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Development of innovative training solutions in the field of functional evaluation aimed at updating of the curricula of health sciences schools

TEACH

MODULE: BIOMECHANICS OF GAIT

DIDACTIC Unit B: BIOMECHANICAL ALTERATIONS IN GAIT

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Contents

1. Objectives

- Learn the types of exaggerated gait.
- Learn the types of pathological gait.
- Learn examples of changes in kinematic and dynamic quantities recorded for selected diseases affecting gait regularity.

2. Introduction

Gait is one of the most complex motor tasks. A person in a standing position is most often described as an inverted pendulum with two degrees of freedom (ankle and knee joints). Sometimes a third degree of freedom is added to this model, which is the hip joint. However, such a description only reflects what can be observed when looking at the examined person in the sagittal plane. In fact, in each of the joints of the lower limb you can indicate three degrees of freedom - flexion / extension, adduction / abduction and rotation. In such a complicated system, maintaining balance is possible thanks to the work of the muscles of the lower limb, as well as by setting individual segments of the upper body. The whole is an extremely complicated task, where multi-oversize drives such as muscles must steer the body so that it does not fall. An additional difficulty is that the body is in constant motion. Such a complex multi-member system during walking must be moved by alternately throwing it off balance and then recovering this balance [[9]].

The need to control such a complex multi-component system means that any defects - diseases - can make this activity very troublesome to perform, and sometimes even impossible. These defects may arise at the level of the control system (brain diseases), transmitting information (all neurological diseases) and at the level of elements transmitting strength (muscle diseases), as well as the skeletal system supporting the whole body (fractures, joint diseases). The influence of so many factors on gait ability also causes changes that can occur in the way you move, depending on what caused them. Therefore, in the further part of the work, defined types of gait will be presented, followed by examples of changes in kinematic and dynamic quantities arising at the occurrence of selected diseases, along with a description indicating in which places the gait of the examined person differed from the pattern adopted as normal gait.

3. Physiological exaggerations in normal gait

Before proceeding to the description of defined examples of pathological gait, examples of the so-called exaggeration in normal gait will be presented. Usually people who notice this type of gait do not have any serious complaints. The appearance of an abnormal gait may be associated with an abnormal movement pattern, which in turn may be due to, for example, abnormal muscle tone, which may have occurred immediately after birth, or due to past injuries and injuries.

Seindler identified the following types of exaggerated gait [[2]]:

Swaying walk

Usually occurs in women, it is characterized by increased pelvic lift and lower movement in the frontal plane, as well as tilting the pelvis on the side of the lap with a simultaneous greater lowering of the shoulder on the side of the support.

Sailor walk

The center of gravity has an exaggerated sideways tilt, but to a greater extent, a swaying gait.

Majestic gait

Excessive acceleration and extension of the leg before the heel touches the ground, it is unnatural and uneconomical.

Stiff walk

It is characterized by not natural reduction of pelvic and shoulder oscillations.

Small steps walking

It can be observed in people with short lower limbs, it is characterized by short stride length but high stepping frequency.

4. Basic dysfunctions that affect mobility

Inability to move properly may be the result of many diseases. Their formation can be the result of both the disease and the external factor. Due to the high complexity of the gait activity as well as the complexity of the human body's functioning, gait abnormalities may be caused by many factors, which may include:

- congenital defects of the musculoskeletal system,
- posture defects
- musculoskeletal diseases,
- neurological dysfunctions of the musculoskeletal system,
- traumatic musculoskeletal injuries.

CONGENITAL DEFECTS OF THE MUSCULOSKELETAL SYSTEM

The term "congenital defects" includes all kinds of pathological changes causally related to the period of the fetal life of the child, which manifest themselves either during prenatal examinations or after childbirth - both at birth and during further development.

The formation of this type of defect may be affected by the following factors that occur during the fetal life of child:

- genetic factors,
- local damage to the child,
- hypoxia,
- toxic compounds,
- infections,
- maternal hormonal disorder,
- improper mother's diet,
- drinking alcohol, smoking or taking other intoxicants,
- ionizing radiation,
- ultraposition (excessive persistence for some time in one position, for example in the flexion of the hips).

Among the birth defects that can affect mobility impairment, the following can be calculated:

- congenital deficiencies and defects of limbs,
- limb developmental disorders, e.g. hip dysplasia, hip dislocation,
- congenital malformations of the chest and neck, for example, funnel-like chest, torticollis,
- congenital malformations of the spine, for example, short neck, lateral curvatures of the spine.

POSTURE DEFECTS

Posture defects are defined as individual deviations of body posture from norms considered to be the norm. Posture disorders, in particular if untreated, can cause the malfunctioning of other organs and internal systems, which not only affects the deterioration of quality of life (including impaired mobility), but can in extreme cases lead to death.

Posture defects are usually associated with incorrect spine positioning. They appear:

- in the sagittal plane, for example, deepened or shallow cervical or lumbar lordosis,
- in the frontal plane as, for example, lateral curvature of the spine, i.e. scoliosis.

The causes of postural defects include:

- neurogenic causes, for example, nerve palsy,
- myogenic, for example due to muscular dystrophy,
- thoracogenic diseases arising, for example, after cardiovascular or respiratory diseases or as a result of thoracic surgery.

MUSCULOSKELETAL DISEASES

Movement organ diseases occur within the structures that make up this organ, i.e. they can occur in the bones, joints and surrounding soft tissues, such as ligaments, tendons and their sheaths, bursitis, menisci etc.

Selected musculoskeletal diseases can be included:

- aseptic osteonecrosis - a disease syndrome whose principal feature is the death of bone and, to a certain extent, cartilaginous tissue, occurring without the participation of pathogenic microorganisms. The disease can result in deformities of the epiphyseal bones or secondary degenerative changes. As a cause, for example, blood circulation disorders resulting from pinching vessels, malformations or injuries.
- inflammatory diseases of the rheumatoid type - systemic connective tissue disease. As a result of the disease, joint deformities and muscular atrophy occur.
- degenerative changes - they consist of degenerative changes occurring mainly in the articular cartilage, as well as in periarticular elements. Causes include injuries and micro-injuries resulting from cyclic joint overloads (for example, as a result of an incorrect pattern of movement).
- discopathy and other changes occurring within the spine and sacroiliac joints - these changes may be, among others, the result of inflammation within the structures stabilizing the spine, degenerative changes and intervertebral hernia. All these diseases are associated with compression of the nerve roots or, in an extreme case, the spinal cord, which results in severe pain that significantly affects the ability and mobility.

NEUROLOGICAL DYSFUNCTIONS OF THE MUSCULOSKELETAL SYSTEM

The most common causes of neurological dysfunction of the musculoskeletal system include damage to or disturbance of the nervous system - both central and peripheral. These disorders affect the impairment or disappearance of skeletal muscle control, and thus motor disorders of the musculoskeletal system, including gait disorders.

The neurological causes of musculoskeletal dysfunction may include:

- brain disease,
- inflammation of the central nervous system,
- spinal cord diseases,
- neuromuscular diseases.

TRAUMATIC MUSCULOSKELETAL INJURIES

Injuries can be divided into macrotrauma and microtrauma.

As a result of injury, both the central and peripheral nervous system can be damaged, as well as soft tissues and bones that build the musculoskeletal system. Bone damage can include any joint fracture or dislocation. Soft tissue injuries include, among others, bruises, crushes, tears and ruptures of structures such as muscles, tendons and ligaments.

Sprain in the joint is an injury that occurs when external forces acting on the musculoskeletal system lead to exceeding the physiological range of motion in the joint. Sprain can lead to stretching or rupture of soft tissues surrounding the joint.

A joint dislocation is a much more serious injury than a sprain, often more serious than a broken bone. It occurs when there is complete loss of contact between articular surfaces - the head of one bone pops out of the acetabulum of the other bone forming the joint. Usually, dislocations are accompanied by soft tissue injuries surrounding the joint, bone fractures, and blood vessel damage.

Fig. 1 Hip dislocation

5. Types of pathological gait

Each of the causes of locomotor damage mentioned in the previous chapter leads to changes in gait biomechanics. Due to the features of the way of movement and the causes of the disorders, several types of pathological gait have been distinguished, which can be included [[1]]:

- steppage,
- ataxic gait,
- duck gait,
- hemiparetic gait,
- parkinsonic gait,
- paretic gait,
- spastic gait,
- pathological gait due to asymmetry in the length of the lower limbs,
- small steps gait,
- bowing gait,
- apraxic gait,
- cerebellum gait,
- stilt gait,

STEPPAGE

Also known as horse gait, roosters gait. Occurs in cases of peroneal nerve palsy, in people with flaccid paresis of both lower limbs. Most frequently and most strongly affect the muscles of the dorsal flexors of the foot. The dominant symptom is the presence of the so-called falling foot. A sick person, wanting to take a step forward and at the same time trying not to get his foot on the ground, is forced to bend the lower limb more strongly in the knee joint and lift it higher.

ATAXIC GAIT

Ataxic gait occurs in patients with posterior funiculis of spinal cord inflammation. It is characterized by dysmetry and uneven steps. It belongs to the wrong types of gait of a symmetrical nature on a broad basis.

Ataxic gait involves throwing the lower limb excessively bent in the knee joint forward. This is accompanied by a strong impact with the foot against the ground. In addition, gait is markedly unstable.

The causes of this condition are proprioception disorders in disease of funiculi of spinal cord. This type of gait therefore occurs in patients with proprioceptive sensory disorders. It is typical for cerebellar and cord ataxia and chorea.

DUCK GAIT

Duck gait occurs in people with paresis of the pelvic girdle and thigh muscles, which in turn results in swaying sideways when walking and difficulty climbing stairs.

The main causes of duck gait are dysplasia, dislocation of both hip joints, myopathies and muscular dystrophy. Duck gait can also be caused by:

- hip pain - e.g. due to degenerative disease or rheumatoid arthritis. In this case, the compensatory, lateral tilt of the torso gives a significant reduction in the amount of load, and thus also pain.
- hip joint abduction muscles failure - with this muscle group weakening, the strength generated by it may not be sufficient to stabilize the pelvis in the single support phase. Weakness of abductors can occur as a result of illness or injury directly affecting the muscles or the structures controlling the nervous system
- structural anomalies of the hip - these include congenital dislocation of the hip (hip dysplasia), deformed hip, juvenile exfoliation of the femoral head. Each of these conditions leads to a decrease in the effective length of the average gluteus muscle, because the greater femoral trochanter moves proximal towards the pelvic edge.

At the beginning of the support phase, paralysis of the gluteus myocardium causes the trunk to retract and the hip to extend forward on the side of the affected limb. Mean gluteus muscle insufficiency is the reason for the lack of stabilization of the pelvis in the support phase. With unilateral insufficiency when standing on a sick leg, the pelvis falls on the healthy side (Trendelenburg symptom). During gait, alternating pelvic tilting to one side and shoulders to the other occurs (Duchenne's symptom).

HEMIPARETIC GAIT

Hemiparetic gait occurs in patients with spastic hemiparesis of cerebral origin (for example, after stroke). The gait enables preserved movements in the hip joint (the patient makes half-circles) with no flexion in the knee joint. The foot remains in clubfoot position. The lack of movement in the knee joint and the position of the foot is the result of spasticity (the so-called Wernicki-Mann arrangement).

The patient during gait, due to the lack of movement in the knee and ankle joints, when making a step with a sick limb, makes a bow ("mows"). He leans towards the healthy side (lateral flexion of the torso). Due to spasticity, the upper limb is often attached and bent at the elbow joint. There is therefore no proper balance of upper limbs and the whole body.

PARKINSONIC GAIT

Parkinsonic gait, also known as small steps gait, is a characteristic symptom of Parkinson's disease. The patient has difficulty initiating and stopping walking. In addition, this is accompanied by a lack of physiological participation of the upper limbs.

The symptom associated with difficulty in movement is associated, among others, with the characteristic figure of the sick person. It is stiffened and leaning forward, and the patient himself has an increased ability to fall. Posture disorders also include deepened kyphosis, flexion of the hip and knee joints.

PARETIC GAIT

Paretic gait is a characteristic type of gait that occurs during flaccid paresis of both lower limbs. It is based on pulling up, piercing and shuffling with feet while knee joints are immobilized due to spasticity. The patient is barely lifting his foot off the ground. He moves slowly and with effort, usually leaning on a cane or using the help of another person.

It is characteristic of bilateral lesions of the pyramidal pathways (most often at the spinal level) or transverse injuries of the spinal cord. It is also a symptom of bilateral changes in the white matter of the brain.

SPASTIC GAIT

Spastic gait, as the name implies, occurs with spasticity in the hip and knee joints. Spastic gait usually occurs in paraplegics.

The patient slightly bends the limbs in the joints, walks with small steps and scratches along the floor with his feet. The lower limbs move slowly and stiffly, and the thighs are strongly attached. As a result, the drumsticks can cross when walking (scissor gait). Feet can be plantarflexed and inverted. In addition, it happens that the patient hooks his toes on the ground. In general, the patient appears to be confined while walking.

In spastic gait, the pelvis often rotates incorrectly. In rotation backwards one leg seems to be more retracted. In turn, a more efficient leg (extended forward) usually takes over most of the load (as in the case of hemiplegia).

In a typical spastic step, not the heel but fingers first hit the ground. If the back is bended and lordosis occurs, excessive kyphosis of the thoracic spine may appear. Due to the uneven distribution of load, different lengths of the lower limbs and other causes of standing and sitting posture asymmetry, lateral curvature of the spine appears.

In addition, excessive swing of the upper limbs or excessive defensive reflexes are observed. For this reason, alternating arm movements are usually lacking. There is an incorrect position of the hands, as in the earlier period of motor development. Shoulder retraction may be accompanied by retraction of the pelvis and hips.

PATHOLOGICAL GAIT DUE TO ASYMMETRY IN THE LENGTH OF THE LOWER LIMBS

Asymmetry in the length of the lower extremities usually causes the person to limp. With a slight shortening of the lower limb (3-5 cm), there is no obvious gait disturbance, because the patient compensates for these defects by pelvic inclination. With a larger shortening (over 5 cm), the length of the lower limbs is equalized by placing the foot of the short limb on the horse and bending the longer limb at the knee.

The stride length decreases on the shorter side. The load time of a shorter limb during walking is not reduced, as is the case when a person limp as a result of pain occurring in one limb. There are also greater pelvic deflections in the frontal plane on the shorter side of the limb, with the shoulders tilting on the opposite side.

Limb shortening can be real or apparent.

Real shortening occurs, among others, as a result of disorders of the ossification process, in states after fractures of the limb, especially where there has been a union with incorrect positioning of bone fragments.

Apparent shortening occurs during muscle contracture in the hip joint and flexion contracture. Abductive contracture causes the apparent extension of the lower limb.

OTHER TYPES OF PATHOLOGICAL GAIT

Small steps gait

In this type of movement, the step forward is unnaturally reduced. As a result, the length of the step is smaller and the number of steps per unit of time greater. It should be remembered that in people with short lower limbs this is a normal type of gait. In other cases, it may be the result of cerebral cortex dysfunction, or may be caused, for example, by stroke.

Bowing gait

Occurs during contracture and stiffness of the hip and knee joints, while limiting lumbar movement.

Apraxic gait

The patient's movements are awkward and uncertain. It is caused by cortical disruption of movement integration processes generally as a result of damage to the frontal lobe.

Cerebellum gait

Caused by damage to the cerebellum tracts or centers, it is characterized by a lack of coordination.

Stilt gait

Is the effect of forefoot amputation.

6. Selected changes occurring in individual stages of pathological gait

When describing the biomechanics of pathological gait, it usually refers to the values and time courses measured for the gait of healthy and properly moving people, i.e. people whose gait does not differ from the average population. This chapter presents selected differences that may appear in the gait of sick people in relation to healthy people, and then as examples of pathological gait, the basic differences appearing in the gait biomechanics of people after hip arthroplasty and stroke are shown.

When describing the walking cycle, a classic description of individual elements is usually used, divided into a support and swing phase, then dividing these phases into smaller periods.

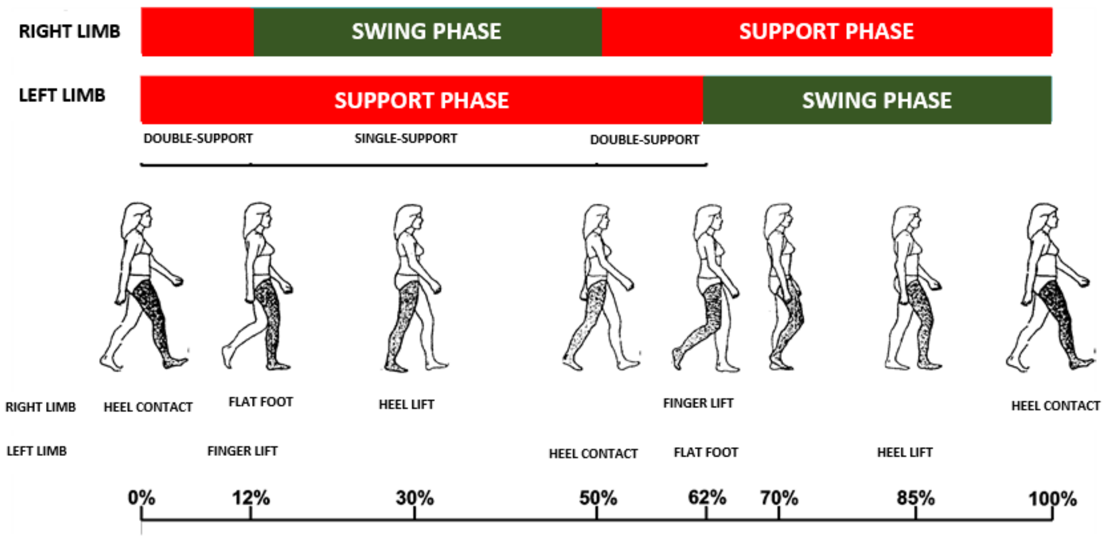


Fig. 2 Gait phases according to the classical notation [[10]]

Considering the fact that in the case of pathological gait some of the events occurring during the gait cycle do not occur or have a changed pattern, in medical applications other ways of describing the gait cycle than the classical one applies. One of the best known is the team developed by the Physical Therapy Department and the Pathokinesiology Service of the Rancho Los Amigos Medical Center in California. This system, from the name of the center, is called the Rancho Los Amigos gait description system. This system identifies 8 successive gait phases that can be directly used in the clinical assessment of gait disorders. Each of the phases refers to the characteristic limb positions or traits of the movement being referred to as critical events. These events are visible in the sagittal plane as the plane in which the largest changes in the angular position of individual segments of the lower limb take place.

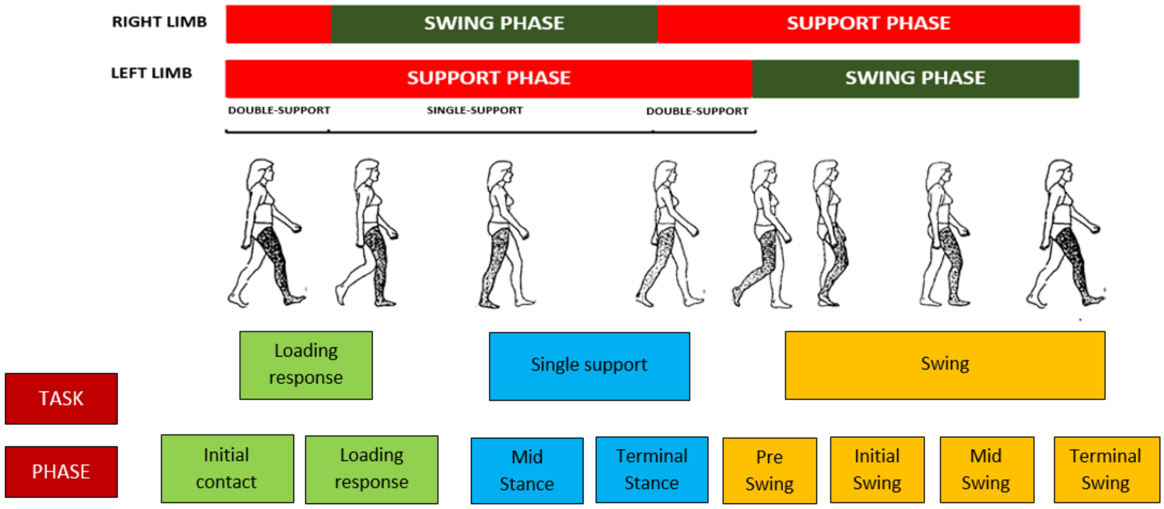


Fig. 3 Further stages of gait in accordance with the Rancho Los Amigos gait description system

The next phases of gait, according to the records from Rancho Los Amigos, are associated with subsequent tasks performed by the lower limb. The following is a description of the subsequent phases of gait along with indications of selected possible deviations from the adopted pattern that can be seen on the basis of the described system [[11]].

Initial contact

The phase corresponds to the contact of the foot with the ground, starting the next walking cycle. In a healthy person, this phase begins with placing the lateral part of the heel on the ground. It is also the beginning of the two-support phase in the analysis of the gait cycle of the opposite limb.

In the case of gait disturbances, the onset of foot contact with the ground may not be from the heel but from placing the whole foot or toes. These disorders may result, for example, from spasticity of the plantar flexor muscles of the foot, reduced mobility in the ankle or factors causing the foot to drop during the swing phase.

Loading response

In this phase, the body weight is quickly transferred to the limb. The adoption of body weight is associated with the cushioning of this force by flattening the foot. This phase lasts until the opposite limb loses contact with the ground. Most muscles work in an eccentric way, i.e. they generate strength while increasing length. This is to partially slow down movement, maintain body weight on the limb, but also to ensure uninterrupted movement of the body forward.

Pathological gait in this phase may be associated with improper, eccentric muscle work or improper foot work, which instead of smooth movement flaps quickly to the ground.

Midstance

This is the first phase in the single support phase of gait. The whole foot adheres to the ground with its entire surface, supporting the weight of the entire body moving forward, and in this phase being exactly above it. An important element of this phase is keeping the limb linearity.

The most common deviations from the norm that can be seen in this phase are the lack of linearity of the limb, knee hyperextension or pelvis falling to the opposite side (Trendelenburg symptom), which indicates the failure of the gluteal muscles of the limb in support.

Terminal stance

There is further movement of the body forward over the lower limb. Body weight begins to be maintained by forefoot. The task of this phase is to bring the center of gravity of the body out of the support plane. This phase ends when the opposite limb is placed on the ground. Proper mobility in the hip and metatarsophalangeal joints is necessary for the proper implementation of this phase. The lack of proper mobility in these joints is associated with deviations from the norm at this stage of gait.

Preswing

This is the finishing phase of the support of the analysed limb. This limb is quickly unloaded by transferring the body weight to the opposite limb. This is preparation for the swing phase, while also constituting the second period of the two-support phase.

The most common problem is the improper, incomplete transfer of body weight to the opposite limb.

Initial swing

This is the first phase of the swing phase. The foot is raised above the ground and the thigh begins to move forward.

The most common problems noticeable in this phase are insufficient functional shortening of the limb or the lack of active dorsiflexion of the foot.

Midswing

During this phase, the thigh continues to move forward. The extension movement in the knee joint also begins. The foot is kept in a neutral position.

Problems appearing in this phase are the same as in the Initial swing phase: insufficient functional shortening of the limb or the lack of active dorsiflexion of the foot.

Terminal swing

It begins when the tibia crosses a vertical line. The work of the limb is to slow down momentum of the lower leg and prepare the limb for subsequent contact with the ground. There is extension of the limb in the knee joint. The muscles work in an eccentric manner when braking.

The most common problem occurring in this phase is improper, eccentric muscle work. This results in a lack of control over the extension movement in the knee joint (improper braking of this movement), which in turn causes the lower leg to be thrown forward at too high a speed.

7. Selected changes in kinematic quantities occurring in pathological gait

Any gait disturbance affects changes in all or at least most of the kinematic quantities used to describe gait biomechanics, i.e. time-space values, gait attributes and determinants, and kinematic values. The type of changes depends on the disease, often being a characteristic symptom that allows confirming the patient's diagnosis.

TIME-SPACE PARAMETERS

The time-space parameters used to describe gait biomechanics are [[10]]:

- gait velocity,
- step or stride length,
- cadence.

Pathological gait is most often associated with changes in the value of time-space parameters. Usually the stride length is shortened. The cadence is also changing. Both of these changes affect the gait speed, which usually decreases.

The determination of changes in the value of the time-space values of gait is usually made by comparing it to the average values. For normal walking, the walking speed of healthy people varies between 4 - 6 km/h. The frequency of steps at this speed is usually in the range of 90 - 120 steps per minute, while the length of the steps 70 - 82 cm [[1]].

The analysis of gait speed change should also be enriched by reference of the measured value to the theoretical value obtained from the formula for comfort speed. Comfort speed is defined as the speed that is theoretically the most natural. It can be determined from the formula below, which takes into account the length of the limb of the examined person [[6], [3], [8]].

$$V_c = a\sqrt{gl} \tag{1}$$

where:

g – gravity constant (9,81 m/s^2)

l – length of limb,

a – proportionality factor.

The coefficient a, according to literature reports is 0.4 according to [[5]] or 0,42 according to [[8]].

Calculation of the walking comfort speed according to this formula makes it possible to determine if the speed measured during the test deviates significantly from that calculated.

The following graphs show the values of walking speed, cadence and stride length obtained for a person after a stroke. Results based on own research.

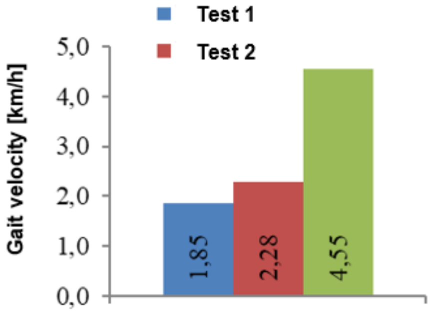


Fig. 4 The gait speed determined before the beginning (test 1) and after the end (test 2) of rehabilitation

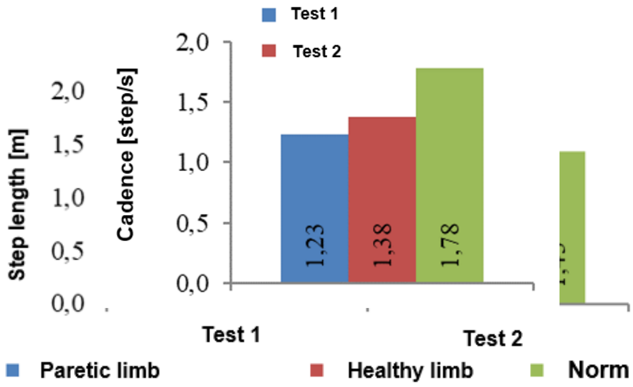


Fig. 5 Cadence determined before the beginning (test 1) and after the end (test 2) of rehabilitation

Fig. 6 Stride length determined before the beginning (test 1) and after the end (test 2) of rehabilitation

JOINT ANGLE COURSES

The course of joint angles belongs to the parameters that most clearly show changes in biomechanics of pathological gait in relation to normal gait. In these waveforms one can observe both subsequent pelvic and limbs positions, mutual positions of individual limbs elements as well as symmetry of movement.

Analysis of the courses of joint angles should be carried out both:

- in terms of angle values in the joints at individual stages of gait, referring to the angles obtained for normal gait,

- in terms of the quality of the movement - whether it is jerky, shaky or following the right trajectory,

- shape of the joint angle change over time - it should be observed whether the resulting graph of the angle change over time is similar to the correct one even when the range of motion, i.e. the values of angles obtained in subsequent stages of movement deviate from the norm.

Below are examples of courses of articular angles and angles of pelvis obtained during own tests on a person rehabilitated in relation to a stroke. The patient had left paresis. The presented results were obtained at the beginning and end of hospital treatment.

The following changes can be observed in the graphs presented:

- alignment of the pelvis in the sagittal plane (Tilt) - the pelvis is tilted forward too much - the norm is about 10°,

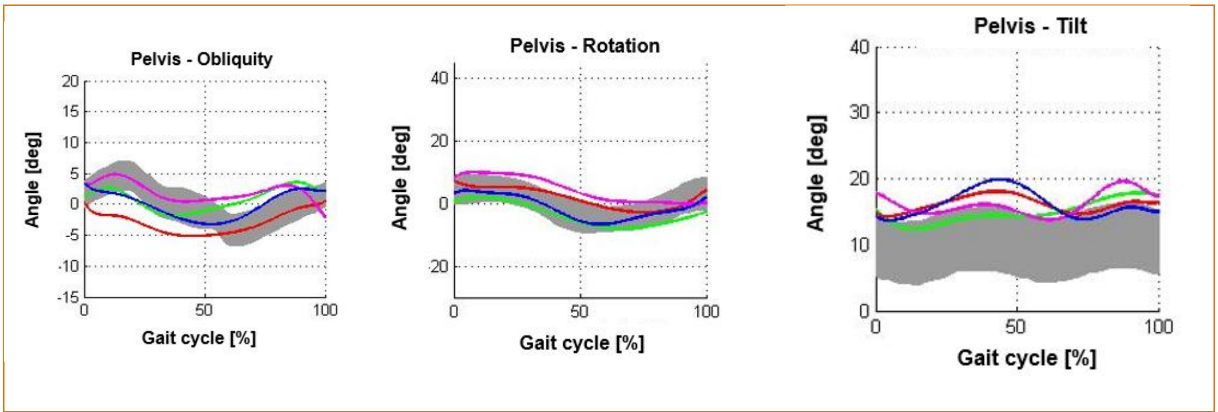
- alignment of the pelvis in the frontal plane (Obliquity) - during the supporting phase of the left limb before rehabilitation (red line), the pelvis drops to the left for most of the gait cycle,

- alignment of the pelvis in the transverse plane (Rotation) - the course is close to normal,

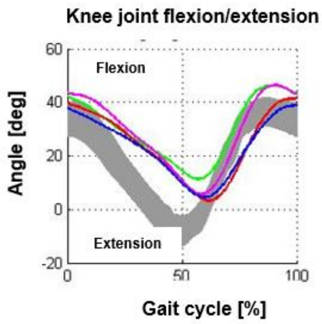
- angle course in the hip joint in the sagittal plane - too little extension during the support phase,

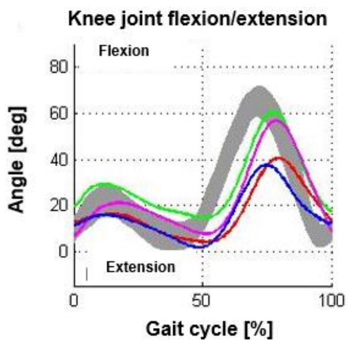
- angle course in the knee joint in the sagittal plane - lack of proper flexion in the left limb in the waveforms obtained both at the beginning and at the end of treatment,

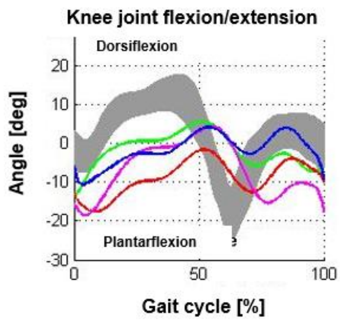
- angle course in the ankle joint in the sagittal plane - no proper dorsiflexion during the support phase. Descent of the right foot during the swing phase.



a) b) c)







d) e) f)

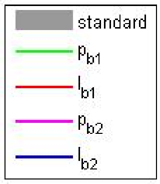


Fig. 7 Examples courses of pelvic positioning a) in the frontal plane, b) in the transverse plane, c) in the sagittal plane and joint angles d) in the hip joint, e) in the knee joint and f) ankle joint in the sagittal plane obtained for a patient treated in connection with a history of stroke. Symbols: standard - correct course, p_{b1} - right limb examination before starting treatment in hospital, l_{b1} - left limb examination before starting treatment in hospital, p_{b2} - right limb examination at the end of hospital stay, l_{b2} - left limb examination at the end of hospital stay. Results based on own research.

8. Examples of changes in dynamic parameters occurring in pathological gait

Changes in gait kinematics are reflected in changes in dynamic parameters. The most frequently analysed include ground reactions. The ground reactions are measured on dedicated dynamometric platforms. During gait analysis, three components of the ground reaction are usually considered:

- vertical component,
- anteroposterior component,
- mediolateral component.

Values of ground reactions are presented as time courses. In order to enable comparison with other people's results, as well as to normalize waveforms, measured values (forces) are refered to the weight of the test person giving the result in percent (where body weight corresponds to 100%). Figure below shows the correct course of ground reaction obtained for normal gait.

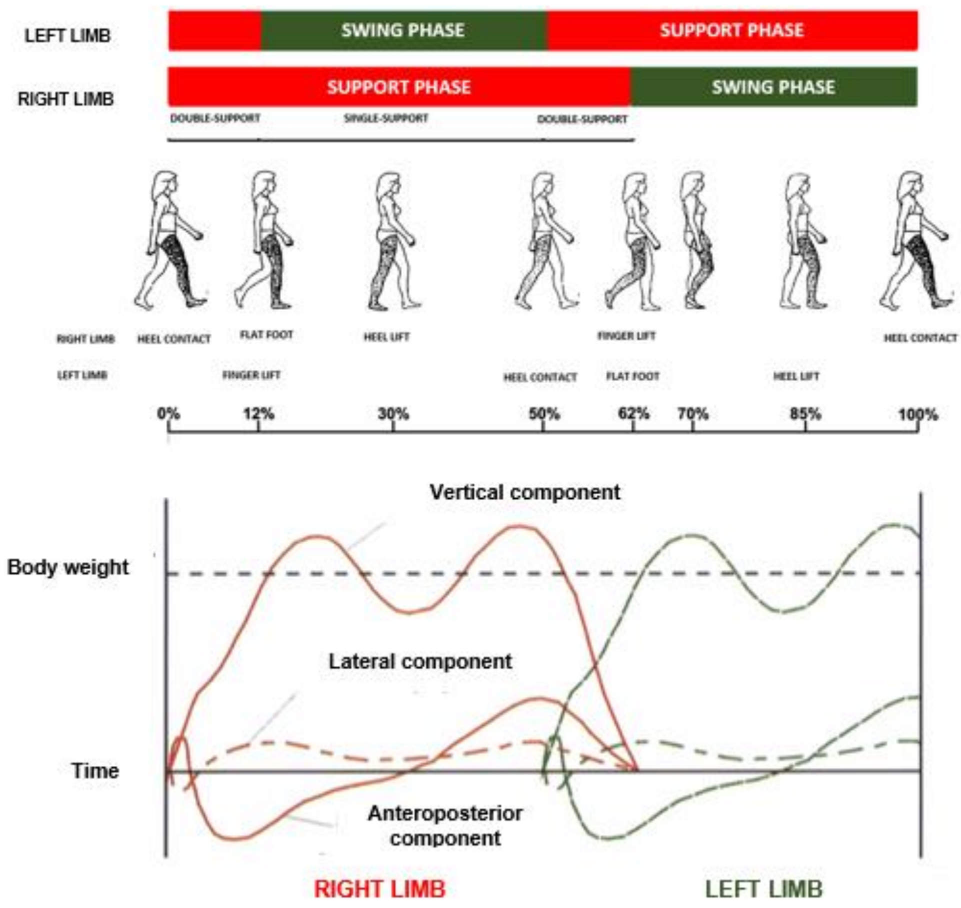
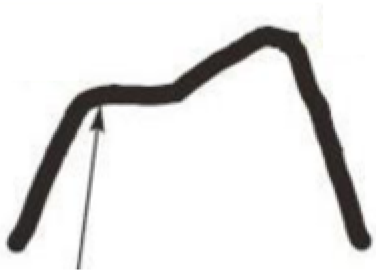


Fig. 8 Ground reaction waveforms obtained for normal gait [[10]]

In pathological gait, the dynamic elements of gait are usually disturbed, i.e. the characteristic maxima of the vertical and anterior-posterior components are flattened. Examples of deviations from the norm in pathological gait are presented in the next examples [[12]].

- no characteristic maximum in the vertical component of the ground reaction in the overload phase (Heel Plateau)

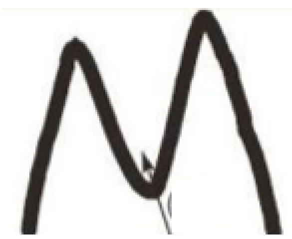


This course of ground reaction may be the result of too fast load transfer to the entire foot. It can occur, for example, in people with a shorter limb. It can also be the effect of gently putting a limb.

- no characteristic reduction in the value of the vertical component of the ground reaction in the unloading phase (Central Plateau)

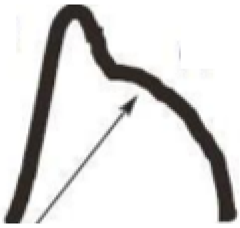
This course of reaction may be associated with too long contact of the heel with the ground. It can also be associated with impairments resulting in weakened or lacking propulsions, for example degenerative changes or other problems with the knee, as well as the gait of people with flat feet.

- excessive reduction of the vertical component of the ground reaction in the unloading phase (Central Depression)



This reaction may mean that there is no contact between the middle part of the foot and the ground. Selected conditions in which this course may occur are spasticity of the foot flexor muscles or problems with the patellofemoral joint.

- no characteristic maximum in the vertical component of the ground reaction in the propulsive phase (Forefoot Plateau)



Appears in people who have a greater heel load than forefoot. It can occur at flat feet, in people with hallux or in the case of improper work of the plantar flexor muscles of the foot (no possibility of active dislocation).

9. Walking on crutches as an example of pathological gait

Damages to the musculoskeletal system may also result in the fact that independent movement is significantly impeded or impossible. An element that can support a sick person are orthopedic crutches. The use of orthopedic crutches significantly changes the way you move. It is assumed that when using a crutch, one should not use one crutch, because it adversely affects the spine as it can lead to inflammatory and degenerative changes.

Common situations requiring the use of crutches are amputations of limbs as well as injuries and mechanical injuries such as bone fractures. However, crutches are also used for lower limb arthritis, which causes severe pain which causes that the patient is not able to move on their own.

The orthopedic crutch must perform primarily two functions: reduce the load of one or both limbs (body weight is partly or completely transferred by the upper limbs), as well as improve balance and stability. It should also allow to maintain an upright position and support the transmission of sensory signals through the hands.

From a biomechanical point of view, the orthopedic ball increases the support plane by introducing an additional support point. It is an extension of the upper limbs and introduces the possibility of using them when moving in support phases. The use of the crutch by means of a specific grip method eliminates a significant number of degrees of freedom of movement, making it easier for the patient to control support and motion activities.

One or two balls can be used. Below is a summary of the degree of unload when using one and two balls [[4]]:

- using one crutch

Locomotion with 1 crutch provides the opportunity to unload the limb from 0 to 50% (crutch kept on the side of the healthy lower limb). Unloading 50% of the limb is conditioned by moving the crutch from the lower limb more than when walking with 2 crutches. If the crutch is more parallel to the lower limb, the unload will be less than 50%.

- using two crutches

2-crutches locomotion provides the opportunity to unload the limb from 0% (full load) to 100% (full unload). Unloading at 0% is equivalent to 100% loading and can be called "walking with crutches". It should be noted that despite the fact that locomotion with crutches with 0% unloading of the limb is possible, in gait learning it is used sporadically.

TYPES OF GAIT ON CRUTCHES

Five walking techniques on crutches can be distinguished:

- four-point gait,
- three-point gait,

- two-point gait,
- swing-through gait,
- swing-to gait.

Four-point gait

It is characterized by the left crutch, right foot, right crutch, left foot sequence. Then repeat the sequence. Due to the fact that three points always touch the ground, very good stability is ensured. This gait is indicated when there is poor coordination or weak legs, and the patient must be able to move each of them.

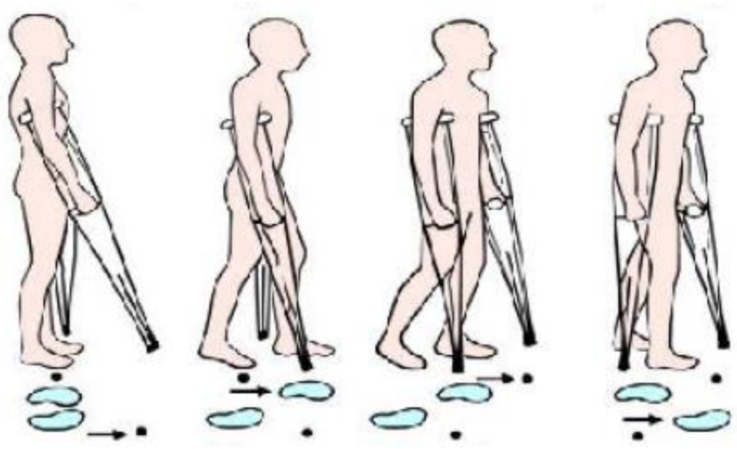


Fig. 9 Four-point gait [[13]]

Three-point gait

The sequence of such a walk is to transfer both crutches and a weaker leg forward, transfer weight to the orthopedic crutches, transfer the stronger limb forward, then repeat the sequence. This gait is quite fast, while unloading the handicapped limb. It is indicated when there is an inability to carry the load on one leg (fractures, pain, amputations)).

Two-point gait

The sequence of such a walk is to move the left crutch and right leg together, then the right crutch and left leg together. Then the sequence is repeated. This walk is faster than a four-bar walk on crutches. Indication is weakness in both legs or poor coordination.

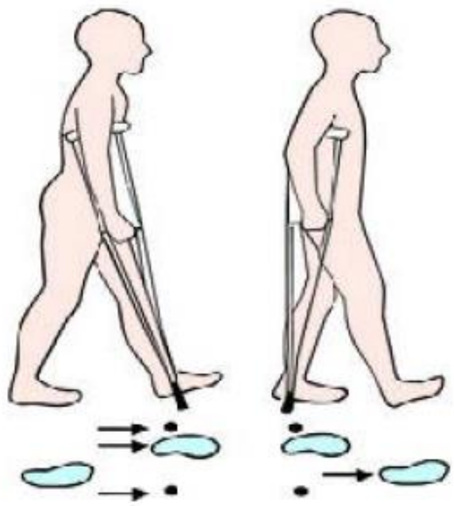


Fig. 10 Three-point gait [[13]]

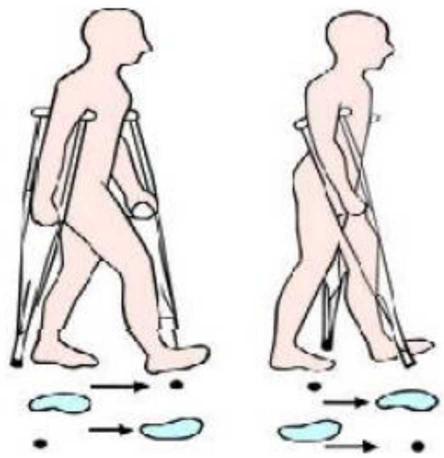


Fig. 11 Two-point gait [[13]]

Swing-through gait

The sequence of such a walk is to move both crutches forward, to lift the lower limbs slightly upwards, having the whole-body weight on both crutches, moving the legs or one leg by swaying. Then repeat the sequence. This is the fastest crutch gait pattern, also used by athletes during competitions. The indication is the inability to carry the load by both legs (fractures, pain, amputations)).

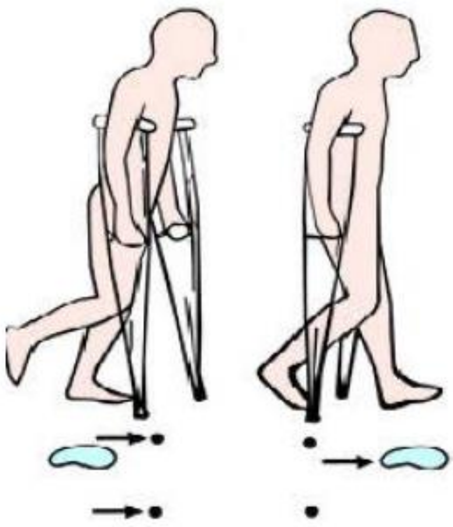


Fig. 12 Swing-through gait [[13]]

Swing-to gait

The sequence of such a walk is loading a healthy leg with body weight, moving both crutches forward, tilting the body forward and moving both limbs forward together with the movement of the limbs being parallel. Then the sequence is repeated. It is a kind of walking with crutches relatively fast and easy to learn. Used when both limbs are weak.

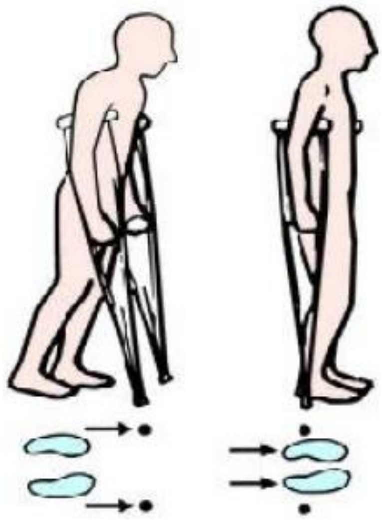


Fig. 13 Swing-to gait [[13]]

EXAMPLES OF COURSES OF JOINT ANGLES DURING SWING-TO GAIT

Below are examples of changes in joint angles and pelvis settings during one cycle of swing-to gait on crutches. The results come from own research.

Pelvis Arrangement

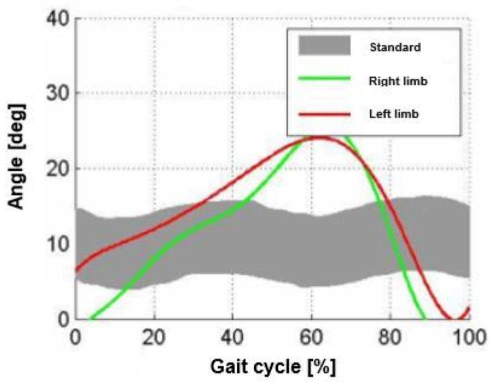


Fig. 14 Arrangement of the pelvis in the sagittal plane

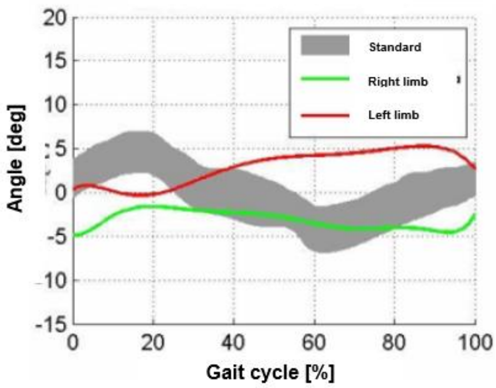


Fig. 15 Arrangement of the pelvis in the frontal plane

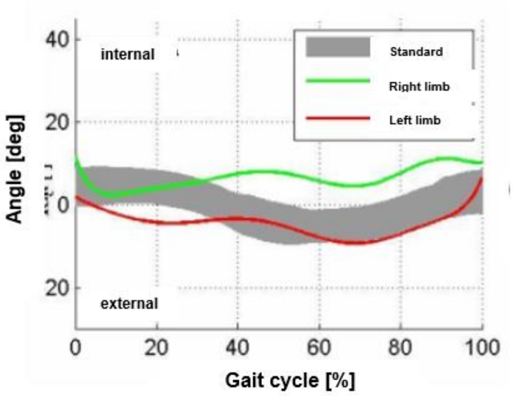


Fig. 16Arrangement of the pelvis in the transvers plane

Hip angles

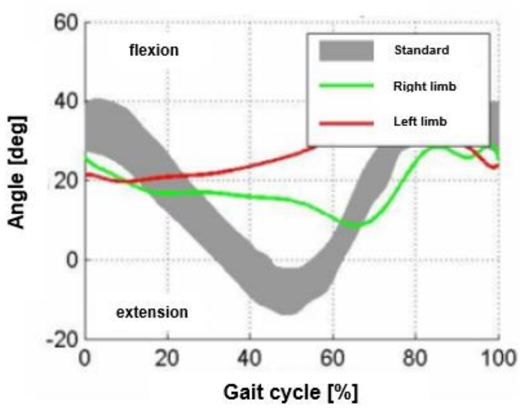


Fig. 17 Changing the angle in the sagittal plane (flexion/extension)

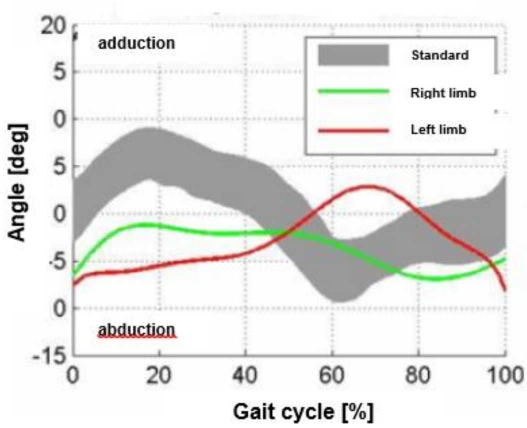


Fig. 18 Changing the angle in the frontal plane (abduction\addiction)

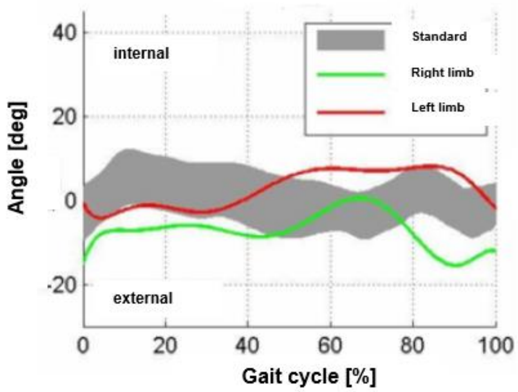


Fig. 19 Changing the angle in the transvers plane (external/internal rotation)

Angle course in the knee and ankle joints in the sagittal plane

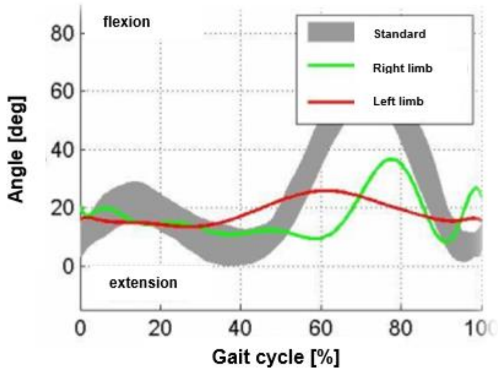


Fig. 20 Changing the angle at the knee joint (flexion/extension)

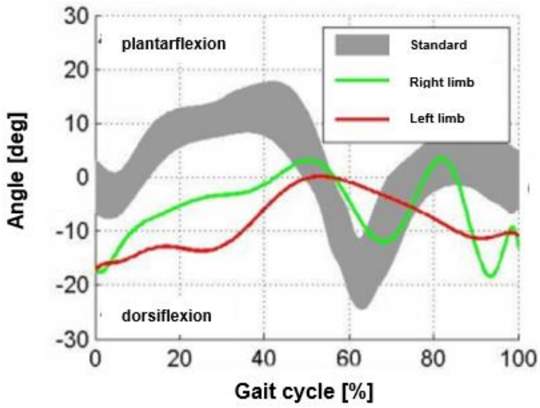


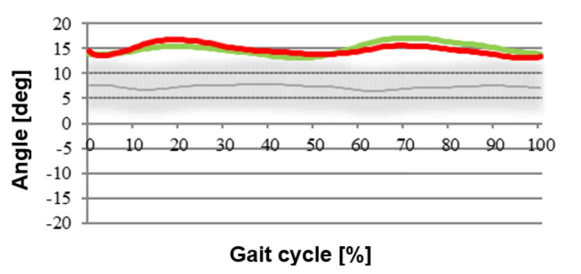
Fig. 21 Changing the angle at the ankle joint (dorsiflexion/plantarextension)

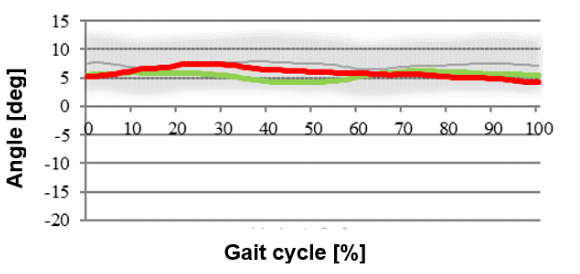
10. Biomechanics of pathological gait - case study

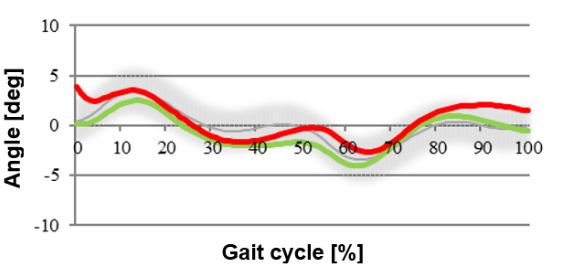
This chapter presents the cases of pathological gait discussed on the basis of own research, the full result of which is presented in a monograph edited by Michnik, Kopyto and Jochymczyk-Woźniak [[7]]. The measurements were performed on children with diagnosed cerebral palsy. Children, apart from standard rehabilitation, were treated using botulinum therapy. The results obtained before and after injection of botulinum toxin are presented. Measurements were made using the system BTS SMART.

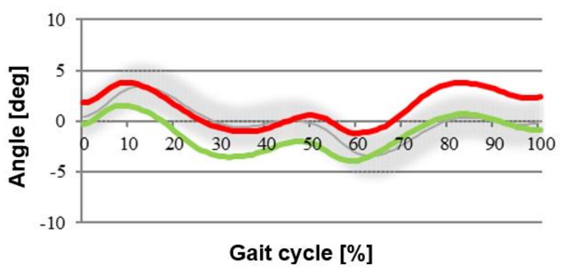
PERSON 1

A patient with diagnosed diplegia at the age of 7, with a body weight of 24 kg and a body height of 128 cm (BMI-14.63, 29th percentile, normal weight).

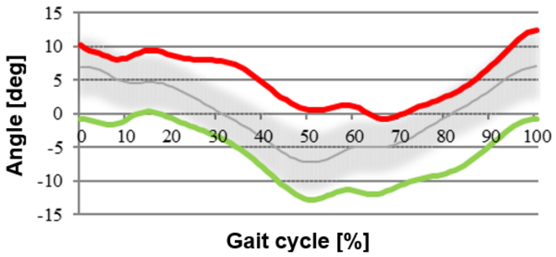
<table>
<tr><th>Examination prior to injection of botulinum</th><th>Examination 6 months after injection of botulinum</th></tr>
<tr><td colspan="2">Pelvic</td></tr>
<tr><td>

sagittal plane: pelvic anterior inclination slightly increased to about 15° (norm to 12°)</td><td>

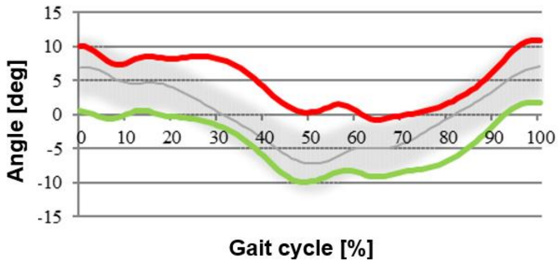
sagittal plane: the sagittal pelvis is positioned correctly</td></tr>
<tr><td>

frontal plane: the pelvis is correctly positioned for most of the walking cycle. Only at the beginning of the support phase of left limb pelvis is slightly inclined to the right (left iliac spine above - pelvis angle of 4 ° at normal 0°)</td><td>

frontal plane: the pelvic movement is close to normal but during the swing phase of left limb the pelvis is slightly inclined to the right (left iliac spine above). Maximum tilt angle of 4 ° at standard 0°</td></tr>
</table>

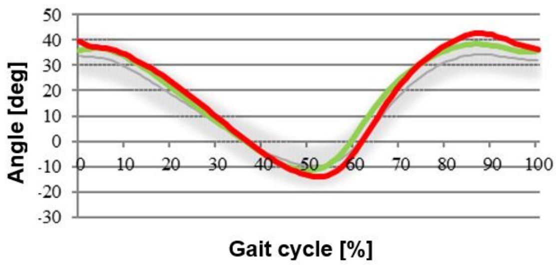


transverse plane: the nature of the movement is similar to normal, however, the pelvis throughout the entire gait cycle in an incorrect position - twisted to the right (left iliac spine too far forward). At the beginning of the support phase of left limb the angle 10° when standard is 7°. Then, during load and propulsion of the left limb the right iliac spine is not fully pushed forward (at the moment of left limb detachment 0 ° when the standard is 5°). Angle at the beginning of the support phase of the right limb is 0 ° when the standard is 7°. At the moment of detachment of the right limb from the ground, pelvic angle 12 ° when the standard is 5°.

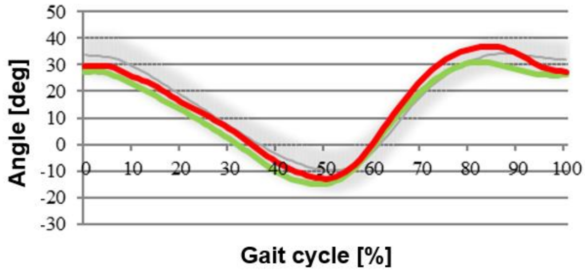


transverse plane: the nature of the movement is similar to normal, however, the pelvis throughout the entire cycle of walking in an incorrect position - twisted to the right (left iliac spine too far forward). At the beginning of the support phase of left limb the angle 10 ° when standard is 7°. Then, during load and propulsion of the left limb, the right iliac spine is not fully pushed forward (at the moment of the left limb detachment, pelvic angle 0 ° at norm -5 °). Angle at the beginning of the support phase of the right limb the angle is 0 ° when the standard is 7°. At the moment of detachment of the right limb from the ground, pelvic angle 8° when the standard is 5°.

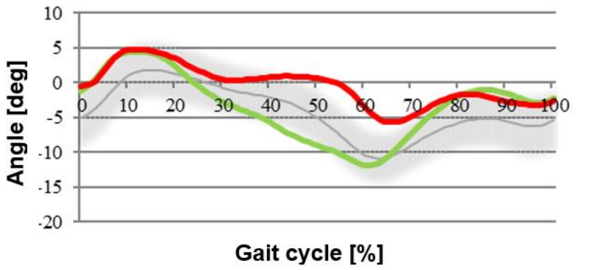
HIP JOINT



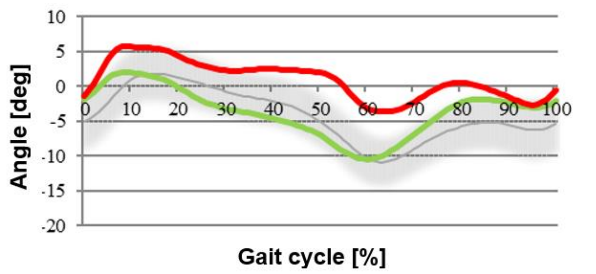
flexion/extension: both lower limbs in correct positions. Only at the end of the swing phase the left limb is too flexed (42 ° when the standard is 34 ° and the angle range is 39°)



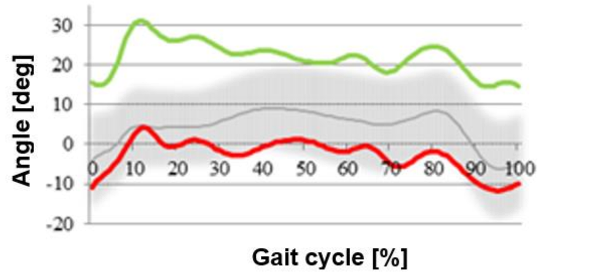
flexion / extension: both lower limbs positioned correctly for the most of the walking cycle. Only at the end of the swing phase too accelerated extension, but the angle of both limbs is within the correct range of angles



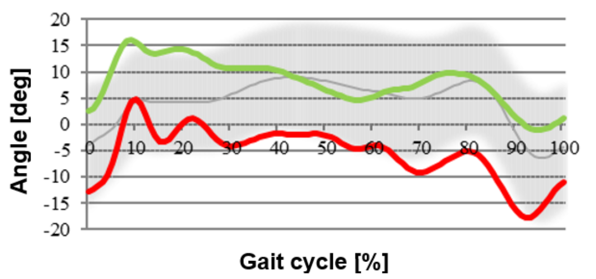
adduction/abduction: movement of the right limb is close to normal, in the second part of the swing phase the angle slightly deviates from the norm (-1 ° at the norm -5 ° and correct angle range -3 °). Left limb set correctly only at the beginning of the support phase. In the second part of the support phase there is no abduction, while in the swing phase the abduction is too small approaching the norm before the next contact of right limb with the ground.



adduction/abduction: movement of the right limb correct. Left limb throughout the entire walking cycle, except for the moment of contact with the ground, 2 ° to 5 ° excessively adducted. When the left foot is deteached off the ground, the angle in left limb is -3 ° when the standard is -10 ° and the correct angle range -6 °.



rotation: in the left limb the curve character slightly deviates from the normal one, but within the whole gait cycle it is within the normal range of healthy persons. No internal rotation - the limb stays close to 0 ° for most of the walking cycle. At the moment of contact of the foot with the ground, the angle -10 ° when the standard is -3°, at the moment of detachment the angle is 0° when the standard is 7°. Very high internal rotation of the right limb. It can also be the result of an unnoticed accidental change in the position of the wand on the thigh.

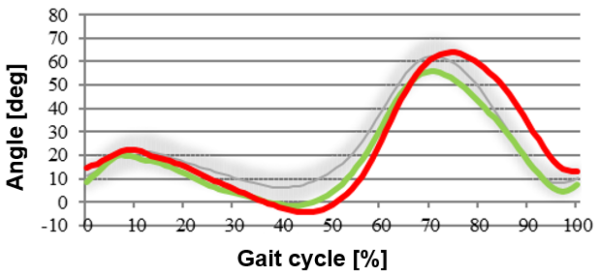
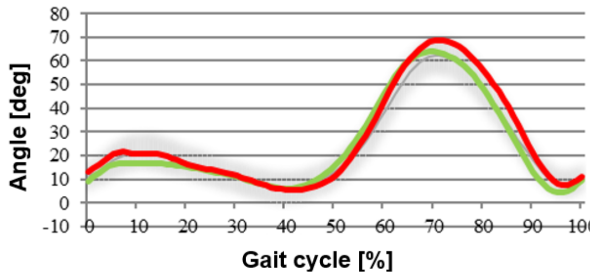
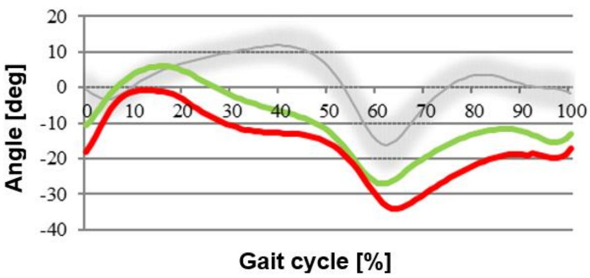


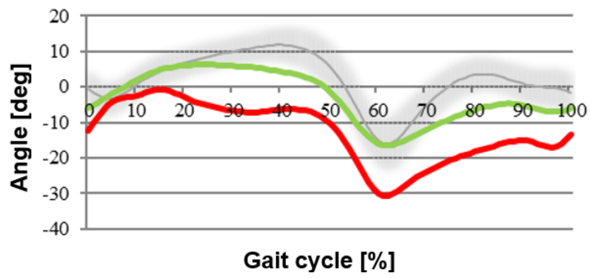
rotation: movement in the right limb, except for the beginning of unloading set correctly. At the beginning of the overload, the right limb rotated internally at the angle 16° at a standard of 5° and a range of the correct motion of 12°. In the left limb the nature of the movement in the support phase is incorrect - large angle fluctuations. Movement in the left limb becomes stabilized in the second half of the support phase and in the further part of the gait cycle the nature of the movement is normal, but it occurs at the limit of normal with the rotated limb externally.

KNEE JOINT

flexion/extension: the angle course in the right limb close to normal. In the left limb the

flexion/extension: correct angle for both libms. Slight asymmetry during unloading in

<table>
<tr>
<td>character of the course is close to correct. Slightly delayed extension in the support phase before detaching the foot from the ground and flexion in the swing phase. A slight increased hyper extension in the left limb (-3 ° at 0 °) and too much flexion in the second part of the swing phase.

</td>
<td>the support phase (about 15%) and the second half of the swing phase (about 10%)

</td>
</tr>
<tr>
<td colspan="2">ANKLE JOINT</td>
</tr>
<tr>
<td>

plantar/dorsal flexion: Foot droping is seen in both limbs. Left limb in plantar flexion throughout the entire walking cycle. At the time of contact, the foot angle in the left limb is -19 ° - plantar flexion – norm is 0°. Then the foot dorsally flexed until a maximum angle of 0 ° is reached (unload phase) and then goes to plantar flexion again. At the moment of detachment, the foot angle in left limb is - 33° when the standar is -15°. Angle in the right limb, when the foot touches the ground, is 10° (plantar flexion) when the standard is 0°. Then, while unloading, the foot reaches an angle of 6° (dorsiflexion) and immediately begin plantar flexion and remain in such flexion until the end of the walking cycle. At the moment of detachment, the angle in the right limb is 27 ° when the standar is 15°. There is an asymmetry between right and left limb.</td>
<td>

plantar / dorsal flexion: the course of the right limb is close to normal. Slight deviations from the norm at the end of the unloading and at the beginning of the propulsion phase (maximum 7°) and during the swing (maximum 11°). At the moment of contact, -5 ° angle, when the foot is removed from the ground -15 ° - both values are within the norm.

The nature of the left limb course is close to normal, while the entire course shifted by 10° to 17° towards the plantar side. At the moment of contact, the angle -11° (norm 0°), at the moment of lifting the foot from the ground -30° (norm -15°). Foot drop is visible.</td>
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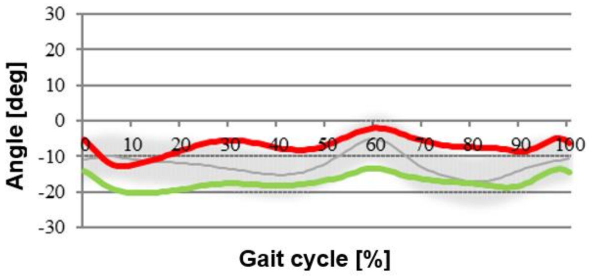
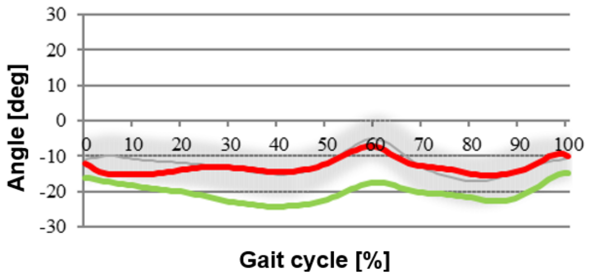


foot rotation: the rotation angles in both feet are within the normal range. Visible asymmetry between the right and left limb - the right foot is in greater external rotation than the left throughout the entire walking cycle. The nature of the movement in both limbs is correct throughout most of the walking cycle - only in the left limb when the foot is unloaded, the foot rotates inwards, while in walking the correct rotation direction is outwards.

At the time of contact, the foot angle of the left limb is -6° - outward rotation - (norm is 10°). At the moment of detachment, the foot angle in left limb is - 1° at the standard -5°. Angle in right limb when the foot touches the ground - 14° (plantar flexion) with the norm 10°. At the moment of detachment, the angle in the right limb is -12° at the standard -5°.

</td>
<td>



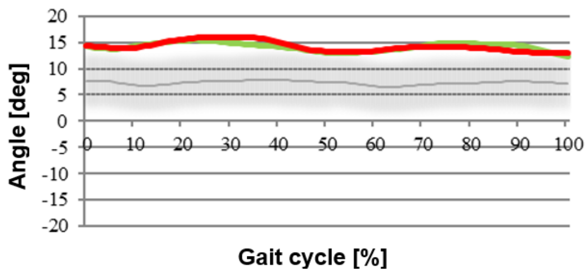
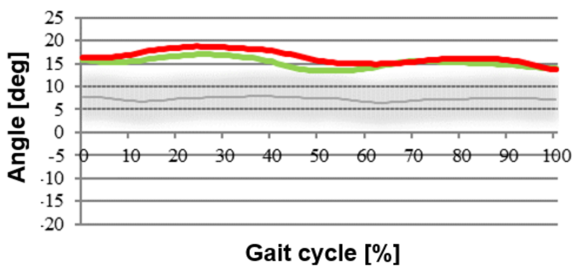
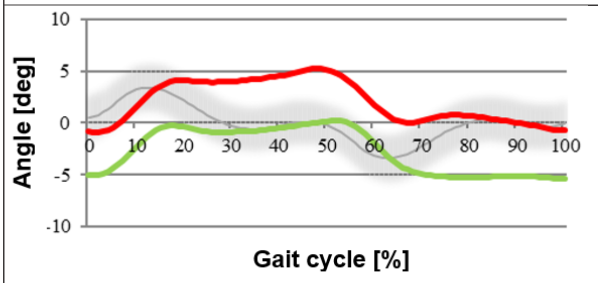
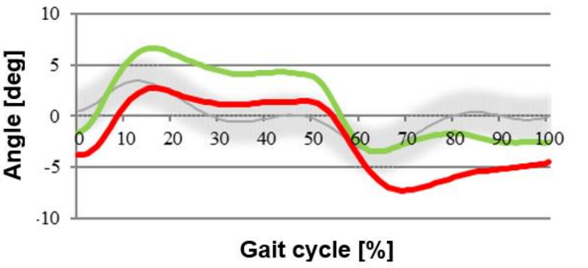
foot rotation: left limb movement is within normal range. In the right limb the foot is in excessive external rotation throughout the entire support phase, and during the swing phase at the limit of normal gait. Visible asymmetry between limbs.

At the time of contact, the foot angle in the left limb is -10° - outward rotation - (norm is -10°). At the moment of detachment, the foot angle in the left limb is -6° at the standard -5°. Angle in the right limb when the foot touches the ground -16° (plantar flexion) when the standard is -10°. At the moment of detachment, the angle in the right limb is -18° at the standard -5°.

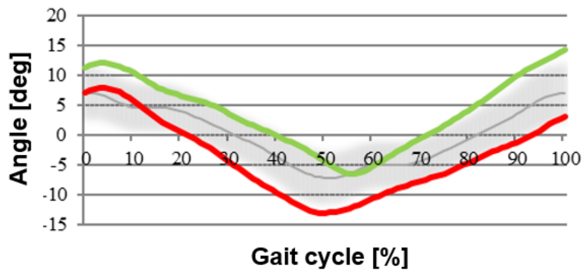
</td>
</tr>
</table>

PERSON 2

A patient with diplegia with paresis of the right side at the age of 3 years and 7 months, with a body height of 100 cm and a body weight of 14 kg. A BMI of 14 (3th percentile) classifies the subject to underweight children. During the second study after 6 months of treatment, the body mass index was 14.7; 19th percentile (height 101 cm, weight 15 kg).

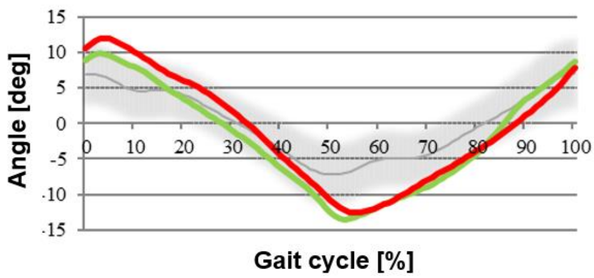
Examination prior to injection of botulinum	Examination 6 months after injection of botulinum
PELVIS	
	
sagittal plane: increased pelvic anterior tilt up to 16 ° (norm up to 12°).	sagittal plane: increased pelvic anterior tilt during the entire gait cycle. At the time of contact with the ground, the angle value is 16° (standard 8°). Then, when taking the load, the forward inclination increases to 19° in the left and 17° in the right limb, to return to both limbs to 15° in the swing phase. Slightly (about 3° - 4°) increased range of motion
	
Frontal plane: too late pelvic lift on the left side in the support phase of the left libm and then to the end of the support phase left limb in pelvic inclination (left side above). During the swing phase of the left limb, the pelvis is parallel to the ground. Lack of elevation of the right side of the pelvis at the beginning of the right limb support phase. Generally, the pelvis is tilted to the right (left ASIS up) or in neutral position.	Frontal plane: At the beginning of the gait cycle of the left limb, the pelvis is positioned at an angle of -4° (norm 1°) and then reach a value of 3° during the support phase. At the swing phase of the left limb pelvic descent to the left. Angle at the beginning of the support phase of the right lim -2°. Then strong pelvic elevation during the support phase (maximum 7° at 3° norm). Then, in the right limb swing phase, the right side of the pelvis goes down (to an angle of -3°) and

remains obliquely until the end of the right limb gait cycle. The nature of the movement has been preserved, however, the range of motion increased to 10° (the norm is 6°). Left falling during the swing phase



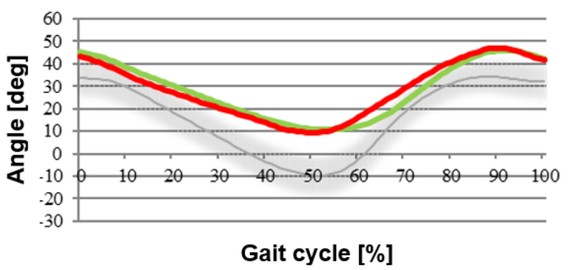
transverse plane: the nature of the movement is preserved, but the right side is much faster and further "pushed" forward during the swing phase.

The angle at the time of contact of the left limb is 7°, while in the right limb 11° (the norm is 7°). At the end of the support phase of the left limb the angle of the pelvis is -13° (norm -6°). This is due to the strong rotation of the pelvis to the right during the right limb swing. The right limb swing is associated with excessive pelvic work - it looks like there is a pelvic swing to move the limb. Left limb swing is much weaker. Probably a problem with left limb. Increased range of motion to 20° (norm 14°).

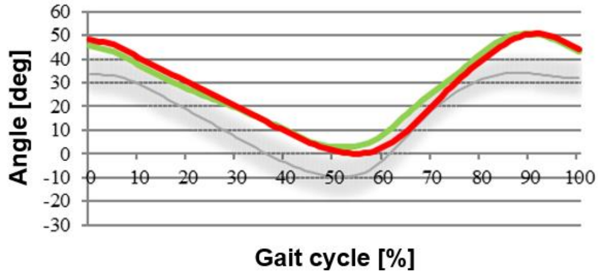


transverse plane: the nature of the movement is preserved, however, with an increased range of motion (24°, norm 14°) - there is a strong deepening of the pelvic rotation at the end of the support phase and at the beginning of the swing phase.

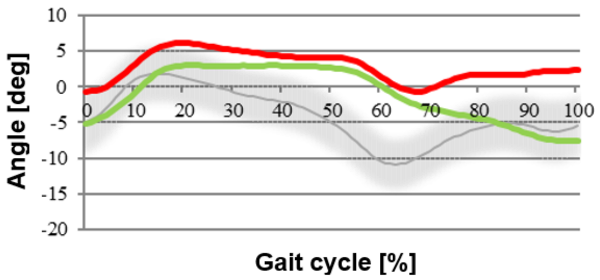
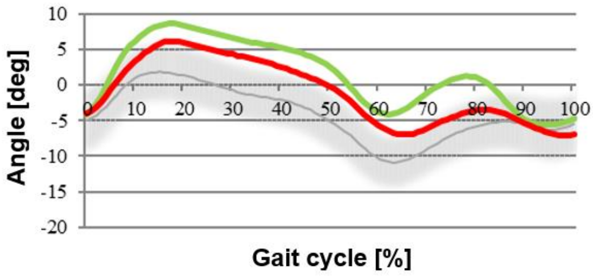
HIP JOINT

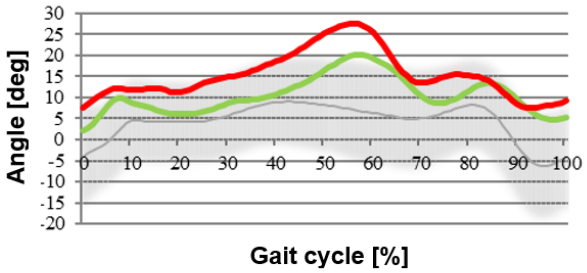


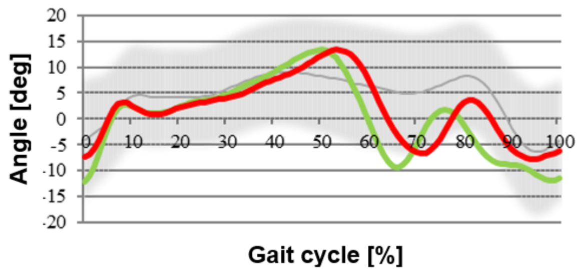
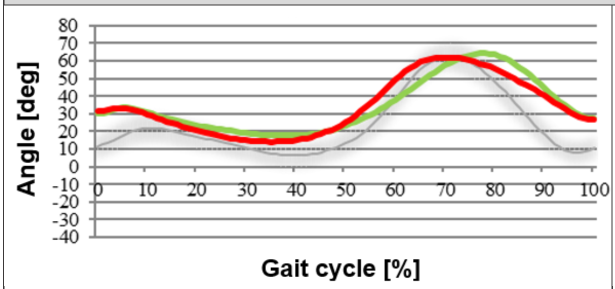
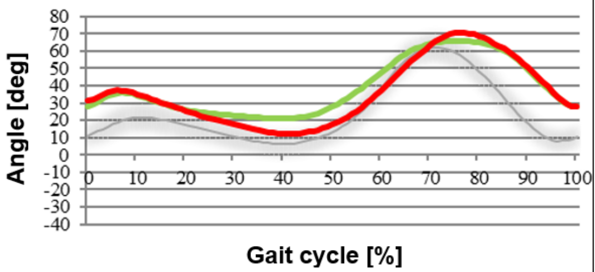
flexion/extension: at the beginning of the support phase the angle in both limbs is 45° (standard 32°). At the end of the support phase, the angle in the left limb is 20° and in the right limb is 10° (norm 0°). Movement range for both limbs 35°. The nature of the movement has been preserved, while

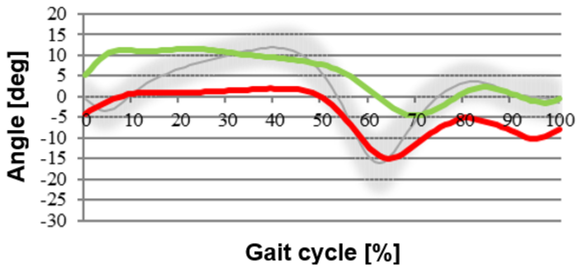
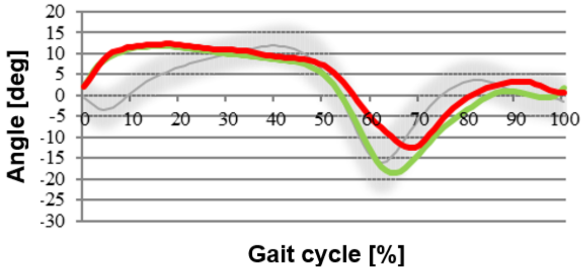


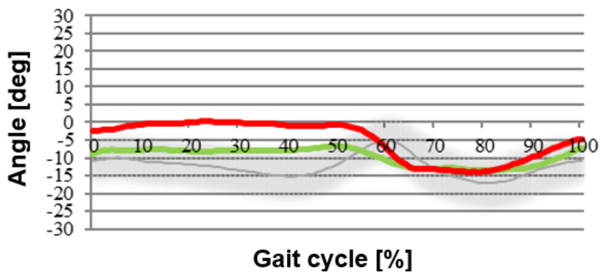
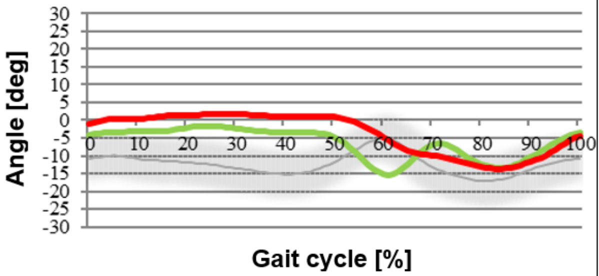
flexion/extension: the nature of the movement is preserved, but both limbs throughout the entire walking cycle are excessively flexed. At the beginning of the support phase, the angle in both limbs is 48° (standard 32°). The 15° to20° difference between the measured course and standard course is maintained throughout the entire

throughout the entire gait cycle the limb is in excessive flexion.	support phase of both limbs. At the beginning of the swing phase, the course approaches standard values. In the second half of the support phase, on the other hand, deeper flexion in the hip joint occurs (50° at standard 33°)
 adduction/abduction: at the beginning of the support phase angle in the left limb 0° (on the border of the norm range, the norm is -5° - abduction). This is followed by proper adduction, which, however, remains constant throughout the entire support phase (about 5°), first falling to zero at the end of the support phase, and then rising to 2° in the swing phase. At the moment of detachment from the ground left limb angle is 0° (norm -10°). Right limb at the beginning of the support phase is set correctly, however, like the left limb, it remains in adduction almost throughout the entire support phase. At the end of the support phase, right limb is adducted (when the right limb is detached, the angle is 0°, norm -11°), continued in the swing phase until normal values are reached at the end of the swing phase. The nature of the movement of both limbs is preserved only at the beginning of the support phase. Movement range in the left limb 7° and in the right limb 11° (norm 13°).	 adduction/abduction: at the beginning of the support phase, the angle in both limbs 0° (normative value). Then both limbs are adducted (6° in the left and 8° in the right limb, standard 2°). At the moment of detachment of the foot from the ground, both limbs at a slight abduction (-5° left limb and -3° right limb, standard -10°). In the swing phase in left limb, the movement is close to normal, in right limb there is first adduction to an angle of 1°, and then abduction to normative values -5°.
rotation: the rotation angle of the right limb is within the upper ranges of the norm. The left	rotation: during the supporting phase, the movement of both limbs close to normal.

<table>
<tr>
<td>limb is excessively rotated inward throughout the entire gait cycle
</td>
<td>During the swing phase, both limbs are first rotated outwards, then there is an internal rotation, and then again an external rotation (left limb at the beginning of the support phase reaches -1° - a value close to the normative - while pkd -12°).

During the first half of the swing phase, the range of motion increased in both limbs
</td>
</tr>
<tr>
<td colspan="2">KNEE JOINT</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>flexion/extension: at the moment of contact the angle in both limbs is 30°, (standard 10°). Then in both limbs an extension movement occurs approaching the normative values during load acceptance by the limbs (left limb angle 15°, right limb angle 18°, standard 10°). Then there is too early extension movement in both limbs, reaching normative values in the middle of the swing phase (maximum flexion in the left limb 62°, in the right limb 65°, standard 60°). In the right limb maximum flexion delayed. In both limbs the nature of the movement has been preserved with a reduced range of motion to 47° (norm 54°)</td>
<td>flexion/extension: the nature of the movement is similar to normal, but for most of the walking cycle both knee joints are excessively flexed. At the beginning of the support phase, the angle in both limbs is 30° (standard 10°). At the end of the support phase and at the beginning of the swing phase, the angle in the left limb approaches the standard value, while in the right limb it remains in excessive flexion throughout the entire support phase. At the detached moment the angle in both limbs is 40° (norm). In the second half of the swing phase in both limbs there is no proper extension.</td>
</tr>
</table>

<table>
<tr><th colspan="2">ANKLE JOINT</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>plantar / dorsal flexion: At the time of contact, the foot angle in the left limb is -5° - plantar flexion (the norm is 0°). Then the foot is set at an angle of 0° and remains in this position almost until the end of the support phase, when the plantar flexion occurs to an angle of -15° (normative value). In the swing phase left limb still remains in the plantar flexion fluctuating between -5° and -10°. Right limb at the moment of contact set at an angle of 5°. Then there is an increase to an angle of 10° in which position the limb remains almost to the end of the support phase. At the end of the support phase, the right foot set in a slight dorsiflexion (2° - norm is plantar flexion -15°). In the second part of the swing phase, the righ limb is set correctly.

In the left limb there is no dorsiflexion during the entire gait cycle. In the right limb, however, there is limited plantar flexion. Range of motion of the left limb is 15°, and in the right limb 16° (norm 28°). Disturbed character of motion in both limbs.</td><td>Plantar / dorsal flexion: in both limbs the angle at contact time is 2° (normal 0°), and then increases to about 10° (dorsiflexion). This value is maintained in both limbs almost until the end of the support phase. Before detaching the foot from the ground, dorsiflexion occurs in both limbs to the maximum value at the beginning of the swing phase -12° in the left limb and -18° in the right limb (norm -16°). Then there is the dorsal flexion movement until reaching an angle of about 2° at the beginning of the support phase.</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>foot rotation: left limb in neutral position (0 °) throughout the entire support phase. At the very end of the support phase, there is an external rotation (at the moment of detachment the angle -5°). The external rotation is maintained throughout the entire</td><td>foot rotation: left limb in neutral position (0°) throughout the entire support phase. At the very end of the support phase, there is an outward rotation (at the moment of detachment the angle -5°). External rotation is maintained throughout the swing phase</td></tr>
</table>

swing phase. In the right limb the angle at the time of contact with the ground is -10° (normative value), and remains almost until the end of the support phase (lack of external rotation to -15°). At the moment of the right limb detachment from the ground and in the swing phase, the external rotation deepens to -13° (norm is -17°), followed by internal rotation to an angle of 10°. In both limbs the character of movement in the swing phase was preserved, whereas it was disturbed in the support phase. In the left limb the range of motion is 15°, and in the right limb 8° (norm is 12°).	(close to normal). In the right limb the angle at the time of contact with the ground is -5° (norm -10°), and remains almost until the end of the support phase (no deepening of external rotation to -15°). In the swing phase, there is alternate external and internal rotation.

11. Key ideas

- Selected dysfunctions of the musculoskeletal system
- Types of pathological gait.
- Selected changes in kinematic and dynamic quantities in pathological gait
- Walking on crutches as an example of pathological gait
- Analysis of kinematic quantities in pathological gait

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