Chapter 2
Input Periphery

2.1 Human Actuators, Input Modalities

A human operator presents actions to the VR system in various forms, for instance, as positions and movements, forces and torques, speech and sounds as well as physiological quantities (see Fig. 1.10, Table 2.1). The choice of method or device to measure such information depends on the physical properties of the information to be transferred and the range of the signal to be measured (Table 2.2). In the next subchapters we will present different basic principles and technologies how to record positions and movements, forces and torques, and physiological data.

2.2 Position and Movement Recording

2.2.1 Physical Measurement Principles

For many VR applications it is required to measure positions and movements of body segments or objects used by the human operator. Measurement of positions and movements can be based on the physical sensory principles, which are described in the following sections.

2.2.1.1 Resistive Sensors

The change of electrical resistance of the sensor reflects the change of position of the object. Typical resistive sensors are potentiometers, which are variable resistors whose resistances are adjustable via a sliding contact called wiper. In general, the wiper is connected to the object being sensed. When the object changes its position, it will also change the resistance of the potentiometer. The correlating change of the circuit's voltage shows how far the object has moved (Fig. 2.1(a)). Potentiometers are available in both linear and rotary types.

R. Riener, M. Harders, *Virtual Reality in Medicine*,
DOI 10.1007/978-1-4471-4011-5_2,

Table 2.1 Examples of different input modalities

Physiological function	Information transferred	Physical quantities	Measurement device examples
Voice, speech	sound, acoustics, words, commands	sound pressure, frequency	microphone
Muscle activities, segmental kinematics and kinetics	posture and body motion; mechanical load	position, velocity, angle, acceleration; force, moment	joystick, gonio-accelerometer
Physiological functions	cardiovascular state, thoughts, well-being	heart rate, temperature, electrophysiological quantities	thermometer, electromyogram (EMG), electroencephalogram (EEG), pulse oxymeter

Table 2.2 Input signal ranges

Input modality	Signal type	Typical ranges	Source
Voice, speech	sound pressure level	$>$ 100 dB SPL	[15]
	frequency when speaking	80 Hz–9 kHz	[9]
	frequency when singing	50 Hz–4 kHz (fundamental tones)	[9]
Posture and body motion	joint angles	150°–180°	[14]
	joint angular velocities	250°/s	
	movement frequencies	12 Hz	[18]
Mechanical load	finger force	50 N	[16]
	fist force	400 N	[1]
	holding load arm	$>$ 300 N	[10]
	joint torque (knee)	220 Nm	[17]
Physiological signal	electromyogram	2 Hz–10 kHz, 50 µV–10 mV	[8]
	electroencephalogram	0.5–100 Hz 2–100 µV	[6]

2.2.1.2 Capacitive Sensors

In capacitive sensors, the position of the object is determined by the voltage changing with the capacitance of the sensor. In general, a sensor contains two plates which are separated by a dielectric medium such as ceramic or plastic. The capacitance of the sensor changes when the distance d between the two plates, the overlapping surface area A of the plates, or the properties/homogeneity ϵ of the dielectric medium change (Fig. 2.1(b)).

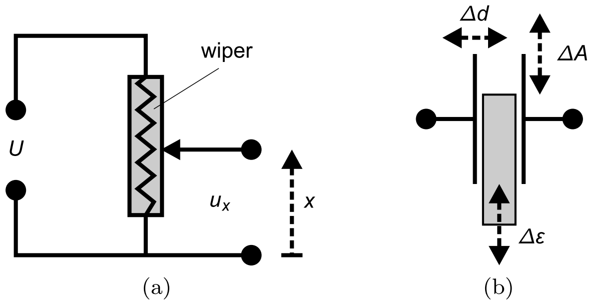


Fig. 2.1 Sensing principles to record positions and movements: (**a**) Resistive, (**b**) Capacitive; $C = \epsilon * A/d$

2.2.1.3 Inductive Sensors

Inductive sensors utilize an electromagnetic field to detect the position of the object. The change of the ferromagnetic core's position with respect to position of the inductive coils induces the voltage change, which yields a mutual inductance of the primary and secondary coils. One example of an inductive sensor is a linear variable differential transformer.

2.2.1.4 Ultrasound and Optical Methods

Running time differences of the sound echo or the Doppler effect can be detected to determine distance or speed, respectively. Alternatively, also light sources or images can be used to detect the position or motion of an object. Examples are cameras or photo-electrical components such as photo diodes, photo transistors, photo resistors or energy producing photo-electrical elements.

2.2.2 Position and Movement Measuring Systems

The position and movement measuring systems can be classified into three categories depending on structure and design. These are desktop systems, body-mounted systems, and contact-free systems.

2.2.2.1 Desktop Systems

Desktop measuring devices are usually placed on tables, boxes or shelves. For example, computer mice and joysticks belong to this kind of category. More complex joystick-type devices exist that allow rendering of several degrees of freedom, for example in spatial (3D) range.

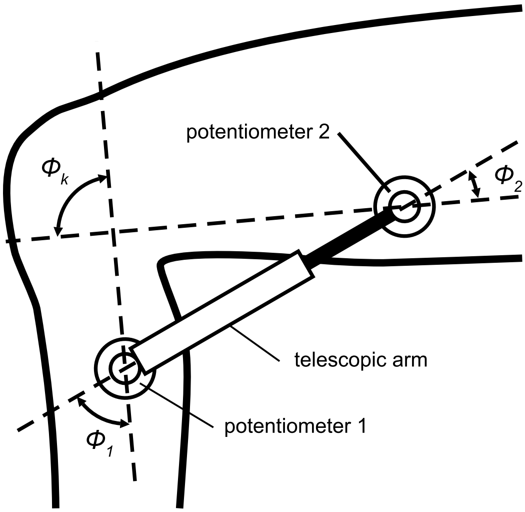


Fig. 2.2 Potentiometer-based goniometer; joint angle ϕ_k can be determined as a geometric functions of the angles ϕ_1 and ϕ_2 measured by the two potentiometers

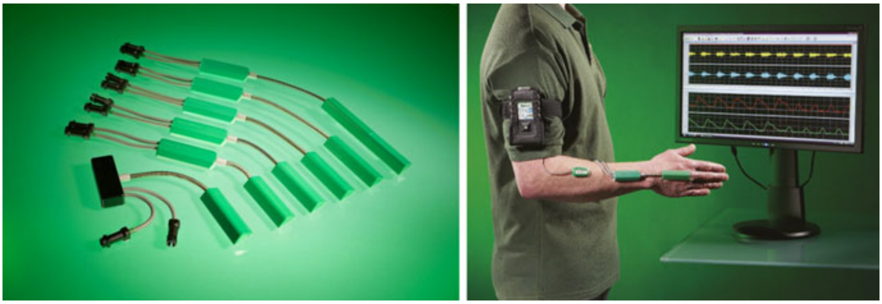
2.2.2.2 Body-Mounted Systems

Body-mounted sensing systems are usually used to measure the posture or movement of the human. The equipment needs to be attached to the body of the subject. Examples are goniometers, gyroscopes, accelerometers and inclinometers in order to measure angles, velocity or acceleration. Inertial sensors, such as accelerometers and gyroscopes, are used to measure motion and orientation. Inertial sensors are widely applied in head-mounted displays to track the angular motion of the user's head.

Goniometers are used to measure joint angles. Many versions are based on resistive measurement principles using potentiometers. For example, goniometers with two potentiometers can be employed to measure the knee joint angles during knee flexion and extension (Fig. 2.2). The two angular potentiometers are attached to the thigh and the lower leg of the subject and connected by a telescopic arm. Also flexible versions of goniometers are available such as the twin axis goniometers from Biometrics Ltd. (Fig. 2.3). A similar flexible goniometer technology, known as *resistive bend sensor*, is integrated in the CyberGlove III (CyberGlove Systems LLC, San Jose, CA, USA) to measure the angles of the finger joints (Fig. 2.4).

ShapeTape™ (Fig. 2.5(a)) and ShapeWrap™ (Fig. 2.5(b)), Measurand Inc., Fredericton, Canada, were developed to measure multiple joint angles with multiple degrees of freedom. Both systems are flexible and work on the basis of a special fiber optics. When the ShapeTape™ is bent or twisted, the frequency and the intensity of the light changes. This allows detection of curvature in short elements, which enables to reconstruct the shape of the tape. From this information one can estimate the body posture and movement of the user.

Gyroscopes are used to measure angular speeds and are often applied in aerospace. Recently, gyroscopes are also integrated in game controllers that allow



(a) (b)

Fig. 2.3 Twin Axis Goniometers; by courtesy of Biometrics Ltd. (www.biometricsltd.com)

Fig. 2.4 CyberGlove III including 18 to 20 sensors; by courtesy of CyberGlove Systems LLC

users playing games by just moving the wireless controller. Conventional gyroscopes are made by a rotating mass. Smaller versions contain a vibrating bar, which is equipped with piezoelectric actuators generating vibrations and piezoelectric sensors measuring gyro effects induced by angular movements.

Accelerometers contain a small mass and measure the inertial force produced on the mass during movements. So called multi-axis accelerometers are designed to detect magnitude of acceleration in different directions. Inclinometers are special kinds of accelerometers that allow the measurement of angles of an object with respect to gravity.

(a) ShapeTape™

(b) ShapeWrap™ III Plus

Fig. 2.5 Multiple joint angle measurement: (**a**) ShapeTape™, (**b**) ShapeWrap™ III Plus; by courtesy of Measurand Inc., Fredericton, New Brunswick, Canada

2.2.2.3 Contact-Free Systems (Remote Systems)

Contact-free systems (remote systems) can capture the position and motion of the body in space without mechanical contacts between the subject and the sensing unit. This type of sensing system is often preferable since it gives a large scope and the users are normally not encumbered by wires and bulky components. Most systems are based on optical, acoustic or magnetic measuring principles.

- **Optical systems** The first optical contact-free system was introduced by Eadweard Muybridge already in the 19th century. The system consisted of two cameras placed orthogonally to each other to capture the motion of subjects from different directions. A grid wall located behind the subject enabled movement quantification. In modern systems, at least two cameras are used to detect 3D positions of optical markers, which are attached to the body of the subject (Fig. 2.6). The markers can be either active (LEDs) or passive indicators (self reflective, color dots). A redundant number of cameras can help to avoid losing the tracking of single markers when the vision is blocked by obstacles or when the markers are getting out of a camera's field of vision. Optical systems are quite sensitive, reaching position accuracy below 1 mm.
- **Acoustic systems** Acoustic or ultrasound systems use a set of microphones to detect the signal from acoustic emitters, which are attached to the body of the subject. The position in space of each emitter is calculated from the time difference that the signal needs for traveling from the emitter to the microphones, whose positions are known. A minimum set of three microphones is required

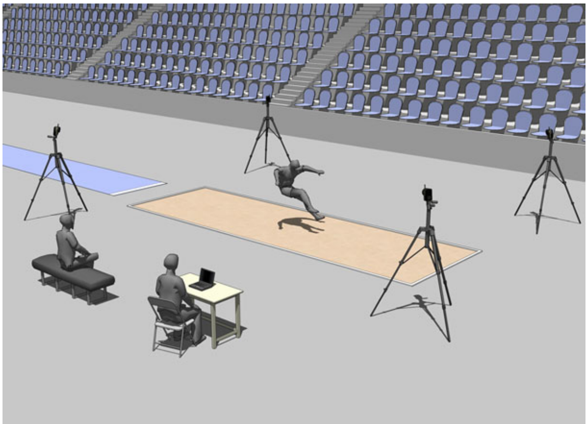


Fig. 2.6 A contact free opto-electronical motion capture system; by courtesy of Qualisys AB, Gothenburg, Sweden

to acquire spatial information of the microphone markers through triangulation. Sound reflections as well as variations in room temperature and humidity usually worsen the tracking accuracy compared to optical systems.

- **Magnetic systems** Magnetic systems consist of markers based on small electrical coils. The markers are attached to the body of the subject and a transmitter placed in the vicinity, which generates a strong magnetic field through the entire workspace. When the markers are moved inside the magnetic field, inductive effects produced in the marker coils allow determining the marker orientation and location. Thus, the system can measure up to six DOF for each marker. The system works even if there are visual obstacles between markers and transmitter. However, ferromagnetic material inside the workspace distorts the magnetic field resulting in measurement errors. Therefore, the accuracy of magnetic systems is in general lower than that of optical or acoustic systems.

2.2.3 Eye-Tracking Systems

Eye-tracking systems are used to detect and record the positions and movements of one or both eyes of the viewer while looking at any real or virtual object, e.g. on a screen. Most popular eye tracking technologies are based on image processing approaches. Other solutions use magnetic coils placed into special contact lenses, or they are based on electrooculographical recordings.

2.2.3.1 Optical Systems

The positions and movements of the eye are tracked by a camera or special optical sensor. Most eye-trackers in this category use the center of the pupil and a corneal reflection to detect eye movement. These optical systems are rather popular because

Fig. 2.7 Head-mounted eye trackers: EyeLink II; by courtesy of SR Research Ltd., Ottawa, Ontario, Canada

they work non-invasively and they are relatively inexpensive. One example of optical eye tracking systems are remote cameras which are, for example, connected to a computer screen. The eye movements are captured and interpreted by image processing techniques. Other examples are eye trackers that are integrated in computer monitors or head-mounted eye tracker systems (Fig. 2.7).

2.2.3.2 Magnetic Systems

A magnetic coil sensor is embedded into a contact lens. The subject is surrounded by a magnetic field. Thus, movements of the eye induce currents in the coil, which allows determining the eye movements and viewing angle.

2.2.3.3 Bioelectrical Systems

The eye positions can also be detected by electrodes attached around the eye measuring the electrical potential produced by the electrical dipole of the eye ball (Fig. 2.8). When the eye moves, a potential is detected between a horizontal and/or a vertical pair of electrodes, producing the signal that is called electrooculogram (EOG). The eye position can be derived from the potential [4].

2.3 Force and Torque Recording

Whenever a user is touching and manipulating objects, forces and torques are interacting between the user and the object. Sensing user interaction forces and torques is important especially for force feedback controllers implemented in haptic devices.

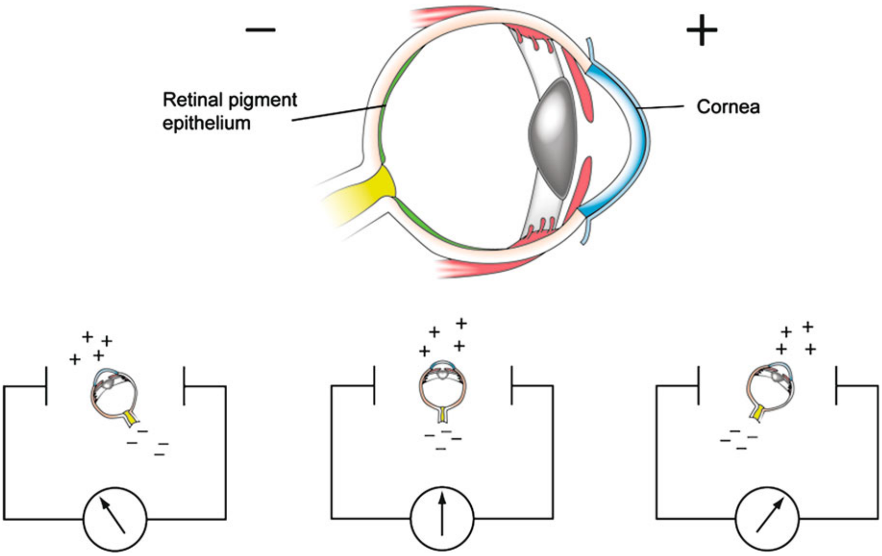


Fig. 2.8 Dipole that can be detected with electrooculogram (EOG) measurement systems; © ADInstruments Pty Ltd. Reproduced with permission

Several physical recording principles to measure these quantities are described in the following sections.

2.3.1 Resistive Methods

Most resistive methods to record forces and torques are based on strain gauges. A strain gauge is an electronic component used for measuring deformation of the object to which the gauge is attached. The resistance of the strain gauge varies in proportion to the deformation of the object caused by mechanical strain. The resistance change can usually be measured using a Wheatstone bridge circuit. A strain gauge contains a long thin fiber arranged in a meander pattern (Fig. 2.9). The strain gauge is usually attached to the surface of the object being sensed. When the object is deformed or subjected to strain in fiber direction, it will cause a change of resistance. Combinations of strain gauges, specially arranged on a mechanical structure, allow measuring force and moment up to six degrees of freedom.

2.3.2 Piezoelectric Methods

Piezoelectric sensors are made of piezoelectric crystals, which deliver an electrical charge when mechanically loaded. The crystal is placed between two conductive

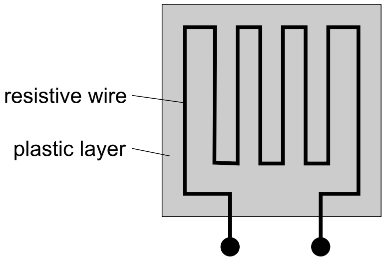


Fig. 2.9 Illustration of a strain gauge

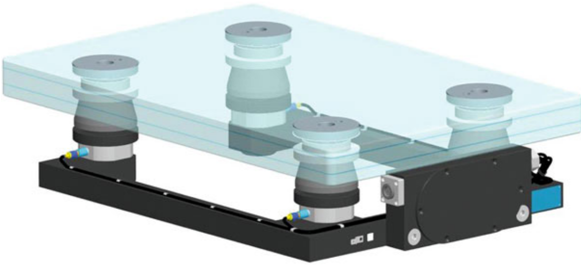


Fig. 2.10 Force plates can measure ground reaction forces and torques (by courtesy of Kistler Holding/Instrumente AG, Switzerland)

plates in order to lead the charge to a high-resistive voltage recorder. The amount of charge is related to the magnitude of force. Layers of three crystal rings of plates allow measuring three orthogonal components of a force. Piezoelectric 3-component force sensors are used in force plates to record ground reaction forces, e.g. in gait analysis (Fig. 2.10).

2.3.3 Optical Systems

Optical systems contain light sources, mirrors, and receivers. When a force is applied, it causes the flexible part of the sensor to move slightly. One can estimate the amount of the forces from the change of light intensity recorded by the internal receivers (Fig. 2.11).

2.3.4 Capacitive Methods

Capacitive pressure sensors use flexible thin conductive diaphragms as plates of a capacitor. Silicone oil or any non-conductive flexible material (e.g. plastic foam) is used as dielectric medium. The diaphragm is exposed to the active pressure on one side and to a reference pressure on the other side. Changes in pressure cause it to deflect, which changes the capacitance, and, thus, the voltage at the capacitor. Instrumented insoles can measure pressure distributions of the foot during stance phase of gait by the means of capacitive methods (Fig. 2.12) [13].

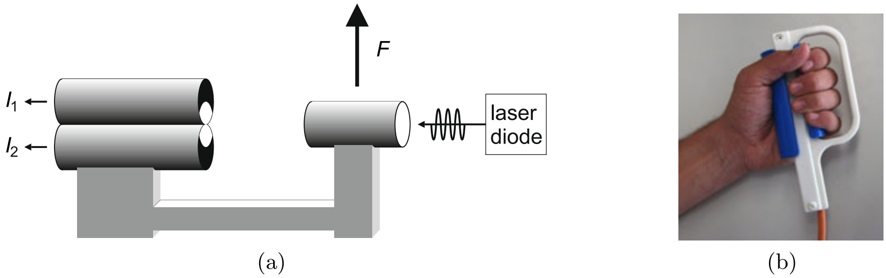
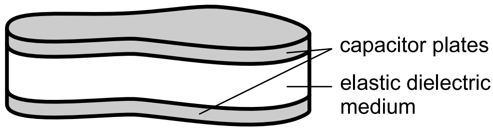


Fig. 2.11 Optical force sensor can be integrated in handgrips of MRI-compatible dynamometers: (**a**) Principle (I = intensity; F = force), (**b**) MRI-compatible dynamometer; ETH Zurich

Fig. 2.12 Schematic diagram of an instrumented insole



2.4 Sound and Speech Recording

There is a large variety of sound and speech recording systems available. They differ from each other in terms of their setup (mounted on a desk, a wall, or the user's head), their connection (with wires or wireless), the number of recording channels (mono, stereo or array of microphones) [3, 7], and the processing technology (e.g., sound detections or speech analysis) [5].

2.5 Physiological Data Recording

Also physiological signals from the human body can be used as input modality for VR systems, for example, to detect if the user of any VR scenarios gets emotionally involved or even stressed. Measurable quantities are, for example, muscle activity, nerve signals, cardiovascular signals, metabolic signals, respiratory variables, body temperature, and skin conductance [2, 12].

2.5.1 Electromyography (EMG)

Electromyography (EMG) is the electrical recording of muscle activity. Muscles are stimulated by signals from nerve cells called motor neurons, which causes muscle contraction. This electrical activity can be detected by electrodes inserted into the muscle or attached to the skin and connected to a recording device. The EMG signals can be used to detect muscle function and activity, for diagnostic purpose or as input signal to drive a device or VR environment, respectively. There are two basic types of electrodes, i.e. self-adhesive surface electrodes and needle electrodes (Fig. 2.13).

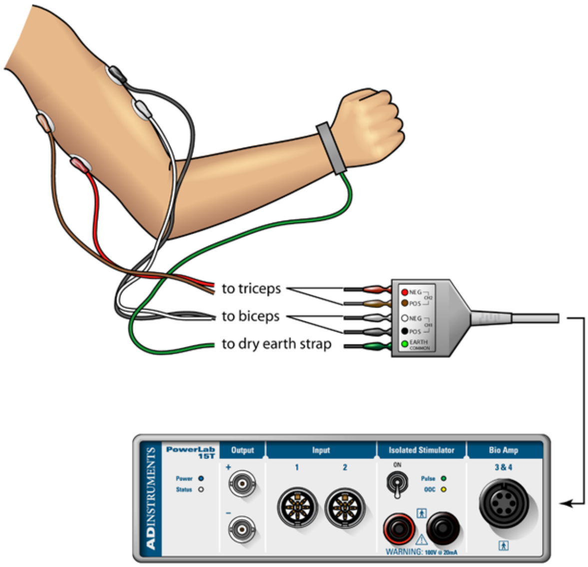


Fig. 2.13 Electromyography, EMG; © ADInstruments Pty Ltd. Reproduced with permission

2.5.2 Electroencephalography (EEG)

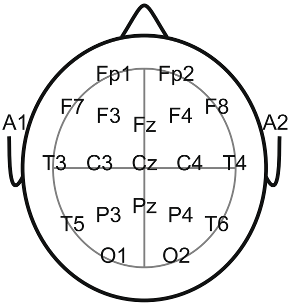
Electroencephalography (EEG) records the electrical activity of the brain by electrodes placed on the scalp (Fig. 2.14(a)). EEG can also be used for brain-computer-interfaces (Fig. 2.14(b)) in order to drive any device or system "just by thoughts".

2.5.3 Electrocardiography (ECG)

Electrocardiography (ECG) is a method that measures electrical potentials associated with heart muscle activity (Fig. 2.15). It is usually applied to detect and diagnose heart abnormalities. An example of an ECG readout is shown on Fig. 2.15(b). The ECG allows to determine heart rate, heart rate variability and other parameters to detect the physical and mental involvement of the user.

2.5.4 Blood Pressure Measurement

Blood pressure can be measured invasively or non-invasively. Invasive arterial pressure measurement with intravascular cannula involves direct measurement of arterial pressure by placing a cannula needle in an artery. The cannula is then connected to a sterile, fluid-filled system, with an electronic pressure transducer. The advantage of this system is that pressure is constantly monitored on a beat-to-beat basis,

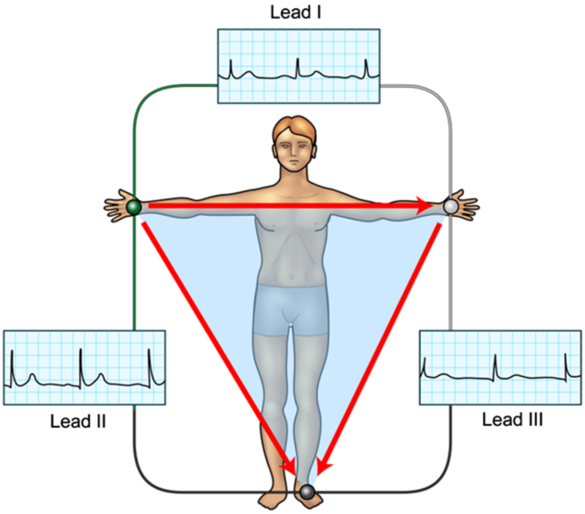


(a)

(b)

Fig. 2.14 Electroencephalographic (EEG) methods: (**a**) International 10-20 system of electrode placement [11], (**b**) EEG-based brain-computer interface; by courtesy of Dr. José del R. Millán

Fig. 2.15 ECG recording and readout: (**a**) The voltage source is assumed to be in the center of the triangle, (**b**) Typical readout of a bipolar Einthoven II ECG-derivation. The intervals between R-waves (RR-interval) is used to determine heart rate and heart rate variability;



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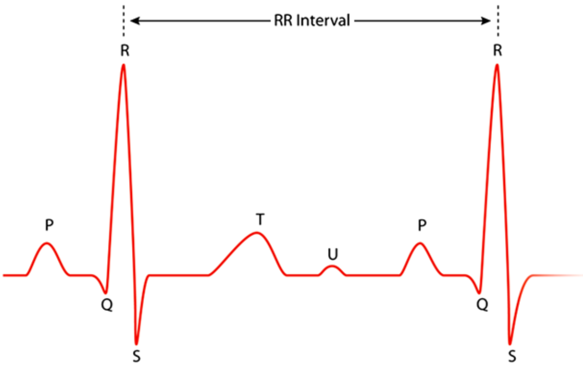

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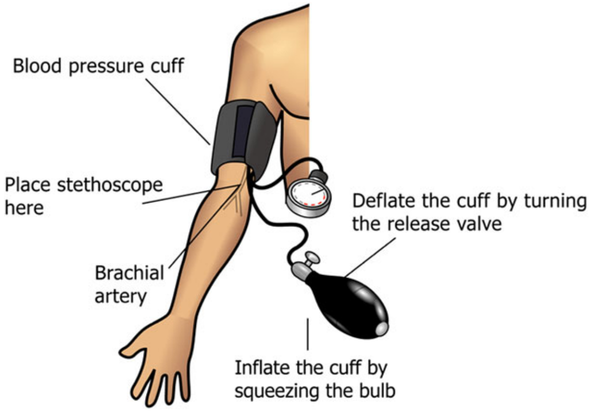
Fig. 2.16 Non-invasive blood pressure measurement principle by Riva-Rocci: (**a**) Setup to measure blood pressure, (**b**) Blood pressure measurement; © ADInstruments Pty Ltd. Reproduced with permission



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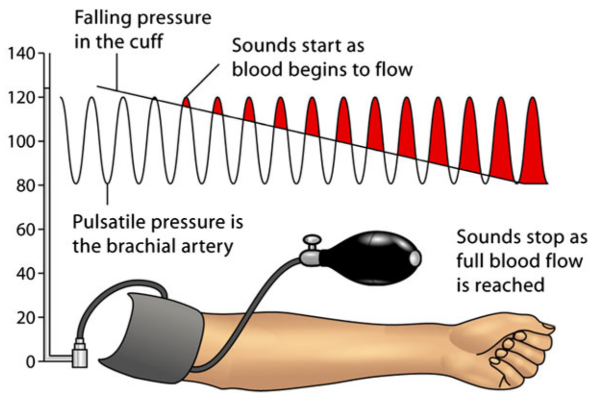

(b)

so that the quasi-continuous time course of the pressure can be displayed. The non-invasive Riva-Rocci method uses a stethoscope and an inflatable cuff placed around the upper arm at roughly the same vertical height as the heart (Fig. 2.16). The cuffs are attached to a pressure measuring manometer. This approach does not allow continuous measurements.

2.5.5 Pulse Oximetry

A pulse oximeter is a medical device that determines the amount of oxygen in the blood. It displays the percentage of arterial hemoglobin in the oxyhemoglobin configuration. Typically, it is based on a pair of small light-emitting diodes facing a photodiode through a translucent part of the patient's body, usually a fingertip or an ear-

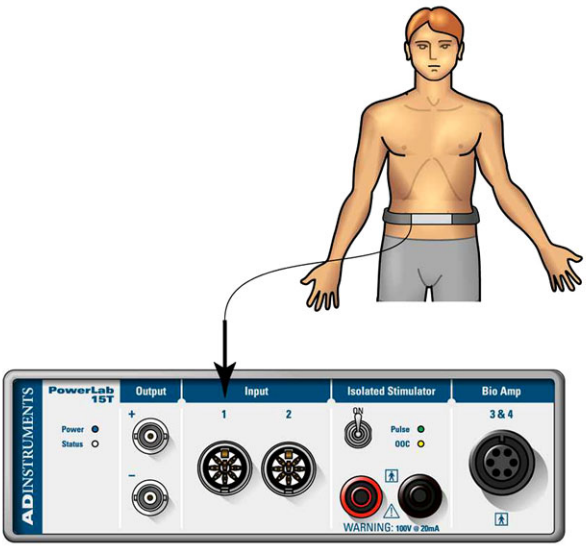

Fig. 2.17 Sensory belt to measure respiration; © ADInstruments Pty Ltd. Reproduced with permission

lobe. One LED sends red and the other one infrared light. Absorption at these wavelengths differs significantly between oxyhemoglobin and its deoxygenated form, so that the oxy/deoxyhemoglobin ratio can be calculated from the ratio of the absorption of the red and infrared light.

2.5.6 Respiratory Measurements

Respiratory gas and other variables of the respiratory system (respiration frequency and breath volume) serve as indicator for metabolic strain during exercise (Fig. 2.17). The average pair of human lungs can hold about six liters of air, but only a small amount of this capacity is used during normal breathing (vital capacity). Breathing mechanism is called *tidal breathing*. Tidal volume and vital capacity can be measured directly with a spirometer (Fig. 2.18).

2.5.7 Skin Conductance

The skin conductance is one of the fastest responding measures of stress response. It is a robust and non-invasive physiological measure of autonomic nervous system activity. The activation of sweat glands leads to changes in the electrical conductance due to sweat production. Skin conductance is measured by passing current through the skin and recording the electrical resistance (Fig. 2.19). Skin conductance is one of the signals used by lie detectors.

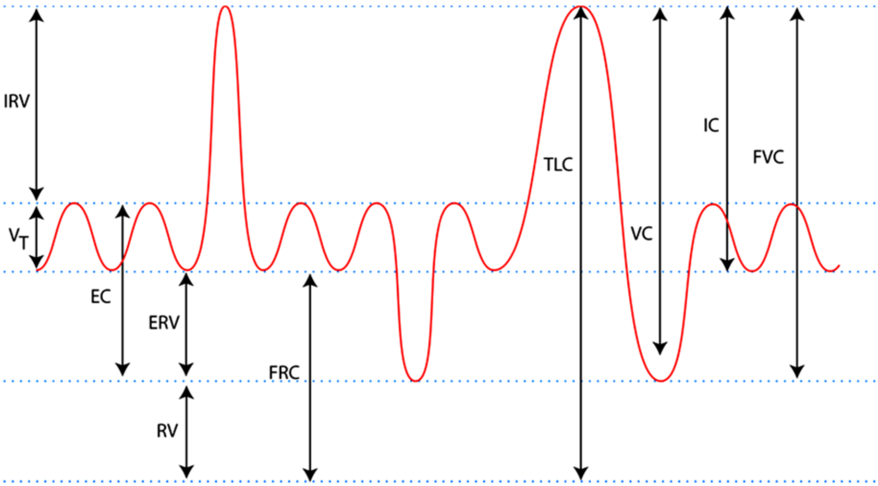

Fig. 2.18 Respiration measurement with a special measurement belt and output graph of measurement with a spirometer (*IRV*: Inspiratory Reserve Volume; V_T: Tidal Volume; *EC*: Expiratory Capacity; *ERV*: Expiratory Reserve Volume; *RV*: Residual Volume; *FRC*: Functional Residual Capacity; *TLC*: Total Lung Capacity; *VC*: Vital Capacity; *IC*: Inspiratory Capacity ; *FVC*: Forced Vital Capacity); © ADInstruments Pty Ltd. Reproduced with permission

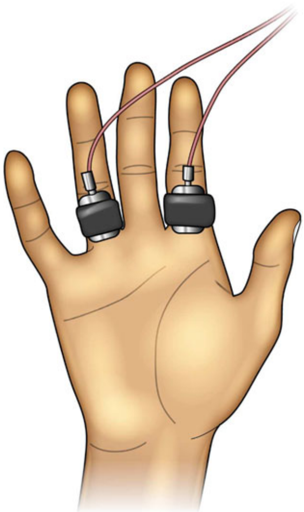

Fig. 2.19 Galvanic skin response (GSR) is usually measured on the fingers; © ADInstruments Pty Ltd. Reproduced with permission

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Virtual Reality in Medicine
Riener, R.; Harders, M.
2012, XII, 294 p., Hardcover
ISBN: 978-1-4471-4010-8