PART II

Instrumentation technology
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INSTRUMENTATION OF SPORTS EQUIPMENT

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Introduction

There are three types of instrumentation in sport: instrumentation of athletes, equipment and facilities. Each type has its advantages, disadvantages and areas of application. One disadvantage of connecting sensors to athletes, for example, is the trade-off between accuracy and the effect on the athlete’s performance. The tighter sensors are connected to the athletes, the more accurate is the measurement but the more disturbing it is for the athletes, thus affecting their performance. Furthermore, fitting an athlete with multiple sensors can be time consuming and tedious. High-speed movements can even result in the loss of the device through disconnection (Sands 2008). Instruments are independent of the athletes and do not affect them if the sensors are attached to or directly embedded in the equipment.

The first routinely instrumented sports ‘equipment’ was the Formula 1 (F1) racing car, where sensors collected engine data. It is convenient for engine companies to have their products tested by the best pilots in the world in a competitive environment, which enables continuous improvement of their products based on the data collected and analysed. This type of instrumentation has two commercial outcomes. Firstly, the technology originally invented for and tested with F1 racing is eventually used in the general automotive industry and will be found in private cars a few years later. A typical example is variable valve timing technology, which was designed for automatically finding the right moment for the valves to open and close and the right amount of valve travel as a function of engine speed, to improve engine power and vehicle speed. Secondly, broadcasting the data obtained from instrumentation during the race makes the F1 sport more interesting and draws more spectators to their TV screens. This is an important business aspect of instrumented equipment when used during competitions. By developing the business factor further, a multitude of data are now available in F1 racing, such as speed, gears, throttle, brake, g-force, position on the racing course and time difference between competitors. The development of data logging and storage, of wireless data transfer, miniature sensors, transceivers and power supply is inseparably connected to the emerging opportunities of measuring instruments.

This chapter covers the basic principles and purposes of instrumented and ‘smart’ equipment, followed by a wide range of applications.
Principles of instrumentation

The purpose of adding instruments to sports equipment is primarily to quantify performance and to optimise training, and secondly for the entertainment of spectators. The entertainment factor explains why instrumentation is also important for the gaming industry. The instrumentation of equipment encompasses a couple of different issues (Fuss 2008), which will be discussed subsequently.

Design

The design of instrumented equipment is constrained by its size and mass and sometimes even by the material used. The selection of sensors, transducers, power supply, transmitters and microcontrollers depends on whether all required components fit into the equipment and do not alter its mass and moment of inertia. Changing the mechanical properties of the equipment may have an unwanted effect on its performance. Instrumentation attached to the surface of an implement can affect its aerodynamic properties. Instrumentation too heavy and embedded in the wrong place can affect the swing weight of a racquet, as well its vibrations and sweet spots.

Obeying the equipment rules is another important design aspect if the ‘smart’ equipment is intended for use in competitions. This is where the material may become important. For example, a tenpin bowling ball has to be constructed of solid material without voids in its interior and must be of a non-metallic composition. Any metallic instrumentation is thus not applicable, if it is to be embedded within the ball. The same applies to cricket bats, which must be manufactured from wood and no material may be placed on or inserted into the bat’s blade or handle.

Rugged design, a standard in military equipment, is of utmost importance, considering the high shock forces to which sports equipment is sometimes subjected or harsh conditions owing to terrain and weather.

Data storage and handling

Data storage, transfer and basic signal processing is the initial step in preparing the data for analysis. Data can be temporarily stored in a small data logger or flash memory and transferred to the computer via USB port or via a transmitter wirelessly, or even immediately transferred (in real time) through wireless technology. Real-time data transfer is constrained by the transfer frequency and the distances involved. The data precision and the number of channels affect the amount of bits transferred per time.

Basic signal processing is intended to reduce or eliminate noise and data drift.

Performance indicators

Once the data are ready for analysis, performance indicators have to be identified. Performance indicators or parameters are those parts of the signal(s) which correlate with, and thus reflect and represent, the performance of the athlete. In general, we distinguish between two different kinds of performance indicators or parameters: conventional parameters and advanced parameters.

Conventional parameters are those which are directly related to the performance, such as speed, and which are directly or indirectly measured in competitions. The athlete who releases most muscle energy to the environment (definition of ‘performance’) and who minimises the
loss of non-conservative energy (e.g. friction and aerodynamic drag) will have the highest kinetic energy and thus the shortest winning time. The winning time is just a single parameter but it can decide between gold and silver medals. However, by just taking the winning time, it is difficult to detect where and when an athlete lost precious milliseconds. Providing these data is one of the primary goals of instrumentation, as this information helps the coach and the athlete to identify the cause of submaximal performance and how it can be improved in the future (e.g. by training). By adding instruments to the equipment of transportation sports, such as skis, bikes, bobsleighs, wheelchairs, boats, we obtain a time series of displacement, velocity and/or acceleration and are able to detect when and where, and even why, the athlete did not perform maximally.

Advanced parameters are those which result from the instrumentation itself; that is, these are new parameters which were not measurable before the era of instrumentation and were thus unknown. Each newly detected parameter has to be validated against existing and well-known conventional parameters to prove its applicability and importance. Actively searching for, and finding, new parameters is one of the innovative goals of instrumentation. Owing to the huge amount of data obtained from instrumentation, a multitude of conventional parameters can be assessed, the sum or combination of which may allow the measurement of performance in the best way. A multiple regression analysis relates all performance predictor variables to the criterion variable (e.g. winning time, jump height or maximal score) commonly used as the judging criterion in competitions. Yet handling a multitude of conventional parameters (predictor variables) may be too complicated to understand and are thus impractical for training, such that the search for a new, advanced parameter is appropriate. This represents the performance and correlates highly with and thereby replaces, a number of conventional parameters.

The identification of conventional and new, advanced parameters requires sophisticated signal processing and the development and application of new processing techniques and routines. A new technique, for example, is the analysis of the fractal dimension(s) of a signal. Biological signals are highly complex, chaotic and self-affine and fractal-dimension signal processing has been applied to electroencephalograph and electrocardiograph signals for clinical purposes. Signal processing with fractal dimension is a new field in sports engineering (Fuss and Nieg 2008a, 2008b; Fuss and Kulish 2012) with promising results, as described in Chapter 4.

**Translating parameters for users**

After the performance parameters, conventional or advanced, have been identified, they need to be visualised graphically and translated to a ‘language’ which can be easily understood by athletes, coaches and even spectators. For real-time monitoring, complicated graphs take too long to retrieve and understand the necessary information, such that effective use of, for example, colour-coded graphical imaging allows quick decision making, in the style of at-a-glance diagnostics. Software-based effective visualisation of performance parameters is thus of paramount importance. Collaboration with athletes and coaches allows the tailoring of the software for their needs.

**Smart equipment**

The term ‘smart equipment’ refers to scenarios where the instrumented equipment ‘knows more about the athletes than they themselves do’ and provides invaluable extra information for the purpose of quantification of performance and optimisation of training. The real smartness of equipment, however, is providing information at a level where the equipment replaces a...
sensory organ that is not simply missing but in fact never existed, and feeds the measured and processed signal back to the athlete. This biofeedback method enables the athlete to ‘see, hear or feel’ his or her own performance. If the signal is processed and analysed either inside the equipment or by an external microprocessor unit worn by the athlete, the signal can be translated in a visual, auditory or tactile language, which is easily understood by the athlete. For example, force, speed or sideward displacement (slippage) can be volume or pitch coded and fed back to athletes via earphones, such that they can ‘hear’ their own performance and react immediately by adjusting or improving their performance level. This type of advanced training is a simple reflex loop, augmented by an additional artificial sensory organ and an artificial ‘part of the brain’. Biofeedback training leads to improvement of performance faster than conventional training and has higher success rates. Feedback signals can be neutral, rewarding (encouraging high performance) or punishing (avoiding decrease in performance).

Commercial product design

Last but not least, instrumented equipment involves commercial product design, which is the driving business factor. A further business perspective is the use of selected data during live broadcast of sports events and competitions, which can be sent, after processing and visualising, to TV screens, stadium screens and even mobile phones.

Instrumented equipment can be used for competitions and for training. The design for these two purposes may be different, as the equipment rules of different sports disciplines do not apply to training scenarios. Some kinds of instrumented equipment can only be used for training, as the rules indirectly forbid any instrumentation, as mentioned above.

The beneficiaries of instrumented equipment are athletes, coaches, spectators, sports engineers and scientists (Fuss 2008; Figure 3.1).

These stakeholders profit from the data in different ways:

- the athletes, mainly from training (e.g. improving training consistency or optimising training with biofeedback methods) but also from competition; (e.g. from post-match analyses);
- the coaches, from both training and competitions, allowing them carrying out advanced performance analysis to be used for decision making (e.g. for player selection and team building);
- the spectators, from the level of information and entertainment, mainly during competitions;
- the sports engineers, for research and development, testing and optimisation of equipment;
- the sports scientists, for research and statistical purposes.

![Figure 3.1](image-url) Application of instrumented equipment in training and competition

*Source:* from Fuss 2008; © Routledge 2008, reproduced with kind permission
The three cornerstones of instrumented equipment are (Fuss 2008; Figure 3.2):

- the sports factor, by using smart equipment for quantification of performance, optimisation of training, consistency and high-performance training with biofeedback methods, selection of team members and prevention of injuries;
- the business factor, by using the processed and visualised data for spectator information during live broadcasts by making additional use of the rapidly developing market of mobile digital media;
- the engineering factor, by creating an advantage through innovation, optimisation of equipment design, customisation of equipment and having equipment tested by élite athletes.

![Figure 3.2 Three angles of instrumented equipment](source: from Fuss 2008; © 2008 Routledge, reproduced with kind permission)

**Sensor selection and application**

Sensor selection depends on the physical quantities to be measured, usually as a time series. This section describes the most common quantities important for sports and provides some examples of sensors. The physical quantities directly measured with smart equipment are length and angle and their time derivatives, velocity and acceleration (linear and angular), direction of movement, force, torque and pressure. Further quantities are calculated from the signal measured, such as the frequency of vibrations (from acceleration or force), the frequency of cycled movements (from velocity, force, or torque), energy (from acceleration, velocity, force, displacement) and power (from velocity, force and energy).
**Length and angle and their time derivatives**

Length and angle and their time derivatives are either linear or angular quantities and they can be measured directly and indirectly.

**Amount of linear displacement or deflection**

Direct measurement:

- Long and almost infinite distances are measured highly accurately with optical navigation technology (ONT) at a resolution of approximately 0.05 mm. ONT is the same technology used in optical computer mice and is successfully applied in skiing. The Global Positioning System (GPS) is far less accurate, with the resolution of a differential GPS in the centimetre range and conventional GPS in the metre range. For long distances, only the relative resolution is of importance, which makes GPS the ideal tracking system.
- Short displacements in the centimetre range can be measured with potentiometers whose change in electrical resistance corresponds to the distance travelled.
- Small displacements in the millimetre and micrometre range are measured with strain gauges or interferometers. Strain gauges are based on conductive materials which change their electrical resistance with the strain of the material. In metal strain gauges, the material is arranged in a zigzag pattern of a number \( n \) of long parallel lines (thin wires or metal sputtered on a flexible backing) such that any amount of strain \( A \) in the direction of the orientation of the parallel lines results in an overall larger strain \( B \) over the effective length of the metal lines, where \( B = nA \). Other types of strain gauges are silicon strain gauges, produced with microelectromechanical systems (MEMS) technology and polymer strain gauges.

Indirect measurement:

- Linear displacement can be converted to angular displacement (e.g. via wheels); the angle is measured and the angular data converted back to the linear quantity.
- If the linear velocity is known, the displacement is calculated from the time integral of the velocity data.

**Amount of angular displacement or deflection**

Direct measurement:

- Large angular movements (more than one revolution) are measured with optical encoders (which count the revolutions or fractions thereof) or magnetic sensors (bike and wheelchair tachymeters; the speed results from the number of revolutions per time). For small angles, inclinometers and electrogoniometers (strain-gauged EGM) are in use.

**Direction of linear displacement and movement**

The direction of the linear displacement vector is measured with magnetometers relatively to the earth’s magnetic field or with GPS, from the longitude and latitude data.
Direction of angular displacement and rotation

The sense of rotation results from the sign of the angular velocity and is thus obtained from these sensors (explained below). EGMs, strain-gauged on both sides, also deliver the sense of rotation, as the strain gauges are alternatively stretched or shortened, depending on the direction of rotation.

Linear velocity

Direct measurement:

- Linear velocity could be directly measured with radar guns embedded in implements or from the Doppler effect of a radio-frequency source located inside the equipment. However, instrumentation of sports facilities, for example with camera systems and radar guns, has proven to be more effective than instrumenting equipment. The Hawk Eye system, with six cameras mounted in the stadium, is a standard measurement system in cricket and tennis matches, delivering speed and flight path.

Indirect measurement:

- from converting linear speed to measurable angular speed;
- from the time derivative of linear displacement data;
- from the time integral of linear accelerometer data.

Angular velocity \( \omega \)

Angular velocity is directly measured:

- with gyroscopes (‘gyros’), which are categorised as mechanical, MEMS and optical gyros (e.g. ring laser gyro and fibre-optic gyro);
- from the radial acceleration \( a_r \) of linear accelerometers and the distance \( (r) \) between the linear accelerometer and the rotation centre \( (a_r = \omega^2 r) \), if known;
- from the back electromotive force (EMF) of electric motors, working passively as generators and driven by the rotation to be measured; back EMF is a voltage signal proportional to the angular speed.

Indirect measurement:

- from the time derivative of angular displacement data;
- from the time integral of angular accelerometer data (tangential acceleration).

Linear and angular acceleration

Linear and angular acceleration are measured directly with linear and angular accelerometers and indirectly from the time derivative of the linear and angular velocity, respectively. The principle of measuring acceleration is based on a proof mass or moment of inertia, mounted on cantilevered beams. The proof mass produces a force or a torque when accelerated (linearly or angularly). Forces and torques in accelerometers are measured with piezoelectric transducers, strain gauge or MEMS (capacitors).
Silicon strain gauges, gyros and accelerometers are increasingly produced from semiconductors (MEMS on a silicon chip), which radically reduces their price, size and mass, and thus makes them conveniently suited for sports applications. A MEMS accelerometer (e.g. ADXL series by Analog Devices, Norwood MA, USA) consists of numerous mobile silicon fingers (Figure 3.3) approximately 2 μm wide and more than 50 μm long, which are attached to a central proof mass. They interdigitate with fixed fingers, attached to the substrate of the chip (Lecklider 2006). The fixed fingers are capacitor plates, electrically connected to form differential capacitors in relation to the central, moveable mass and fingers. Thus, two capacitances are measured: one increases when the moveable mass is deflected in a specific direction, the other decreases for the same direction of motion (Lecklider 2006).

Inertial measurement units (IMU) comprises a three-dimensional (3-D) linear accelerometer, a 3-D gyro and magnetometer (e.g. MTi by Xsens, Enschede, The Netherlands). These units thus provide the linear acceleration in three directions, the angular velocity about three axes and the direction of movement in three directions. The disadvantage of this type of standard IMU is that the displacement cannot be easily determined accurately, as it requires double integration of acceleration data. Integration is affected by signal offset and drift and also depends on the initial conditions. This disadvantage can be easily overcome by combining IMUs with GPS (such as MTi-G by Xsens, Enschede, The Netherlands). The GPS is accurate only over longer distances, owing to its resolution in the metre range, whereas double integration of

Figure 3.3 Scanning electron microscope image of the MEMS structure found on an Analog Devices ADXL202 dual axis iMEMS® accelerometer die

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acceleration can result in a large error over longer distances. Data fusion provides the solution, by correcting GPS data and displacement data, obtained from acceleration, against each other (Brodie et al. 2008). MTi-G (by Xsens, Enschede, The Netherlands) uses an on-board digital signal processing function with an implemented sensor fusion algorithm.

Smart phones, such as the iPhone (Apple Inc., Cupertino, CA, USA) and similar phone-less devices, such as the iPod touch, have integrated 3D accelerometers and 3D magnetometers at their disposal. The iPhone includes GPS and 4G+ (4th generation, introduced in the second half of 2010, and subsequent generations) iPhones and iPod touches are even fitted with 3-D gyros. This makes the 4G+ iPhone a fully functional advanced IMU, which is mobile, easy to use and has an acceptable size, mass and resolution. Thus, iPhones reduce tedious experimental set-ups with several devices to a minimum. They can be directly attached to equipment of transportation sports such as bicycles, wheelchairs, boats, skis. The data are wirelessly transmitted to the computer for further processing. Alternatively, the data can be directly processed and graphically visualised by the iPhone itself through special software ‘apps’ (applications).

**Applied forces, torques and resulting pressure (surface or internal)**

Applied forces, torques and resulting pressure can be measured directly and indirectly. Forces, torques and pressure are applied to the equipment either by:

- the athlete; for example, grip force and pressure between hand (or glove) and handles (golf club, racquets, bats); force applied when kicking a ball (disregarding that soccer boots count in fact as sports equipment) or throwing a ball (cricket, rugby, tenpin bowling); torque applied to human powered vehicles (bikes, wheelchairs); force applied to artificial holds when climbing;
- other sports equipment; for example, the interaction between balls and racquets, bat or clubs; collision between rugby wheelchairs;
- the environment: for example, between ski and snow, skates and ice, helmets and ground (impact forces and force rates), wheels and ground (friction force); sports shoes and surfaces (e.g. turf); fluid-dynamic forces to balls or boats (drag and lift forces).

Forces other than applied forces are obtained from mass, acceleration (inertial forces and gravitational force), angular velocity and turning radius (centrifugal force).

**Applied force**

Direct measurement:

- with piezoelectric transducers, containing piezoelectric crystals for one- or three-dimensional force measurement.

Indirect measurement:

- via displacement sensors such as strain gauges and interferometers; the relationship between displacement and force depends on the stiffness or modulus of the material and is usually obtained through calibration.
- via pressure, obtained with resistive and capacitative sensors with a defined size (area) for 1D force measurement.
**Applied torque**

Torques are measured indirectly by determining the applied force and multiplying it by the shortest distance (moment arm) between the force vector and the rotation axis. Typical examples of torque measurement are torquemeters integrated in bicycle cranks (e.g. SRAM power meters, SRAM LLC, Chicago IL, USA) and the SmartWheel (Out-Front/Three Rivers Holdings LLC, Mesa AZ, USA) for measurement of torques and forces applied to the push-rim of a wheelchair.

**Load cells and force plates**

Six degrees of freedom (df) load cells measure three forces and three moments in the three orthogonal directions. These 6-df transducers are either strain-gauged or comprise minimally three, usually four piezoelectric transducers (force balances, plates and platforms). When connecting two 3-D force transducers with a bridge, we obtain a 2-D (two geometrical dimensions in the directions of $x$ and $y$ forces), 4-df (measuring three forces and one moment about the $y$ axis) force plate. The four equations, based on three force equilibriums and one moment equilibrium, deliver four unknowns, which are the magnitude of the three forces and the $x$ coordinate of the centre of pressure. The centre of pressure is the origin of the 3-D force; that is, the point of application of the force. If the force is applied over an area, then the resulting pressure is not necessarily evenly distributed. The centre of pressure is defined by the intersection of lines, the moment about which is zero. The moment is produced by the force vectors, times the shortest distance between their origin and any line passing through the centre of pressure, which are in equilibrium about this line. The force vectors result from the pressure multiplied by the reference area across which the pressure is averaged. The higher the resolution of pressure measurement (that is, the smaller these reference areas are) the more accurate is the location of the centre of pressure. In force plates, the centre of pressure is calculated directly from the moment equilibrium, independent of the size of the area, over which the force is applied to the transducer. As mentioned above, in 2-D, 4-df force plates, the centre of pressure is defined by an unknown $x$ coordinate (to be calculated from the moment equilibrium) and the known $z$ coordinate, which is the distance between the origin of the force plate and its surface. If the surface is not parallel to the $x$ axis (that is, inclined or even curved) then the $z$ coordinate is a function of the $x$ coordinate and provides one more equation for solving for the unknown $z$ coordinate. There is no $y$ coordinate of the centre of pressure since the force plate is only two dimensional.

In 3-D, 6-df force plates, we obtain three force and three moment equilibriums (that is, six equations) which are solved for three forces, the $x$ and $y$ coordinates of the centre of pressure and the free moment applied perpendicularly to the surface of the force plate.

Piezoelectric sensors contain materials which generate an electric charge once loaded (direct piezoelectric effect). These materials are crystals such as tourmaline and quartz (silicon dioxide), ceramics (lead zirconate titanate) and polymers (polyvinylidene difluoride PVDF). A force applied to these materials deforms the crystal lattice and produces an electrical dipole moment (Bill 2002; Figure 3.4). The longitudinal (Figure 3.4) and shear effects are independent of size and shape of the crystals, whereas the transverse effect depends on their geometrical dimensions. Piezoelectric sensors are required to be temperature stable, hysteresis free, linear (when preloaded) and highly sensitive. This distinguishes them from resistive sensors, which are non-linear and show distinct hysteresis between loading and unloading.
Applied pressure and internal pressure

Pressure is measured indirectly by measuring a force and dividing it by the area over which the force is applied. The area equals the cross-sectional area of the force transducer. Typical pressure transducers are:

- piezoelectric sensors for determining the internal pressure (e.g. cylinder pressure in engines);
- capacitors;
- conductors which measure the change of resistance with pressure; e.g. conductive rubber sensors, such as Inastomer® sensors by Inaba Rubber, Osaka, Japan; conductive electrode sensors, with up to 248 electrodes/100 mm², by Tekscan, Boston MA, USA;
- Fuji Prescale films (for static measurement only).

Tekscan® pressure sensors are available for different purposes and applications, such as insoles for shoes, pressure sensitive gloves and pressure foils, which can be cut to any shape and size for customised applications.

Figure 3.4 Principle of the longitudinal piezoelectric effect (a) unloaded crystal, (b) loaded crystal and method of increasing the charge yield, (c) by connecting several crystal plates mechanically in series and electrically in parallel; $F_x$ = load, $x$ = loading direction, $O$ = oxygen atom, $Q_x$ = charge in $x$ direction, Si = silicon atom, $+$ = positive charge, $-$ = negative charge

Source: reproduced from Bill 2002; © Kistler Instrumente AG, Winterthur, Switzerland, reproduced with kind permission
Pressure sensors can be used for measuring forces, when multiplying the pressure obtained from a specific sensor by its measurement area (integration of pressure over the measurement area). It has to be borne in mind, however, that the force resulting from this principle is just the normal force and that shear or friction forces do not produce any surface pressure and thus cannot be measured with pressure transducers.

**Measurement chains**

The purpose of a measurement chain is to obtain the magnitude of a measurable physical quantity, preferably as a time series and in digital form, relative to a unit of measurement. The measurand (the physical quantity) is converted with signal processing to a measured value; for example, in terms of a digital number. Measurement chains consist of different components which are listed and described subsequently.

1. Sensors convert a non-electrical to an electrical measurand. For example, force measured with piezoelectric materials is converted to an electric charge, with the unit coulomb. Equally, capacitive load cells convert force to capacitance, with the unit farad (coulomb/volt).
2. Transducer units transform the electrical measurand to an electrical signal, which is usually a voltage.
3. Amplifiers improve the signal strength if the voltage signal is too low.
4. Low-pass filters cut off the higher frequencies of white noise.
5. Sample-and-hold circuits sample the voltage signal continuously changing with time and hold the signal value constant for a specified period of time.
6. Analogue-to-digital converters (ADC) transform the input analogue voltage to a digital number, which is proportional to the magnitude of the voltage signal.
7. If the ADC is not, or cannot be, connected to a computer by cable, either:
   (a) a data logger is required, which stores the data temporarily before uploading them to a computer, or
   (b) a wireless transmitter with antenna is required, which produces a radiofrequency signal (e.g. Bluetooth®, ZigBee®).
8. The digital data transmitted wirelessly are picked up by a receiver, which feeds them into a computer.
9. Computer software finally processes the data further through signal processing and visualises them.

In smart phones, steps 1–6 are combined in a single device and the data are both stored and transmitted wirelessly (step 7) or processed internally through smartphone applications (step 9).

**Placement of sensors**

Motion sensors such as IMUs and GPS are placed on the mobile system or link. Special tachometers, such as encoders or electric motors, are connected to the frame and receive their input from the mobile link.

Force and torque transducers are rigidly embedded in the fixed or mobile link. The fixed link refers to any equipment rigidly connected to the ground with the athlete moving with respect to it. For example, the forces applied to parallel bars can be measured with transducers incorporated into the frame of the bars. The mobile link refers to any mobile equipment with
moves with respect to the athlete’s body. For example, the torque applied to bicycle cranks by the cyclist’s legs or to a racquet by the ball, can be determined with transducers embedded in the crank or in the racquet handle. Strain gauges for indirect force and torque measurement are attached to a surface.

Pressure sensors are usually connected to a surface, either rigidly or loosely, as in insoles for sports shoes.

The most suitable placement of force, torque and pressure transducers depends on two factors:

- force should flow through the transducer(s) by 100 percent (that is, force shunts must be avoided) and
- a thorough free-body diagram (FBD) analysis must precede any design considerations, to be sure that all possible forces are accounted for.

The rule of the thumb for equipment-related FBDs is that the equipment, or a part thereof, is ‘cut out’ of the environment, whereby the centre(s) of pressure of the applied force(s) and the transducers are located at the boundary between the environment and the free body. For example, if a transducer is inserted between the throat and the handle of a tennis racquet, then the free body comprises the throat, the hoop and the string face; the ball, impacting the string face, and the handle is considered to be the environment (and so is the athlete’s body). The force measured by the transducer is not identical to the impact force of the ball and this is where the free-body force analysis comes in. As the racquet is accelerated in the direction of the force applied by the ball on impact, the inertial force of the free body is opposite to the applied force and the difference of these two forces is measured by the transducer. Equally, the force measured by the transducer is not identical to that transmitted to the hand of the athlete, as the handle is not free of mass. If the ball hits the centre of percussion on the string face (of a stationary racquet), then the applied and inertial forces of the racquet cancel each other and the shock force at the hand is zero. However, as the free body corresponds to the racquet minus the handle, the inertial force of the free body is smaller than that of the entire racquet. Thus, the transducer still records a force that has the same magnitude but opposite direction as the inertial force of the handle, such that measured force and the inertial force of the handle cancel each other out and the force at the hand is zero. Instrumenting the handle with a pressure-sensitive foil, even with a high resolution, would be comparatively more complicated and, worse, far less accurate. An example taken from the literature illustrates this principle.

Analysing the ground reaction forces (Figure 3.5a) during skiing offers theoretically several possibilities for instrumenting a ski:

1. The entire undersurface of a ski can be covered with pressure-sensitive foil. As mentioned above, pressure can only be converted to normal forces; however, the goal in skiing is to reduce the friction coefficient to a minimum (approximately 0.05), such that the friction force can be neglected.
2. Force transducers can be inserted between the binding and the ski, between binding and boot or embedded in the binding.
3. A pressure mapping insole can be inserted between boot and foot.

Solution 1 is complex, as the pressure foil has to be tightly connected to the ski and should neither delaminate off the ski nor affect the properties of the gliding surface, even when waxed. If the ski is put on the edge, the pressure foil would not be able to measure forces any more.
Solution 2 requires some technical modification of the binding but is able to measure any force applied to the ski, including its centre of pressure.

Solution 3 is easy to apply; pressure-mapping insoles (e.g. F-Scan® by Tekscan) can be cut to any shoe size and shape.

Haid et al. (1993, 1994) used pressure-sensitive insoles for measuring forces applied to the skis during the steering phase in alpine skiing (Haid et al. 1993) and the take-off phase in ski jumping (Haid et al. 1994). The forces, derived from the pressure recorded with insoles, served for quasi-statistically calculating the external knee moment, quadriceps tendon force (patellar ligament), cruciate ligament forces and knee joint forces. At first sight, the application pressure-mapping insoles seems logical, as the friction force under the ski can be neglected. However, the insole is not placed under the ski but, instead, inside the boot, beneath the foot sole or, rather, between socks and boots. A proper FBD analysis reveals the problem associated with insoles.

Firstly, the data obtained from pressure-sensitive insoles allow calculating the position of the centre of pressure but the centre of pressure can only be inside the insole and never outside. The reason for this is that the insole is always subjected to compression and never to tension. To calculate a centre of pressure located outside the insole, one has to remove most parts of the boot but the sole, glue the insole to the boot sole and the socks and foot soles to the insole. Under these circumstances, the insole is almost rigidly sandwiched between foot and the boot reduced to its sole, and thus also subjected to tensile forces. Owing to the natural shape of the boot, this awkward procedure is not necessary and this is where the FBD analysis comes in.

According to the rule of thumb outlined above, the FBD comprises ski, binding and boot in the analysis of Haid et al. (1993, 1994). The ground reaction force is applied to the ski at the boundary between environment and FBD (Figure 3.5b). The sensor (pressure insole), by

![Figure 3.5](image-url)
definition, is located at the boundary between FBD and environment, and thus the athlete is considered the ‘environment’. When analysing all forces acting on the FBD, we realise that some forces acting on the inner side of the boot do not pass through the insole and thus constitute a typical force shunt (Figure 3.5). These forces, for example, are applied in forward and backward direction to the shaft of the boot and upward to the dorsal part of the boot located above the foot. This dorsal part, serving the same purpose as latches and straps in sandals, keeps the shoes or boot to the feet and provides a force couple through compressive forces only. One force points downward on the dorsum of the foot and the other points upward to the heel sole. Without the dorsal part of a shoe or the shaft of a boot, this force couple can only be generated when gluing the foot sole to the shoe sole. As the instrumentation with a pressure-sensitive insole misses out several forces applied to the inner side of the boot, the force calculated from the insole is by no means representative of the force transmitted from the boot to the foot and shank and can thus neither be used for calculating the external moment applied to the knee nor for determining the muscle, ligament and joint forces. This problem could be solved when wearing pressure-sensitive socks, bearing in mind that such wearable sensors do not measure friction forces between boot and foot and that they must be tight fitting and elastic to accommodate the foot’s shape.

This problem can be ideally solved when converting the ski into a 2-D, 4-df upside-down force plate, by instrumenting the binding (above, below or inside) with two force transducers. This transducer arrangement measures the three components of the ground reaction force and its centre of pressure (Figure 3.5c). This type of instrumented binding was, for example, developed by Kiefmann et al. (2006). Once the origin, direction and magnitude of the ground reaction force at the ski are determined, the athlete’s body, or parts thereof, can be included in the FBD and used for further biomechanical analysis.

Summary

This chapter provides an overview of the purpose and opportunities of instrumenting sports equipment. The advancement of sensor technology in terms of miniaturisation and cost effectiveness facilitates the development of instrumented equipment. The critical issues of instrumentation are: maintaining the equipment properties; observing sports equipment rules; selecting, properly placing and making the sensors more rugged; data storage, transfer and basic signal processing; identification and visualisation of performance parameters; and implementation of biofeedback systems.

References


