Protocol for the Baltimore longitudinal study on aging : gait and respiration analysis

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Protocol for the Baltimore Longitudinal Study on Aging. Gait and Respiration Analysis

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Summary

The results of the aging process are reflected on changes in the functioning of human beings. The changes in the gait of elderly are investigated by researchers and also the differences between men and women. There are many age-related changes in stride parameters (speed, cadence, step length), in force patterns, joint moments and balance control. For gait analysis, many systems and methods are developed which differ in the kind of information obtainable, the freedom of movement, costs and the time duration of the analysis.
Changes in the respiratory function have also been investigated. A decline in lung capacity and in oxygen use or consumption during exercise has been shown as people age.

A system which is suitable to use for BLSA studies and for a long period, is the ELITE system and its software packages for several applications. This automatic motion analyser is developed at the Centro di Bioingegneria in Milan and at the Politecnico di Milano, Italy. The system measures the 3-D coordinates of several passive markers applied to body landmarks. The markers are lightweight small hemispheres coated with retro-reflective paper. The coordinates of the landmarks are measured with a system configuration with 2-8 TV cameras at a sampling rate of 10 up to 100 Hz. Different experimental set-ups are possible depending on the application. The ELITE system can be used for gait analysis, respiration, posture analysis, small movements, jaw movements, surface reconstructions, ergonomics, sport applications and so on.

For gait analysis, the SAFLo approach has been developed in which a multifactorial analysis is made possible by the use of the ELITE system (four TV cameras), TELEMG (a multichannel electromyographic system), one or two Kistler force platforms and a software package ELICLINIC.
For respiration analysis, the ELITE system (four TV cameras) and the software package is used to measure the kinematics of the chest wall. The advantage of this method is that it is non-invasive, non-ionising and an analysis of the upper thorax, lower thorax and abdomen and of the left, and right volume compartments is possible.
The use of the ELITE system for these applications is suitable for routine use and the experimental sessions are easy and quick set-ups and leave the subject maximum freedom of movement.

A kinematic and kinetic gait analysis of three elder volunteers are performed and differences between these and a normal database are shown. Differences are mainly seen in the joint angles (hip, knee and ankle joint), joint moments and the power absorption and generation. The results of the respiration analysis show that the method is able to provide a lot of information (volume changes, motor coordination, volume partitioning, typical patterns) starting from kinematic data. This can allow a better understanding of the pulmonary function and of its alterations.

1 Introduction

The Baltimore Longitudinal Study on Aging (BLSA), a project from the department of the Gerontology Research Center, has started many years ago. They investigate age-related changes of human functions. Therefore every two years each participant of the U.S.A. comes to the research center and participates in about forty tests. There are at least 1100 participants and the age of these participants varies from 20 to 97 years.

The analysis of the elderly has shown a great interindividual variability depending on the style of life and a number of other reasons.
Several factors are responsible for the decay of motor performance with aging:

- Slow down in nerve conduction.
- Decrease of proprioceptive efficiency.
- Decrease in muscle strength.
- Loss of bone.
- Change in properties of ligaments.

The decay of motor performance is mainly a function of breakdown in interactive mechanisms more than a lesion of a specific organ.

The BLSA would like to investigate also locomotion. The researchers at the Centro di Bioingegneria have a great experience with this kind of research. So the aim of these project was to investigate which equipment is suitable for gait analysis in a Baltimore longitudinal study. By doing a literature search, results of studies dealing with locomotion and elder adults and the used equipment in gait analysis, especially the ELITE system, were studied.
The BLSA investigate the changes in pulmonary function among other studies. Because the respiratory function can also be investigated by the ELITE system, this study was extended with a study of changes in the pulmonary function and with a description of this method. With the system, a respiration and a gait analysis were performed.

At the Centro di Bioingegneria, Politecnico di Milano and Fondazione Pro Juventute Don Carlo Gnocchi in Milan, the ELITE system has been developed and is used for gait analysis, respiration, posture analysis, sport activities, surface reconstructions and so on. For these applications, software packages are specially developed and clinically tested.
The ELITE system, an automatic motion analyser, uses special TV cameras which detects the markers suitable placed on the body during movement. It is a very flexible, user-friendly system and can be used in fields where monitoring and controlling movement is required. The ELITE system and two applications, respiration and gait analysis, are described in this report. Also the results of a gait and respiration analysis of three elder volunteers are included and analysed.

2. Age and human function relations.

Age-related changes have been investigated for several human functions. In this chapter, age relations with locomotion and with respiration are described as a result of a literature study.

2.1 Changes in the gait of the elderly.

Review of literature data(5, 7, 14, 17, 26, 30, 33, 36, 37, 38, 41, 42, 43, 45, 50, 51, 52, 53, 54, 55)

2.1.1 Introduction.

Many articles deal with gait and elder subjects. In this part age-related changes of gait parameters are mentioned without a description of the used method and the subjects because:

- making it conveniently arranged.
- some studies obtained only kinematic data while others also obtained the kinetic data and/or EMG signals and the results are mainly similar. On the other hand results may differ depending on the used equipment, the experimental set-up, and the age of the subjects.

Only similar results are mentioned below because most studies based their results of the investigation on a few subjects. Especially the results of gait parameters are contradictory. For example, one study concluded age-relations in speed, step length, step frequency, and cadence; another concluded no or small age-related changes in cadence, step frequency and speed.

2.1.2 Gait parameters.

- A reduction of gait speed (at normal and fast speed) and step length, but small changes of the step frequency. Cadence differences are noticed.
- Increase in stance time, double support time (contact time) and decrease in swing phase (women).
- The range of movement of elderly women is less but it is not known whether they documented age-related or cadence-related differences.
- Significant interaction effect of age and sex in the step length, gait velocity and step frequency.
- Adults: Females natural cadence is higher than that of males. There is not a height-related trend. Height is a dominant factor in stride length and maybe in velocity.

2.1.3 Angle parameters.

- Smaller Achilles tendon angles at toe-off by the younger adults reflect greater inversion of the foot. The rear foot angle and the shoe sole angle both reveal trends for decreased foot movement with increased age. The elderly display less movement.
- There is not a significant age-related trend in joint angle differences.
- Women showed smaller excursions of hip flexion-extension and slightly less transverse rotation of the pelvis than did the men. Decreases in these two excursions appear to be the major kinematic factors producing the shorter step and stride lengths.

2.1.4 Force parameters.

- Longer time intervals between touch down and the onset of the vertical, anterior-posterior and medio-lateral force peaks.
- A reduction in the maximum braking forces and smaller force peaks in the medial direction.
- Loss of muscle strength in the dorsiflexors of the ankle.
- More variability in the organization of postural adjustments and a change in the ordering of postural muscle activation, tonic co-contraction of agonist and antagonist postural muscles. These are accompanied by longer reaction times and smaller centre of pressure displacements for the movement tasks.
- Push-off work is significantly lower and the absorption of energy by the knee flexors at this time is significantly greater. The net vigour of push-off is greatly reduced and a resultant change is a reduced step length.
- A number of force amplitudes are smaller. It is speculated that these differences may due to an increase in joint stiffness with increasing age and/or a consequence of an attempt to reduce foot movement during walking to account for their need for safety and balance.

2.1.5 Balance control differences.

- Measurements that relate to balance, tripping and slipping are toe clearance, heel contact horizontal velocity and covariance between hip and knee moments of force.
- The basic pattern of the muscle response organization is the same in majority of younger and older adults.
- Response time of some can be disturbed, with the proximal muscles activated before the distal muscles.
- A significantly higher probability of activation of the antagonist muscles at a given joint is shown when the elderly compensate for a postural sway.
- A hip strategy is significantly more often used in response to platform perturbations on a normal support surface.
- The elderly can stay well within their limits of stability when either visual or somatosensory inputs are reduced or removed. When both of these sensory inputs are reduced and vestibular inputs are the main source of sensory information available for balance, the elderly begin to lose balance.

- Initiation of gait is a unstable event because the body's centre of gravity is made to fall forward and outside the stance foot.
- The head Anterior/Posterior acceleration is significantly higher, making the head platform less stable. Heel contact velocity is significantly higher which increases the potential for a slip-induced fall at this critical time of weight acceptance. A decrease in the %COV between the hip and knee moment profiles is noticed. This is related to how well the motor pattern at the hip and knee collaborate to control both the dynamic balance of the upper body and collapse against gravity.
- The hip extensors and flexors have a dominant role of balance of the Head, Arms and Trunks (H.A.T.) against inertial perturbations and postural responses to gravitational loads of H.A.T. Therefore the hip moments profiles are so variable.

2.1.6 Summary.

- Changes in force, time and movement variables may always be due to changes in age and/or changes in walking speed.
- The elderly comprise a wide range of fitness levels and varying degrees of degeneration or even early stages of gait-related pathologies.

2.2 Age-Related Changes.

Review of literature data(10, 15, 24, 27, 29, 32, 34, 36, 40, 47, 49)

In this part age-related changes related to the respiratory function are mentioned and which are in line with this report.

- Lung capacity is the total amount of air that can be expired in a single breath. Lung capacity falls with age by about 40 percent between the ages 20 and 80, and that decline is a purely aging process. Smoking or a disease influence the rate of the decline [40].
- The data show significant correlations between spectral parameters of heart rate variability and respiration but support also the hypothesis of age-related alterations in the autonomic cardiovascular control mechanisms. Age is significantly inversely related to total power, i.e. overall heart rate variability, mid-frequency and respiration related heart rate fluctuations [49].
- There is an age-dependent linear relationship between walking velocity and oxygen consumption [29].
- Oxygen uptake and heart rate are linearly related at submaximal levels during normal gait [10, 29].
- Oxygen use or consumption during exercise declines as people age. A major reason consumption of oxygen declines, is that muscle mass is also declining [40].
- The heart adapts to the effect of age; it increases its output during exercise because the older heart is unable to increase the pumping rate as much as a younger heart [40].

- Range of motion of the cervical spine decreases in aging adults and may result from inactivity and/or structural changes of the tissues. Women show a greater cervical range of motion values than men in the age groups 20-30 and 70-90. The older group compared to the younger group show less flexion, less extension, less lateral flexion, less rotation, and a wider variation of cervical range of motion values [34].
- There is a general theory of age-related decline in physical performance. This decline in performance is seen in subjects older than sixty years, and for women difference in performance began earlier.
  Physical performance, predominantly anaerobic, is more affected by change in muscular fibre distribution and loss of both motor unit numbers and fibre numbers rather than change in muscle energy metabolic potentials [24].
- Increased physical activity in older adults is associated with improved: muscle strength, reaction time, joint flexibility, lower percent fat body mass, physical fitness, lower exercise heart rate and aerobic capacity. Exercise may also play a role in improving a number of sensory-motor systems that contribute to balance and stability [27, 36].
- Physical fitness declines about 5 to 10 percent per decade on the average. The highest oxygen consumption rate achieved during exercise is generally considered the most objective measure of cardiovascular-respiratory fitness [15, 40].

3. Basis requirements of a gait analysis system.

- Useful for many years.
- User friendly.
- Applicable to a large group of participants.
- Present data rapidly, efficiently and in a form readily to analyse.
- Meaningful results, age relating changes noticeable and correlatable with the functional capacity of the participant.
- Freedom of movement, walking pattern as natural as possible.
- Data obtained should be comparable and realistic.
- The analysis should require simple tests.
- Test time no longer than a hour.
- Costs not too high.
- Existing system of the Centro di Bioingegneria.
- The measurements have to be acquired in a not-dark environment.
- Reproducibility.
- Repeatability; the correlations between the various reproductions of the movement of the same subject in the same session.
- Accuracy; the capacity of the system to faithfully reproduce the movement of a subject without making too many mistakes.
- Reliability; the capacity of the system to give a faithful representation of movement in different sessions.
- Easy and fast calibration.
- Objective.
- flexible.

4. Equipment for gait analysis.

Review of literature(3, 5, 13, 16, 17, 19, 21, 23, 25, 28, 29, 30, 31, 39, 43, 44, 45, 46)

4.1 Introduction.

In this part equipment used in gait analysis are mentioned as a result of a literature study and as a result of the experience at the Centro di Bioingegneria. But first the terms, kinematics and kinetics are explained.

Kinematics is the study of motion of particles and rigid bodies, without regard for the forces responsible. Kinematic data do not provide information on biomechanical efficiency (oxygen consumption, oxygen cost), joint torques, joint power, or ground reaction forces. An individual can walk with stable kinematic patterns yet show considerable variability in kinetic patterns.

Kinetic or dynamic studies investigate the relationship between the factors causing motion such as forces and torques and the motion itself. At each joint a state of equilibrium exists such that the internal joint forces and moments generated by muscles, ligaments, and bone structures balance the externally applied forces.

4.2 Kinematic parameters.

Average values of simple parameters (cadence, mean speed and step length) are easily obtained using a tape measure and a stop watch. But generally there is a difference in movements on the right side and left side that can't be obtained in this way.

Observational gait analysis:
Observational gait analysis is simple observing a subject's gait without the use of any equipment. This is best done by systematically concentrating first on one body part and then on another. A trained observer can recognize many gait deviations during both stance and swing phases. An obvious limitation of observational gait analysis is the difficulty in observing multiple events and multiple body segments concurrently. It has been pointed out that events happening faster than 1/12 of a second (83 msec) cannot be perceived by the human eye. Motion videotapes can help overcome this problem. However, any form of observational gait analysis has limited precision and is more descriptive than quantitative.

Basographic systems:
For the measurements of the periods of ground contact, sensors of various types are used. The sensor gives a signal while the subject is walking along a walkway. The acquisition of events such as toe-off and heel-strike of both feet makes it possible to identify in temporal terms the phases of loading response, initial contact, stance phase and swing phase.

Electrogoniometric instruments:
An electrogoniometer is a device consisting of two rigid links, that are attached to a proximal and a distal limb segment, connected by a potentiometer that measures the interposed angle. Electrogoniometers are used to acquire information (2-Dimensional, 2-D or 3-D) relating to the relative angle between limb segments at a particular joint. The system for 3-D analysis is made up of three potentiometers positioned on the three principal axes of movement of the joint: flexion/extension, abduction/adduction, internal/external rotation. It does not give the translatory movement or the absolute angle of a single segment. The acceleration and the velocity are the results of calculations.
The advantages of these goniometers are easy data acquisition and the production of a large amount of reliable and reproducible data; the resulting data are available in real time; relative low costs. Problems arise with these instruments because of their mass and the difficulty of effectively securing them to body tissues without restraining the movement desired (the positioning of these instruments takes a long time). The lack of perfect accuracy in positioning causes a defect in the co-linearity between the centre of rotation and the electrogoniometer.

Cinematography:
Several cameras are available. The 8 millimetre (mm) ones are the smallest and the easiest to handle, but because of the small size of the film they do usually not permit accurate measurements. Thus 16mm ones are preferred. It is necessary to take into account the sensitivity of the film, the environmental light, the subject, the exposure time (the speed of the camera) to obtain the most detailed acquisition of the movement. By manually digitizing the location of markers placed over anatomic landmarks on a frame by frame basis, the marker position could be quantitatively determined in two dimensions with respect to the focal plane of the camera. By using two or more cameras, the 3-D marker position can be determined. The overwhelming disadvantages of cine analysis and manual digitizing are the extensive processing time necessary to digitize the data and the need for extensive operator training. Thus enormous amount of work is required in manual digitization of the data, relatively high inaccuracy of the digitization procedure depending on the operator skill, and the practical impossibility to obtain a reliable 3-D reconstruction.

Television:
The greatest difference between television and film is that television has a fixed frame rate, in Europe 50 fields/sec., in North America 60 fields/sec. The scanning speed is not always sufficient for athletic events. Brightness, contrast and focus are regulated electronically. The greatest advantages are the possibility of instant replay and automatic image processing.

Video technology:
Relatively inexpensive video technology is used to improve on observational gait analysis with a single camera. Slow-motion replay and freeze-frame features available on VCRs allow significant improvement over unaided visual observation. Several cameras and a splitter are used to simultaneously observe motion in the sagittal and coronal plane. Computerized systems, such as Selspot, Watsmart and Vicon, using multicamera video information can provide 3-D motion analysis.

Multiple-exposure photography:
This is one of the most simple and economic techniques of image analysis. It makes use of a dark environment, a camera whose lens remains open for the whole duration of the event, a stroboscopic that illuminates the subject (20 times/sec.), reflective strips and markers placed on the subject. The final exposure is a stick diagram of the subject, with the position of the leg at equal time intervals. Because of superimposition of the images, the evaluation potential at slow speeds is limited. Disadvantages are the costs of the (film) materials and the results are not directly available.

Optoelectronic systems:
Small markers (active, usually diode phototransmitters or passive, reflective markers) are placed on the relevant points of the body, and two or four television (TV) cameras take the subject during movement. The human body is modelled by a set of rigid links connected by hinges (markers indicates these points). Active marker systems offer the advantages of higher sampling rates (200 to 300 Hz), but require that the subjects wear power packs. In these systems light emitting diodes (LEDs) are pulsed at a predetermined frequency. The passive marker systems allow sampling at 50-100 Hz. Passive markers require an illumination source (typically infrared to minimize subject distraction) usually at or near the camera and require the use of algorithms to identify the centre marker position for accurate tracking.
In both active and passive marker systems, the location of the markers with respect to anatomic landmarks is critical to the overall accuracy of the system. The 3-D coordinates of a marker can be determined when seen by at least two cameras. If a marker is not seen by at least two cameras simultaneously, then its position has to be estimated. Swing of the upper limbs and the arms can lead to some of the markers being hidden.

A tridimensional recognition of the body segment takes place by measuring the movement of a plane identified by three non co-linear markers. This system can measure the absolute movements by defining an inert system of reference and these are used for the calculation of forces and moments. The data is also used to calculate anatomical kinematics: segment and joint angles, angular velocities and accelerations; joint and segment linear displacements, velocities and accelerations; total body centre of mass displacements velocities and accelerations. The measurements are very accurate and video representations as stick diagrams, solid diagrams are possible. Bilateral vision makes camera positioning difficult, this problem has been solved in the SAFLo arrangement (at the Centro di Bioingegneria in Milan). To minimize sources of error, an accurate method of camera and system calibration is needed.

4.3 Kinetic parameters.

Force plate:
These systems are used to capture the ground reaction forces and several meters are available: endurance extensometers, piezoelectric accelerometers, inductive and capacitive elements. They yield the following signals: vertical force, anterior-posterior and medial-lateral shear forces, centres of pressure in the anterior-posterior and medial-lateral directions, shear torque about the centre of pressure. The vertical force pattern in normal subjects walking at a

fixed cadence is a M or (half) butterfly shaped curve with peaks typically about 110% body weight. The ground reaction vector but also shear and centre of pressure measurements are effected by position and motion of all body segments such as head, arms, trunk, pelvis and legs. Changes in cadence affect the magnitude and duration of the vertical load curve (and have a direct effect on the slope of the butterfly curve, which reflects the rate of limb loading).
If the force platform signals are combined with the kinematics of the human body, the kinetics of the movement are calculated. Estimates of reaction forces and moments-of-force at each joint are made. Moment analysis can give insight into subtle functional musculoskeletal adaptations.
Also the kinetic and potential energy of each segment, the total energy and the mechanical power generated, absorbed and transferred by the muscles at each joint are calculated. Integration of the area under each phase of the power curves yields the work done by the muscles. Positive work indicates the phases where new energy is generated to maintain or increase speed. The subject have to place the foot on the force plate and that may be difficult in case of people with real impairments.

Pressure sensitive insole systems:
Ground reaction forces can also be measured by pressure sensitive insole systems (EDG, EMED, F-Scan). These systems allow analysis of on-going step to step variations in normal walking.

Accelerometric instruments:
Piezoresistive accelerometers or endurance extensometers are positioned on specific parts of the body and permit the measurement of absolute accelerations in one or three orthogonal directions simultaneously. Because the movement of a segment generally includes rotation and translatory motion, the result of the tri-axial transductor is significant only if combined with kinematic information. Some disadvantages are the costs, because you need a lot of accelerometers for a complete description of the acceleration in 3-D and they restrain the freedom of movement. Information about acceleration, velocity (integration of the data) and position (double integration of the data) can be obtained.

4.4 Electromyography.

Electromyographic (EMG) records give information about the timing of muscle activity and the relative intensity of muscle activity, the action potentialities of the motor units. EMG signals approximate the relative tension in the muscles and are available in pinpointing excessive spasticity and co-contraction as well as inappropriate burst of activity. The electric signal coming from muscle activity can be measured by electrodes.

Both fine wire electrodes and surface electrodes are used for EMG analysis. Surface electrode data are more repeatable than wire electrode data, but surface electrodes show less discrete phases of muscle action. Surface electrodes show group muscle actions only; wire electrodes are needed to identify the activity of specific muscles.

Both cable and telemetry systems are available. Cable systems can encumber the subject with multiple cables, but are reliable and less expensive than telemetry. Radio telemetry is vulnerable to electromagnetic interference and can require frequent technical service. New combined cable telemetry that sends multiple signals on a single cable is now available and offers the advantages of both systems.

There can be a change throughout the gait cycle in multiple factors, known to affect the relationship between the EMG signal and the force generated, such as the joint angle, the muscle fibre length, and type of contraction. Dynamic EMG does not give information about the strength of the muscle, whether the muscle is under voluntary control, or whether the contraction is isometric, concentric, or eccentric.
There is a shift in spectral content of the EMG signal with fatigue and this spectral shift may affect the EMG signal amplitude.

At the Centro di Bioingegneria an eight channels portable unit allows for measurements of the stimulus EMG activity of eight muscles by using bipolar surface electrodes with an incorporated preamplifier to improve the signal to noise ratio.

4.5 Treadmill vs. floor walking.

The conclusion of this study [39] is:

> In general, treadmill walking was not found to differ markedly from floor walking in kinematic measurements or EMG patterns.

Advantages of the treadmill:
- Permits locomotion within a small environment.
- Use of various types of monitoring equipment that requires attachments to the subject is possible.

Disadvantages of the treadmill:
- Costs treadmill vs. costs walkway.
- Ground reaction forces can not be measured with a force plate and than kinetic analysis can't be performed.
- Subjects need to practice walking on a treadmill for at least 30 minutes.

Some differences were found:
- A trend is found for all three speeds (slow, normal and fast) namely: shorter step length, faster cadence, shorter swing phases and longer double-limb-support periods on the treadmill than on the floor.
- Increased averaged EMG activity during treadmill walking.
- The vertical excursions of the head are smaller during treadmill walking at all three speeds.
- Average heart rate is significantly higher during fast speed treadmill walking.

4.6 The experience at the SAFLo approach.

At the Centro di Bioingegneria they have developed the SAFLO approach to analyse gait, in which multifactorial analysis is made possible by the use of the ELITE system, TELEMG (a multichannel electromyographic system) and one or two Kistler force platforms. A software package (ELICLINIC) which supports all the data management to data acquisition and elaboration until the final report, are used efficiently even by not very skilled operators. Some problems such as positioning of the cameras and the covering of hidden makers, have been overcome.

The purpose of the SAFLo approach is to allow measurements of the total body kinematics in subjects during standing and walking and to allow the estimation of joint moments and powers. Eight EMG signals are used to investigate the role of the muscles in walking performance and to interpret the data. Some problems occur in case of large rotations of the body or large bending. The model can be used in running, jumping, walking on a spot or with ambulation devices, rising from a chair or sitting down if the backrest of the chair is removed.

This system is very flexible and may useful for the BLSA, but is especially suitable for clinical applications. The data acquired can have considerable relevance for patient assessment and treatment.

Anthropometric measurements are required for the estimation of the joint centres of rotation (hip, knee and ankle joints) and for obtaining internal reference points. The TV cameras are positioned at each side of the subject and look at the subject from behind in order to detect simultaneously the markers. The correct location of the markers is extremely important even if the technical markers are located on easily identifiable anatomical points. Some troubles can occur in case of very fat persons or with severe deformities. It is important that the subjects walk spontaneously and don't feel hindered by the equipment and no voluntary attempts must occur to reach the correct position of the feet on the platform.

The SAFLo total body model includes: the two upper limbs, the head, the column, the pelvis and the two lower limbs.

Variables that can be obtained by the SAFLo protocol:
- Static-temporal parameters.
- Space orientation of body segments.
- Relative angles (joint angles).
- Centre of gravity, trajectory and velocity.
- Joint moments in the sagittal and frontal plane.
- Joint powers.
- Ground reaction forces.
- In the phase of validation (models): muscle length excursion, moment/angle relationship (joint stiffness).
- By adding EMG recordings, all the above biomechanical variables can be correlated to the myoelectric signals.

5. Which parameters and systems may be useful for the Baltimore Longitudinal Study on Aging?

First the possible systems to measure either the stride temporal phases or the ground reaction forces or the joint angles or the EMG signals, are described.
Then comprehensive systems that are available for the BLSA taking the requirements into account, are described and finally some considerations are made.

5.1 Stride temporal phases.

Device:

A) Walkway, two infrared light cells, a computer and a printer.
B) Walkway, two photocells, self-aligning electrogoniometers, a computer and a printer.
C) Walkway, sensors, a computer and a printer.

Acquisition conditions:

B) Subject walks at different speeds (slow, normal and fast) performing several trials. The use of goniometers restrict the freedom of movement because of the cables and the electrogoniometers and the difficulty in positioning accurately.
A/C) Subject walks at different speeds performing several trials. Freedom of movement.

Kind of information:

A) Horizontal walking speed.
B) Gait speed, step length, cadence and step frequency during slow, normal and fast speed.
C) Moment of toe-off and heel strike of both feet, initial contact, stance time, swing phase, step duration and double support time.

5.2 Ground reaction forces.

Device:

Walkway, force plate (Kistler), a computer and a printer.

Acquisition conditions:

Subjects stand or walk at different speeds (slow, normal and fast) performing several trials. It may be difficult to place one foot on the force plate. The test requires little time and relative inexpensive equipment, permits complete freedom of movement and is simple in use. The results (vector diagrams) are directly available, are sensitive to small variations in gait and show good reproducibility, even if obtained at different times.

Kind of information:

Ground reaction forces Fx, Fy and Fz during walking and standing, contact time, centre of pressure and vector-diagrams. Each vector of the vector-diagram represents the projection on a plane of the ground reaction with its amplitude, inclination and point of application in instants of time uniformly discretized. The diagrams are easy to read and to interpret and show a significant relation with the functional characteristics of subjects, particularly in regard to dynamic behaviour [25].

5.3 Joint angles.

Device:

A) Walkway, markers, two 16mm cameras (Locam II), a Vanguard M-16 projector, digitizer, a computer and a printer.

B) Walkway, interrupted light photography (a strobe light flashes 20 times a second), reflected targets, a computer and a printer.

C) The ELITE-system (markers, two or four cameras, reference system, computer and printer.

D) Walkway, goniometers, a computer and a printer.

Acquisition conditions:

ABC) Subject stands, sits or walks at different speeds (slow, normal and fast) performing several trials. Markers have to be placed on the human body. Freedom of movement. Information depends on the positions and the number of markers.

A) Quantification of the gait parameters requires a quite long measurement procedure.

B) Evaluation at slow speeds is limited. The final exposure is a stick diagram, measurements take place in a dark environment and results are not directly available.

C) A complete set of kinematic parameters is measurable and is easy to obtain, a lot of test possibilities, results are directly available. Anthropometric measurements are required for the estimation of the joint centres of rotation hip, knee and ankle and for obtaining internal reference points.

D) Subject walks at different speeds performing several trials. Reduction of freedom of movement because of the accelerometers and the cables.

Kind of information:

ABC) Static-temporal parameters, space orientation of body segments, relative angles (joint angles), centre of gravity, trajectory and velocity,

D) Relative joint angles, velocity and acceleration as a result of calculations. Accelerometers measure absolute accelerations.

5.4 EMG signals.

Device:

Walkway, an eight channel portable unit, computer and printer.

Acquisition conditions:

Subjects stand or walk at different speeds (slow, normal and fast) performing several trials. Freedom of movement.

Kind of information:

Activity of individual muscles and the relative tension in the muscles. EMG signals are available in pinpointing excessive spasticity and co-contraction as well as inappropriate burst of activity. For clinical applications electromyography is an useful tool. EMG signals provide useful and/or necessary information for a doctor for the choice of therapy, the improvement of diagnosis, the efficacy of the therapy or the rehabilitation procedure adopted etc.

5.5 Comprehensive systems and suitable for the BLSA.

1) It is composed by **1C and 2** (referring to above).
   Equipment: walkway, sensors, force plate, computer and printer.
   Information: step parameters and ground reaction forces.
   Reasons:
      -System **1A** is too limited in acquiring data because cadence and stride length are the determinants of walking speed and to acquire true age effects, you need to measure these three (age-related) variables.
      -System **1B** is not suitable because the electrogoniometers restrict the freedom of movement and the difficulty in positioning accurately.
      -Vector diagrams are easy to interpreted and this comprehensive system satisfy the requirements.

2) It is composed by **2 and 3C.**
   Equipment: walkway, forceplate and ELITE system.
   Information:
      Static-temporal parameters, space orientation of body segments, relative angles (joint angles), centre of gravity, trajectory and velocity, ground reaction forces (vector diagrams), joint moments in the sagittal and frontal plane, joint powers, kinetic and potential energy of each segment, the total energy and the mechanical power generated, absorbed and transferred by the muscles at each joint.
   Reasons:
      -System **3A** requires a quite long measurement procedure for the quantification of the gait parameters.
      -System **3B**: evaluation at slow speeds is limited, measurements in a dark environment and results are not directly available.

-System **3D**: reduction of freedom of movement.
-This system is used at the Centro di Bioingegneria and satisfy the requirements.

3) It is composed by **2, 3C, 4.**
Equipment:
SAFLo approach: the ELITE System, TELEMG (a multichannel electromyographic system) and one or two Kistler force platforms, a software package (ELICLINIC).
Information:
The same as comprehensive system 2) and all these biomechanical variables can be correlated to the myoelectric signals. In the phase of validation (models): muscle length excursion, moment/angle relationship (joint stiffness).

5.6 General considerations.

- The weight and the height of the subjects have to be measured for normalizing the data and to make comparisons with other gait patterns.
- It is possible to achieve the same movement from a score of different combinations of muscle patterns. If the patterns of a subject differ after a few years, you can just guess at the cause of the differences in the gait patterns. There are many age-related changes in force patterns and in balance control.
- The determined kinematic and kinetic patterns which are atypical may due to primary or secondary problems or at an adaptation to these problems.
- The effect of walking speed on the magnitude of kinematic and kinetic measures of gait must be accounted for when motor patterns are interpreted [43]. Cadence and stride length are the two determinants of walking speeds. How these parameters are altered is also important when comparing gait data across populations. For the younger adults, the upper limits of walking speed are achieved through higher cadences and not by stride length changes. But the older adults tend to be unable to achieve faster walking speeds and higher cadence.

  The hip moment is an example of a parameter which changes as a result of changes in speed. The causes of changes in the hip moment differ for younger and older adults because of the different way they alter walking speed. So to delineate true age effects, separate data on each of the three variables: walking speed, cadence and stride length is necessary.
- Because of the complexity of many movements, the only system which can capture all the data relative to a movement is a system of images. Combined with a forceplate, an almost complete pattern of the subject is acquired.
- Some disadvantages of measuring the EMG patterns are an increase in the test time, require more equipment and knowledge, will not simplify the gait analysis method. On the other hand, electromyography is an useful tool for clinical applications.

Measuring only the gait time parameters is not sufficient for the BLSA. It is interesting to have an insight in the cause of the differences between age groups and between an individual over a few years. Data acquisition of kinematic and kinetic parameters is available to determine age-related changes, provides meaningful results for the BLSA and satisfies the requirements of a gait analysis system. Using a force platform, also information about the total body stability can be obtained. Measuring also the EMG signals might be interesting for the BLSA because these give insight in the activation of the muscles and may be useful combined with other studies of the BLSA.

So the ELITE system composed with a force platform will be a suitable gait analysis system for the BLSA. This system is very flexible, can be used efficiently and also by not very skilled operators, two persons perform the test procedure and it will be useful for many years. Maybe at this moment not all the possibilities of the system will be used in the BLSA but it is suitable for expansion of the parameters you would like to analyse (you have already measured the parameters) or to measure also the EMG signals. The ELITE system has also other applications, as described in these report.
Another possibility is the use of comprehensive system 1. The test requires little time, one or two persons perform the test procedure and relative inexpensive equipment, permits complete freedom of movement and is simple in use. The results (vector diagrams) are sensitive to small variations in gait and the diagrams are easy to read and show a significant relation with the functional characteristics of subjects.

5.7 Conclusion.

Taking into account the requirements of a gait analysis system and the set-up of the BLSA, the use of the ELITE system will be very suitable for a longitudinal gait study. It is suitable to capture all the data relative to a movement and in combination with a forceplate and EMG a almost complete pattern of the subject is acquired.
On the other hand the ELITE system has also many other applications (for example: posture analysis, respiration, surface reconstruction) and may be useful for other studies. The system is very flexible and data acquisitions take a short time but the system is relatively expensive.
In the following parts the ELITE system will be described.

6. The ELITE system.

The ELITE system is an important tool for analysing body motions. This chapter provides a description of the ELITE system and its application for gait and respiration analysis.

6.1 The ELITE system in general.(3, 8, 9, 18, 19, 21, 23, 45, 46, 48)

6.1.1 Introduction ELITE system.

In different scientific areas the analysis of movement plays an important role. Movement is the result of a complex data processing performed under the control of the central nervous system. Impairments of the locomotor system are the results of aging, many diseases, various lesions located in different sites of the body: central nervous system, muscles, bones, joints, ligaments, etc. A better understanding of the mechanisms involved in motor control and the related strategies as well as procedures for early diagnosis and therapy assessment in motor disorders, and other scientific fields (advanced technical applications in robotics, process automation, prostheses, orthoses, input variables to biomechanical and neuromuscular models), require quantitative analysis of voluntary movements. So, the quantitative analysis of movement is becoming an important tool in a clinical environment, as well as in industrial applications.

The ELITE system belongs to the generation of systems for motion analysis and has been developed at the Centro di Bioingegneria, Politecnico di Milano and Fondazione Pro Juventute Don Carlo Gnocchi in Milan, Italy.

The ELITE system may be regarded as a measuring instrument that detects, with a given sampling rate, the marker position on the target of one or more cameras and computes their coordinates. The recognized markers are displayed in real time on a monitor and their coordinates are sent, via a DMA interface, to a personal computer together with the data provided by other instrumentation. The computer is able to reconstruct their 3-D coordinates in a short time and calculates more complex kinematic variables.

The analysis requires simple tests and the subjects don't feel hindered by the equipment. Good performances are possible in the presence of reflexes or noisy background. The experimental sessions are easy and quick set ups, and the automatic and fast data processing is suitable for routine use.

The system is very flexible and allows for different choices of markers number (even more than 100) and positions. Examples of application of ELITE which use specially developed and tested software packages, are: orthopaedics, prosthetics, neurology scoliosis, ergonomy, dental and sports.

The system is capable for the extraction of parameters useful for the assessment of the motor system function, also in clinical environment and for statistic purposes, as intra and inter-individual comparisons and normality definition. It is also accurate, repeatable, reliable, userfriendly, and shows a good reproducibility.

In this part the ELITE system and its application for gait analysis and respiration analysis are described in more detail.

6.1.2 Equipment.

The scheme of the ELITE system is shown in figure 1.

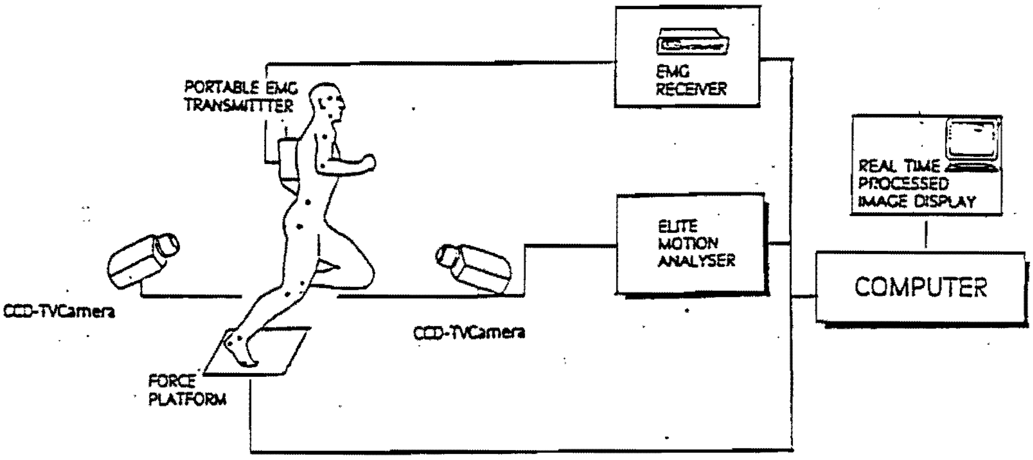


Fig. 1 Scheme of the ELITE system.

Three parts can be considered:

- The external devices: markers, TV cameras including an electronic shutter and an infrared source of light.
- A first level: the main processor.
- A second level: a general purpose computer.

The system performs the following operations:

1) To recognize the presence of one or more markers of a predetermined shape in the environment.
2) To compute the x and y coordinates of the marker centroids.
3) To perform the previous operations in real time (within the time of the frame duration) but operation 2 is split between real time and PC.
4) To classify each marker.
5) To perform the routine data processing for:
   -Distortion correction by calibrating procedures.
   -reconstruction of point trajectories by best fitting techniques.
   -3-D analysis by stereometric techniques when two or more cameras are used simultaneously.
6) To develop further data processing specifically devoted to the problem approached, generally based on a mathematical model of the system depending on the problem.

The operations 1), 2), 3) require very high-speed processing (approximately 5-9 ns/operation) which had been obtained by a specially designed full parallel hardware device. The operations 4), 5), 6) are carried out by a general purpose computer.

These functions will be described in more detail in the next parts.

6.1.3 Interface to the Environment.

The external devices consist of the following components: markers, TV cameras including an electronical shutter and an infrared strobe. The TV cameras adopted are of the solid state CCD type. The field of view is 20 cm up to tens of meters second the focal length of TVC objectives. The TV cameras take images from the subject during movement by detecting the position of the markers placed on relevant points of the human body. The recognition of the markers is performed by their shape and dimension instead of their brightness. So the system is able to recognize the markers even in the presence of other lightsources and this gives flexibility of the experimental set-up. An infrared lightening is used to avoid any disturbances to the subject for indoor applications. The lightening system is realized by a circular ring of I.R. LEDs coaxial with the lenses. The shutter system also allows the recognition of the markers in the daylight.

Marker detection is based on a pattern recognition technique and it is possible to vary the pattern to be recognized which provide the system great flexibility and allow its use even in the presence of disturbances brighter than markers.
In practice, small passive hemispherical reflective markers are used for the following reasons:

- They can be easily fixed to the body.
- The use of these gives the subject maximal freedom of movement.
- Their image doesn't change if they rotate on their axis of symmetry.
- Their image doesn't significantly change if they rotate on the two other axes up to approximately +/- 70°.
- The reflective material increases the contrast, thus improving recognition reliability.

The passive markers are lightweight small plastic hemispheres coated with reflective paper and allow a minimum interference of the measuring system with the subject.
The marker dimensions can be varied depending on the size of the segments analysed, on the amplitude of the movement, and on the distance from the TV camera. This flexibility allows the system to be used for very different set-ups.
The TV signal is sent to a hardware parallel processor.

6.1.4 Fast Processor for Shape Recognition.

The second block of the first level is called the Fast Processor for Shape Recognition (FPSR) and is hardware implemented. This constitutes the core of the system and analyses the TV signal from the solid state TV cameras. It performs the recognition of the markers and the computation of their coordinates. This specially designed processor uses very fast VLSI chips arranged in a parallel architecture and operates under the direct control of the general purpose computer (i.e. the CPU, Central Processing Unit).

For 3-D measurements at least two TV cameras must be used. Therefore the FPSR also provides the necessary signals for synchronization.

The FPSR digitizes every frame of the analog TV signals at a sampling frequency of 5 MHz (for the 50 Hz model) and processes a 256 x 256 pixel matrix each pixel characterized by its grey level. Sixteen grey levels are considered and coded on four bits by the A/D converter. Then provides in real time a bidimensional cross correlation between the actual digitized image and a predetermined 'mask'. In this way the markers are automatically recognized, within the whole volume under analysis, only if their shape (spots of light in the television field) matches the predetermined 'mask' which the CPU provides. The 'mask' or kernel (see figure 2) is a 6x6 pixel matrix and is designed to achieve a high correlation with the marker shape and a low one with the background. The implementation has been done by using fast VLSI chips in a pipe-lined structure. The shape detecting algorithm requires 1.5 million of operation in nearly 10 ms (100 Hz system) and this can be accomplished by the specially designed parallel hardware structure.

The output of the cross-correlation is processed by a threshold detector, and the centroid of the over threshold points is computed by the PC.

This point is the coordinate of centroid of each marker. The 2-D coordinates of the markers as registered during the movement are sent in real time to the general purpose computer which performs the remaining operations.

The parallel hardware implemention of the cross-correlation algorithm allows the simultaneous recognition of an unlimited number of markers, a very high rejection to reflexes and background noise and a great reduction of the information conveyed to the general purpose computer.

-7	-7	-7	-7	-7	-7
-7	-1	0	0	-1	-7
-7	0	7	7	0	-7
-7	0	7	7	0	-7
-7	-1	0	0	-1	-7
-7	-7	-7	-7	-7	-7

Fig. 2 Kernel.

The procedure allows for a great reliability of the marker detection and for a high accuracy in the computation of the coordinates. It recognizes markers in a noisy environment, including daylight, and there is no restriction on the number of markers which can be simultaneously detected. The real-time processing is essential to avoid the storage of the large amount of data necessary to describe a sequence of images.

6.1.5 Central Processing Unit.

The second level is able to associate each 2-D view to a predefined model of points arrangement on the body to be analysed and to reconstruct their 3-D coordinates in a short time.

In order to get the 3-D description of the movement, it corrects the distortion of the perspective views on two or more cameras and performs a 3-D intersection.

So, several tasks are performed and they may divided into 4 phases: 1) acquisition, 2) markers classification, 3) calibration, 4) further elaborations (see figure 3). Phase 2, 3, and 4 are executed by the computer. Special software packages, modularly organized, have been developed for these phases and allow an easy approach also for untrained people. The software is designed for IBM AT computers or compatibles working under MS-DOS operative system. The ELITE modelling package allows to define any model of the body, to analyse as a set of points by links, performs a completely classification of the detected markers, and provides the reconstruction of the position of the markers temporary hidden by body segments overlapping them during the movements.

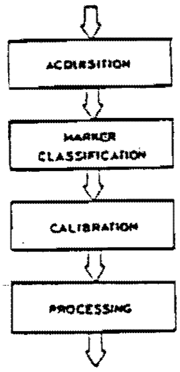


Fig. 3 Phases of data processing.

A description of the four phases follows.

1) **Acquisition**

The acquisition of both kinematic data and analogic data (i.e. EMG signals, force platform signals) is controlled by the computer. The acquisition phase is performed on-line with the FPSR and during this phase the computer collects data from the FPSR and stores them for further processing.

2) **Marker classification**

Marker classification is performed because the computer receives the coordinates of the markers in an order which are not related to the arrangement of the landmarks of the body. The coordinates of markers, disappeared during the movement for a few frames, must also be reconstructed.

For these purposes a special designed program Knowledge based Automatic Tracking

(KAT) have been developed. This procedure is based both on trajectory prediction and on body modelling. The algorithm assigns a label to each pair of coordinates so that a landmark is always identifiable. The procedure also takes into account a model (for example: compounded of segments and hinges) used to schematize the subject. A model is defined for each different movement and is entered in the computer.
The raw data collected with the ELITE system by a couple of TV cameras and the model are fitted by the program and the operator classifies the markers of the first two frames. The third frame is classified with a linear two-point predictor and then equation (1) is used to proceed further.

$$x(n+1) = 5/2[x(n) + 2x(n-1) + 1/2x(n-2)] \quad (1)$$

So, KAT, starting from these two frames, automatically tracks down each marker frame by frame, reconstructing the coordinates even when the overlapping of body segments occurs.
After this procedure, a 3-D reconstruction is carried out by a triangulation algorithm.

3) Calibration

The calibration is acquired in order to put a relationship between the positions of the TV cameras and the space in which the movement will take place and in order to preset the whole system and to correct the distorted camera coordinates due to the lenses of the TV camera. To transform the distorted coordinates into undistorted ones, the calculation of correction coefficients is performed by using standard least-squares techniques. An acquisition of a fixed standard grid of markers is used for this purpose. The calibration procedure (described in appendix 7) must be carried out every time the configuration of the cameras is changed to start a new set of acquisitions, however little time is required for calibration.

4) Elaborations

These phase is performed in order to extract information of general interest from raw data. General data filtering is needed before further elaborations (i.e. differentiation of the biomechanical data). In fact raw data is affected by a certain quantization noise which has a high frequency spectrum when a marker is moving. By using a low-pass or smoothing filter it can be eliminated. In general a frequency domain filtering is used as standard. After filtering many physical quantities can be calculated and represented graphically depending on the specific application.

So basic operations as kinematic data enhancement, tracking and reconstruction of the hidden markers, correction of distortion, 3-D reconstruction and representations of the physical quantities belong to this level.

6.1.6 Human body modelling.

A measurement has a significance only if referred to a model of the human body. To determine the relation between the human body and the model during movement, markers, placed on relevant anatomical landmarks of the human body, are detected by the ELITE system. There is no limitation of the number of markers detectable and the dimension of the passive markers are 1 mm up to 1 cm diameter.

The technical markers are located on the body according to the following basic requirements:
1) they must be easily detectable by the measurement system.
2) they must be as far as possible well connected to the anatomical structure (bones) and minimise the artifacts due to skin, soft tissue, muscle and bone movements.
3) The number of landmarks should be enough to describe, with a good approximation, all the movements.
4) The distribution of landmarks should be suitable for the application.
5) The positions of the landmarks should be easily identifiable in order to ensure an easy application of the markers and a good experiment reproducibility.

The correct location of the markers is extremely important. Even if the technical markers are located on easily identifiable anatomical points, some troubles can occur in case of very fat persons or subjects with severe deformities.
The anatomical markers refer to points that can be easily identified in a X-ray picture and can be used to define the bone segment axes, the relation between technical markers and the internal points, and so on.

If the relationship between technical markers and anatomical markers is known, at least in one position, by assuming that such a relationship does not changes with movement, it would be possible to compute the position of the internal points in a reference system defined by the external technical markers, and then to compute the movement of such points in the laboratory space.

6.1.7 Accuracy and resolution.

The ELITE system has a very high resolution (that is the smallest measuring step) but also a high accuracy (that is a small standard deviation from real measure). The resolution is 1/65536; the final accuracy is experimentally proved to be 1/2800 of the whole field of view even in the case of detection of small markers.
On a 280 mm field of view a 0.8 mm of marker diameter leads to an accuracy of 0.1 mm.

6.1.8 Summary.

The ELITE system can be used for:

- * Kinematic data elaboration: real time measurements body positions and movements in three dimensions.
- * Analogical signals:
    - * Ground reaction force measurements are possible.
    - * Electromyographic signals can be recorded (maximal eight signals).
    - * Analogical signals from any other kind of transducer can serve as input for the system.

Characteristics of The ELITE system:

- Use of small lightweight passive markers, and so a complete freedom of movement is achieved.
- Very short times required for subject preparation, data acquisition and data processing.
- Direct results and a multifactorial investigation with a high accuracy and precision.
- Is very simple to use; all software levels allow an easy approach also for untrained people.
- Together with other instrumentations, it can be used for a comprehensive multifactorial analysis.

Software packages available:

→ Gait analysis
    -for rehabilitation.
    -design, testing, and adaptation for prothesis.
→ Posture analysis
    -prediction of evolution.
    -assessment of spinal deformities.
→ Respiration
    -status of the respiratory system.
    -the effects of rigidity of the spinal column.
→ Ergonomics
    -industrial.
    -job seat design.
→ Sport application
    -athletics.
    -gymnastics.
→ Small movements
    -jaw movements.
    -writing and drawing.
→ Surface reconstruction
    -plastic surgery.
    -surface reconstruction and volume calculation.

6.2 Application of the ELITE system for gait analysis.(3, 8, 9, 18, 19, 21, 23, 45, 346 48)

6.2.1 Introduction.

Gait analysis has been used for example for evaluation of the efficacy of a therapy or a rehabilitation procedure, age-relations, effects of training etc. Kinematic, kinetic and electromyographic data are obtained and are simultaneously taken on the subject during the motor act. The multifactorial analysis is possible by the use of the ELITE system, a multichannel electromyographic system (TELEMG) and one or two force platforms (Kistler). Body's segments are represented by links and joint articulations by hinges. The movement description is obtained by the trajectories of the hinges which are marked and sufficient to identify the body structure.

For the analysis of body movements in various conditions and environments the ELITE system is very flexible. The system is simple in use, rapid, reliable, capable in a clinical and in a research environment. A complete package for clinical gait analysis is available (SAFLo) which includes protocols, models, software, different forms of report and database.

6.2.2 Method.

The kinematic analysis of gait is performed by the ELITE system. The system measures the markers placed on relevant landmarks of the human body at a sample rate of 50 or 100 Hz. As the human body is very complicated and in order to simplify the data collection, the anatomical segments are modelled as rigid bodies and connected by hinges.

The measurement is carried out by using a set of four TV cameras which survey the subject from behind. The TV signal is sent to the FPSR which performs, in real time, a shape recognition of the markers with the necessary accuracy and computes their 3-D coordinates and sends the coordinates to the central processing unit (CPU). The FPSR also provides the necessary signals for synchronization.

The second level in gait analysis, performing the remaining operations, consist of a computer (CPU) and an A/D converter for con-temporaneous and synchronized collection of data from the electromyographic system and from the force plate in order to calculate muscle moments and forces. It computes a set of variables related to kinetics and muscular kinematics. These include trajectories of the various points, angles between links, their first and second derivatives, mechanical moments acting at various joints, internal loads, power interchange at different joints, etc. A program for hidden markers reconstruction by interpolating techniques has been developed because in human walking analysis some markers can be hidden during the cyclic oscillation of the arms.

6.2.3 Analysis.

In gait analysis the subject walks or runs on a walkway with a length of at least 8m for walking and 15m for running analysis. The analysis can be performed for normal, slow or fast speed in both conditions. For measuring the ground reaction forces, the subject must place one foot on the platform. Each foot will be measured in this way and it is important that no voluntary attempts to reach the correct position of the feet on the platform occur. The subjects should walk or run spontaneously and maintain a steady state velocity in the field of the analysis. The operators must take care to avoid fatigue or any kind of discomfort to the subject that can arise because of the stay in the laboratory.

For the kinematic analysis, markers with a diameter of usually 8 mm are used and for the electromygraphy, an eight channel portable unit and bipolar surface electrodes are used. It is important that the subjects don't feel hindered by these equipment. The unit allows for measurements of the simultaneously EMG activity of eight muscles. The selection of muscles to analyse depends on the point of interest, for example: large muscles with a well defined function in the sagittal or frontal plane; four muscles of each leg for comparisons between right and left leg; at least two antagonists for each joint.

The method provides a direct measurement of the kinematic, kinetic and EMG parameters described in part 4.6 in a 3-D reference frame.

Other set-ups like standing, stepping on the spot, stair walking, jumping, athletic events are also possible and measurable.

The method leaves the subject maximum freedom of movement during the test and no constraints are given to the movement. The experimental sessions are easy and quick set-ups and the automatic and fast data processing is suitable for routine use. It shows good accuracy, reliability and reproducibility.

The investigation takes less than one hour and in simple cases almost half an hour including the preparation of the subject.

Indication of the maximum amount of time the set-up and the analysis take in minutes for ten trials:

1	System calibration	15
2a	Subject preparation without EMG	5
2b	Subject preparation with EMG	30
3	Data acquisition	20
4	Anthropometric measurements	10
5	Further elaborations	+ 30
	Total	110

The analysis takes totally 35 minutes without EMG and 60 minutes with EMG.

The time necessary for the data acquisition and for the further elaborations depends on the number of trials. The calibration phase should be performed when the position or the orientation of the TV cameras has been changed.

6.2.4 Human body model.

The human body has been modelled as a set of rigid links connected by hinges to simplify the data collection. The relevant body points are marked and the trajectories of these describe the movement of the body. The total human body is divided in four sections (see figure 4):

section 1:	the pelvis and the two lower limbs
section 2:	the column
section 3:	the head
section 4:	the upper limbs

Each section, except the first one, can be analysed only if the previous ones are included. Normally most attention is given to the model of the pelvis and the lower limbs. This model is used also in conjunction with ground reaction forces for computing the joint moments and joint powers.
Anthropometric data concerning the location of the barycenters and the mass and the moments of inertia are obtained from data published by Zatsiorsky and Seluyanov (1983).

- V. Zatsiorsky and V. Seluyanov. The mass and inertia characteristics of the main segments of the human body. In Biomechanics VIII-B, Int. Series on Biomechanics, Human Kinetics Publishers, Champaign, Illinois, pages 1152-1159, 1983.

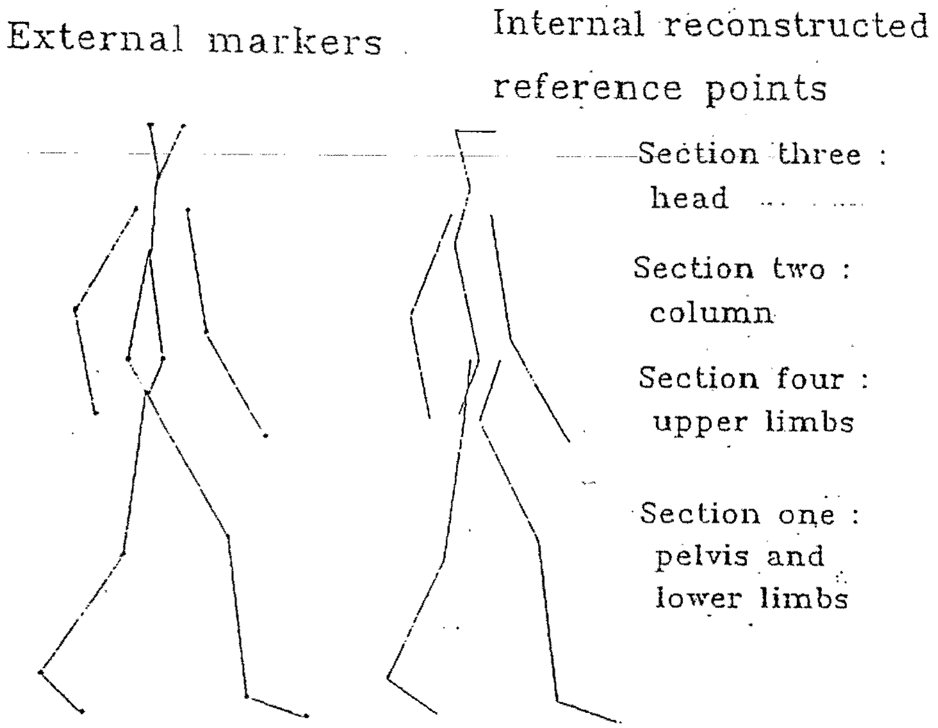


Fig. 4 Human body model.

6.2.5 Anthropometric measurements.

Anthropometric measurements are required for the estimation of the joint centres of rotation of the hip, knee and the ankle and for obtaining internal reference points. So for every subject these data have to be obtained. They are described and shown in appendix 1.

6.2.6 Markers positioning.

On the relevant body points which are easily identifiable anatomical points, markers are suitable placed and the trajectories of these describe the movement.
They are located in such a way that they are easily detectable by the cameras. The external markers on both sides of the body are located in the total body configuration (see figure 5) as follows:

number 1 is related
to the head section

number 2, 3 are related
to the column section

number 4-8 are related
to the lower limb section

number 9-11 are related
to the upper limb section

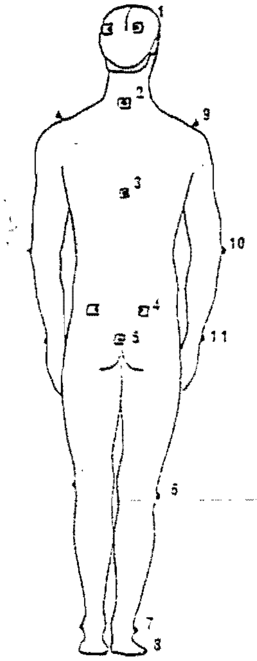


Fig. 5 Marker positions.

The location of the markers (appendix 2) and the internal points reconstruction are described. The marker arrangement is suitable for running and walking analysis. The markers on the posterior iliac spines should be positioned symmetrically and on a line that is parallel to the line of the two iliac spines. The distance between the two markers is not influent, because the width of the pelvis will be directly measured on the subject.

6.2.7 Working volume.

The working volume depends on the laboratory sizes and the kind of analyses which will be performed. For gait analysis, referring here to the SAFLo laboratory in the Centro di Bioingegneria, the two pairs of TV cameras are placed at least 3.5-4 metres (m) from the mean progressive plane of the walkway and each on one side of the walkway. The force platform will be at least at a distance of 3.5-4 metre perpendicular to the plane in which the two pairs of TV cameras are positioned. The part of the walkway which includes the force plate will be detected by the TV cameras and is a volume of 3 x 2 x 1.2 m (the calibrated volume). The equipment and the operator need a place which is not in the field of vision of the TV cameras. The walkway for walking analysis need to be at least 8m for normal walking speed analysis. So, the size of the laboratory for walking analysis should be at least 8 x 8 x 3 m and for running analysis you need a walkway of at least 15 m but a longer walkway is preferred. The size of the laboratory can be the same as in walking analysis taking into account that a corridor is a continuation of the walkway.

6.2.8 TV cameras arrangement.

Two couples of TV cameras are positioned at each side of the subject in a vertical arrangement (see figure 6).
Both couples look at the subject partially from behind in order to detect simultaneously the markers on the lateral aspect of the human body as well as those located on the back. The angle between the plane on which each couple of TV cameras lye and the plane of progression is about 45:50 degrees. A smaller angle will give some troubles in detecting the markers of the foot, especially in the case of abnormal intrarotation. Angles of view bigger than those proposed will give some troubles in detection of the markers on the back, especially in the case of large rotations of the pelvis or the trunk.
The vertical distance of the two TV cameras on each side must be correlated to the distance from the centre of the working volume. An angle between the two optical axes of about 90 degrees would be optimum for reducing the estimation errors in the three dimensional reconstruction. This optimum value is far to be achieved in most cases, firstly because the ceiling is in general not sufficient high, and secondly because in that case there are situations in which the foot is hidden by the upper parts of the body. An angle of about 30 degrees is a good compromish anyway.

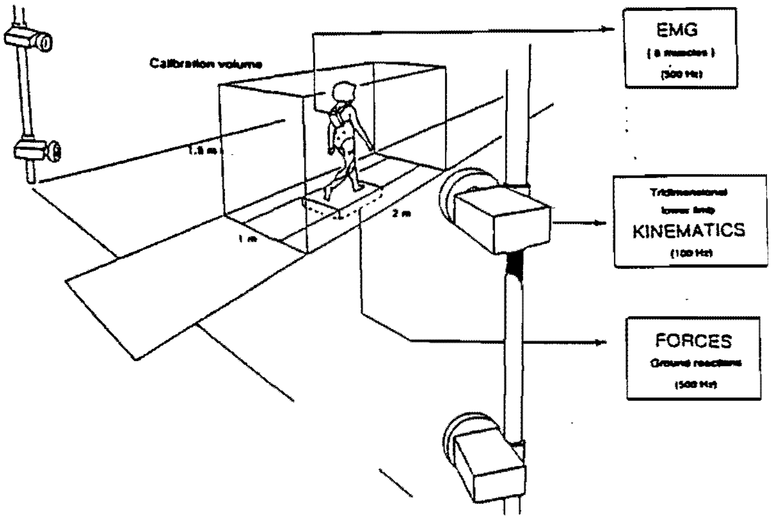


Fig. 6 SAFLo-laboratory.

6.2.9 Calibration and accuracy.

A grid of (4x5) markers is used for calibration. The calibrated volume is a volume of 3 x 2 x 1.2 m. Due to the different orientations of the TV cameras it must be ascertained that each of them can see a volume slightly larger than this.
The final accuracy, accounting also for distortion corrections over the whole field of view, is experimentally proved to be 1/2800 of the field of view, even in the case of detection of very small markers (i.e. the accuracy with a 280 mm field of view and a 0.8mm of marker diameter is 0.1 mm).

6.2.10 Results and application.

The experimental set-ups in gait analysis are:
- walking with normal, slow and fast speed.
- running with normal, slow and fast speed.
- stair walking.
- standing.
- stepping on the spot.
- hopping.

The kinematic data can be completed with EMG signals and ground reaction forces.

The main quantities which are computed, are (see also part 4.6):
- the time courses of angles at various joints (absolute values and projections on the main plane) and several derived parameters like maximal extension, flexion or total excursion.
- linear and angular velocities and accelerations.
- graphic representations of trajectories and movements in all planes.
- time course of the three components of the ground reaction and the vector diagram representation.
- the rectified, integrated and normalized EMG patterns of the investigated muscles compared with the temporal phases of the stride.
- total moments at hip, knee, and ankle joint giving information about the muscle forces and role.
- power and energy provided or absorbed at the same joints giving information about concentric and eccentric contraction of the muscles.

These data are useful for:
- obtaining a normal data base for different age groups (it is in great demand).
- understanding in motor control and the changes and to get insight into stability.
- clinical applications; for the choice of the therapy, the improvement of diagnosis, the prevention of secondary defects, the evaluation of the efficacy of the therapy or the rehabilitation procedure adopted.
- identification of specific 'pathogenic profiles' which are typically related to a given pathology (prosthesis, orthosis, lesions at joints and ligaments, cerebral palsy).
- other scientific research environments.

6.3 Application of the ELITE system for respiration analysis.(1, 2, 12, 20, 22, 47)

6.3.1 Introduction.

Investigation of the respiratory function by the use of the ELITE system is a new method. A kinematic analysis of the chest wall motion is performed for the assessment of respiratory system function. The respiratory function reflects on the action of its passive and active components. By special software, the system extracts automatically several parameters (tidal volume, frequency, inspiratory and expiratory times, contribution of thoracic and abdominal volume to total volume, right and left compartments, and inspiratory and expiratory range in unrestrained voluntary breathing,) from the kinematics of the chest wall. Volume variation of the chest wall and its time course can characterise the status of the respiratory system. Diseases of the respiratory system as well as neuromuscular and skeletal disorders reflect on abnormalities of chest wall motion. Changes due to the aging process can be acquired and in this way it is possible to obtain a normal database for every group of age. The system, which is simple in use, rapid, reliable, is capable in a clinical and in a research environment for statistics purposes, as intra and inter-individual comparisons and normality definition.

6.3.2 Method.

The method for kinematic analysis of chest wall motion is based on the use of the ELITE system, which measures the volume change of the trunk by automatically computing, in real time, the 3-D coordinates of small passive markers (6-8 mm diameter) placed on relevant landmarks of the thorax and abdomen at a sample rate of 100 Hz or sub multiples. The measurements are carried out by using a set of four TV cameras which survey the subject from above and aside. The TV signal is sent to the hardware parallel processor which performs, in real time, a shape recognition of the markers with the necessary accuracy and computes the trunk volume and its splitting into horizontal and vertical volumes. Partitioned volume analysis allows an evaluation of the efficacy of the different muscular groups involved in the respiration. Besides, the contribution of each compartment is affected by the compliance of the passive viscoelastic structural components.
The method has been validated by comparing the computed volumes with those obtained by several kinds of spirometers and pneumotachographs, showing a good agreement between the two measures.

6.3.3 Analysis.

The analysis can be performed in different postures: standing, sitting, supine and on the side and for long periods of time. No constraints are given to the movement. No cues are given to the subject how to breath or how to use the different sections. In sitting position, the subject is seated on a table with the hands onto the table. In the case of the supine experimental set-up, the posterior frame is not acquired. The thoraco-abdominal volume is computed by using the model of the body and with fictious markers for the back.

This new method provides a direct measurement of the volumes in a three-dimensional reference frame. Other measurements like antero-posterior, rostro-caudal and latero-lateral diameter variations vs. time can also be computed. The system can be used without a single subject specific calibration and allows to monitor the true spontaneous breathing of the subjects without adding any dead space or requiring cooperation. The method is also non-invasive, non-ionising and leaves the subject maximum freedom of movement during the test. The experimental sessions are easy and quick to set up and the automatic and fast data processing is suitable for routine use. It shows good accuracy, reliability and reproducibility.

In a normal data acquisition, subjects are asked:
1) to breath spontaneously, data is collected for 3 minutes.
2) to perform 4 deep breathings, data is collected starting from normal breathing.
3) to breath spontaneously and than to expire maximal followed by a maximal inspiration and again a maximal expiration and continue to breath normally (vital capacity).

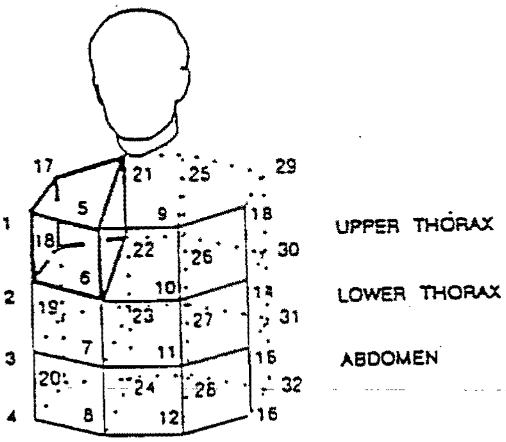
Indication of the maximum amount of time a normal data acquisition takes in minutes:

1	TV camera positioning	15
2	System calibration	30
3	Subject preparation	20
4	Data acquisition and tracking	30
5	Further elaborations	+ 20
	Total	115

The set-up takes totally 45 minutes.
The analysis takes totally 50 minutes.

6.3.4 The human body model.

Through a specially designed model, the trunk volume and its splitting into horizontal and vertical volumes can be estimated on-line. A model is based on 54 tetrahedrons which can be grouped into 9 compartments and into three horizontal and three vertical sections. Each of the 9 compartments (see figure 7) is delimited by 8 markers: four on the front and four on the back (with some markers common with other compartments). The markers identify a twelve-faced polyhedron (see figure 8) which can be further subdivided into 6 tetrahedrons. The whole body is thus split in 54 (6*9) tetrahedrons (see the vertices of which are reported in figure 8). The volume of each tetrahedron (volume unit) is computed starting from the coordinates of its vertices by simple geometric formulas. The sum of all or part of these volume units leads to the total volume and the sum of subsets of volume units gives the section volumes as indicated in figure 7.



Tetrahedron	Vertices
1	1.2.6.18
2	1.5.6.18
3	1.5.17.18
4	5.21.17.18
5	5.21.22.18
6	5.6.22.18

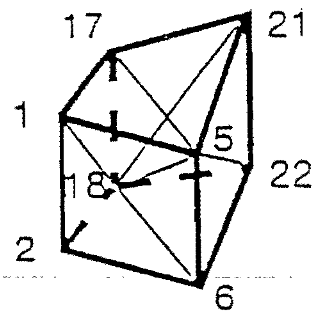


Fig. 7 Volume compartments of the trunk.
Fig. 8 Tetrahedron and vertices.

The three horizontal sections represent the upper thorax (mainly reflecting the action of the neck-sternomastoid and scalenus) and parasternal muscles and the effect of pleural pressure), lower thorax (mainly reflecting the action of the diaphragm and the effect of abdominal and pleural pressure) and abdomen (mainly reflecting the action of the diaphragm and the effect of abdominal muscles) and allow the analysis of the breathing pattern. The two vertical sections (left and right trunk) point out asymmetries between right and left side. The contribution of each compartment is affected by the compliance of the passive viscoelastic structural components. Thus a geometrical model allow to compute the contribution to ventilation due to lung rib-cage, abdominal rib-cage, and abdominal wall or due to left or right trunk. The number of rows and columns, and thus of compartments and sections, can easily be varied by varying the model and the number and position of the markers. The computed values do not depend on the position of the body in the space.

6.3.5 Markers arrangement.

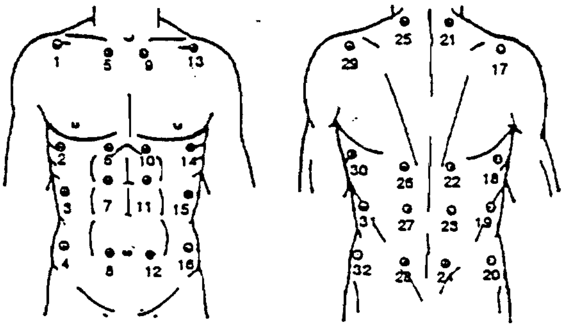


Fig. 9 Markers arrangement.

The external markers are located in the total body configuration as shown in figure 9. Depending on the used model, several markers arrangement are possible and some examples follow:

Standing and sitting position:

-The subject wears 32 markers, arranged on an anterior four by four frame and a symmetric posterior one. The anterior frame consists of four horizontal rows (2nd rib, xiphoid process, 10th rib and abdominal transversal line) and four vertical equally spaced rows starting from a position between the anterior and the mid axillary lines.

-Forty landmarks are arranged on an anterior 4x5 grid and a symmetric posterior one. The anterior frame consists of the same four horizontal rows and five vertical rows included between the 2 anterior axillary lines symmetrical with respect to the central line of the thoraco-abdominal wall. This arrangement allows the computation of the volume of 12 compartments which can be grouped into horizontal and vertical sections.

supine position:

20 Passive markers are arranged on the anterior frame just like in the sitting/standing position. The posterior frame is not acquired. The posterior markers are supposed to be fixed on the plane on which the subject lies.

However, only the 40 marker model is used for the data acquisitions because it is more accurate. The number and the positions of the markers satisfy the requirements laid down in part 6.1.6. So, the markers are suitable arranged for computing the volume with the use of the 3-D geometric model.

6.3.6 TV cameras arrangement.

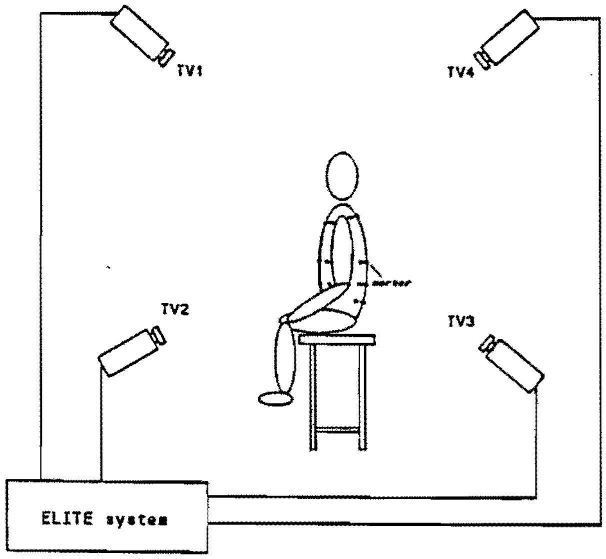


Fig. 10 TV cameras arrangement.

A set of four TV cameras survey the region of space where the subject is located (see figure 10). Two cameras are placed in front and two behind the subject who sits/stands in the middle of the working volume. Each camera-pair is arranged vertically, one above the other. This arrangement allows a good visibility of all of the markers during the respiratory movements. The vertical distance of the two TV cameras must be correlated to the distance from the centre of the working volume. An angle between the two optical axes of about 30 degrees would be sufficient.

6.3.7 Working volume.

The ELITE system works well in a calibrated volume of 1.0 x 0.5 x 0.7 m. At the Centro di Bioingegneria one pair of TV cameras is placed 3.5 metre in front of the subject and the other pair is placed 3.5 metre behind the subject. The equipment and the operator need a place which is not in the field of vision of the TV cameras. So, the size of the laboratory should be at least 4 x 8 x 3 m but of course it depends on the sizes of the used room.

6.3.8 Calibration and accuracy.

The calibration is performed by surveying a grid of points of known geometry. Both software and grid for calibration come with the ELITE system. For the small displacements considered here, the standard deviation of the error on the 3-D coordinates for the used working volume of 1.2 m side is 0.06 mm (one part in 20000 of the field of view).
The errors induced by a spirometer are bigger than those due to the limited accuracy of the ELITE system.

6.3.9 Results and application.

The possibilities in experimental set-up in respiratory analysis are:

- sitting position
- standing position
- supine position
- aside position

EMG signal measurement is not reliable because the respiratory muscles are not lying beneath the skin and are thus not easily to detect with bipolar surface electrodes or with non-invasive techniques. Also pressure measurements are not obtained because these are invasive measurements.

The kind of information obtained:

- The volume variation of the chest wall.
- Abdominal, lower and upper thoracic volume.
- contribution of each sector to total volume.
- frequency.
- inspiratory and expiratory times, Ti/Te.
- variation of FRC.
- Lung Volume Compartments (see figure 11):

ERV	Expiratory reserve volume
FRC	Functional residual capacity
IC	Inspiratory capacity
IRV	Inspiratory reserve volume
RV	Residual volume
TLC	Total lung capacity
VC	Vital capacity
V_T	Tidal volume

FRC, RV, and TLC can not be measured as absolute value.

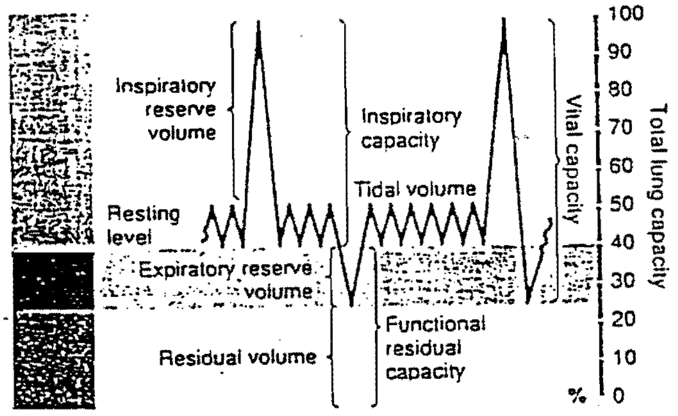


Fig. 11 Lung volume definitions.

These data are useful for:

- The method provide information of volume changes, motor coordination, volume partitioning and typical patterns and allows a better understanding of the breathing pattern and its alterations.
- An analysis of the volume variations in selected compartments will allow a better understanding of physiology.
- Understanding of differences in strategies to perform the several breathing tasks and of asymmetrical differences and differences in the volume of the compartments which refer to the muscle groups.
- To quantify the effects of rigidity of the spinal column.
- The volume variation of the chest wall and its time course can characterise the status of the respiratory system, also in several pathologies (neuromuscular diseases, stiffness of the ribcage, COPD).
- The method has shown its potential for the task of matching each patient with respiratory disease to its ventilator.
- Measurements of what happens when the ventilatory frequency changes during the breathing, is possible. This can point out a volume variation with frequency and in particular a different role of various compartments.
- The results obtained allow both an immediate assessment of the breathing pattern and a quantitative evaluation of its main characteristics.

7. Experimental set-ups for the BLSA.

7.1 Introduction.

In this part several possible set-ups which may be interesting for the BLSA are described. The advantage of the BLSA is the amount of volunteers that participate in their studies. A gait study which includes all age groups, will be interesting. The influence of lifestyle on motor functioning can also be considered. It may be possible to combine the gait and/or respiration analysis with other BLSA studies.

7.2 Gait analysis.

For gait analysis the SAFLo approach has been developed as described in part 'Equipment for gait analysis'. Analysing the kinematic, kinetic and EMG parameters for slow, normal and fast walking speed, will have considerable relevance because:

1) The elderly comprise a wide range of fitness levels and varying degrees of degeneration or even early stages of gait-related pathologies, a normal data base of several age groups is in great demand and the BLSA has the possibility to provide one.

2) An investigation to analyse the differences in motor performance between men and women belongs to the possible studies.

3) In many studies it is not clear if changes in force, time and movement variables are due to changes in age and/or changes in walking speed. The BLSA will be able to investigate these.

4) A result of the BLSA is that vision declines with age. As I reported in part 'changes in the gait of elderly', balance control will be less when both visual and somatosensory inputs are reduced or removed and vestibular inputs are the main source of sensory information available for balance. So, a possible research may be to analyse the influence of vision, walking and age.

5) Also balance control and reaction time change with aging. Initiation of gait is a unstable event. To analyse the initiation of gait at a moment a sign is given, will give some information about the reaction time, the activation of the muscles, changes of muscular functioning, and the balance control.

6) Loss of muscle strength, changes in the muscle activation, longer reaction times, smaller force amplitudes are results of some studies.
It is speculated that some of these differences may due to an increase in joint stiffness with increasing age and/or as a consequence of an attempt to reduce foot movement

during walking to account for the need for safety and balance. With this method it is possible to investigate these changes.

7) The applications mentioned in part 'Application of the ELITE system for gait analysis'.

7.3 Respiration analysis.

For respiration analysis the ELITE system and a special software package have been developed. Measuring the trunk movements during normal respiration, deep breathing and maximal in- and expiration (as described in part 'Application of the ELITE system for respiration analysis), will have considerable relevance because:

1) The status of the respiratory system can be characterized and changes of the respiratory function reflect on variations of chest wall motion.

2) An investigation to analyse the differences between the upper thorax, lower thorax and abdomen to analyse the breathing pattern and/or between the left, and right compartments, to point out asymmetries, belongs to possible studies.

3) Lung capacity falls with age, and the BLSA can also investigate with this system what kind of variables influences the rate of the decline.

4) The applications mentioned in part 'Application of the ELITE system for respiration analysis'.

7.4 Studies to investigate relations between human functions.

Monitoring the subject walking (with different speeds for example) on a treadmill with the ELITE system, and also measuring the heart rate and/or the oxygen consumption, will have considerable relevance. Because there is an age-dependent linear relationship between walking velocity and oxygen consumption and studies have shown that oxygen uptake and heart rate are linearly related at submaximal levels. An increase in walking speed requires corresponding increase in energy expenditure.
These data (heart rate and oxygen uptake) can also be compared to data gathered during quiet sitting and quiet standing.

Investigations of age-related changes in the muscular system by comparing the muscles functioning involved in respiration and in gait and investigations of differences between men and women by using the obtained data of the gait and respiration analysis can be studied.

Investigations of physical activity and muscle strength, reaction time, joint flexibility, percentage body mass, physical fitness, and aerobic capacity by using available data of the other BLSA studies and the obtained data of the gait and respiration analysis may be interesting.

8. Gait Analysis of Three Elder Volunteers.

8.1 Introduction.

Results of investigations have shown age-related changes in human gait as reported in part 'Changes in the Gait of Elderly'. The results of studies do sometimes not agree because of:

- the used method and equipment.
- differences in the age and the sex of the subjects.
- different requirements of "healthy" subjects.
- the used statistical analyse and representation of the parameters.
- the used normal data base.

Several reports are concerned with normal gait to provide a valid normal reference data base. But these results are often based on relatively small numbers of subjects, as well as for men as for women between the age of 20 to 40 and the results are dependent on the used method. The aim of this study is to present data on gait parameters of elder subjects by the use of the ELITE system and to show differences between the volunteers and the used normal data base. A statistical analysis has not been performed because of the number of subjects involved in these study. Because of the same reason differences between men and women are not analysed.

8.2 Subjects.

Two women (70 years of age) and one man (71 years of age) were examined. Their daily physical activity were considered, using a questionnaire (appendix 3) and some results of these are mentioned in table 1. The participants were able to dress, to wash, to cook, to vacuum, to clean the house, to do the shopping all by themselves. So, they could perform normal daily activities without real problems.
One women has asthma and the man has a lesion of the vestibular system.

Activity	Man	Woman A	Woman B
Lives in house of their own	y	y	y
Married, living together	y	y	y
Weight (kg)	82	56	53
Height (cm)	178	163	168
walking .. km a day	2-4	2	0
climbing .. stairs a day	3-4	1	0
watching TV .. hours a day	2	2	2
reading .. hours a day	3	1-1.5	1
kind of sport activities	biljart	gardening	
kind of sport activities when he/she was younger	swimming tennis		
has smoked or smokes	n	n	n
uses medicines	n	n	anti asmathic
other functioning problems	vest.sys	n	asthma

Table 1. Activities of the subjects.

8.3 Analysis.

The gait analysis method used is the ELITE system and one Kistler force platform, developed at the Centro di Bioingegneria in Milan. The gait laboratory has a walkway about 8m long. The ELITE system, an automatic motion analyser, measures the 3-D coordinates of several markers applied to body landmarks by the use of four TV cameras at a sampling rate of 50 Hz. For the analysis the lower limb model was used which includes the pelvis and the lower limbs. Kinematic and kinetic data were obtained during walking with normal speed. The subject had to walk at a self-determined speed and data were collected for six trials; three times the right foot and three times the left foot reached the correct position on the force platform. The subjects didn't know the exact position of the force plate and no attempts were made to reach the correct position. After the trials the anthropometric data were obtained. The total analysis took 20 minutes for each subject.

8.4 Results.

The results are compared with a normal data base. Characteristics of the data base are:

- age: 39 - 49.
- height, weight and anthropometric data are known.
- the results of each subject are passed one's medical to make sure that these were normal gait patterns.

The differences in gait parameters, compared to the normal data base, are shown in table 2. The "expected" values are the values as a result of a literature search, described in part 'Changes in the gait of elderly'.

Subjects	Velocity	Stride period	Step length
Women	+	-	0
Man	-	+	-
Expected	-		-

Table 2. Gait parameters compared to the normal data base.
+: significant greater
-: significant greater
0: no significant differences

All the subjects showed greater ground reaction force amplitudes at toe-off (TO) than at heel contact (HC).

The man has a dominant hip flexion, knee extension and a more plantarflexion of the ankle. From 20% of stride a greater flexion and smaller extension moment and a smaller hip extension angle are shown. Also the hip generates and absorbs less energy than normal subjects. Probably, the dominant muscle pattern was the rectus femoris (anterior muscles). This indicates a more backward postural lean than normal.
From HC to 40% of stride the knee doesn't flex and a small knee extension moment and less power generation or absorption of the knee are noticeable. From 40% of stride the knee starts to flex to 70-75% of stride (early swing). The small knee flexion moment is associated with the small power absorption. The knee is mainly in extension and may be a result of his lesion or a result of other problems (stiffness).
The low power production of the ankle before TO is related to the lower amplitude of the ground reaction forces and a resultant change is the reduced step length. This is consistent with the results in literature that push-off work is greatly reduced and also step length.

The ground reaction force vector diagram of woman A shows a greater amplitude at TO which may be related to the greater power production by the hip and the ankle during TO. From 10% to 40% of stride the ankle dorsiflexion and the ankle moment are smaller. Than a burst in the ankle moment and in power absorption are shown.
The hip and the knee are more flexed during the whole stride period. From HC to 20% of stride a burst in the hip production is shown. During late swing a burst of power absorption in the knee is shown which may necessary to decelerate the swinging limb before HC. The greater velocity may be the cause of these burst.

The ground reaction force vector diagram of woman B shows a greater amplitude at TO which may be related to the greater power production by the hip during TO.
For the left foot the greater production of power by the hip during HC may relate to the first number of ground reaction force vectors which show greater amplitudes.
During the swing phase the hip flexion and extension moments are greater and also the power absorbed and produced.
The knee angle shows greater peaks in extension and flexion and this is reflected in the knee moment and power which also show more flexion/extension respectively more absorption/production.
During late swing the burst of power absorption in the knee may also necessary to decelerate the swinging limb before HC. The greater velocity may be the cause of these burst.
From 10% to 50% of stride the ankle dorsiflexion and the ankle moment to 30-35% are smaller. Also less power is absorbed.
The onset of the moments (knee and ankle) and the power peaks are later in the stride period.

8.5 Conclusion.

The three subjects have all different gait patterns with some similarities and these show also differences with the results of other studies. The results of these study shows great interindividual differences, especially in the power absorption and generation.
The need for a normal data base for different age groups and for slow, normal and fast speed to make comparisons between affected gait patterns and normal patterns of the same age group is in great demand and necessary. Reference data may be used for comparisons as intra- and interindividual, between healthy persons and those with a neuromuscular or other pathology.

8.6 Acknowledgement.

I wish to thank S. Boccardi, C. Fossati, and C. Cellario for their participation in this study.

9. Respiration analysis of three elder volunteers.

9.1 Introduction.

A new method which is non-invasive and non-ionising, has been developed to investigate the respiratory system and the strategies of the respiratory act execution.
Partitioned volume analysis allows an evaluation of the efficacy of the different muscular groups involved in respiration and to study the dynamic interaction between the respiratory muscles and the passive viscoelastic structural components.

The aim of this study is to present data of the respiratory function of elder subjects by the use of the ELITE system and to analyse these. In this way, the possibilities of the method and the kind of information is shown. A statistical analysis has not been performed because of the number of subjects involved in these study.

9.2 Subjects.

Patients of the 'Ospedale Valduce' near Como in Italy without respiratory pathologies, were asked to take part in these investigation. Two women (59 & 78 years of age) and one man (68 years of age) participate in this study. They were all wheelchair patients and followed a revalidation program. The man had been a runner when he was younger and has now cerebral ictus. The two women had physiotherapy for arm movements; the oldest woman for her right arm and the younger woman for her left arm.

9.3 Analysis.

The ELITE system was used for the respiration analysis which measures the 3-D coordinates of several passive markers. Four fixed TV cameras took the markers placed on the trunk of the subject. The 40 marker model was used in sitting position and the 20 marker model in supine position (just by taking away the markers of the posterior frame). The markers were arranged on an anterior five by four frame and a symmetric posterior one. Starting from these coordinates, the thoracoabdominal volume was computed by using a model of the trunk compound of twelve polyhedrons and the total volume is the summation of the twelve polyhedrons. These compartments allow also the computation of the contribution to ventilation due to the lung ribcage, the abdominal ribcage, and the abdominal wall useful for the analysis of the breathing pattern; and the contribution due to right and left trunk useful to point out asymmetries.
During the data acquisitions the subjects were not allowed to move or to talk because than the markers will move as a result of respiration and of this movement.
The subjects performed several breathing manoeuvres first in sitting position and than in supine position.

The subjects were asked to breath quiet and to perform the following manoeuvres in both positions:

1. Quiet breathing.
2. Four deep breathings.
3. Vital capacity; to perform maximal expiration, followed by a maximal inspiration and to expire again maximal and continue to breath normally.

It was not possible to obtain the data of all manoeuvres because the subjects had other arrangements to go to.
The experimental set-up is shown in table 3.

SET-UP:

		Breathing performance		
Position	no. of markers	Quiet	4* Deep	Vital Capacity
Sitting	40	10 Hz	25 Hz	25 Hz
Supine	20	10 Hz	25 HZ	25 Hz
Time duration		180 sec.	≈ 30 sec.	≈ 30 sec.

Table 3 Experimental set-up and the frequency and time duration of the measurements.

9.4 Results.

In Table 4 the manoeuvres, that every subject performed, are shown.
Because the older woman got backpain during the data acquisition in sitting position, only three performances were obtained.

		Breathing performance		
Subject	Position	Quiet	4* Deep	Vital cap.
Man 68 years	Sitting	X	X	X
	Supine	X		X
Woman 78 years	Sitting	X		X
	Supine		X	
Woman 59 years	Sitting	X	X	
	Supine	X	X	

Table 4 Acquired data (X = acquired).

The graphics of interest of the subjects are shown in appendix 6.

An unusual partitioning of the total volume among the three horizontal components (upper and lower thorax, abdomen) are shown in the graphics of the man (sitting position). Normally the abdominal volume variation is 30-40% of the total volume variation and this subject showed for all manoeuvres in sitting position an abdominal volume variation of ≈ 50%. The contribution of the upper thorax is reduced and so the total volume variation of these three manoeuvres are normal. These results may due to stiffness of the ribcage and/or weakness of the respiratory muscles, especially the sternal-cleido and costal muscles or as a result of his lesion, cerebral ictus.
In the vital capacity manoeuvre more noise is seen during the maximal inspiration which indicates more stiffness of the upper and lower thorax. An asymmetry in the volume contribution of the right and left compartments is shown in the upper and lower thorax during this manoeuvre. In scoliosis this asymmetry has always been seen.

The graphics of this subject in supine position during quiet breathing and during vital capacity appear normal. Only a big asymmetry in the volume contribution of the lower thorax and the abdomen are shown. These are not normal and really strange especially because these results are also shown in the abdominal compartments. The explanation for these results can be that the subject wasn't laying straight. A synchronism among the three horizontal components (upper thorax, lower thorax, and abdomen) can be observed for all manoeuvres in both positions.

The graphics of the older woman during quiet breathing in sitting position appear normal. During the vital capacity manoeuvre, the abdomen is in counterphase with the thorax. For the deep breathing manoeuvre a low volume variation of the lower thorax and the abdomen is shown. These results for the special manoeuvres are shown more often in untrained (naive) subjects. A synchronism among the three horizontal components can be observed for all manoeuvres.

The graphics of the 59 years old woman during quiet breathing in both positions show a bit high frequency and a lower total volume variation. In supine position and during quiet breathing also an extremely low volume variation of the abdomen is shown (the volume variation is just like in sitting position).

For the deep breathing manoeuvre in sitting position, a reduction of the lower thoracic and the abdominal volume is shown. The volume compartment variations of these are also very low and asynchronous. These results for this special manoeuvre are shown more often in untrained (naive) subjects.

During quiet breathing in both positions and the deep breathing manoeuvre (only supine position) a synchronism among the three horizontal components can be observed.

9.5 Conclusion.

Because of the variation of the age of the subjects and because they were (wheelchair) patients, the obtained data are not suitable for a normal data base. As can be seen by these preliminary results, the method is able to provide a lot of information (volume changes, the effects of stiffness, motor coordination, volume partitioning, typical patterns) starting from kinematic data. This can allow a better understanding of the breathing pattern and of its alterations in a non-invasive and non-ionising way.

9.6 Acknowledgements.

I wish to thank F. Molteni and A. Aliverti for the opportunity to perform the data analysis and the three patients for participating in this study.

10. Conclusion.

Changes in the gait of elderly are shown in literature and in the results of the gait analysis of the three elder subjects obtained in these study. The results of this study show great interindividual differences. Determined kinematic and kinetic patterns which are atypical may due to primary or secondary problems or at an adaptation to these problems.
However, there is not a normal data base for all age groups which is useful to make inter- and intra-individual comparisons and to analyse the effect of lifestyle, physical fitness, nutrition, diseases and so on. A complete data base is in great demand which is useful to have a better understanding of locomotion, for developing and evaluating therapies, and to determine relations with other human functions.

Changes in the respiratory function have also been investigated and a decline in lung capacity and in oxygen use or consumption during exercise has been shown as people age. One of the three elder subjects analysed had instead of a normal volume contributions a decreased upper thorax and a increased abdominal volume contribution. These can be the result of stiffness of the ribcage or weakness of the respiratory muscles. Investigating the pulmonary function with the ELITE system can reveal stiffness of the spinal column, scoliosis, and several pathologies in a non-invasive and non-ionising way.

At the Centro di Bioingegneria the ELITE system is used for gait and respiration analysis. This system is suitable to use for BLSA studies and satisfies the requirements of a gait analysis system. The freedom of movement, the quick data acquisitions are advantages of the system. One disadvantage is that the system is relatively expensive.
The ELITE system and its software packages are suitable for many applications (for example: gait, posture, respiration, surface reconstructions, small movements) and is thus very flexible. For gait analysis, an almost complete pattern of the subject is acquired in combination with a forceplate and EMG.
The analysis of the upper thorax, lower thorax and abdomen and of the left, and right volume compartments are possible and so the respiratory function is analysed.
The use of the ELITE system for these applications is suitable for routine use and the experimental sessions are easy and quick set-ups and leaves the subject maximum freedom of movement.
So, the use of the ELITE system in the BLSA could be a good investment because of the flexibility (many applications), the freedom of movement for the subject, easy in use, quick data acquisitions, present data rapidly and in a form readily to analyse.

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Appendices

APPENDIX 1

Anthropometric Measurements.

Anthropometric measurements are acquired for the estimation of the joint centres of rotation of the hip, knee and the ankle and for obtaining internal reference points.
The measurements points are (see figure 12):

1) Pelvis width.
2) Pelvis height (this is obtained on the subject seated on a rigid support by measuring the distance between the upper iliac crest and the support plane).
3) Vertical distance between the posterior iliac spines and the upper iliac crest.
4) Thigh length (between greater trochanter and lateral femoral condyle).
5) Shank length (between lateral femoral condyle and lateral malleolus).
6) Diameter of the knee (intracondylar distance).
7) Diameter of the ankle (intramalleolar distance).
8) Width of the foot (distance between first and fifth metatarsal heads).
9) Foot length (from heel to big toe).
10) Height of the lateral malleolus from the floor (with foot flat on the floor).
11) Horizontal distance between lateral malleolus and heel (with the foot flat on the floor).

Fig. 12 Anthropometric measurements.

All the measurements, except those related to the pelvis, are required for both lower limbs. Measurements number 10 and 11 are required for graphical purposes only. Measurements number 4, 5 and 9 will be used by other elaboration programs.

APPENDIX 2

Location of the markers for gait analysis.

1) Pelvis and lower limbs:

Two markers on the posterior iliac spines supported by small brackets in order to avoid the marker on one side to be seen by the contralateral couple of TV cameras. One spherical marker on the sacrum bone supported by a pin (this marker must be seen from both sides). The distance between each marker and the skin is fixed.
Two markers on the lateral femoral condyles.
Two markers on the lateral malleoli.
Two markers on the lateral aspect of the fifth metatarsal heads.

2) Column:

One marker on the spine process of the seventh cervical vertebra and one on the point of maximum kyphosis (middle point between the scapular apexes, approximately the T7-T8 spinal process). These markers are supported by a pin at 1.5 cm from the skin surface.

3) Head:

Two markers are symmetrically located in the arieto-occipital area by means of small brackets. Each of them must be seen by only one couple of TV cameras.

4) Upper limbs:

Two markers are fixed to the acromion bone means of brackets. Two markers are fixed to the lateral homerus epicondyles (elbow), and two at the stiloideus process (wrist).

APPENDIX 3

Questionnaire(32)

This is a questionnaire to investigate your daily activities. I would like to associate these results with the results of the gait analysis. I will be very grateful if you will answer these questions. Anyway, I will thank you very much to participate in these investigations and I wish you well.

1. What is your age?
   ..... years

2. In what kind of house do you live?
   - House of your own
   - Apartment
   - Flat
   - Bungalow
   - Service flat
   - Others: ....

3. Do you live on your own/independent/alone?
   ....

4. Can you perform the following acts by yourself? (classify as follows: 1) no problems; 2) need some help; 3) not able at all)
   - dressing
   - washing
   - cooking
   - do the dishes/washing-up
   - vacuum
   - cleaning the house
   - stair walking
   - shopping
   - carrying heavy bags
   - garden
   - others: ....

5. If you go out, you will go by:
   classify as follows: 1) normally; 2) sometimes; 3) never i.e. very few times.
   - foot
   - bike
   - car
   - bus or tram

- taxi
- metro
- others: ....

6. If you go by foot, why do you go out normally?
    - for shopping
    - for just walking around (for example in a park)
    - for visiting friends
    - for others:.......................

7. How many kilometres do you walk a day?
    ..... kilometres a day

8. How many stairs do you walk a day?
    ..... stairs a day

9. What kind of other activities do you perform sometimes and how often a week?
    - dancing ... times a week
    - aerobics ... times a week
    - cycling ... times a week
    - running ... times a week
    - swimming ... times a week
    - playing cards ... times a week
    - others: .... times a week
      .... times a week
      .... times a week

10. Do you watch television and how many hours a day?
    - ..... hours a day

11. Do you read (news) papers or books and how many hours a day?
    - ..... hours a day

12. Do you use some medicines and what kind of medicines?
    - ....
    - ....

13. Do you have some problems or are you not able to do some kind of activities?
    - ....
    - ....

14. What kind of work did you do and when did you stop? (sitting, standing etc)
    - ....
    - stopped working in 19..

15. Did you ever sport and so, what kind of sport and when?
    - ....
    - ....

16. Have you ever smoked and what did you smoke?
    - ....

17. If you have smoked, for how many years did you smoke and how many cigars/cigarettes a day?
    smoked for .... years
    smoked .... a day

18. Will you give a scheme of your daily activities?
7.00-8.00: ....
8.00-9.00: ....
9.00-10.00: ....
10.00-11.00: ....
11.00-12.00: ....
12.00-13.00: ....
13.00-14.00: ....
14.00-15.00: ....
15.00-16.00: ....
16.00-17.00: ....
17.00-18.00: ....
18.00-19.00: ....
19.00-20.00: ....
20.00-21.00: ....
21.00-22.00: ....
22.00-23.00: ....
23.00-24.00: ....

19. Do you have some remarks?
    ....
    ....
    ....

APPENDIX 4

Definitions of gait parameters(43)

Sagittal Plane:
is a vertical plane that divides the body into right and left parts.

Coronal (Frontal) Plane:
is a vertical plane that divides the body into anterior and posterior parts.

Transverse (Horizontal) Plane:
is a horizontal plane cutting through the body at right angles to the sagittal and coronal plane.

Initial Contact (IC):
is the instant when the foot or shoe makes first contact with the ground, independent of how it makes contact with the ground.

Heel Contact (HC):
is the instant when the heel of the foot or shoe makes initial contact with the ground.

Foot Flat (FF):
is the first instant during stance when the foot or shoe is flat on the ground and is independent of how IC was made.

Heel Off (HF):
is the instant during stance when the heel leaves the ground. It usually is closely related to the start of push-off.

Toe Off (TO):
is the instant when the toe of the foot or shoe leaves the ground. It usually defines the end of the stance and the start of the swing.

Mid Swing (MSw):
is the mid point in time between TO and IC.

Stride period:
is the period of time for two steps, in seconds, and is measured from an event of one foot to the subsequent occurrence of the same foot. Usually stride period begin with IC of one foot to the next IC of the same foot. It is also commonly expressed as 0 to 100% for comparisons.

Step Period:

is the period of time for one step, in seconds, and is measured from an event of one foot to the subsequent occurrence of the other foot. Usually step period begin with IC of one foot to next IC of the other foot.

Double Support:

is the period of time in walking when both feet are in contact with the ground expressed in seconds or as a percentage (%) of the stride period. Right double support is the time between IC of the left foot and TO of the right; left double support is the time between IC of the right foot and TO of the left.

Single Support:

is the period of time when only one limb is in contact with the ground expressed in seconds or as a % of the stride period. For walking, it is exactly equal to the swing period of the contralateral limb.

Stance Period:

is the period of time when the foot is in contact with the ground expressed in seconds or as a % of the stride period. Stance has been subdivided into several sub-events: weight acceptance, mid-stance and push-off.

Weight Acceptance (WA):

is the period of time between IC and the time of maximum knee flexion of the support limb during stance, expressed in seconds or as a % of stride.

Push Off (PO):

is the period in time late in stance when the lower limb is pushing away from the ground and ankle plantarflexion occurs, expressed in seconds or as a % of stride.

Mid Stance (MS):

is the period of time between WA and PO. In slow to fast walking normals, this represents 15% to 40% of stride period.

Swing Period:

is the period of time when the foot is not in contact with the ground, usually expressed in seconds or as a % of stride period. Swing has also been broken into sub-events: lift-off and reach.

Lift-Off (Early Swing):

is the period of time between TO and MSw, expressed in seconds or as a % of stride period.

Reach (Late Swing):

is the period of time during swing between MSw and IC when the knee is extending, expressed in seconds or as a % of stride period.

Cadence:

is the number of steps per unit time, expressed as steps /min. Natural or free cadence is the cadence that the subject achieves when the given instructions to walk as naturally or freely as possible. Fast or slow cadences are forced cadences above or below natural cadence and must be specified by the researcher.

Stride Length:

is the horizontal distance covered along the plane of progression during one stride; it is the distance covered from IC to IC of the same foot expressed in meters, and is equal to the sum of two step lengths. The stride length is equal for left and right limbs if the person is walking in a straight line.

Stance/Swing Ratio:

is the ratio of stance period to swing period.

Step Length:

is the horizontal distance covered along the plane of progression during one step; it is the distance measured from a point on one foot to the same point on the other foot expressed in meters. Specific step lengths for right and left side must be measured to specify an average step length over many strides.

Gait Velocity:

is the average horizontal speed of the body along the plane of progression measured over one or more stride periods. It is reported in m/s or m/min.

Reaction Force:

is the resultant force acting on or at any point in the skeletal system. The internal reaction forces at any point are in static or dynamic equilibrium with the externally applied forces and the inertial forces distal to that point. The unit is Newton (N). Reaction forces are usually calculated only at joint centres.

Moment of Force:

is the name given to the product of a force acting at a distance about an axis of rotation, and which causes an angular acceleration about that axis. The unit is Newton-meters (N.m). Joint moments of force are the net result of all internal forces acting on that joint and include the moments due to muscles, ligaments, joint friction and structural constraints. Moments of force are in static or dynamic equilibrium with the external moments due to externally applied and inertial forces distal to that joint. Torque is a synonym for moment of force.

Mechanical Energy:

is the energy state of any limb segment or total body system at an instant in time and represents the potential of that system to do work. It is measured in Joules (J). It comprises potential energy, translational kinetic energy and rotational kinetic energy.

Mechanical Power:

is the work performed per unit time, and is used to quantify the rate of generating or absorbing energy by muscles or the rate of change of energy of a segment or body system. It is measured in Watts (W). Muscle mechanical power is the product of the muscle force and its velocity (linear) of shortening or lengthening. The joint mechanical power (generated or absorbed) by all muscles and ligaments crossing a joint is the product of the moment of force and the angular velocity at the joint. At any given time some muscles crossing a joint can be generating energy while others are absorbing energy; the net rate of energy generation or absorbing is evident in the joint mechanical power.

Myoelectric Signal:

is the name given to the total signal seen at an electrode or differentially between electrodes. It is the algebraic summation of all motor unit action potentials within the pick up area of the electrode(s). When amplified, the signal is called an electromyogram (EMG).

APPENDIX 5

Definitions of respiration parameters.

Lung Volume Compartments:

ERV	Expiratory reserve volume. The maximum volume of air that can be exhaled from the end expiratory level (i.e., the functional residual capacity).
FRC	Functional residual capacity. The volume of air remaining in the lungs at the end of a normal expiration.
IC	Inspiratory capacity. The maximum volume of air that can be inhaled (i.e., to total lung capacity from FRC). Thus: $IC = TLC - FRC$
IRV	Inspiratory reserve volume. The maximum volume of air that can be inhaled (i.e., to TLC over and above the tidal volume). Thus: $IRV = IC - V_T$
RV	Residual volume. The volume of air remaining in the lungs after a maximum expiration. Thus: $RV = TLC - VC$ $= FRC - ERV$
TLC	Total lung capacity The volume of air in the lungs after a maximum inspiration, or the sum of all the compartments of the lung.
VC	Vital capacity The maximum volume of air that can be expelled after a maximum inspiration (i.e., from TLC).
V_A	Alveolar gas volume.
V_D	Dead space volume.
V_T	Tidal volume. The volume of air inhaled or exhaled with each breath during breathing.

APPENDIX 6

Graphics of the respiration analysis.

The graphics of the horizontal compartments are printed as follows: at the top the upper thorax, the lower thorax and than the abdomen.

The graphics of the vertical compartments show the right compartment at the top.

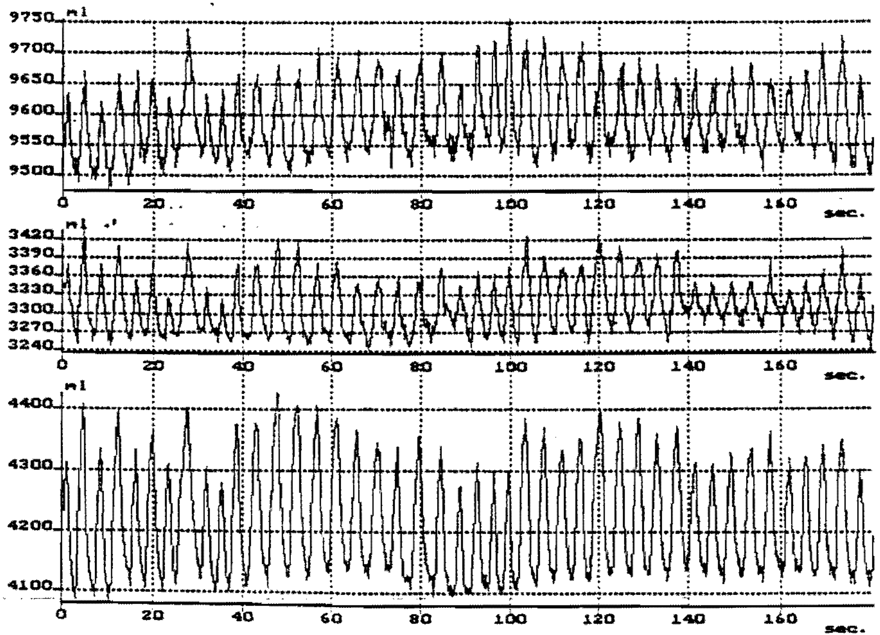

Fig. 1 The man, sitting position, quiet breathing.

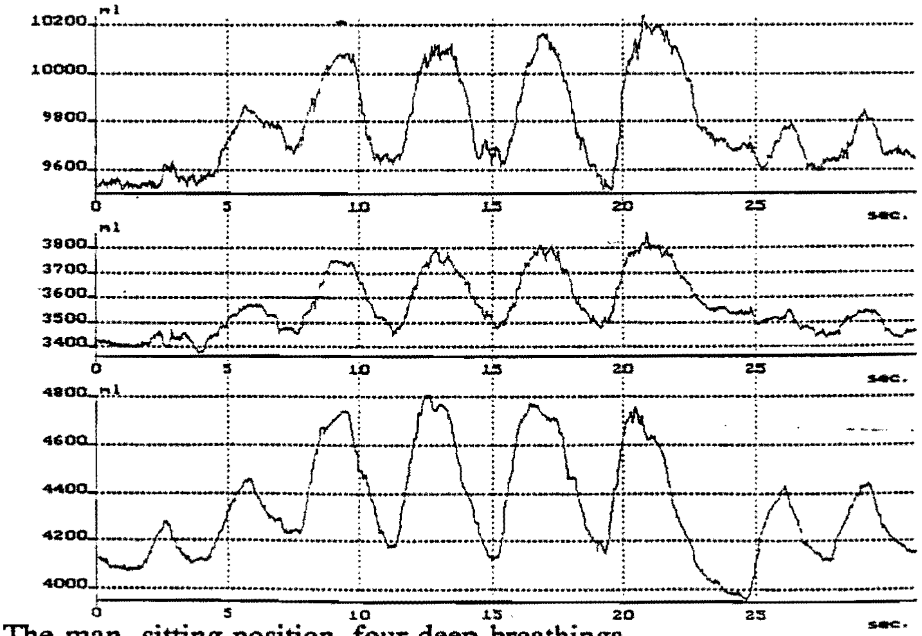

Fig. 2 The man, sitting position, four deep breathings.

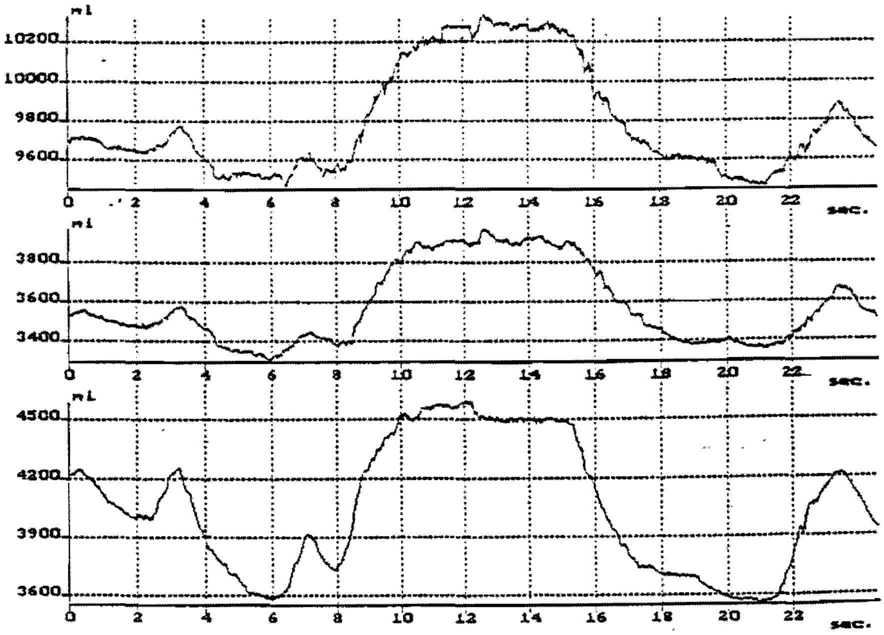

Fig. 3 The man, sitting position, vital capacity.

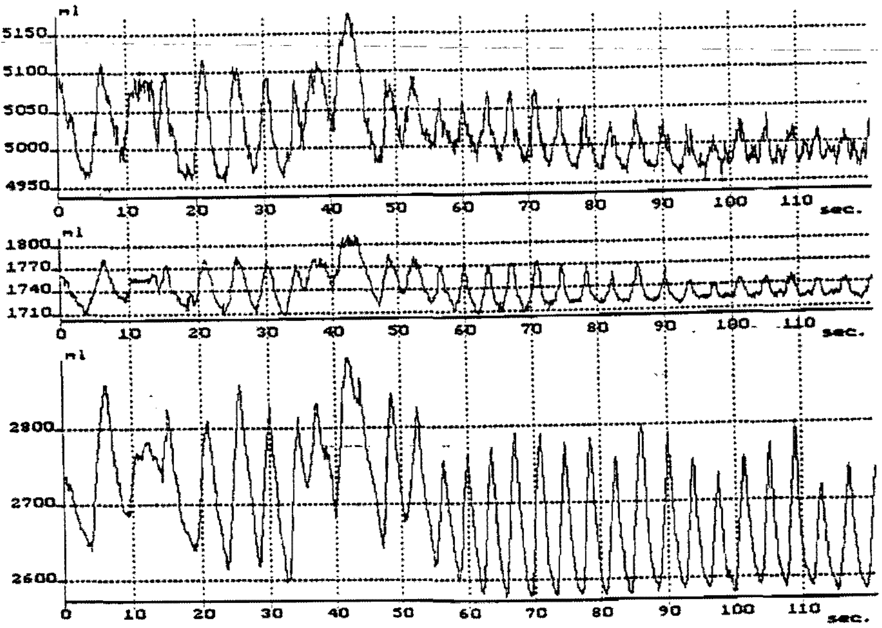

Fig. 4 The man, supine position, quiet breathing.

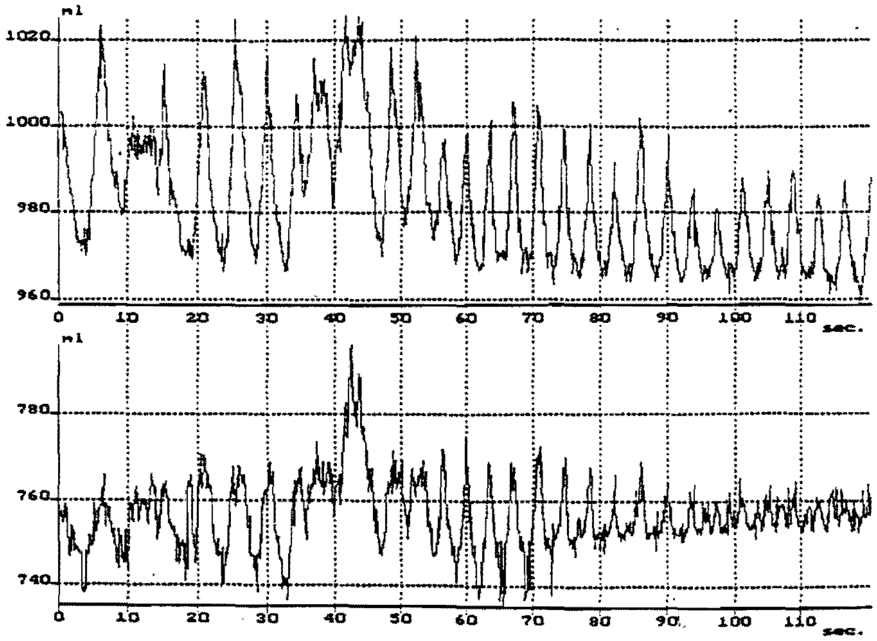

Fig. 5 The man, supine position, quiet breathing, vertical compartments, lower thorax.

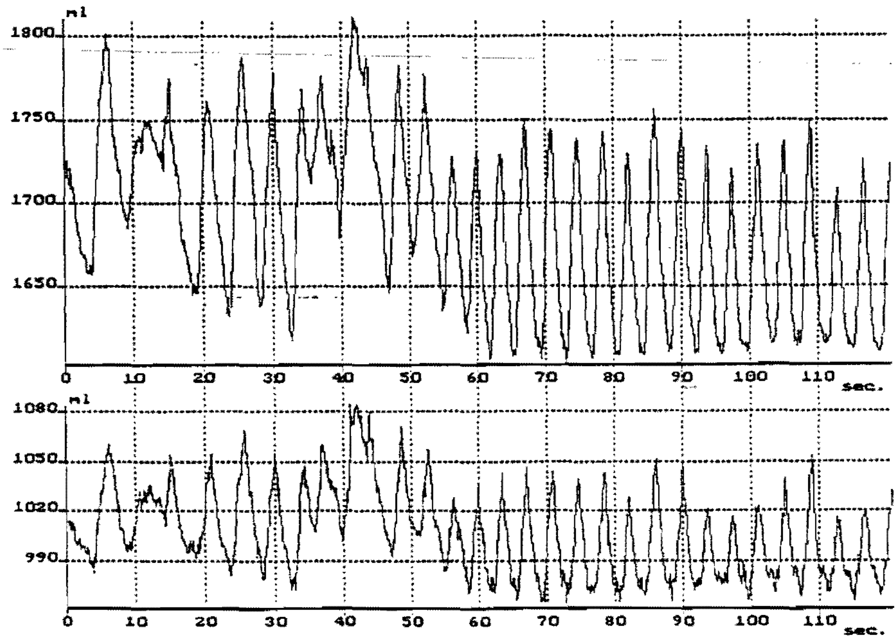

Fig. 6 The man, supine position, vertical compartments, abdomen.

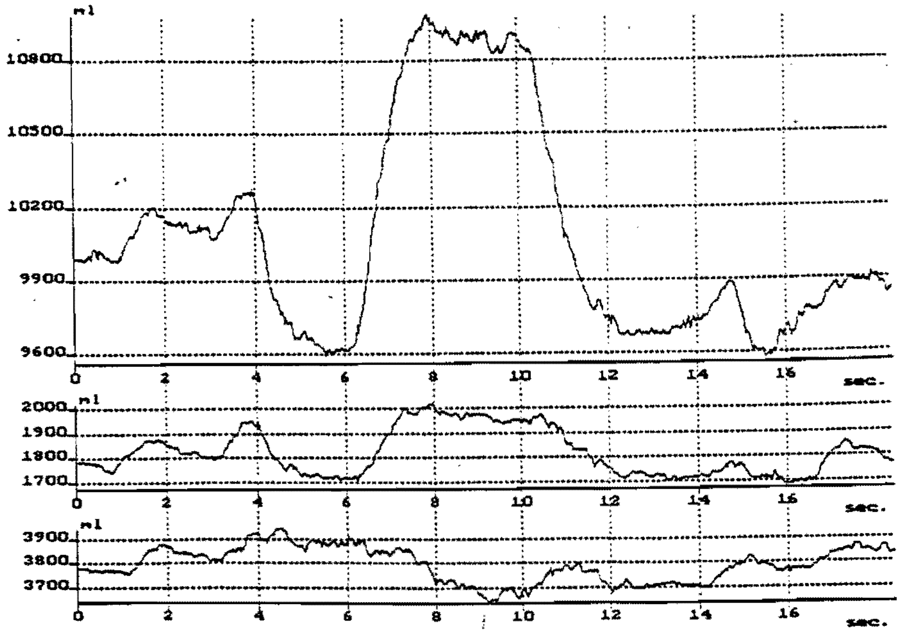

Fig. 7 The woman, sitting position, vital capacity.

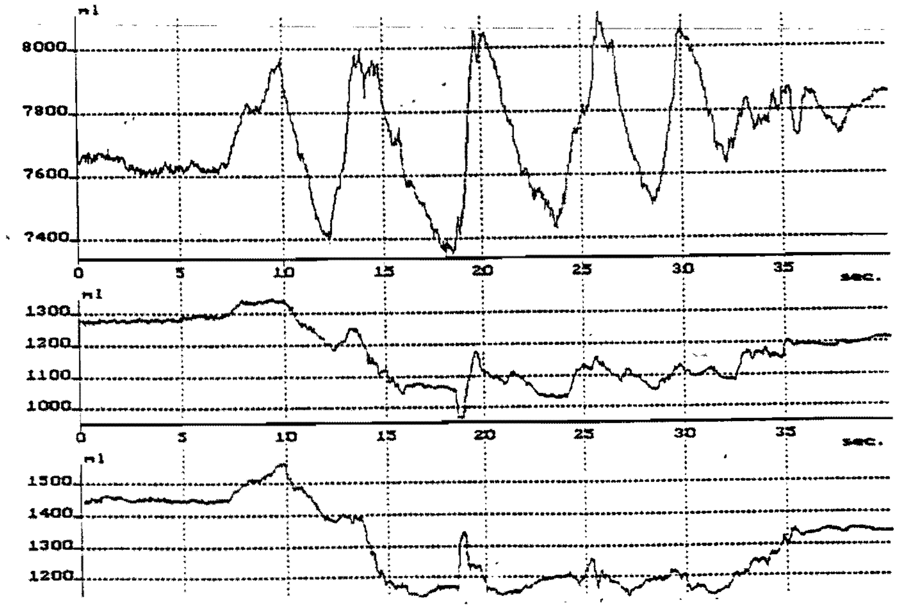

Fig. 8 The woman, sitting position, four deep breathings.

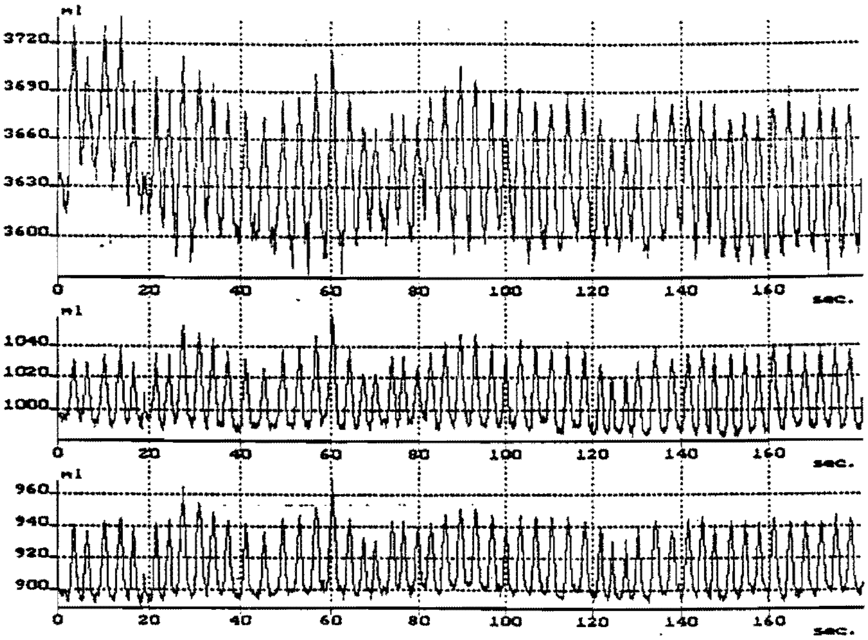

Fig. 9 The man, supine position, quiet breathing.

APPENDIX 7

Calibration procedure.

First, recognition of all grid markers is necessary for all cameras used in the system. Therefore, the cameras are focused on a grid with fixed markers. The zoom and the angles of every camera are initialised in a way that the grid will be seen into the monitor while varying the depth of this reference grid. This determines also the volume in which movement will be taken place during the data acquisition.

After this procedure, the various set-up parameters (angles of the cameras and distances towards the grid) are put into the computer. With these rough values, the computer can calculate the final, exact values by means of a convergence algorithm.

Now the cameras will have to stay in this fixed positions. For calculating the correction of the optical distortions (a square will not be recorded as a square when the camera position is not in front of it) another procedure has to be carried out. The grid will be placed in front of every camera. This will give a "real" square on the monitor. With this information, the computer can correct for the optical distortions in the acquired data of every camera.