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Requirements of clinical gait analysis

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Clinical protocols on gait analysis should be focussed on the medical problem which has to be solved. As a number of different medical specialists are engaged in the treatment of disorders of human locomotion, there are accordingly a variety of questions. Neurologists, physiatrists, orthopaedic surgeons, rehabilitation engineers, orthotists and prosthetists as well as physiotherapists, all have their specific interests. Why should they want instrumented gait analysis as a help to their own qualitative visual assessment of the people they are treating? How different are their fields of interest?

Human walking represents a highly integrated activity, which relies on many functions of the nervous system, from the brain to the spinal cord and the peripheral nerves with their motor and sensory connections. Almost all striated muscles are activated during the different phases of a walking cycle. Any disorder of bones and joints tends to affect gait. Gait is a highly constant phenomenon with typical changes related to body proportions and growth, as well as to ageing and to specific pathological conditions. Consequently, gait movements are typical for a particular person and they can be tested repetitively with a high constancy of results (Kadaba et al. 1989). For clinicians, factors of gait such as energy production and efficiency of locomotion, phasic muscle innervation and the distribution of joint loads, even the quality and quantity of the exchange of kinetic energy between the body segments are of interest. Gait analysis provides a large amount of clinically relevant data which are useful guides for diagnostics and qualitative tests of function.

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The Motion Analysis Laboratory in Basel was set up as a tool for planning and controlling the effect of treatment by orthopaedic surgeons. What does gait recording and analysis bring to clinical orthopaedic surgery and rehabilitation and how should its protocols be devised?

The overall quality of walking is best measured by energy consumption under steady state conditions for a unit of distance (Rang and Wright 1989). Walking speed, step length and step frequency must be measured. Optimal performance of a specific person is related not only to body parameters such as heigth, weight, leg length, but also to the structural and functional integrity of the locomotor system.

Recording and documenting normal gait at different ages permits comparison of the stages of locomotion from small children to the elderly as a help for defining age-related functional goals (Sutherland et al. 1988). The reduction of step length and step frequency in older subjects is often connected with a decrease in hip extension and transverse pelvic rotation (Baumann 1980).

Recording and documenting gait before and after orthopaedic surgical interventions in case of skeletal deformity or joint damage of the spine and lower extremities provides information which is as essential as radiographs for planning treatment. Several aspects of gait cannot be analysed without the help of instruments because our senses cannot see the details of the rapid movements of foot and leg at the transition from swing to stance phase and cannot feel the vector components of ground reaction force (Baumann et al. 1982). The complexity of walking movements is such that their assessment requires repetitive viewing of photographic documents as well as the intensive analysis of the quantitative data.

Treatments aimed at improving function must be controlled for their quality by functional and dynamic analysis as opposed to a prevalently static approach. For many orthopaedic problems, either static examinations based on radiographs or single joint functional tests devoid of considerations for integrated locomotor function still prevail.

In patients with cerebral palsy, documented information of pre- and postoperative walking function has permitted better assessment of the short- and long-term effects of many treatment modalities (Baumann 1988; Gage et al. 1984; Sutherland and Baumann 1981). It has claryfied the importance of muscle contractures as well as that of the co-contraction of antagonistic muscle groups. Many developments with positive therapeutic effects grew out of critical assessment of quantitative and qualitative gait recordings of patients with not so favourable short- and long-term results which had been obtained with other methods of treatment. The replacement of hamstring transfer and peripheral tendon lengthening by fractional aponeurotic muscle-tendon elongation is such an example.

The Gait Laboratory has produced valuable documented information for the preoperative design of surgical procedures, such as intertrochanteric rotational osteotomies of the femur and tibia as well as for aponeurotic lengthening of hip adductors and hamstring muscles. Like Gage et al. (1987) we have tested and controlled therapeutic indications and results of patients with spasticity and reduced knee flexion in swing phase. The surgical procedure of distal rectus transfer by Perry (1987), has proved to be a valuable help under specific conditions. Such recordings permit progress in connection with follow-up examinations which test for weak areas in schedules for treatment.

Force plates have brought and continue to bring new insights into force transmission by normal and deformed feet to the ground. Varus deformity of the heel impairs normal shear force vectors in a lateral direction during early stance phase, while a valgus deformity enhances lateral shear. Knees affected by ligamentous injuries and attempts to compensate the defects by muscle-tendon transfer procedures can lead to vibration emanating from the knee into the whole of the leg during stance phase. Combining the use of force plates with accelerometers attached to the head has permitted the study of the transient shock-wave travelling from the heel to the head in about 5 msec when the heel hits the ground at the beginning of stance phase. But normal compensatory changes in the walking movements of such patients and shock damping shoe heels can reduce these transients (Baumann et al. 1984).

These examples indicate, that the measuring system and the clinical protocol should be adaptable to specific purposes. Optimal measurement systems for the knee joints of spastic patients, for club foot assessment and scoliosis, in paraplegia and in diabetic neuropathy may differ considerably.

Particular requirements for clinical gait analysis

If one considers clinical gait analysis as a field which is still open to diversity of instrumentation and developments as well as to the use of different systems ranging from simple set-ups to highly complicated applications of hardware and software, it is important to be aware of some basic rules:

- Gait analysis tests a repetitive phasic phenomenon. Optimal evaluation demands that the procedure for recording and measuring must be repeatable under standardised conditions. Fixed installations are therefore desirable.
- A representative number of step cycles must be evaluated and presented, usually 5. The variability within a series of steps represents a clinically important factor for gait assessment.
- The recording and testing instruments must provide sufficient temporal and spatial resolution for detecting important phenomena at the transitions from swing to stance phase and vice versa.
- While measuring errors in biological systems are usually relatively large, excessive errors must be strictly avoided because they produce results which are not only quite useless, but which can also be misleading and dangerous.
- It must be possible to check the accuracy of recorded measurements and the calculations which are performed on their basis. Complicated systems for recording and data evaluation can suffer from occasional defects.

Multiple measurements need systematic links to time recordings over each of several gait cycles. They include:

- recording of the spatial and temporal positions of body segments,
- force measurements,
- electromyographic records,
- muscle-tendon tension,
- foot contact switches,
- accelerometers,
- energy expenditure by walking a distance over time.

Clear distinctions have to be made between gait analysis with its raw and processed data on the one side and gait assessment on the other. The recording and data evaluation represents a clearly defined task in applied physics. Gait assessment on the other hand has to correlate recordings and measurement results with complicated anatomical structures and a number of physiological, i.e. functional, factors, which are equally complex.

Setting up standardised clinical protocols on gait analysis demands the inclusion of basic information such as:

- speed of walking,
- step length and step frequency,
- the duration of single stance for the right and left leg,
- the duration of double stance when shifting from left to right and from right to left,
- swing phase left and right.

The graphic representations of joint angles and force plate outputs over time which are based on the work by Eberhart et al. (1947), have found standardised representations in most gait evaluations. In scientific presentations, the indication of standard deviations, systematic corrections for distorsions from the projection in 3D space as well as high spatial and temporal resolutions seem desirable in many instances. Reports should either contain images of the walking person of photographic quality or a 3D computer model.

Useful but not always obtainable

In order to solve specific clinical questions, standard gait analysis using either 16 mm instrumentation cameras or video cameras and force plates must frequently be supplemented by other sensors:

- *Electromyography* using surface or wire electrodes can add highly useful information on neuro-muscular activity. The value of electromyography is greatly enhanced by a lightweight radiotelemetry system. Kinesiological electromyography reveals the best information when using wire electrodes and by representing the raw EMG, but with proper restrictions surface electrodes are permissible (Perry and Hoffer 1977).
- *Muscle-tendon tension*. Clinical orthopaedics would be helped by measurements of musculo-tendinous tension. Because of its close relationship with muscle tension, intramuscular pressure is a useful indicator, but difficult to measure on a walking person (Baumann et al. 1980).

- Measurement of *stress and strain in bones* would be desirable in normal and pathological fractures and their treatment, as well as in osteoporotic patients. Measuring such values and transferring the data to a recording device from a bone implant is still difficult, however, with todays technical means.

Areas of particular need for further improvement in gait analysis

In order to increase the amount of relevant information from gait analysis and to improve the quality of gait assessment, a few areas need particular attention:

- Gait protocols must regularly include information on *body parameters*. Standing height, sitting height and body weight are a minimum. 3D measurements of the standing person with stereometric reconstruction of segmental body volumes, segmental centers of gravity and total body center of gravity are desirable. On such a 3D body model the definition of anatomical coordinate systems for each body segment is necessary (Schaer et al. 1989).
- In persons with physical handicaps, mass distribution among and within the body segments can be greatly altered in comparison to normal conditions. This is of clinical relevance (Sheffer et al. 1989).
- For 3D modelling of gait movements careful attention to the location of the centers of motion of the major joints is needed.
- At least a part of every gait analysis should realistically document total body movements because gait is a total body movement, and clinical assessment must include movements of the head, trunk and arms even when disturbances in lower extremity function are of primary interest.
- Angular velocities and accelerations at the major joints such as hips, knees and ankles are of considerable clinical interest. Reliable data on acceleration demand sampling rates which are difficult to achieve in sufficient spatial resolution by optical systems. Accelerometers are desirable for some specific applications.
- Rotatory movements of body segments around the longitudinal axes of the segments are particularly important factors to be evaluated. Measurements of transverse rotations must therefore be done with acceptable accuracy and expressed in relation to anatomical axes as well as in laboratory space coordinates.

- High spatial resolution of recording cameras or other spatial position sensors is wanted in order to make it possible to assess the relevant details in total body movements and to measure complex joint movements between body segments.
- In order to see vibrations and fast movements at foot contact time, a recording frequency of at least 100 IPS and an exposure time of not longer than 1/500 of a second is necessary.
- Evaluation of optical records of the whole person in motion at spatial resolutions which are sufficient to measure 3D segmental positions accurately in time, are now economically feasible by digitizing cinefilm records with the help of a digital CCD array camera. The same techniques could provide more accetable graphics for clinical protocols than offered by stick figures if high resolution CCD video cameras of sufficient speed would be employed.
- By using digital image processing techniques, reliable and useful protocols from gait analysis for clinical applications are now easier to produce.
- Graphic presentations of time-based series of spatial positions of a 3D model showing relevant human anatomy are desirable.

Qualitative and quantitative gait analysis are both necessary for clinical assessment but there must be links between them. Quantitative analysis of transverse rotations, for example, must be achieved with the highest possible accuracy and resolution. Gait analysis must provide better insight into the pathophysiology of locomotion than is available today for it to be of real value for the clinician. It is not enough to obtain vague impressions from such measurements. Simple and cheap instrumentation for quantitative gait analysis is not available. It can be used successfully for purely qualitative assessment, however.

The assessment of the clinical importance of quantitative gait analysis may be supported by the application of inductive learning techniques (Kirkwood et al. 1989).

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