Noninvasive diagnostic methods for perceptual and motor disabilities in children with cerebral palsy

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Abstract

The field of neuroorthopedics centers on chronic diseases demanding close clinical monitoring. We shall use several examples to show how the various noninvasive diagnostic instruments can be used to obtain insight into the central nervous system as well as into the musculoskeletal system and its morphology. The choice of the most appropriate method depends on the problem; that is, whether the method is to be applied for clinical use or for basic research. In this report we introduce various technical examination methods that are being used successfully in the fields of pediatrics, orthopedics, and neurology. The major examination instrument in pediatric diagnostics is sonography, which is being used in this report as a research instrument for the biomechanics of the musculoskeletal system, but which also gives insight into neurofunctional sequences. In orthopedics, pedography is used for diagnosing deformities of the feet. In neuroorthopedics for children pedography acts as a functional monitor for apraxia and thus allows, for example, a classification of the degree of neurological malfunctions in the lower extremities. The 3D bodyscan is used to minimize x-raying in patients with neurogenic scoliosis. This report introduces examples of the application of MRI and fMRI for basic research. The biometric measuring methods introduced provide precise data in the areas of diagnostics and monitoring and are highly valuable for further neuroorthopedic basic research. In future we expect the ever-evolving technical measuring methods to enable a deeper understanding of the primary neurological causes of and the implications for patients with cerebral palsy and other neuroorthopedic conditions. This may allow the development of new forms of therapy not necessarily predictable today.

Introduction

In neuroorthopedic consultation we meet primarily children diagnosed with cerebral palsy, spina bifida, and genetic disorders. The reasons for the referral from the general practitioner usually are dyskinesia, defective positioning of joints and axes, or neurogenic deformities of the spine. The predominant investigation is of the neuroorthopedic state to decide whether a conservative or a surgical type of therapy is indicated, and how often a follow-up is required. Because the field of children’s neuroorthopedics deals with diseases that are chronic or chronically progressive, regular follow-ups must be done. Moreover the neuroorthopedic pediatrician needs to keep the level of exposure of the growing skeleton to X-rays as low as possible.

The parents of a disabled child in institutional care will ask primarily for new treatment methods and demand causal research, which is being funded also by public foundations. These demands vary from educational aid to basic neurobiological research. Because neuroorthopedic diseases are incurable, the responsibility of the medical practitioner extends to the sociomedical area. The incurability of neuroorthopedic diseases leads to the emergence of many paramedical treatment methods with no sound neurophysical basis. Therefore objective proof of the effectiveness of these treatments is being demanded; for example, the use of medicomechanical aids, which are being prescribed extensively, needs to be based on precise justification. With regards to the lower extremities and the foot, pedographic measuring is a quick way of diagnosing and reassessing, and therefore contributes to quality assurance. Obviously, when reviewing possible causes of cerebral palsy it seems feasible to consider the chances of neuronal reorganization of cerebral defects. For this the highly specialized analytical method of functional MRT is most appropriate and should indicate long-term chances for further development of the damaged brain. On the other hand, this method allows for displaying cerebral access to the paretic extremity in the individual child and for determining which kind of therapy is most promising in supporting this (e.g., training of the motor function and dexterity), and what would disturb this process.

In our report we demonstrate the use of standard measuring methods in orthopedic and pediatric practice in clarifying various questions concerning neuroorthopedic pediatrics, and we point out ways of researching with these methods. The use of noninvasive machines, avoiding patients’ exposure to radiation, is being introduced by means of a specific research concept.

Materials and Methods

The neuroorthopedist starts with the clinical examination of the patient. In addition, an X-ray is needed to verify neurogenic scoliosis and to eliminate neurogenically decentered hips in the case of obviously defective positions of axes. Further examination requires referral of the patient to a neuroradiologist for an MRI or to a neuropediatrician or neurologist for an EEG. From these data, we shall show how six different measuring systems are being used to answer specific key questions.

Plantar pressure distribution

The soles of the feet are a human’s interface with his/her surroundings. All forces and the full body weight are transmitted via the soles to the ground. Although the foot is the most distal body part, it holds a key position owing to this basic function. It makes sense, therefore, to depict the function of the foot and the dimensions of the forces involved with the help of modern measuring methods. To judge the influence that an orthopedic insole has on the overall pressure distribution or the effectiveness of an orthopedic shoe, measuring the distribution of pressure inside the shoe is helpful. For this, the measuring sole is put on top of the orthopedic insole, thereby allowing the distribution of the pressure to be recorded directly from the plantar sole of the foot.

Full body scan

With the aid of a 3D full body scan it is possible to obtain an image of the body in ambient space that far exceeds simple photography. The resulting 3D surface data can be analyzed further to survey scoliosis in neuroorthopedic cases, dislocated hips, gradually changing body proportions, etc.
Sonography

Along with X-ray radioscopy, sonography is the standard equipment for examination in orthopedic and neuroorthopedic pediatrics. The sonographic equipment available in most orthopedic pediatricians’ practices is employed mainly to obtain monographic images of hip joints and soft tissue. On the other hand this method, which is simple to apply without strain on the patient’s system, can be used in fundamental research on the biomechanics of soft tissues.

Magnetic resonance imaging and measuring volume

In research, MRI is employed often to measure the volume of soft tissue structures in the body, as these are clearly differentiated in MRI sections. In each of the various cross-sections the area of the anatomical structures to be examined is marked (segmented) and assembled into a volume image in a 3D graph.

Functional magnetic resonance imaging

Recently, brain research has given us a very detailed view of the function of the brain. By applying functional magnetic resonance imaging (fMRI) it is possible to locate and depict the metabolic processes in the brain. However, the measurability is subject to the condition that the activity is repeatable or can be evoked periodically and repeatedly by external impulses. By comparing the images between phases of activity and phases of rest, the center of activity (e.g., in the motor cortex) can be determined and differentiated from other brain activity.

Eyetracking

We use an eyetracking system to investigate the visual perception of children with infantile cerebral palsy (Figure 10A). The eyetracking analysis is as follows. The child is fitted with a spectacle frame (without eye glasses). Three cameras are mounted on this frame. Two infrared cameras are focused on both eyes, which are lit by two infrared-LEDs. The scenery camera sits on the forehead and returns the field of view of the child (Figure 10A). In the infrared light the pupils of the eyes are reflected so that their position can be determined (Figure 10B). From the position of the pupil in the infrared video picture, the gaze points of both eyes in the scenery picture can be calculated and illustrated (Figure 10A, light blue and green marks). In this manner the movements of the eyes and the head while reading and in other everyday situations like walking, climbing stairs, or wheel chair driving can be analyzed.

Results

Plantar pressure distribution

Pedography is a well-established method for examination of foot deformities. These problems are a common reason for pediatric neuroorthopedic consultation. Noninvasive pedography is helpful in defining and planning the necessary orthopedic aids. Thus the effectiveness of the results and their degree of consistency with the original plan may be controlled. For the measurements the patient walks along a level and straight surface for a minimum of 30 double paces at his/hers normal walking speed. This may be repeated with several orthopedic insoles or shoes. The resulting data are registered by a mobile datalogger or transmitted in real time to a computer.

Figure 1(A) shows the pressure distribution in a young woman with unilateral spastic cerebral palsy and a spastic pes equinus. The pedograph in Figure 1(B) shows the diagnostic pressure distribution, which serves as a pattern for the production of the medicomechanical aid that will relieve pressure on the forefoot. In this particular case, the goal was to obtain a better bedding and pressure relief for the forefoot. The pedograph in Figure 1(C) shows the respective pressure distribution after the patient was supplied with a specially crafted orthopedic aid with a slightly elevated heel and a leather lining lifting the plantar arch. The comparison of the difference in pressures in Figure 1(D) shows the changes obtained with the orthopedic insole and the local pressure relief or additional pressure caused by the insole. The lifting of the

Figure 1. (A) Patient with right-sided hemiparesis; measurement of the plantar pressure distribution while walking. (B) and (C) Maximum pressure pictures without use and with use of orthopedic insoles. (D) Differential pressure distribution; parameter graphs depict the ground force (left) and upper part of the ankle joint moment (right): graphs are a greater number of superimposed single steps (curves in dark colors) and in each case one averaged step (curves in bright colors) of the healthy and of the paretic foot.

Figure 2. Biomechanical Law of Levers: internal joint moment (h·f) and external moment (H·F) in equilibrium. The external force F (i.e., bodyweight) acts via the lever H on the upper part of the ankle joint and is in equilibrium with the internal muscle force f multiplied by the internal lever length.
metatarsus in this example of use of an orthopaedic aid shows as increased pressure on the metatarsus on the paretic side. Directly in front of and behind the lifted metatarsus there is relief of pressure. At the toes the pressure is amplified, possibly owing to the increase in volume inside the shoe caused by the insole. The shoe needs to provide adequate space for the foot as well as for the insole. In addition, the heel pressure is relieved, which was not desired therapeutically and requires additional corrective measures to the insole.

In addition to a purely anatomical examination we use measurements of plantar pressure distribution for functional diagnostics, especially for fundamental research. The two graphs in Figure 1 show the functional kinetic parameters of the gait cycle derived from the pressure distribution. The graph of the ground force in the left diagram results from the integral of the pressure over the area of the sole of the foot. The graph shows the double peak typical for the ground force during walking, caused by the impact on stepping down and lifting the foot off the ground. The graph of the paretic right leg shows a reduction of the area and of the duration of ground contact during the total cycle of heel-to-toe contact. The diagram on the right side reflects the torsion moment in the upper part of the ankle joint. This curve depicts the degree of the pes equinus vividly. The graph of the healthy patient in Figure 1 shows the typical shape of this parameter during the stance phase of the foot, with some plantar flexion immediately on the heel strike, the angular moment of dorsal extension gradually increasing to the point of propulsion of the forefoot when lifting it off the foot (compare Figure 2). The patient’s paretic foot initially touches the ground with the forefoot. During the whole period of ground contact the vector of the force remains far in front of the axis of the upper part of the ankle joint. Thus the levering distance of the ground force to the joint remains constant while the shape of the moments graph becomes similar to the shape of the ground force graph. The possible graphs of the intermediate structures enable us to quantify the degree of the pes equinus, thereby enabling an exact assessment of the progression of the pes equinus deformity.

Full body scan

The 3D surface scan provides a data net of the client’s body surface. These data can be reassembled into a surface diagram as in Figure 3. It is possible to choose any point to reconstitute an earlier perspective for comparison with previously collected data. This allows for exact clinical reference and follow-up. Scoliosis in children with cerebral palsy often progresses rapidly and requires closely meshed follow-up. It is standard procedure to
measure the lateral curvature of the spine according to the Cobb angle shown on the radiographic image. The element of torsion included can be classified according to Moe. However, in youths frequent follow-ups through radiography are very rarely justifiable owing to the exposure to radiation. On the other hand, the 3D surface scan does permit the assessment of the lateral deviation of the spine. Typical asymmetries of the torso allow for sufficiently precise mathematical deduction of the rotation. As the software saves the surface data as a table of numbers, it is possible to overlay volume diagrams in such a way as to highlight changes in posture and deviations from the normal position. In particular with neurogenic scoliosis the progression of a rib hump, flank bulge, or dislocated hip now can be quantitatively ascertained.

The 3D surface data facilitate additional analysis with regards to various questions in many areas. For example, Figure 4 shows a section projected on to the body’s frontal plane. The intersection of this plane with the body surface describes the thoracic and lumbar deformities of the scoliotic spine with mathematical precision. The rotation element can be derived from the asymmetric deformation of the cross-sectional area as in Figure 5, whereby the actual transfer of the rotation of the spine into the asymmetries of the contour line needs to be checked by comparison with the radiograph. While the 3D surface scan cannot replace the radiographic image completely, with its exact and documented visual check-up facilities it offers to significantly reduce the overall exposure to X-irradiation by allowing interspersal of the X-rays with the 3D surface scans.

Sonography (isometric plantar flexion and ligament quality)

Figure 6 shows a single photograph taken from a video sequence, depicting simultaneously the camera picture with the force vector superimposed, an ultrasonic video of the area where the Achilles tendon joins the muscle, the measured muscular activity, the measured force and lever distances, as well as the outer and inner torque and calculated traction force of the muscle. The test person is lying face down on the examination couch. A measuring device is mounted vertically on the wall. The test person presses his forefoot against the metal sheet of the device, which then measures the size, direction, and point of origin of the force vector. The ultrasonic head records the motion of the tendon insertion. The criteria examined are the extension properties of the Achilles tendon, the changing directions of the muscle fibers while the load increases, the electrical activity within the muscle and, above all, the amount of voluntary ability to work the

Figure 6. An experiment to measure the muscle force of the plantar flexors and the relationships of forces and levers at the upper part of the ankle joint. Upper left: an ultrasonic video showing the insertion of the Achilles tendon and the muscle; upper right: a camera synchronized with an overlay of the force vector; middle left: the calculated external and internal angular moment; middle right: measured muscle activity; lower left: measured force; and lower right: lever lengths (compare with Figure 2).

Figure 7. (A) Cross-section slightly above the knee joint space and outline of the gastrocnemius muscle. (B) Cross-section through the middle of the calf and outline of the soleus muscle.
paretic muscle as compared to the healthy side. The forces and torques acting from outside the body are opposed by those within. There is an exact balance between the two angular moments always. This fact is equivalent to the Law of Levers. The force and the ratio between the levers determine the amount of the inner muscular force necessary to maintain the equilibrium. The lengths of the inner levers: the distance to the upper part of the ankle joint and to the Achilles tendon, are defined by the anatomy of the skeletal structures and are (nearly) constant. The levers of the external forces can be considerably longer than their counterparts within the body. Accordingly the force required to maintain this inner equilibrium is considerably larger than the external one.

Sonography facilitates determining the elastic properties of the tendons under action. This is of importance particularly in patients with spasticity, as their tendons need to bear a different strain to those under a normotonic load. The orientation of the myofibrils within the muscular fibers varies under stress and contributes substantially to the elastic properties of the muscle-fascia complex. It cushions the sudden impact from quick movement. In patients with cerebral palsy we find that the ability to voluntarily activate motor functions often is considerably less than could be expected from the results of the gait analysis and the measurements of the electrical muscular activity. For walking, these children revert to reflex mechanisms rather more than a healthy person would. This becomes obvious in the typical gait of a person with spasticity. These reflex mechanisms should be available as a resource to them rather than losing them because of unnecessary surgical intervention.

Magnetic resonance imaging and volume measuring

Apart from the typical pathological motion patterns of spastic hemiparesis, the loss of efficiency and reduced access to motor functions are accompanied by a noticeable atrophy of the affected half of the body. Since the spastic muscle activity is reduced, it seems self-evident that this is reflected in the loss of muscular volume. Feldkamp\textsuperscript{1} reports that strong spasticity goes along with deterioration of the contractibility of the hypertonic muscle. Therefore the reason for the diagnosed loss of volume of the spastic muscle can be found in its reduced ability to contract and relax.

As in Figure 7 (A and B) the muscles and muscle groups can be segmented from a series of layered MRI images, from which the muscle volume can be calculated. Muscle groups that differ in their functional or anatomical aspects were compared as to their volume.\textsuperscript{2} The comparison of the volume of the muscles of the...
thigh and the calf showed a significantly higher decrease in volume of the calf of the paretic leg than of the thigh. When taking the average of all probands' muscle volumes, separated for all different muscles, we found a reduction of the paretic calf muscle volume to 72% of that of the healthy calf muscle. The reduction of the paretic thigh muscles was less. Their volume averaged 83% of the volume of the healthy muscles. In individual cases the volume decreased to less than 50%.

Comparing the volumes of fiber type 1-dominanted muscles to fiber type II-dominated muscles yields a statistically significant result ($p<0.01$). Type I muscles predominantly serve to hold static loads, whereas Type II (also called the fast fiber type) are used for moving quickly. The average reduction of tissue volume of type I-dominanted musculature on the paretic side was found to be 69% of that of the healthy side. Type II-dominanted muscles showed a reduction to 79% of that of the sound side. The human muscle fibers are the same at birth and only become either type I or type II fibers when activated by the motor nerves. The human body has the ability to change the fiber type of a muscle within certain limits, therefore adapting the capacity of the particular muscles to the motor demands placed on them. For example, if a predominantly type II muscle is being used or trained to hold static loads, it will evolve eventually into a type-I-dominated muscle. The muscles that functionally differ, in being connected to either one or two joints or function as flexors or extensors, do not show a significant difference of volume.

**Functional magnetic resonance imaging**

Infantile cerebral palsy that results from a brain defect during birth or early infantile development may lead to various symptoms of the sensorimotor cortex, resulting in functional restrictions of motion. In contrast to apoplectic patients a child with cerebral palsy therefore is not able to resort to skills already learned. These deficiencies may be compensated for partly by some reorganizational activity of the brain. The example in Figure 8 depicts typical activity in the motor cortex during finger opposition in a patient with right spastic hemiparesis. Tapping the fingers of the sound left hand is controlled by the sound right motor cortex, while tapping the fingers of the paretic right hand is managed by both cerebral hemispheres. However, the healthy hemisphere is able to repair the restricted motor functions to a certain extent only. It still remains to be elucidated by further research if intensive training of the paretic hand will impair the motor function of the sound hand owing to excessive demands on the healthy hemisphere.

On a cellular level we expect new synaptic alignment to occur as in normal learning processes. Additionally much more extensive and expansive plasticity is possible in the long term than was previously assumed possible (e.g., extension or shifting of the area of activity). This reorganization process is more likely to succeed if several sections of the sensorimotor functions are involved. For example, Spitzer discovered that active engagement in music influences the maturation of the brain in a positive way. Between the auditory cortex (the part of the neocortex concerned with processing sounds and acoustic input) and the motor system (the part that is concerned with movement and posture) there are dense connections. Playing a musical instrument evoke reactions not only in those areas related to attention and emotion, but also in those related to motion control. Of course a change in the morphological structure of the cerebrum or a complete rebuilding of the defect originating from early infantile brain damage is impossible. Figure 9 shows the measurements of the motion of hands and fingers while playing the piano taken from a patient with right-sided cerebral palsy. The reflecting markers affixed to the hands allow for measuring the angular movement of the interphalangeal joints with infrared cameras. The Musical Instrument Digital Interface (MIDI) of the electronic piano facilitates synchronous recording of the timing and strength of impact of the key stroke.

**Eyetracking**

While seeing one differentiates eye movements between fixations (when both eyes view a certain point) and saccades (both eyes jump to the next point of fixation). During the saccades no picture processing takes place in the brain. The eyetracking system permits the recording and evaluation of different parameters; for example, the mean duration of the fixations, the jump distance of the saccades, correspondence or divergence of the gaze points of both eyes, and one-sidedness of the eye movements. The visual perception, or the subsequent treatment and interpretation of the seen picture in the brain, can be disturbed. The movements of the eyes (also of the head) can be affected. While reading a text the eyes move from syllable to syllable from the left to right, and then move back to the next line quickly, with back jumps (regressions) more or less often (compare Figure 11). Reading
curves allow the differentiation between optical or oculomotor problems and difficulties understanding the text. The use of an eye-tracking system allows analysis of deficits in eye-hand coordination of patients. This helps to adapt therapies or to optimize the configuration of the patients’ workplace.

Discussion

There is no controversy about the fact that radiation-free examination methods like sonography are desirable for day-to-day use in neuroorthopediatric and neuropsychiatric surgeries as well as for basic research. This report refers to the various measuring methods used as a diagnostic instrument to evaluate patients’ motor disorders. In terms of orthopedic questions and to monitor the development of a child these measuring systems yield more objective data than the purely clinical examination does, while at the same time being independent of the examiner. In addition, to reduce the exposure of the growing skeleton to radiation, these noninvasive means can be resorted to for monitoring, as they provide data at least equivalent to that of X-ray images. Only pedography and 3D body surface measuring are relevant on a day-to-day basis and are quite useful. Ultrasound examinations are a long-standing standard in pediatrics. However, the example provided here is a rather unusual but nevertheless significant use of this method, in particular for researching the underlying biomechanical properties of the skeleton. Each one of the procedures described in this report is useful and above all noninvasive and radiation-free. In the end, however, the problem in question determines the choice of the measuring method.

Pedography primarily facilitates evaluation of the effectiveness of orthopedic aids for the foot and ankle, but it is employed also in diagnosis and basic research. For example, in patients with spasticity the remaining capacity of the plantar flexors can be quantified during walking. The major advantage of measuring the pressure within the shoe is the mobility of the plant. This means that the examination does not have to be performed in a fixed position. The possibility of measuring with a pressure-measuring insole allows for deduction of a number of further functional kinetic parameters, such as the muscular plantar flexion moment.

Many orthopedicians use the 3D surface scan as a means of surveying scoliosis in their patients, for example provided here is a rather unusual but useful. Ultrasound examinations are a long-standing standard in pediatrics. However, the example provided here is a rather unusual but nevertheless significant use of this method, in particular for researching the underlying biomechanical properties of the skeleton. Each one of the procedures described in this report is useful and above all noninvasive and radiation-free. In the end, however, the problem in question determines the choice of the measuring method.

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5. Altenmüller EO, Bangert MW. Mapping perception to action in piano practice: a longitudinal DC-EEG study. BMC Neuroscience 2003;4:26.

6. Mitternacht J, Wetter O, Schaff P. Biomechanische Messmethoden am Menschen – Die mobile Mikroelektronik auf dem Vormarsch. Dynamened 1996;1:12-8.

7. Lampe R, Mitternacht J, Schrödl S, et al. Einsatz des Ganglabors bei klinisch-orthopädischen Fragestellungen in der Kinderorthopädie. Klinische Pädiatrie 2004;216:72-8.

8. Lampe R, Mitternacht J, Gradinger R. Der Kinder- und Jugendfuß bei sportlicher Aktivität. Z Pädiatrie 2004;2:5-12.

9. Mitternacht J, Lampe R. Ermittlung funktioneller kinetischer Parameter aus der plantaren Druckverteilung. Z Orthop Ihre Grenzgeb 2006;144:410-8.

10. Ertl-Wagner B. Pädiatrische Neuroradiologie. Berlin, Springer; 2007.

11. Schneider F, Fink GR. Funktionelle MRT in Psychiatrie und Neurologie. Heidelberg, Springer Medizin; 2007.

12. Schneider S. Using musical instruments to improve motor skill recovery following a stroke. J Neurol 2007;254:1339-46.

13. Struppler A, Dengler R. Entwicklungen in der Neurologie. Hameln, TM-Verlag; 1989.

14. Stotz S. Therapie der infantilen Cerebralparese. München, Pflaum; 2000.