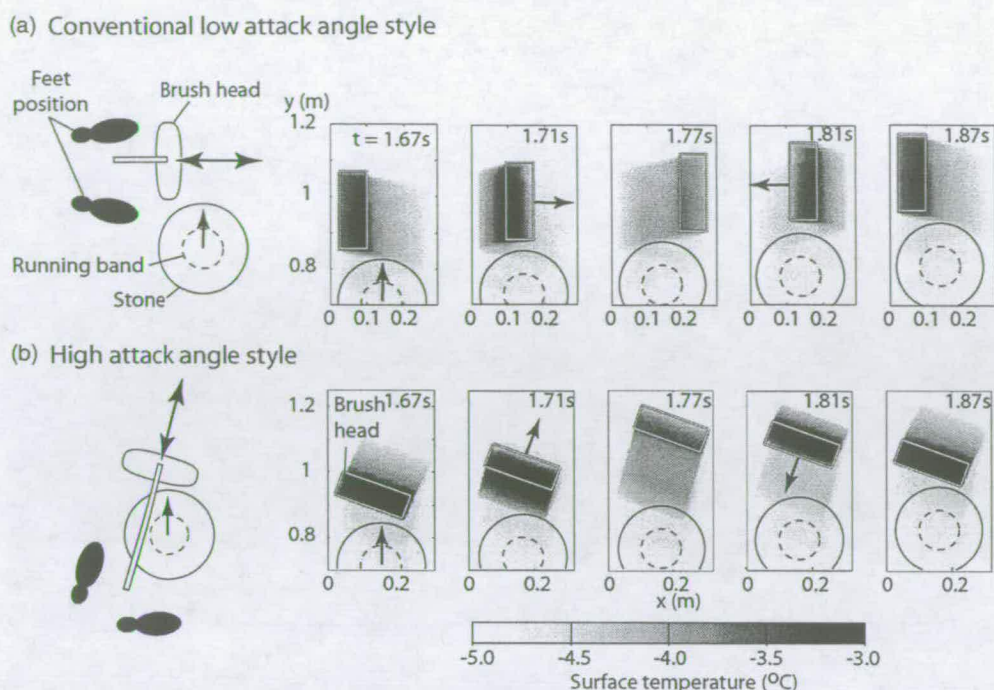


Fig. 4 Thermal footprint produced by two popular sweeping styles with schematic representation of feet and brush position. The surface temperature is taken as the mean temperature in the upper 0.1 mm of the ice. (a) A conventional low attack angle with frames showing modelled ice surface temperature for one complete sweeping cycle and (b) a high attack angle style of sweeping. Each successive stroke overlaps the previous one, thus producing elevated ice surface temperatures

(Fig. 4(a), frame 2). Highest temperatures occur where successive strokes overlap each other, where temperature increases of 2.0 °C are produced.

A popular variation from the conventional sweeping style is when curlers place their feet behind the stone and sweep over it with a high attack angle with respect to the x -axis (Fig. 4(b)). A significant advantage of this style is that the brush tends to sweep over the same piece of ice several times adding heat each time resulting in surface temperatures ~ 0.4 °C higher than for an equivalent force-velocity profile with a conventional sweeping style (Figs 4(b) and 5(a)). The maximum heat generation also occurs closest to the player's feet and lies in a band directly in front of the stone. The thermal footprint is, therefore, less asymmetric than a conventional sweeping style (Fig. 4(b)).

5.2 Efficiency of sweeping pattern

The purpose of sweeping is to raise the temperature of the ice that comes in contact with the running surface of the curling stone. Once sweeping of a section of ice has ceased, it rapidly cools towards the bulk temperature of the ice rink (-5 °C). It is, therefore, vital that the ice surface is heated as close to the approaching stone as possible. Figure 5

shows the surface temperature profile in ice after 3 s sweeping before a stone with a velocity of 0.5 m/s and the relative position of the trailing curling stone. The geometry of the stone is such that the running surface lies 50 mm from the outside of the stone (Fig. 5). There is, therefore, a period of time before the running surface reaches a section of swept ice (i.e. 0.1 s in the case of a stone moving at 0.5 m/s).

The maximum temperature rises occur where successive strokes overlap. Overlapping strokes, when a conventional style is used, tend to form triangular areas with high temperatures close to the approaching stone (at 1.5 m, Fig. 5(a)). High attack angled strokes tend to overlap in the centre of the stroke some distance from the stone (Fig. 5(b)). The ice, therefore, has longer time to cool before the stone arrives and the ice temperature in contact with the stone is ~ 0.2 °C lower than when a conventional style is used.

5.3 Additional distance stones travel due to sweeping

The deceleration of curling stones is dependent on the coefficient of friction between ice and granite, which varies with the velocity of the stone v_s and

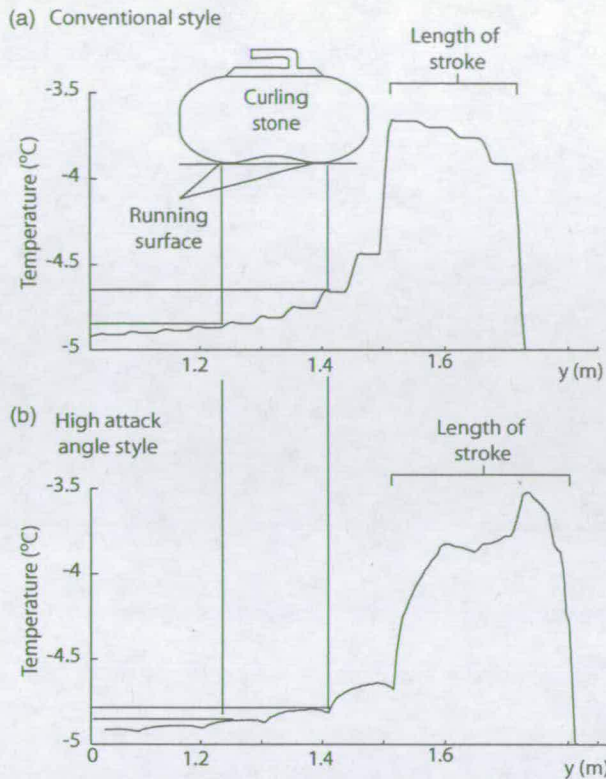


Fig. 5 Surface temperature profile taken parallel to the y -axis through the centre of the stroke after sweeping for 3 s in front of a stone moving at 0.5 m/s. The relative position of the curling stone and its running surface are also shown. (a) A conventional sweeping pattern has its thermal maximum close to the stone. (b) The high attack angle style has a higher thermal maximum, but it occurs well ahead of the stone so that much of the heat has dissipated before the stone arrives

the temperature of the ice according to [14]

$$\mu = C \frac{(T_m - T)}{\sqrt{v_s}}, \quad C = \frac{2k}{\sigma\sqrt{\pi}\kappa l_c} \quad (6)$$

where T_m is the melting point of ice (0°C) and l_c is the length of contact, which for ice pebbles in contact with the curling stone's is on average 11 mm. Equation (6) best replicates the motion of a curling stone on -5°C ice when $C = 0.0134$. Given that the thermal properties of the granite curling stone are $k = 2.1 \text{ W/M/K}$ and $\kappa = 3.29 \times 10^{-6} \text{ m}^2/\text{s}$, the load per unit area must be 2.1 MPa. This is consistent with the sum surface area of approximately 25 pebbles with circular contact areas of 2 mm diameter, supporting the 18.6 kg stone.

Equation (6) was used to estimate the length added to the distance travelled by curling stones due to different sweeping styles (Fig. 6(a)). At each

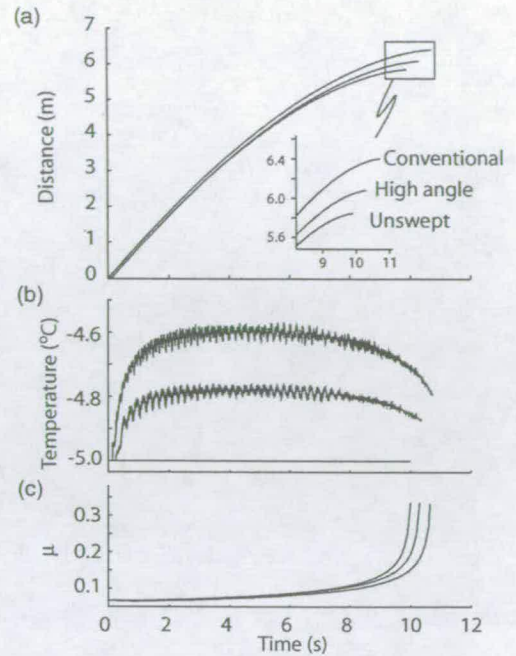


Fig. 6 Comparison of the effects of using different sweeping styles compared with not sweeping at all. (a) The distance a stone travels if sweeping begins when its velocity is 1.0 m/s. A conventional style results in the stone sliding 0.55 m further than an unswept stone, whereas a high attack angle style slides only 0.15 m further. (b) The temperature of the ice that is in contact with the running surface of the curling stone. The conventional style results in ice $\sim 0.2^\circ\text{C}$ hotter than a high attack angle style. (c) The coefficient between ice and the granite curling stone. The higher ice temperature for the conventional style (Fig. 5(b)) reduces μ , thus allowing the stone to slide further

numerical time step, the temperature of the ice in contact with the curling stone's running surface was substituted for T in equation (6) and v_s reduced by $\mu\Delta T$. Commonly, the last third of a stone's journey has its path swept. Figure 6 shows how sweeping, using different sweeping styles, increases the length that a stone slides. A stone with an initial velocity of 1.0 m/s will slide for 5.84 m. The model predicts that sweeping in front of the stone, using a high attack angle style makes the stone slides at 6.08 m and a conventional style makes it slide at 6.40 m.

The use of a conventional sweeping style resulted in the stone sliding 0.32 m further than the use of a high attack angle style. The large overlap of successive strokes when using the high attack angle style produces higher surface ice temperatures than the conventional style (Fig. 5). However, the maximum temperature tends to be located far from the stone

so that much of the heat has dissipated before the arrival of the stone's running surface (Fig. 5). The running surface, therefore, comes in contact with ice that is $\sim 0.2^\circ\text{C}$ warmer when a conventional style is used (Fig. 6(b)), resulting in lower μ between ice and granite (Fig. 6(c)) and in less deceleration.

6 DISCUSSION

6.1 Assumptions and simplifications that affect the results

A potentially important factor not included in the numerical model is the effect of millimetre-scaled pebbles on the curling ice surface. The model assumed that the curling brush-ice interface is in perfect thermal contact. This is most likely not the case, as the valleys between pebbles may not come in contact with the overlying nylon brush head and therefore not be heated directly by frictional heat generated by sliding or by conduction of heat from the warmer brush head. The load per unit area is also likely to be higher, as only the sum area of the tops of the pebbles supports the downward pressure applied by the curler. The heat of friction calculated in equation (2) is therefore likely to be higher and results in localized surface temperature maxima associated with the high points of pebbles.

6.2 Effects on the stone trajectory

The different thermal patterns associated with the different sweeping styles can be exploited to control the lateral deflection of curling stones. The curved trajectory of rotating curling stones increases with the ratio between rotational velocity ω and translational velocity v_s [16]. The asymmetric heating pattern produced by the conventional style can be used to apply a torque on the trailing stone, thereby varying the ratio ω/v_s and the stone's curvature. Consider a counter-clockwise rotating stone with a player sweeping from the left (Fig. 4(a)). The ice temperature is greatest on the left side of the stone so that μ is lower relative to the right side. This produces a clockwise torque that reduces ω/v_s and reduces the curvature of the trajectory.

The high angle sweeping style produces a much less asymmetric thermal pattern and therefore does not effect the ratio ω/v_s . Curlers may view this as an advantage, because the high angle style will produce more consistent trajectories. The lack of asymmetry means that the trajectory will be the same and is not dependent either on who sweeps before the stone or what the players fatigue levels are. Players can also change the curvature of the stone by subtly changing their attack angle.

6.3 Designing better brush heads

The frictional heat produced by rubbing with a curling brush is dependent on the characteristics of the brush head itself. The geometry of the brush head is important, as this controls the surface area in contact with the ice. As the surface area is reduced, the force per unit area is increased as is the amount of frictional heat produced (equation (2)). However, the greatest temperature increase in the ice occurs where successive strokes overlap each other (Fig. 4) and a small brush head would reduce the area of overlapping strokes. Ideally, a large brush head would be used with a dimpled surface to reduce the real area of contact.

The thermal diffusivity of the brush head material is important. The brush head accumulates frictional heat and becomes progressively hotter. A large component of the temperature rise in the ice is due to the conduction of heat from the relatively hot brush into previously unswept ice. As thermal diffusivity of the brush head material is reduced, less heat conducts away from the brush head surface, and the amount of heat that conducts across the interface into the ice increases.

Maximizing the coefficient of friction between the brush head material and ice (equation (5)) can also increase the frictional heat produced by rubbing. Some care must be taken here as one of the few brush design laws, that is strictly in force by the sports-governing bodies, is that the brush head must not damage the ice. If μ is very great, then the ice will wear at a noticeably high rate and the brush design will be barred.

7 CONCLUSION

A numerical model was developed that determines the amount of heat produced by sweeping with a standard curling brush and solves thermal conduction equations to determine the thermal history of the ice related to sweeping with a curling brush. Typical forces and velocities were applied to the model on the basis of measurements recorded with a sweep ergometer. The numerical model was calibrated using laboratory-based experimental results that measured the temperature change 2 mm below the surface of ice being rubbed by a nylon brush head with velocities and pressures akin to those in the sport of curling. Laboratory measurements indicated that sweeping is most effective when downward pressure is sacrificed for greater head speed. The numerical model shows that the greatest increase in the surface temperature of the ice is achieved using a high attack angle style of sweeping, as successive strokes tend to overlap, resulting in

localized maxima in temperature. However, these thermal maxima tend to occur some distance from the trailing curling stone and will have dissipated before the arrival of the stone's running surface. Conversely, a conventional low attack angle style raises the ice temperature less, but the thermal maxima are located closer to the stone's running surface and, therefore, have a greater effect on reducing the coefficient of friction between ice and the granite curling stone.

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APPENDIX

Notation

C	specific heat capacity
f	sweeping frequency
F	friction force
K	thermal conductivity
l_c	length of contact
Q	heat
t	time
T	temperature
T_m	melting point
v	velocity of brush
v_s	velocity of stone
x, y, z	Cartesian coordinates
$\Delta x, \Delta y, \Delta z$	mesh element side lengths
Δt	numerical time step
κ	thermal diffusivity
μ	coefficient of friction
ρ	density
σ	load per unit area
ω	rotational velocity