Erasmus+

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 A: BIOMECHANICS OF NORMAL GAIT

Politechnika Śląska
IBV INSTITUTO DE BIOMECÁNICA DE VALENCIA
VNIVERSITAT DE VALÈNCIA
AMSE THE ASSOCIATION OF MEDICAL SCHOOLS IN EUROPE

Contents

1. Objectives

- Find out how gait is defined.
- Learn how gait is described - division into phases.
- Find out what the attributes and determinants of gait are.
- Find out what kinematic parameters are used to describe the biomechanics of gait and what changes these parameters subject during the gait cycle.
- Find out what dynamic parameters are used to describe the biomechanics of gait and what changes these parameters subject during the gait cycle.
- Find out what muscle work looks like during a gait cycle.

2. Outline of the history of biomechanical gait analysis

The beginnings of biomechanical motion analysis consisted in determining the position changes of the analysed objects in time. One of the first to conduct this type of research in relation to gait biomechanics was **Edward Mybridge** (1830 – 1904) [[3]]. He constructed the first device for taking pictures of moving objects and a projector that enabled the display of "moving" pictures (Fig. 1,Fig. 2)

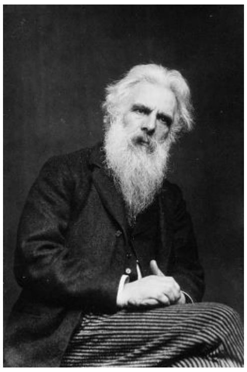

Fig. 1 Edward Mybridge (1830 – 1904) [[3]]

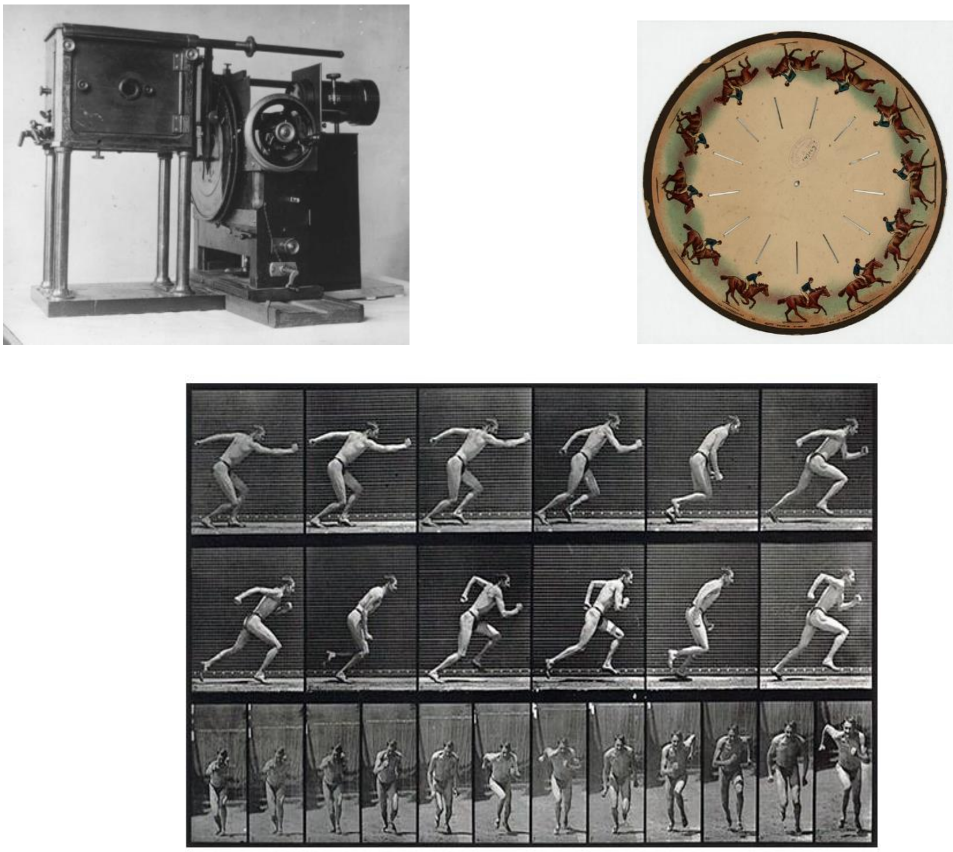

Fig. 2 Equipment used by Mybridge to conduct research [[39]]

Etienne Jules Marey (1830-1904) is considered a precursor of biomechanical motion analysis. He constructed a chronograph and in 1883 made the first human gait diagram [[3]]. The device constructed by him differed from the one made by Mybridge in that subsequent photographs were recorded on the same photographic plate. E Marey was also the first to develop a method for recording walking phases (Fig. 3, Fig. 4). For this purpose, he used pneumatic sensors attached to the shoes of the examined person. They made it possible to register the support and swing phase during walking. He also developed, together with his student **Georges Demeny** (1850 - 1918), a platform enabling measurement of the vertical component of the ground reaction, using the results of these measurements to conduct gait energy analyzes [[3]].

Fig. 3 Etienne Jules Marey (1830-1904) [[3]]

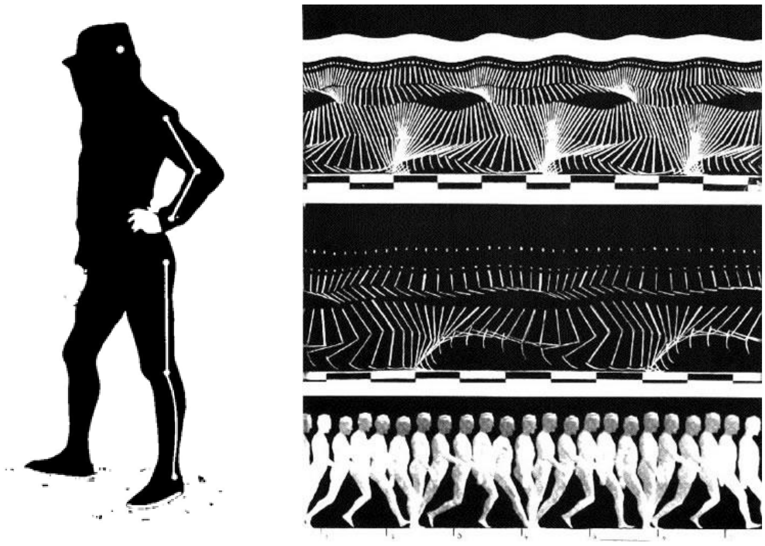

Fig. 4 The suit used by Marey and subsequent gait sequences recorded [[38]]

Marey's research was continued, among others, by **Otto Fisher** (1861–1717) and **Wilhelm Braune** (1831–1892), who developed a suit for motion analysis and, by analyzing the measurement data, made a manual graph of subsequent lower limb positions. They were also the first to carry out a three-dimensional gait analysis (Fig. 5, Fig. 6).

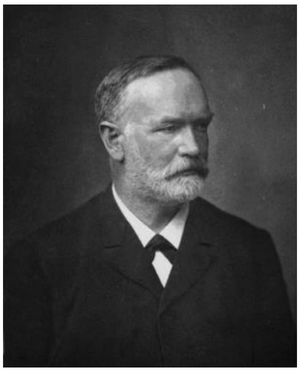
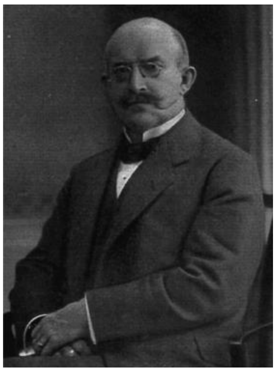

Fig. 5 Wilhelm Braune i Otto Fischer [[3]]

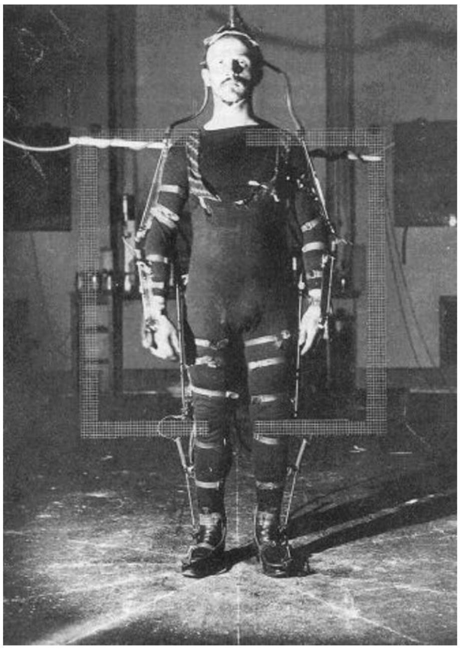
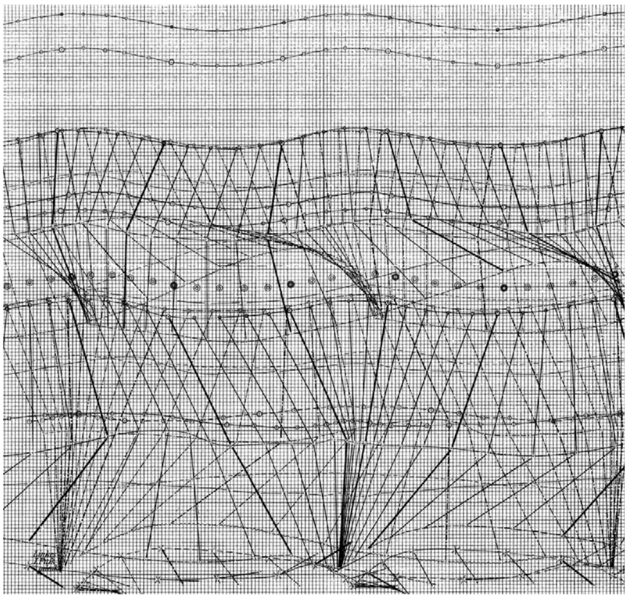

Fig. 6 The suit and hand chart of subsequent lower limb positions (1891) - Fisher and Braun study [[3]]

In subsequent years, more and more devices enabling more and more accurate measurements were used in research. Jules Amar (1879 - 1935) was the first to construct a measuring platform recording three components of the ground reaction during walking, and Cunningham and Brown were the first to record all six components of the ground reaction - forces and moments of force. A breakthrough in biomechanical gait analysis was the use of computers that enabled the simultaneous analysis of many recorded variables, such as location, linear and angular velocity, and linear and angular acceleration. In addition, the use of computers allowed to conduct model calculations that allow identifying the forces generated by muscles during movement.

3. Normal gait - basic definitions

Morecki [[20]] defines locomotion as a movement leading to a change in the place occupied by an object in relation to the adopted reference system. On the other hand, Błaszczyk defines the concept of human locomotion as follows [[5]]: „Locomotion is a process of active movement of organisms associated with the implementation of specific life needs. Depending on the speed range, the bipedal locomotion can be divided into several forms differing in the coordination of movements of individual body segments: gait, run, sprint, jumps." Gait according to Dega [[11]] can be defined as alternating loss and regaining balance in alternately changing phases of support and swing of the lower limbs.

From the point of view of implementation, locomotion is the most complex motor task that a person must learn almost in the earliest period of his life. Over time, learned movement patterns become such a natural activity that it takes place without the participation of conscious control over each movement made. [[5]].

In order to make a biomechanical analysis of gait, you first need to familiarize yourself with the axes and planes of the human body, against which individual movements are often defined. The human body is built according to the two-sided symmetrical figure type, i.e. the body halves - right and left - are separated by a plane and are similar to each other like a reflection in a mirror.

There are three basic types of planes in the human body (Fig. 7):

- sagittal planes (plana sagittalia) - these planes are perpendicular to the earth's surface, and divide the body into right and left parts. The sagittal plane, running through the main axis, is called the median plane (planum medianum) or the plane of symmetry.
- frontal planes (plana frontalia) - they run parallel to the forehead and perpendicular to the sagittal planes, dividing the body into the front and back.
- transverse planes (plana transversalis) or horizontal (plana horizontalia) - run perpendicular to the sagittal and frontal planes, dividing the body into the upper and lower parts.

We also distinguish the following body axes:

- vertical axis or longitudinal axis (axis longitudinalis) - it is perpendicular to the surface on which a person stands. It connects the top of the head with the last coccygeal vertebra. This is the main axis around which rotational movements take place.,
- sagittalis axis - runs from front to back and is perpendicular to the vertical and horizontal axis. There are abduction and adduction movements around this axis.
- horizontal axis or transverse axis - it connects two equally placed points on the right and left half of the body. It is perpendicular to both previously mentioned axes. Bending and straightening movements are performed around this axis.

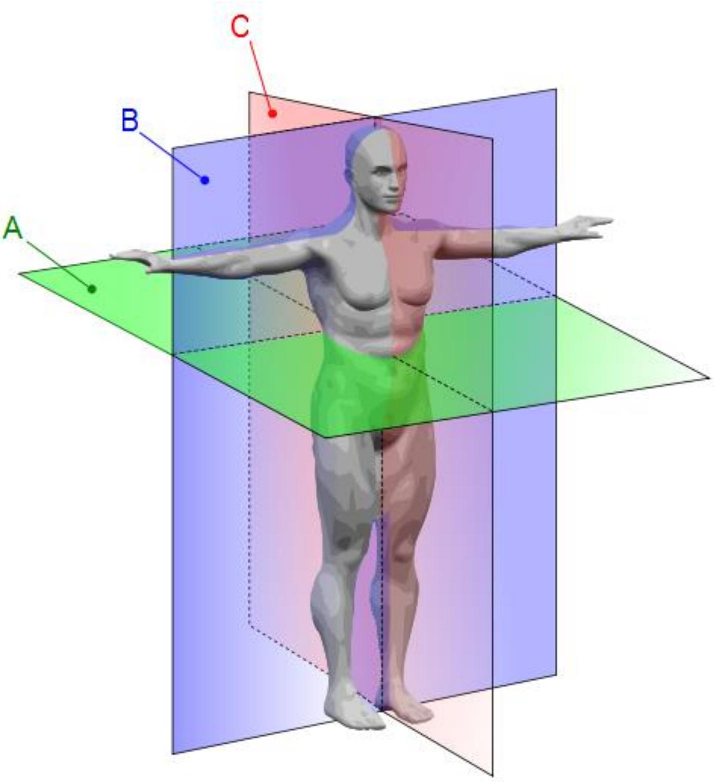

Fig. 7 Human body main planes: A – horizontal (transverse) plane, B – frontal plane, C – sagittal plane [[37]]

Normal gait is characterized by the fact that it is:

- Two-legged - to move, man uses both lower limbs at the same time
- Alternating - movements of the lower limbs are synchronized and performed alternately, i.e. the right and left lower limb are performed alternately. Lower limb movements are synchronized with upper limbs movements and full body movement.
- The movement occurs forward.
- Symmetrical - both the left and right sides of the human body work together equally well. The right and left side movements of the body with normal gait are approximately symmetrical
- Harmonious: isometric (same length of steps); isochronous (same duration of steps); isotonic (same muscle tone in both lower limbs).

Biomechanical gait analysis is usually carried out on the basis of the so-called gait cycle using the values determined during experimental tests and using mathematical models. Gait analysis is most commonly assessed in biomechanical analysis by means of:

- gait attributes
- determinants of gait,
- temporally-spatial parameters,
- kinematic parameters,

- ground reaction forces,
- muscle bioelectric activity,
- values of moments of muscular forces acting in the joints,
- the values of forces generated by muscles,
- power,
- reactions in the joints.

4. Description of the normal gait - division into phases

In gait, as the repetitive activity, one can distinguish the so-called cycle, i.e. subsequent movement activities repetitive over time and performed in a specific sequence. The gait cycle is the basic concept of gait and lasts, in the case of normal gait, from the contact of the heel of one limb with the ground to the contact of the heel of the same limb with the ground. One walking cycle therefore includes two steps - one right limb step and one left limb step. The description of gait biomechanics always refers to the gait cycle [[6], [30]].

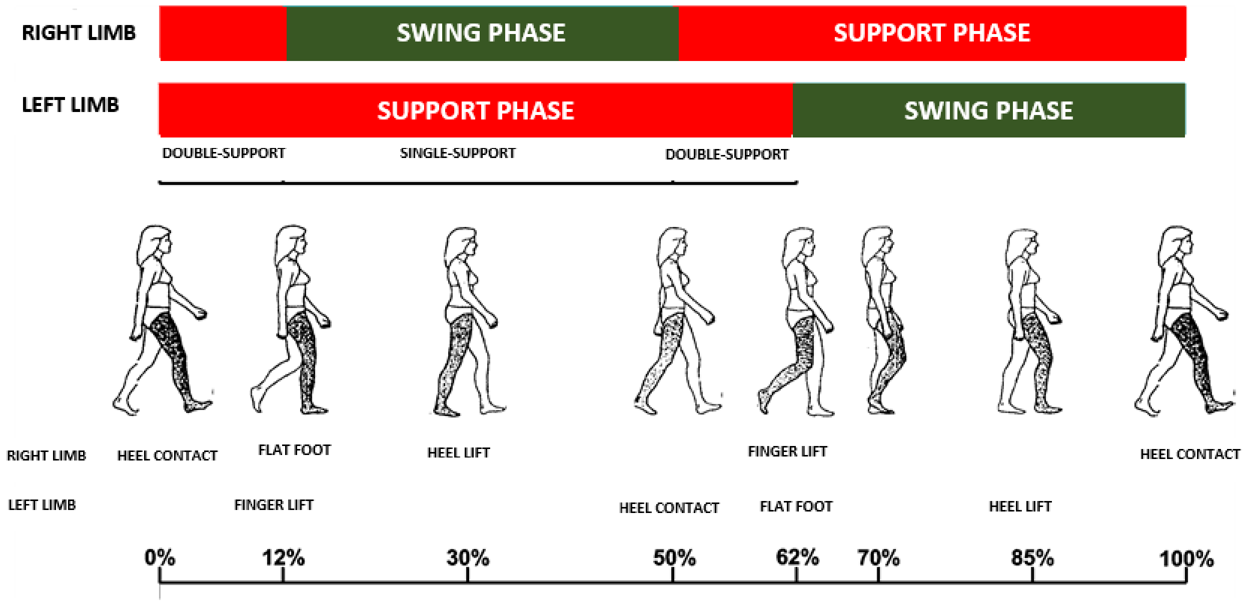

Fig. 8 Gait cycle phases for the right and left limb [[33]]

The gait cycle is divided into phases [[33]]. The following phases can be distinguished:

- Support phase.
- Swing phase.
- Double-support phase.

The support phase of a given limb occurs when the limb is in contact with the ground. Therefore, we are talking about the support phase of the left limb and right limb. The support phase begins when the foot contacts the ground and ends when the foot detaches from the ground.

The swing phase occurs when the limb is not in contact with the ground. The swing phase begins when the foot is removed from the ground and ends when it contacts the ground again. Here, too, we are dealing with the swing phase of the right and left limb.

A fragment of the gait cycle when both limbs are in contact with the ground simultaneously is called the two-support phase. It occurs when the first limb ending the support phase is still in contact with the ground through forefoot and toe, and the second limb has finished the swing phase and comes into contact with the ground. The double-support phase is the basic element that distinguishes gait from running in which the two-support phase does not occur and the flight phase appears in its place.

Walking at so-called volunteer speed is usually carried out at a speed of 4 km / h. At this speed, the walking cycle lasts about 1.1 seconds, while the individual phases, in relation to the entire walking cycle, last:

- Support phase around 62% of the gait cycle
- swing phase about 38% of the gait cycle
- Double support phase around 12% of the gait cycle.

It should be mentioned here that the first two phases add up to a full 100% gait cycle and concern the separation of the right and left limbs, while the double-support phase includes movement of both limbs.

For normal gait, the duration of the support and swing phase of the right and left limbs should be approximately the same. Most often in clinical evaluation it is assumed that any asymmetry between the right and left side should not exceed 10%. The duration of individual phases depends on the speed of the gait - as the speed increases, the time of the support phase is shortened, while the swing phase is extended.

SUPPORT PHASE

During the support phase, the limb's task is to transfer the load resulting from body weight. The support phase, due to the functions of the lower limb and taking into account courses of individual ground reactions, can be divided into [[33], [15]]:

- Overload phase, which lasts about 20% of the support phase
- Unloading phase, which lasts about 30% of the support phase
- Propulsion phase, which lasts about 50% of the support phase.

The overload phase begins with foot contact with the ground - this should be the heel for normal gait. The end of the overload phase occurs when the entire foot is placed on the ground. This phase entirely coincides with the two-support phase. For the entire gait cycle, the overload phase lasts 12% of the gait cycle.

The unloading phase begins when the entire foot is placed on the ground and ends when the heel is removed from the ground. During the entire unloading phase, the body weight rests on one limb. Regarding the walking cycle, the unloading phase lasts from 12% to 30% of the walking cycle.

The propulsion phase begins when the heel is detached from the ground and ends when the toes are removed from the ground. With respect to the gait cycle, the propulsion phase lasts from about 30% of the gait cycle to 62% of the gait cycle. During the propulsive phase, the centre of mass is moved forward and the horizontal velocity increases in the direction of walking to the maximum. At the end of the propulsive phase, the other (opposite) limb comes into contact with the ground, i.e. the two-support phase begins.

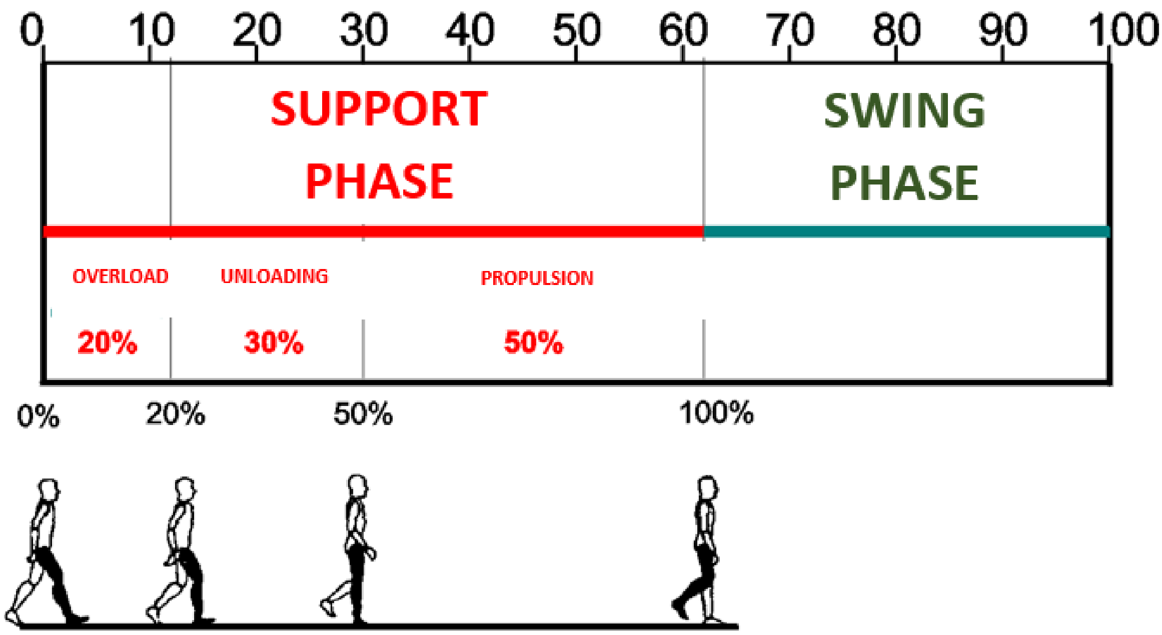

Fig. 9 Division of the support phase into phases [[33]]

SWING PHASE

The swing phase begins when the fingers are removed from the ground. It is divided into the following phases [[33], [15]]

- The active swing phase, lasting about 20% of the swing phase
- A passive phase lasting about 40% of the swing phase
- Braking phase, lasting about 40% of the swing phase.

The active swing phase (from about 62% to about 70% of the gait cycle) begins when the fingers are removed from the ground. There is a strong action of the hip flexor muscles, due to which the limb increases its speed and there is a displacement from up and forwart. In this phase, maximum flexion takes place in the knee joint.

The passive swing phase lasts from about 70% to about 85% of the gait cycle. During this phase, the lower limb moves further forward, but mainly due to the inertia force using the speed given in the active swing phase.

The breaking phase lasts from about 85% to about 100% of the gait cycle. During this phase, limb momentum is produced by the eccentric work of the hip extensor muscles and knee flexor muscles. The whole limb is also prepared to accept the load at the beginning of the support phase.

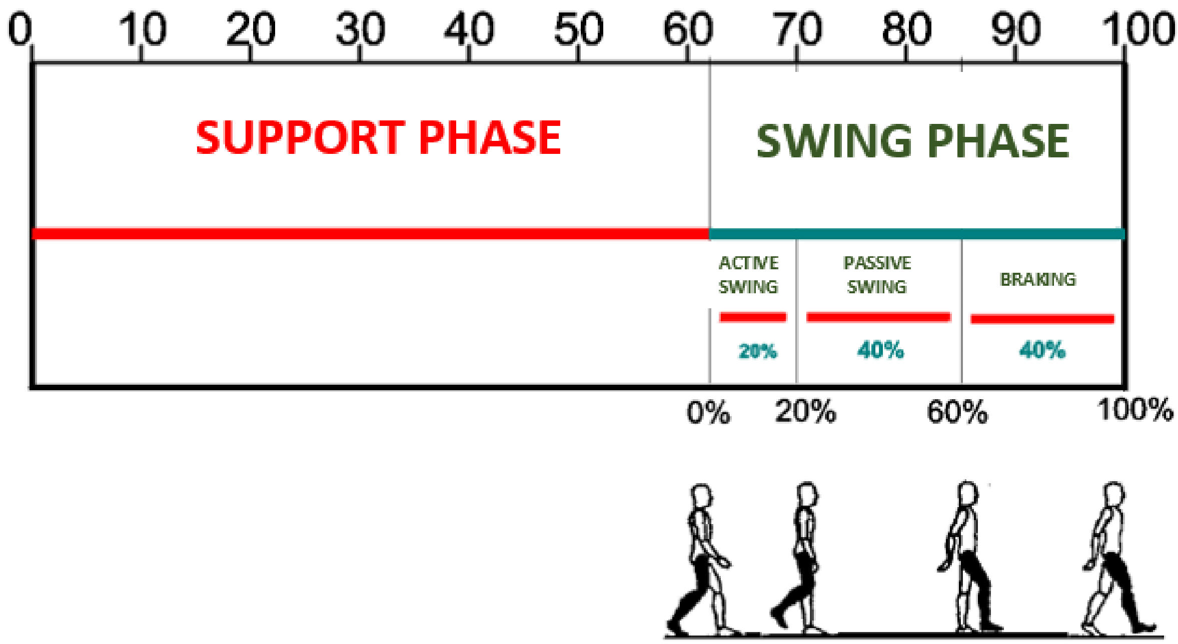

Fig. 10 Division of the swing phase into phases [[33]]

NOMENCLATURE USED IN GAIT BIOMECHANICS

The following determinations are used in gait biomechanics analysis:

- cadence - this is the number of steps taken in one minute. Studies have shown that the natural rhythm of locomotion in women is on average 122 steps per minute, while for men 116 steps per minute,
- stride length - this is the distance between successive, same support points of the same limb, for example the points at which a given limb started the support phase or ended the swing phase (Fig. 11),
- step length - this is the distance between the selected but the same points of the right and left limb, for example the distance between the position of the heel of the right and left limb. The step length may be different for the right and left limb (Fig. 11).

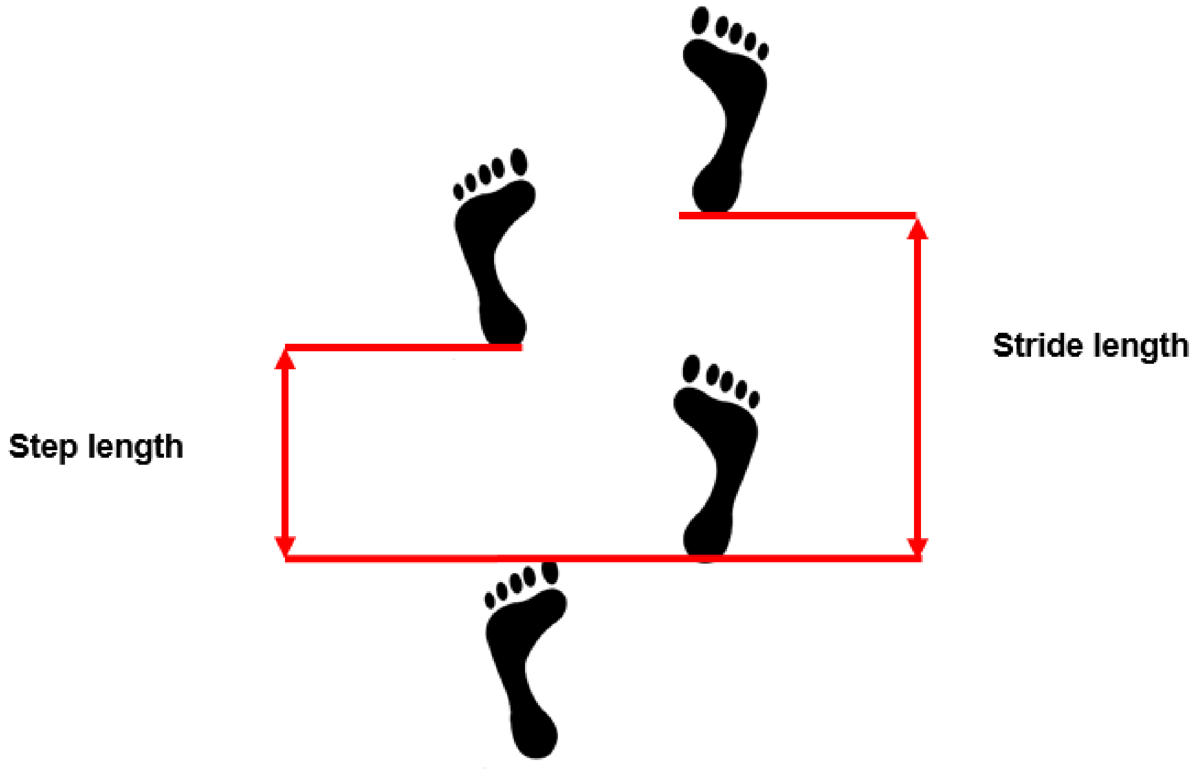

Fig. 11 Stride and step lengths

5. Attributes and determinants of normal gait

The main purpose of walking is to allow people to move. Gait as a cyclical activity is characterized by a specific pattern for which there are slight individual differences, however, the size and scope of these differences is so small that it allows to specify a standard gait pattern, which can be described using different parameters. These values include gait attributes and gait determinants.

GAIT ATTRIBUTES

The first group of this type are gait attributes.

The following five walking attributes can be distinguished:

- support stability
- correct clearance under the foot during the swing phase, i.e. proper limb raising. About 18 cm is considered to be correct.
- appropriate positioning of the foot before the beginning of the support phase, which, when walking correctly, begins when the heel contacts the ground.
- appropriate stride length
- minimization of energy consumption

GAIT DETERMINANTS

Another group of parameters describing normal gait are gait determinants that are closely related to the last gait attribute - minimizing energy consumption. They were described by Dec [[10]]. Dec assumed that while performing locomotion, man tries to control them in such a way that the energy expenditure is as low as possible. During walking, a cyclical upward and downward movement of the centre of mass can be observed. These movements are associated with alternating changes in kinetic and potential energy. Because gait is movement consisting in moving the body forward, the minimal energy expenditure will be ensured when the trajectory of the centre of mass movement is close to a straight line, i.e. the following centre-of-body mass movements will be limited:

- the maximum lifting of the centre of body mass during the whole walking cycle is reduced,
- the descent of the centre of mass at the boundaries of the support and swing phases of gait is limited
- lateral displacements of the centre of body mass during the whole walking cycle are limited.

All these elements are excessively emphasized in the sport gait, where the main training goal is to minimize energy expenditure, and thus fatigue of the player.

Based on this assumption, Dec in the 1950s identified those body movements during gait that had the greatest impact on increasing or reducing energy expenditure. They were called gait determinants. Non-optimal values of determinants may indicate the possibility of health problems affecting movement or a fixed incorrect walking pattern, because changing the value of the determinants increases energy expenditure during walking.

There are six determinants of gait (Fig. 12 – Fig. 16):

- Pelvic rotation in a horizontal plane
- Pelvic obliquity in the frontal plane
- Pelvic lateral movements
- Knee flexion during the support phase
- Functional shortening of the limb during the swing phase
- Foot movement and angular changes in the ankle joint in the sagittal plane

Pelvic rotation in a horizontal plane

Pelvic rotation is described in the horizontal plane, i.e. around the long axis of the body. This determinant concerns the correct positioning of the pelvis, and thus the hip joints, in the transverse plane in the double support phase. The forward movement of the lead limb in the swing phase is combined with the pelvic rotation movement following this limb by means of forward movement of the lead side of the pelvis. This movement occurs symmetrically and alternately for both limbs and allows the length of the steps to be extended. Pelvic rotation lengthens the stride. At a speed of about 4 - 5 km/h, the pelvis rotates about 4 - 5° in each direction. An increase in walking speed leads to an increase in the angle of rotation.

Pelvic obliquity in the frontal plane

This determinant describes the position of the pelvis and hip joints in the frontal plane, i.e. the rotation of the pelvis around the sagittal axis. The pelvic movement in the frontal plane consists of the pelvis positioning slightly obliquely by falling to the side of the limb in the swing phase with simultaneous lifting on the side of the limb in support. Simultaneously with the described pelvic movement, there is a slight adduction of the lower limb in support (about 5°) and abduction of the lower limb in the swing phase (also by about 5°). All this increases the effective length of the lower limb that is in the swing phase and the lifting of the centre of gravity of the body is reduced.

The protection against excessive pelvic descent towards the limb being in the swing phase is the work of the middle gluteus muscle on the opposite side to the limb being in the swing. Pelvic descent should be around 5 °. Excessive pelvic descent is referred to as a Trendelenburg symptom and is a symptom of some diseases.

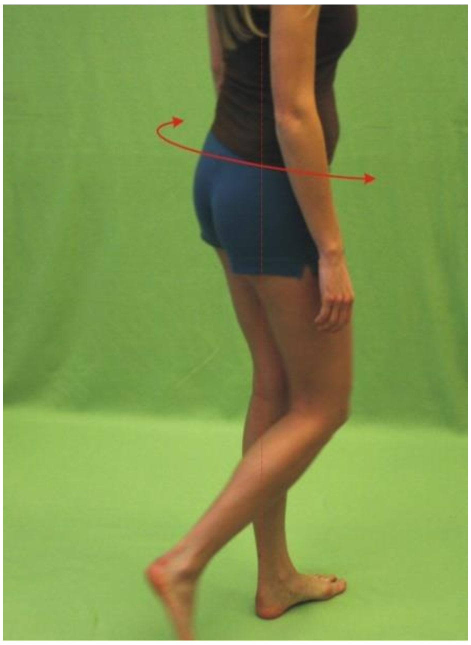

Fig. 12 Pelvic rotation in transverse plane [[33]]

Fig. 13 Pelvic obliquity in the frontal plane [[33]]

Pelvic lateral movements

The lateral movements of the pelvis result from alternate loading of the lower limbs and are the result of the pelvis moving towards the support leg. This pelvic follow-up is due to the fact that the gait control system attempts to bring the body in such a way that the centre of gravity projection is above the foot or area containing both feet and between them, i.e. when only one leg is in the support, the pelvis moves so that the centre of mass is moved. above the foot of this limb.

These types of movements are most evident during slow gait. Along with the displacement of the pelvis, there is also a simultaneous adduction of the lower limb in hip joint equal to a few degrees. It results from the fact that the pelvis moves laterally in relation to the limb in the support. Because this limb cannot follow the pelvis, there is an adduction movement in the hip joint.

Fig. 14 Pelvic lateral movements [[33]]

Knee flexion during the support phase

This determinant describes the value of the flexion angle of the knee of the support limb in the phase of full load. Movement of the limb in the knee joint during the support phase begins with the flexion movement, which lasts until the other limb is detached from the ground. Then the flexion in the knee joint reaches the maximum value - about 15 ° - 20 °, followed by a extension movement so that at the very end of the support phase flexion begins again. Such a sequence of movement along with the achieved maximum flexion angle makes it possible the movements up and down of the centre of gravity of the body are minimal, which in turn means that energy expenditure is minimized.

Fig. 15 Sequence of flexion and extension movement in the knee joint [[33]]

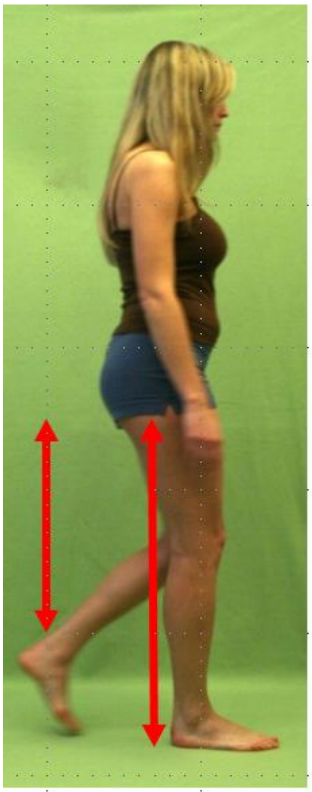

Fig. 16 Functional shortening of the limb [[33]]

Functional shortening of the limb during the swing phase

Functional shortening of the limb in the swing phase describes the required amount of apparent shortening of the lower limb in the swing phase so that, despite the pelvis falling slightly on the side of the swing limb (second determinant), the foot does not touch the ground. The shortening value is determined when the transverse axis of the ankle joint passes the main frontal plane of the body. Shortening occurs in all the joints of the lower limb (hip, knee, ankle), but the highest value is achieved in the knee joint. For the gait to be normal, the knee must be able to bend to 65 degrees.

Foot movement and angular changes in the ankle joint in the sagittal plane

Correct positioning of the foot, i.e. the correct angle in the ankle joint, when the heel hits (dorsiflexion) and when the limb is detached from the ground (plantar flexion) increases the effective length of the lower limb.

A correct gait must meet the following conditions:

- the steps of both lower limbs must be of the same length,
- the loading time for both lower limbs must be the same,
- proper coordination of the entire torso and upper limbs with the work of the lower limbs must be ensured. It consists in the fact that simultaneously with the inclination of the lower limb there is a rotation of the torso towards this limb combined with a swing of the upper limb on the same side as the lead leg,
- heel contact with the ground is connected with the movement of the foot, which movement ensures correct positioning of the lower leg and thigh in external rotation,
- detachment of the foot from the ground is accompanied by the adduction of the foot, which movement begins the internal rotation of the lower leg and thigh.

6. Time-space parameters describing gait biomechanics

The basic values describing the gait include time-space values. These values can be determined using very simple measurement methods; therefore, they belong to one of the most often determined and analyzed values. You can include them:

- gait velocity
- stride length
- cadence.

The average walking speed of healthy people varies between 4 - 6 km / h (Fig. ****). For this speed, the frequency of taking steps (cadence) is in the range of 90 - 120 steps per minute, while the length of the steps is 70 - 82 cm [[6]].

The average length of a single step of an adult is about 0.7-0.82 m, whereas for a child it is approximately equal to his body height

The length of the stride depends on several factors, including body height, sex and the technique of movement (Fig. 18 – Fig. 21).

The frequency of steps is about 90-120 steps per minute

The following figures show selected relationships between individual parameters as well as relationships between these parameters and sex and age. Walking speed depends directly on the length of the steps and the frequency of steps. Linear relationships occur between these quantities, as shown in Fig. 22 and Fig. 23. Walking speed is also dependent on age, as shown in Fig. 24 – Fig. 28.

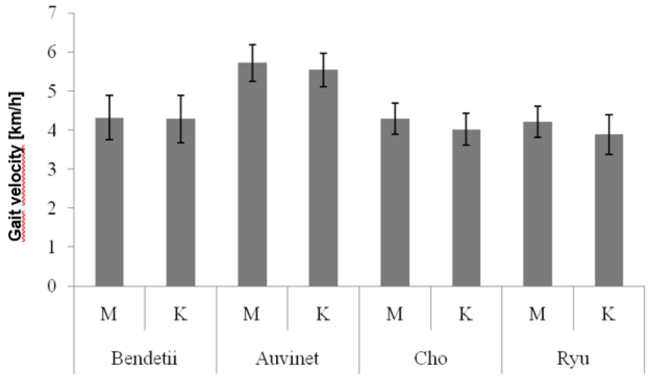

Fig. 17 Gait velocity according to various studies with division into women and men [[2],[4],[7],[26],[33]]

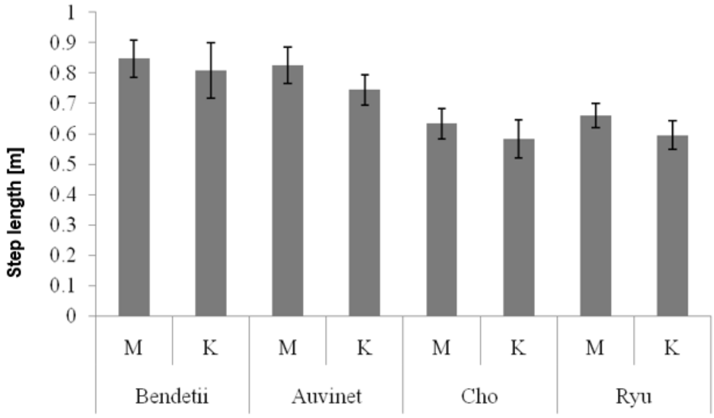

Fig. 18 Step lengths according to various studies with division into women and men [[2], [4], [7], [26],[33]]

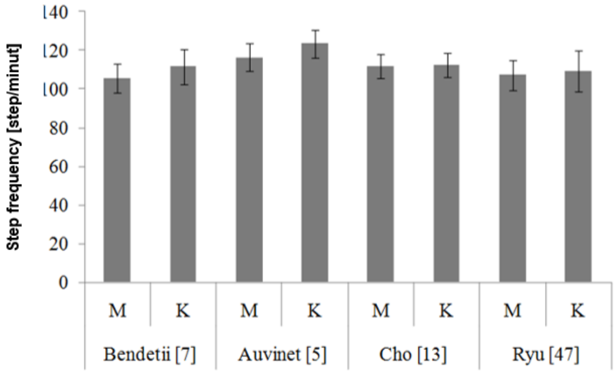

Fig. 19 The frequency of taking steps according to various studies with division into women and men [[2], [4], [7], [26],[33]]

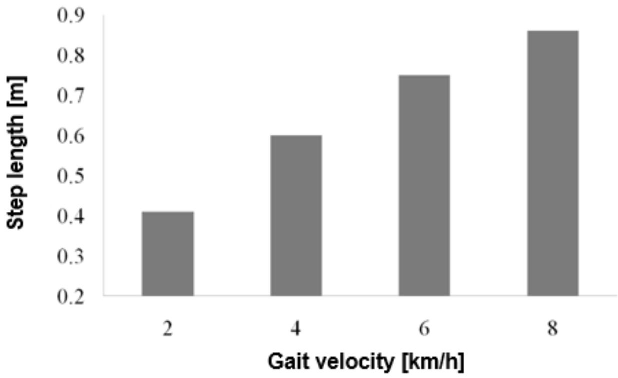

Fig. 20 Changes in the length of the steps depending on the walking speed [[29],[33]]

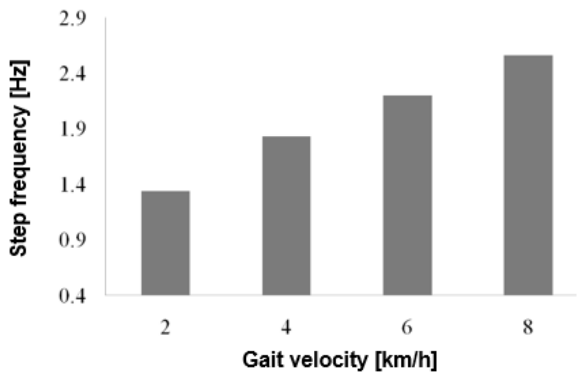

Fig. 21 Changes in the frequency of steps depending on the walking speed [[29],[33]]

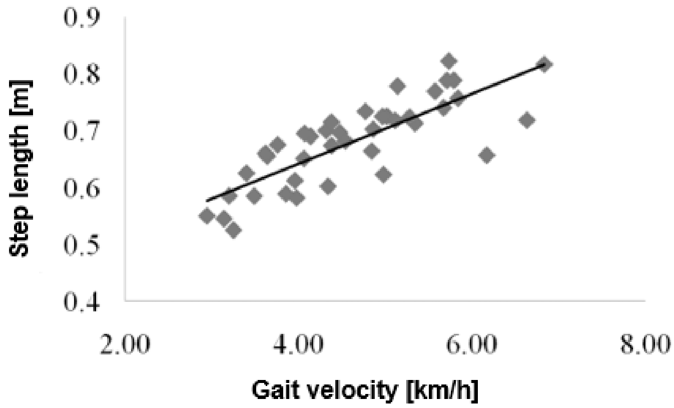

Fig. 22 The relationship between the walking speed of healthy people and step length [[28],[33]]

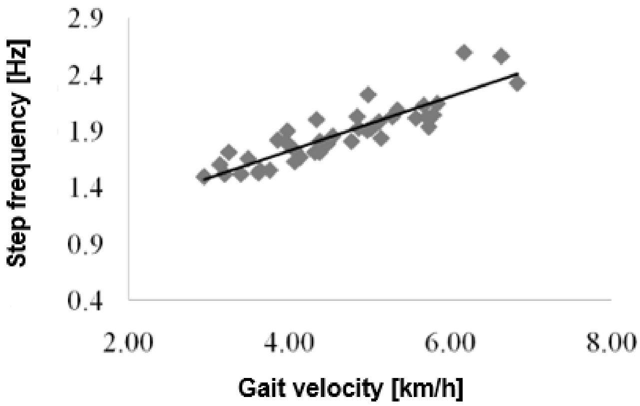

Fig. 23 The relationship between the walking speed of healthy people and the frequency of steps [[28],[33]]

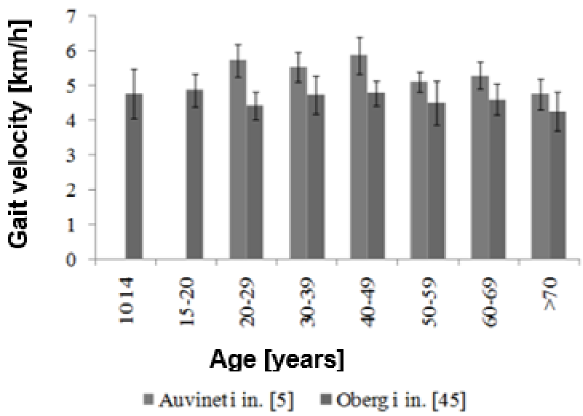

Fig. 24 Walking speed in different age categories according to different authors [[2], [23],[33]]

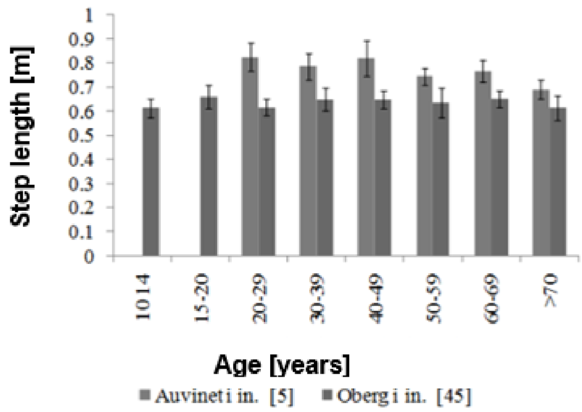

Fig. 25 Step length in different age categories according to different authors [[2], [23],[33]]

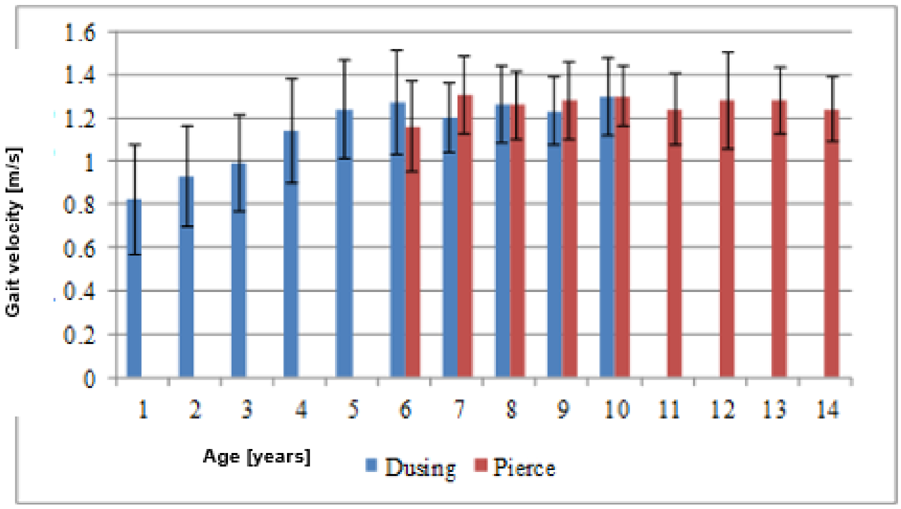

Fig. 26 Walking speed of children of different ages [[24], [12],[19]]

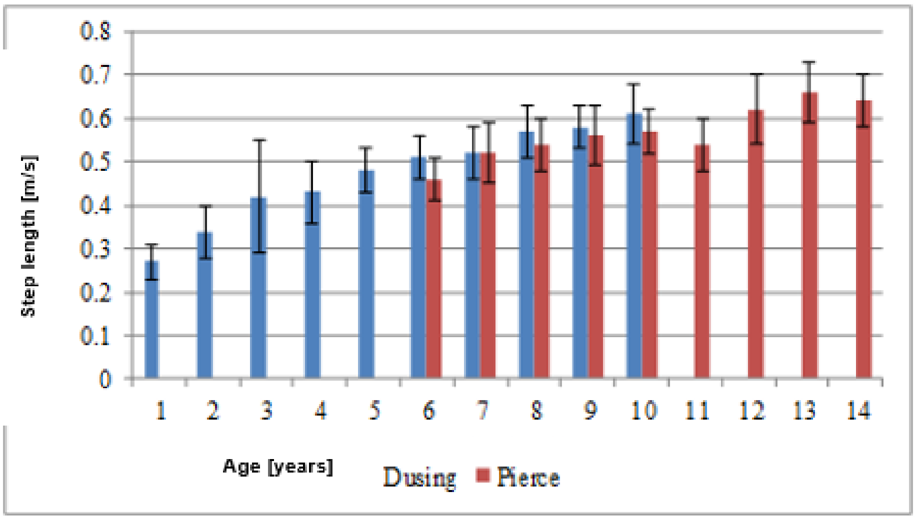

Fig. 27 Step length when walking at different ages [[24], [12],[19]]

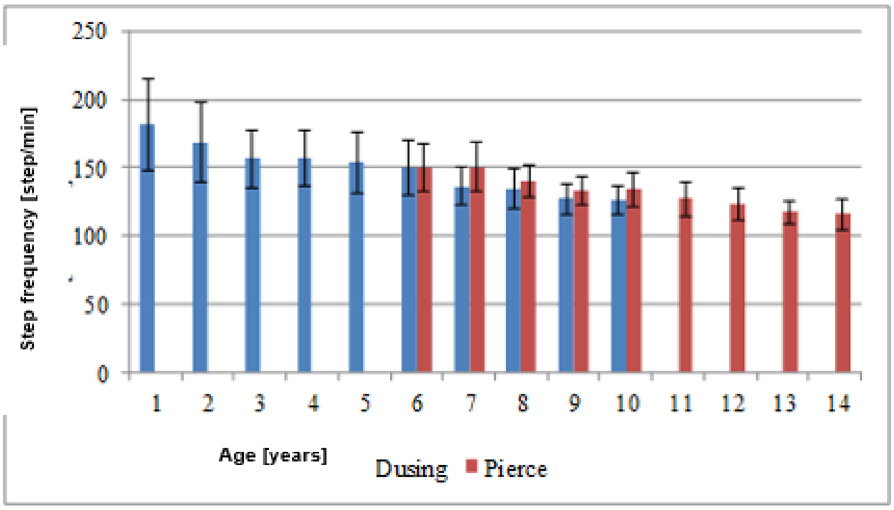

Fig. 28 The frequency of walking steps for children of different ages [[24], [12],[19]]

7. Kinematic quantities describing gait biomechanics - joint angles

Next parameters describing gait biomechanics are kinematic parameters. The courses of individual joint angles are most often analyzed, however, it is also possible to determine the trajectories of selected body points as well as linear and angular velocities and accelerations.

The analysis of joint angles consists in determining the course of individual anatomical angles in the joints (usually the lower limb) and angles describing the position of the pelvis. The determined values of angles and their waveforms in time are then referred to the standard waveforms obtained for healthy people. The analysis is usually performed for the following angles:

- in the case of the pelvis, these are pelvic tilt in the sagittal plane, lateral movements of the pelvis in the frontal plane (obliquity), and pelvic rotation in the transverse plane,
- for the hip joint, these are the angles of flexion and extension in the sagittal plane, abduction and adduction in the frontal plane, and rotation around the vertical axis,
- flexion and extension of the knee in the sagittal plane,
- dorsal flexion and plantar flexion of the foot in the ankle and foot position in the frontal plane.

All angular waveforms are determined and analyzed in relation to the walking cycle, where the beginning of the graph coincides with the beginning of the support phase. The following charts will show the ranges of valid values for individual articular angles.

POSITION OF THE PELVIS

During the gait cycle, slight pelvic movements occur in all anatomical planes of the body. In the sagittal plane, during normal gait, the pelvis moves the least, maintaining an inclination (Tilt) in the range of 8° - 10°. In the frontal plane, there is an alternating movement of pelvic elevation and descent (Obliquity). At the beginning of the support phase, the pelvis slightly rises on the side of the limb being in support, followed by the pelvis falling down towards the same limb, which in the meantime ends the support phase and begins the swing phase. Rotation movements have the largest amplitude of about 4° to the right and left. At the beginning of the support phase, the pelvis is pushed forward on the side of the limb in support, and then when the limb moves towards the swing phase, the pelvis is withdrawn on the side of this limb. [[33]].

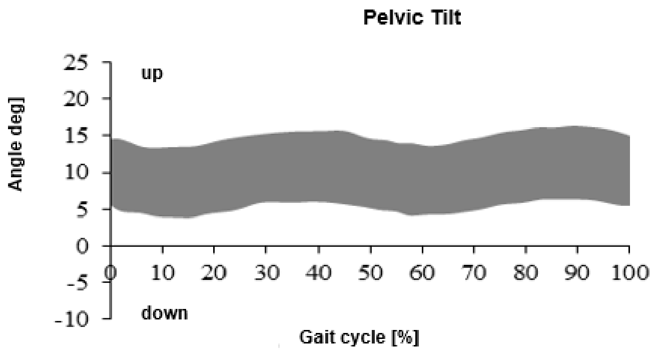

Fig. 29 Pelvic Tilt in saggittal plane [[33], [8], [16], [36]]

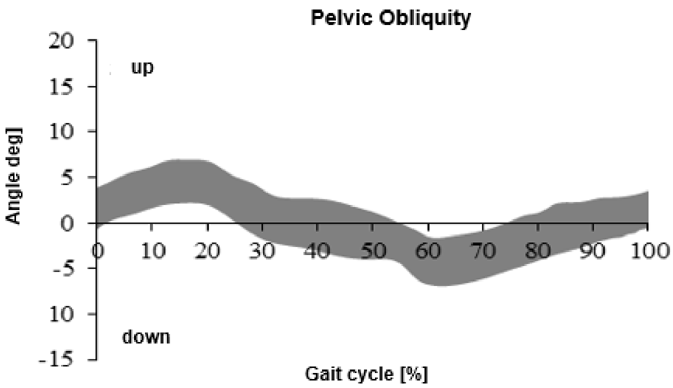

Fig. 30 Pelvic Obliquity in frontal plane [[33], [8], [16], [36]]

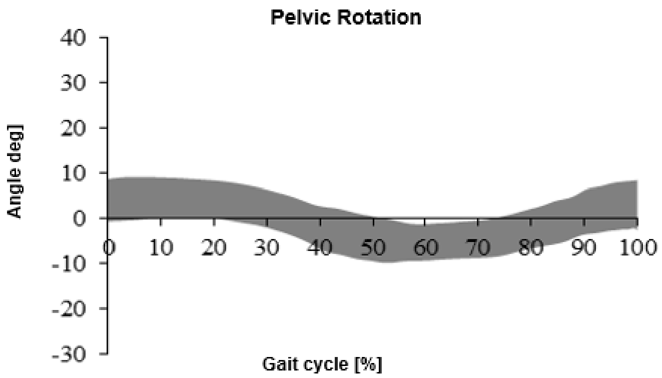

Fig. 31 Pelvic rotation in transvers plane [[33], [8], [16], [36]]

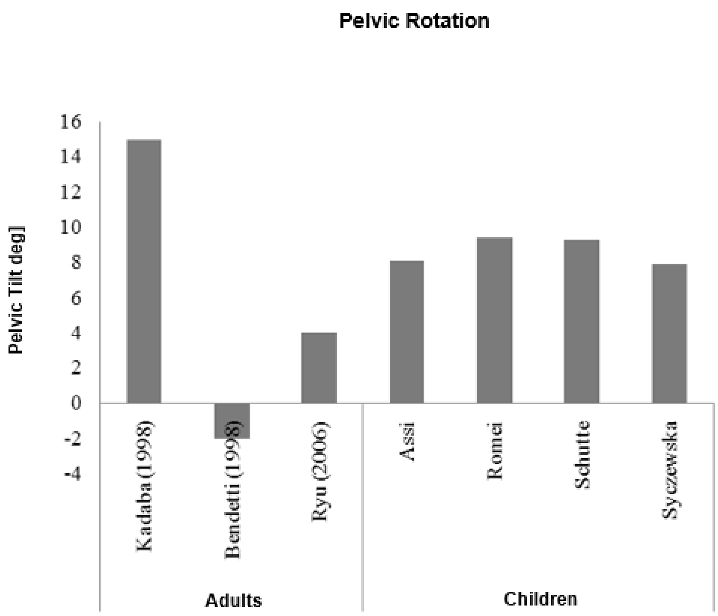

Fig. 32 Average pelvic tilt angle in gait [[33], [1], [4], [13], [25], [26], [27], [31]]

ANGLE COURSES IN THE HIP JOINT

During walking in the hip joint there are movements in all three planes [[33]]. The most extensive movement is the flexion-extension movement. At the beginning of the support phase, the limb is positioned such that the flexion angle in the hip joint is about 35°. This is followed by extension so that at the end of the support phase an extension is about -10°. In the swing phase flexion is approximately 35 °.

In the frontal plane, at the beginning of the support phase, the limb is in slight adduction, which increases to a value of about 7 ° and begins to decrease. During the swing phase, the limb is in slight abduction.

Rotation movements throughout the entire gait cycle are insignificant - their range is several degrees.

The movement of flexion and abduction in the hip joint during the swing phase is to lead to functional shortening of the limbs, and thus enable the lower limb to be moved above the ground.

The graphs included in the work show the courses of joint angles in time and the maximum values of flexion and extension obtained during measurements made by various authors.

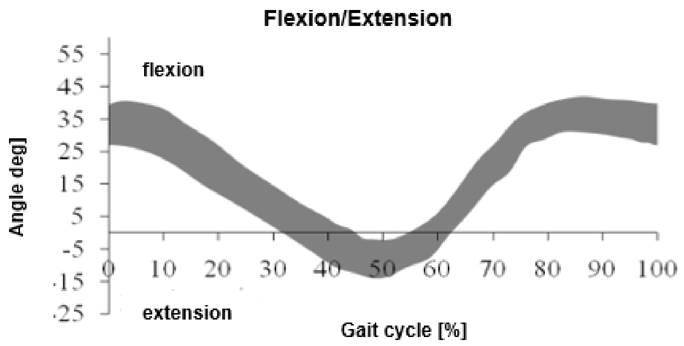

Fig. 33 Flexion-extension angle at the hip joint [[33], [8], [16], [36]]

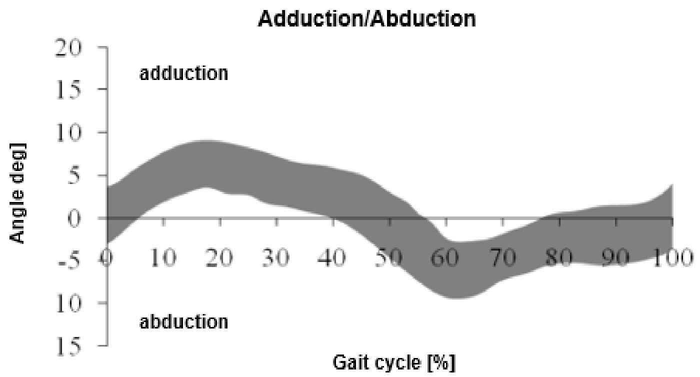

Fig. 34 Abduction-adduction angle in the hip joint [[33], [8], [16], [36]]

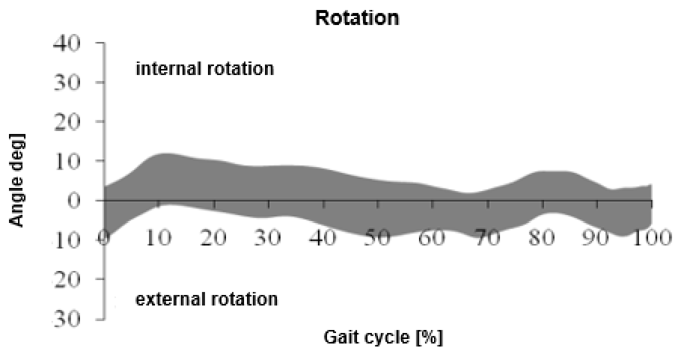

Fig. 35 Angle of rotation in the hip joint [[33], [8], [16], [36]]

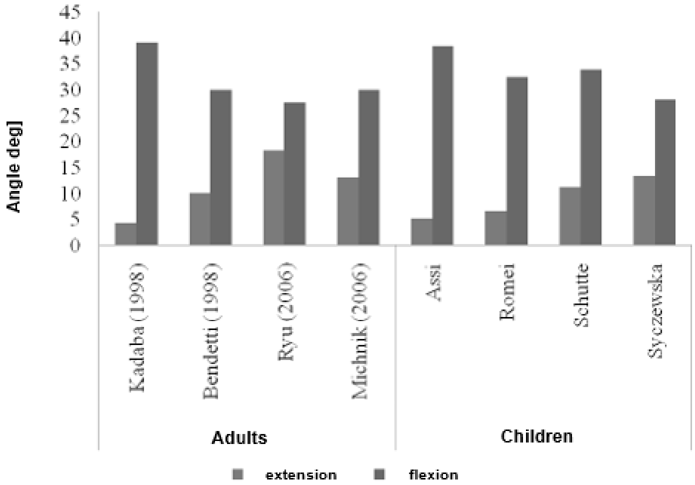

Fig. 36 The value of the maximum angle of flexion and extension in the hip joint during gait [[33], [1], [4], [13], [25], [26], [27], [31]]

ANGLE COURSES IN THE KNEE JOINT

At the beginning of the support phase, the knee joint is in a small flexion of about 8° - 15°. During the support phase, further flexion, then extension and subsequent flexion occur sequentially. In the swing phase, further flexion takes place, which reaches a maximum of about 60° - 75° at about 75% of the gait cycle. Then extension movement starts until reaching the value which is also the initial value of the support phase. Such a large flexion angle in the knee joint during the swing phase results from the necessity of functional shortening of the limb, which allows this limb to be moved freely above the ground [[33]].

Due to the very small abduction-adduction and rotation movements in the knee joint, these quantities are usually not analyzed.

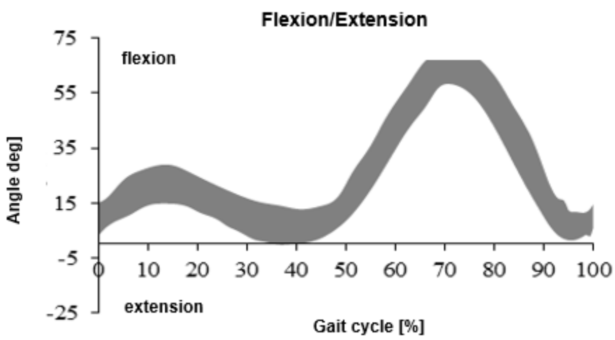

Fig. 37 Flexion-extension angle in the knee joint [[33], [8], [16], [36]]

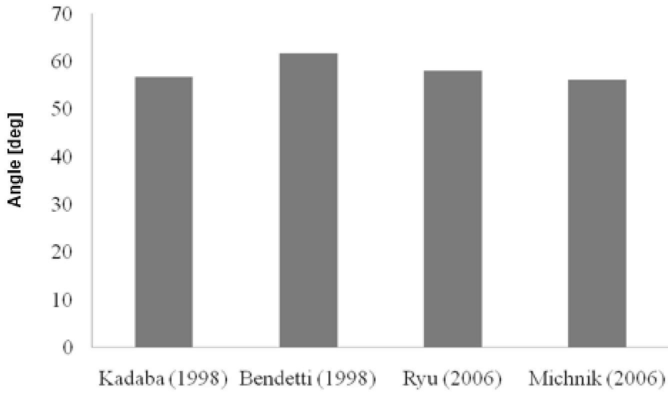

Fig. 38 The value of the maximum angle of flexion and extension in the knee joint during walking [[33], [4], [13], [18], [22], [26]]

ANGLE COURSES IN THE ANKLE JOINT

At the beginning of the support phase, the foot, which is in a slight (several degrees) dorsiflexion begins plantar flexion and remains in the plantar flexion until the end of the double-support phase. Then there is dorsiflexion, which reaches its maximum (foot in dorsiflexion equal about 10°) at about 40% of the gait cycle. Then the heel begins to detach from the ground and the foot begins plantar flexion until the end of the support phase reaching its maximum at the end of the support phase (plantar flexion about 15° - 20°). At the beginning of the swing phase, rapid dorsal flexion occurs. The foot reaches a position close to 0° or remains slightly dorsiflexed until the end of the swing phase. This arrangement of the foot allows free movement of the lower limb above the ground [[33]].

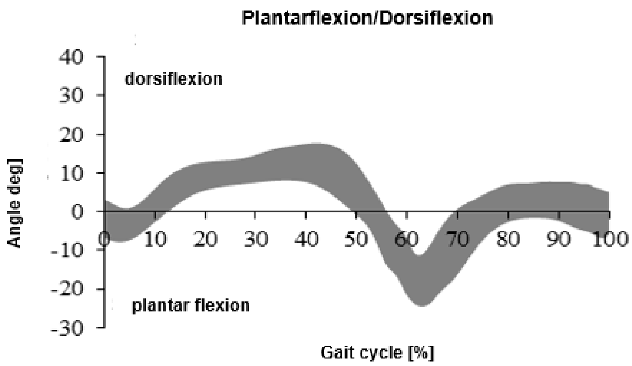

Fig. 39 Dorsiflexion and plantar flexion in the ankle joint [[33], [8], [16], [36]]

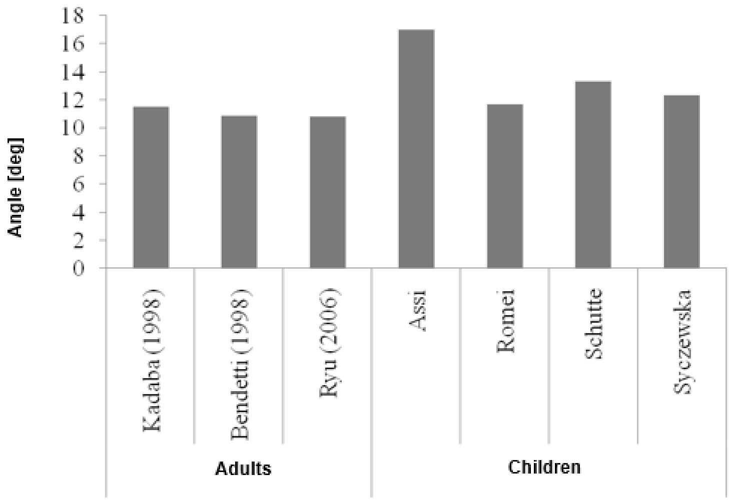

Fig. 40 Maximum values of the dorsiflexion angle in the ankle joint during gait [[33], [1], [4], [13], [25], [26], [27], [31]]

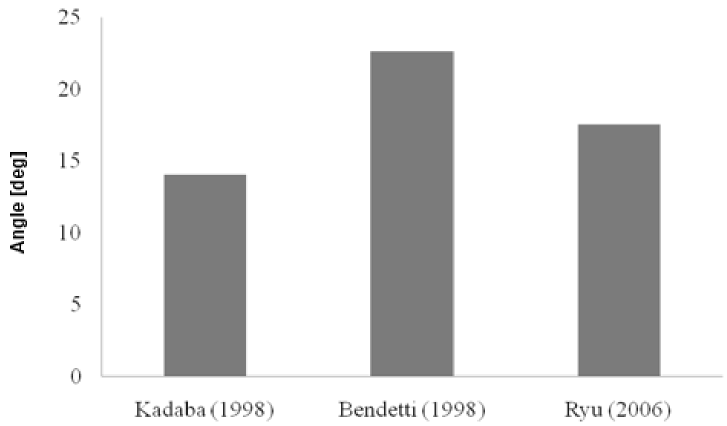

Fig. 41 Maximum values of the plantar flexion angle of the ankle joint during gait [[33], [4], [13], [26]]

8. Dynamic quantities describing biomechanics of gait - ground reactions

Gait is a dynamic activity in which the whole body is propelled and kept in balance by skeletal muscles that generate forces that affect the human skeleton. In addition to muscular forces, the body is also influenced by forces such as gravity, inertia and ground reactions. The measurement of the latter is an important element of the analysis and description of gait biomechanics [[33]].

Ground reactions are forces that affect a human body (when walking they affect on feet) as a response to body pressure on this ground, according to Newton's 3rd law of dynamics, which says that if one body affects the other, the other affects the first with the same force in value and direction, but with the opposite sense.

In the biomechanical description of gait, three ground reactions most often occur, which are actually three components of the ground reaction distributed over three forces parallel to the three axes of the coordinate system [[33]]. These three components are:

- vertical reaction parallel to the vertical axis of the coordinate system,
- anteroposterior reaction parallel to the horizontal axis of the coordinate system determined in accordance with the gait direction of the test person,
- lateral (transverse) reaction parallel to the horizontal axis of the coordinate system traced in a direction perpendicular to the walking direction of the test person.

Measurements of ground reaction are usually made using measuring platforms, measuring mats or shoe inserts. Due to their design, individual devices allow measurement of other quantities. Measuring platforms allow the measurement of all three components of the ground reaction, while measuring mats and shoe inserts give the ability to measure only the vertical component of the reaction, but additionally they measure the distribution of foot pressure on the ground.

The measured values of the ground reactions are presented in the form of the course of changes of these values over time. On the other hand, the reaction values are often presented in a normalized form to the body weight of the examined person. This normalization enables direct comparison of results of different people with each other as well as reference of the obtained results to standard courses determined from measurements carried out on healthy and properly moving people.

Fig. 42 shows courses of ground reactions for the right and left lower limb in relation to individual phases of the gait cycle.

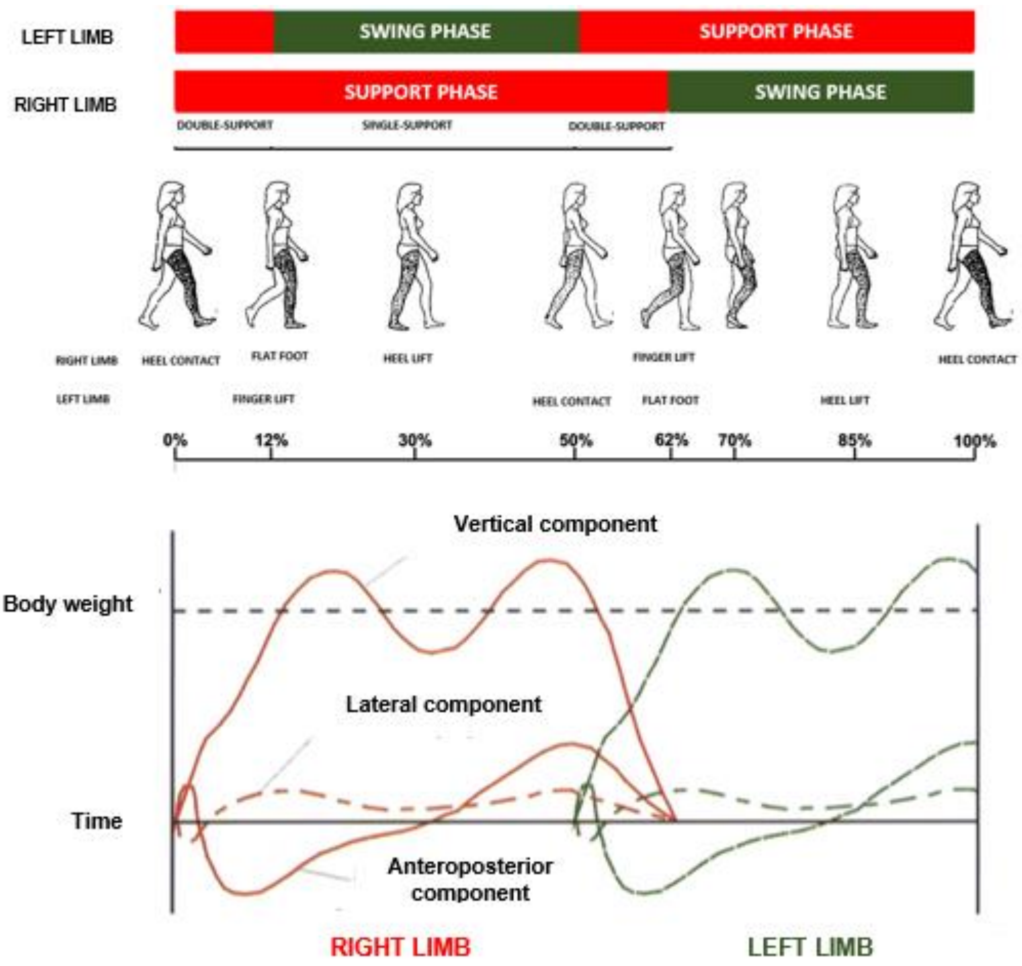

Fig. 42 Reactions of the right and left lower limbs along with an indication in which phases of the gait cycle occur [[33]]

VERTICAL COMPONENT OF GROUND REACTION

The vertical component has a characteristic waveform with two characteristic maxima (Fig. 43). The first of these is related to the heel hitting the ground and body braking. The second maximum results from accelerating the body to the next step. The values of these maxima usually exceed body weight by about 15% - 20% and depend on the walking speed (Fig. 44). Between the two maxima, the reaction value decreases and reaches a value lower than body weight. The average value of the vertical component in this phase is 80% of body weight, but its value is also dependent on the speed of walking. Due to the characteristic course of the vertical component, the support phase was divided into the phase of overload, unloading and propulsion [[33]].

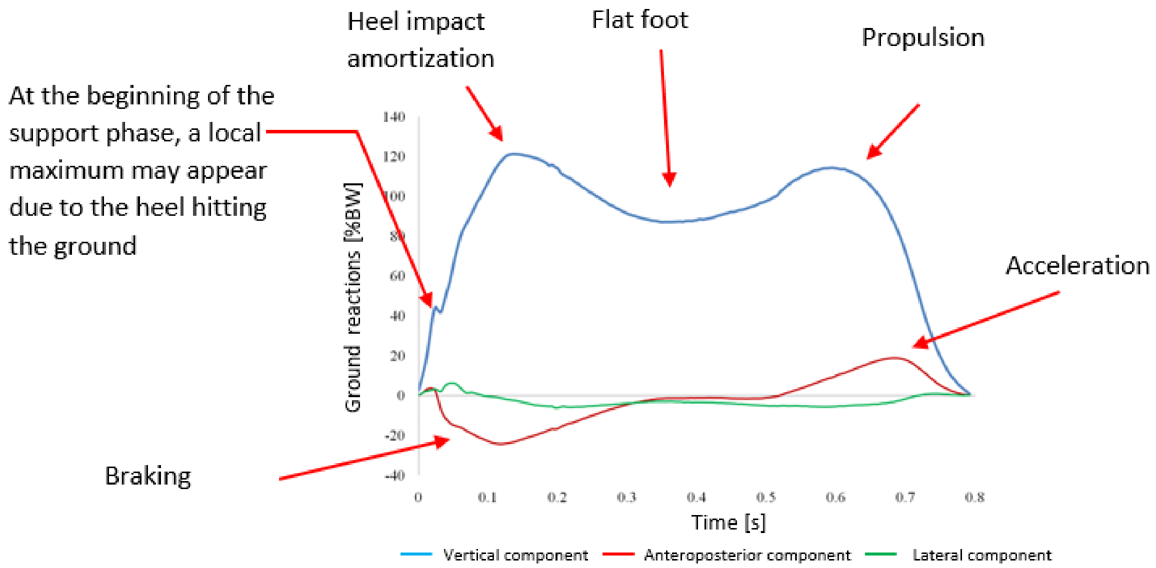

Fig. 43 Individual elements of the foot position during the support phase visible on the ground reaction graph

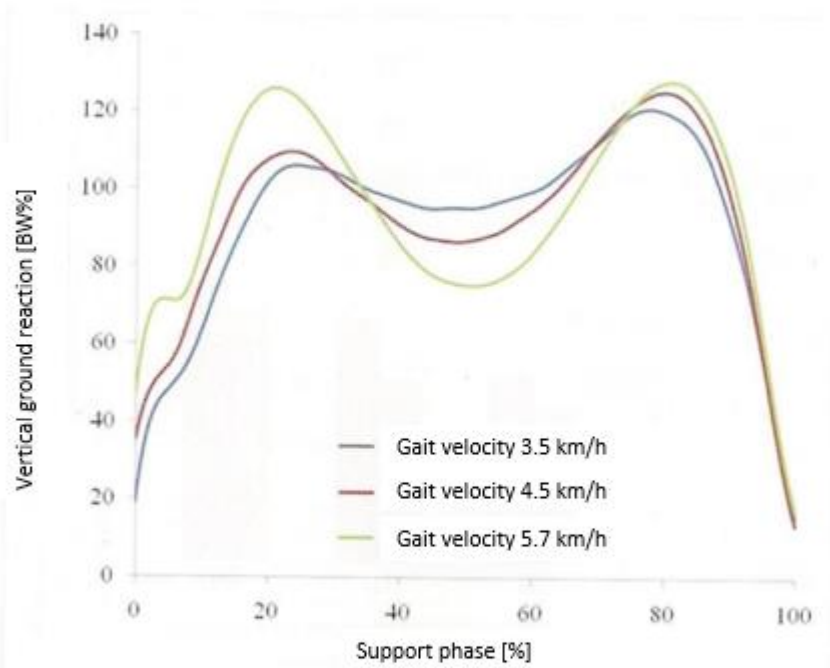

Fig. 44 Dependence of the vertical component of the ground reaction on the walking speed [[28]]

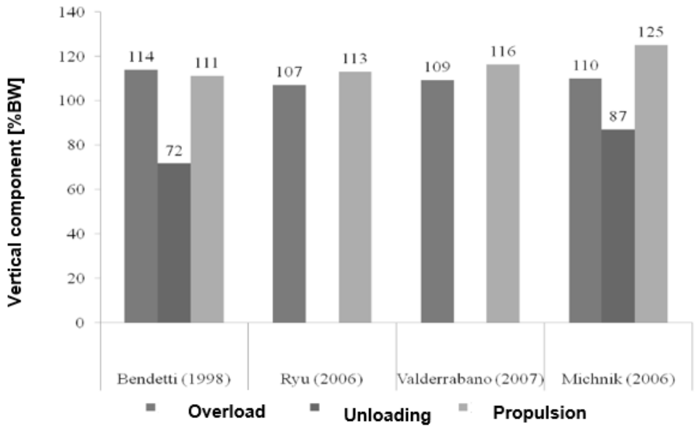

Fig. 45 Maximum values of the vertical component of the ground reaction during walking obtained in various studies [[33], [4], [18], [26], [34]]

ANTEROPOSTERIOR COMPONENT OF GROUND REACTION

A characteristic feature of the anteroposterior component is the change of the sign approximately in the middle of the support phase. This change shows that in the first half the body brakes, while in the second half the body accelerates until the next step. When braking, the foot tries to move forward on the ground, which is not allowed by the friction force acting on the foot in opposition to the sense of the motion vector (gait direction). During acceleration, the foot attempts to slide backwards over the surface, and the resulting friction force then has a sense consistent with that moving. The first maximum on the graph of this component arises about 12% of the walking cycle, i.e. when the double-support phase ends. The second maximum occurs when the next double-support phase begins, i.e. when the opposite limb begins contact with the ground (about 50% of the walking cycle) [[33]].

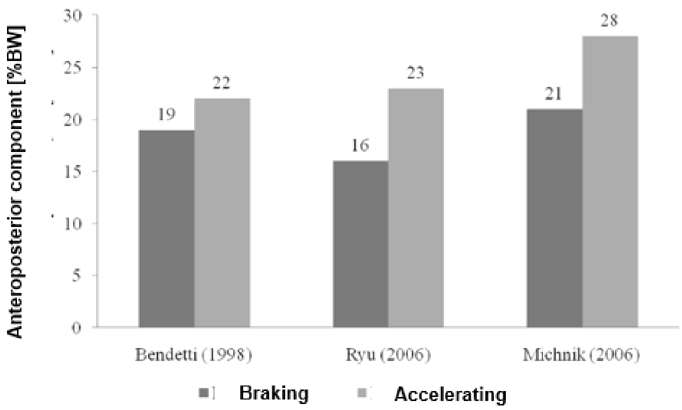

Fig. 46 Maximum values of the anteroposterior ground reaction component during gait obtained in various studies [[33], [4], [18], [26], [34]]

In the charts, depending on whether the walking takes place in accordance with the sense of the coordinate system axis parallel to the walking direction or opposite to this sense, the value of the anteroposterior reaction will be negative in the first half, and in the second positive or you can also encounter reverse writing - the value is positive in the first half and negative in the second half. This follows from the convention for recording the force sign - positive if the sense of the force is consistent with the sense of the coordinate system axis in which we write the values, and negative if the sense is opposite to the sense of this axis.

Fig. 46 shows the maximum absolute values of the antero-posterior ground reaction component obtained during various tests, separately for the braking and acceleration phases.

MEDIOLATERAL COMPONENT OF GROUND REACTION

The mediolateral component of the ground reaction results from displacements to the sides of the centre of mass and is the effect of placing feet outside of the centre line determining the direction of movement. Larger sideways tilting will result in higher mediolateral component values.

PARAMETERS ANALYSED DURING BIOMECHANICAL EVALUATION OF GAIT ON THE BASIS OF GROUND REACTIONS

By conducting quantitative analysis of gait biomechanics on the basis of ground reaction, certain values are determined that describe the correctness or gait or may indicate deviations from the norm. Each of the presented parameters, except for those referring to the double-support phase, are determined separately for the right and left limbs.

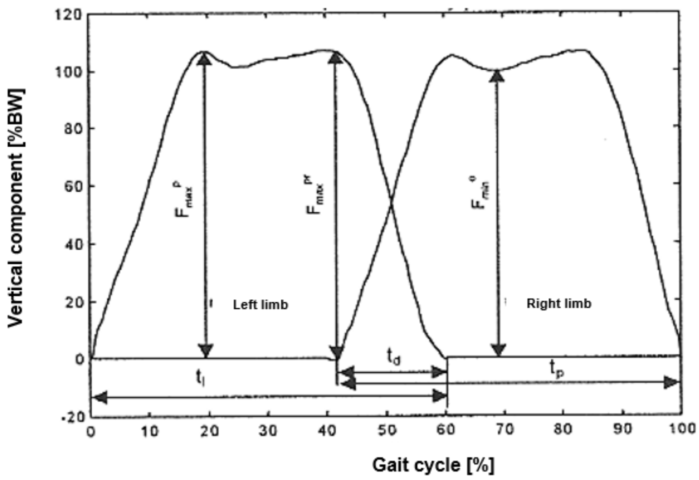

Fig. 47 Parameters analysed on the basis of the vertical component of the ground reaction

Description of the symbols contained in Fig. 47 showing the vertical component of the ground reaction:

- t_l, t_p – contact time of the left and right foot with the ground,
- t_d – duration of the double-support phase,

- F_{max}^{p} – maximum of the overload phase,
- F_{min}^{o} – minimum of the unloading phase,
- F_{max}^{pr} – maximum of the propulsive phase.

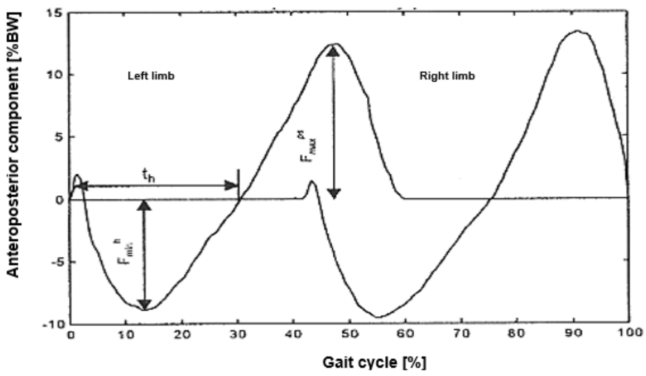

Fig. 48 Parameters analysed on the basis of the anteroposterior component of the ground reaction

Description of the symbols contained in Fig. 48 showing the anteroposterior component of the ground reaction:

- t_h – braking time
- F_{min}^{h} – minimum of the braking phase
- F_{max}^{ps} – maximum of the acceleration phase

Description of the symbols contained in Fig. 49 showing the mediolateral component of the ground reaction:

- F_{max}^{p} – maximum of the overload phase,
- F_{min}^{o} – minimum of the unloading phase,
- F_{max}^{pr} – maximum of the propulsive phase.

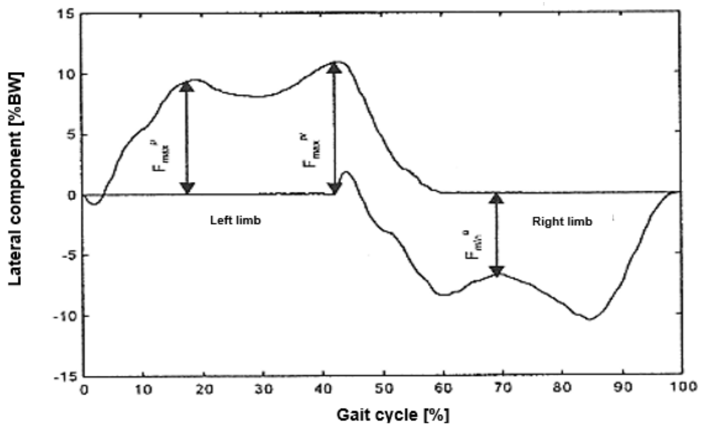

Fig. 49 Parameters analysed on the basis of the mediolateral component of the ground reaction

9. Other dynamic quantities describing biomechanics of gait

Ground reactions presented in the previous chapter are the basic parameters used to describe gait biomechanics. Mathematical calculations also allow to determine many other quantities, among others moments of muscle forces in the joints and power. Currently, these values are not so often used in diagnostics of the musculoskeletal system. This chapter presents the courses of these two quantities in relation to the percentage of the gait cycle.

MOMENTS OF MUSCLE FORCES IN THE JOINTS

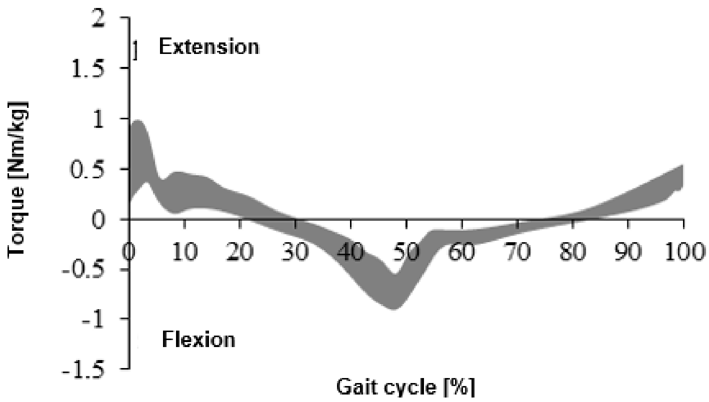

Fig. 50 Moment of muscle forces in the hip joint [[33], [8], [17]]

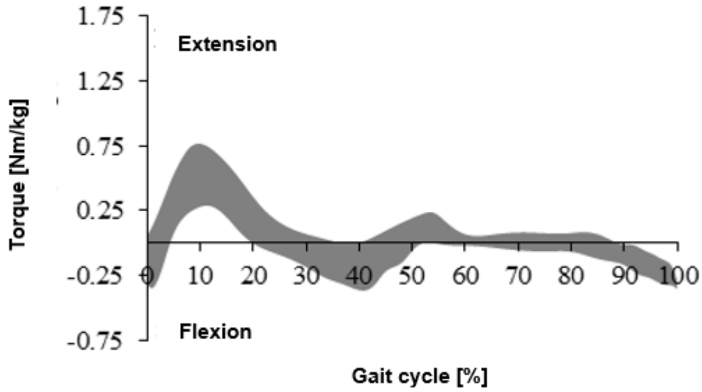

Fig. 51 Moment of muscle forces in the knee joint [[33], [8], [17]]

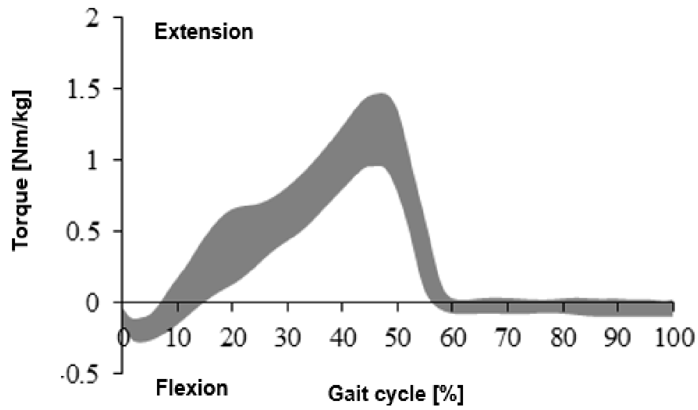

Fig. 52 Moment of muscle forces in the ankle joint [[33], [8], [17]]

POWER IN INDIVIDUAL JOINTS

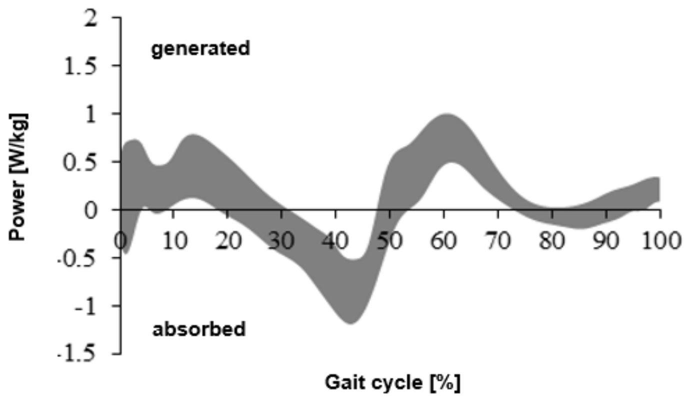

Fig. 53 Power in the hip joint [[33], [8], [17]]

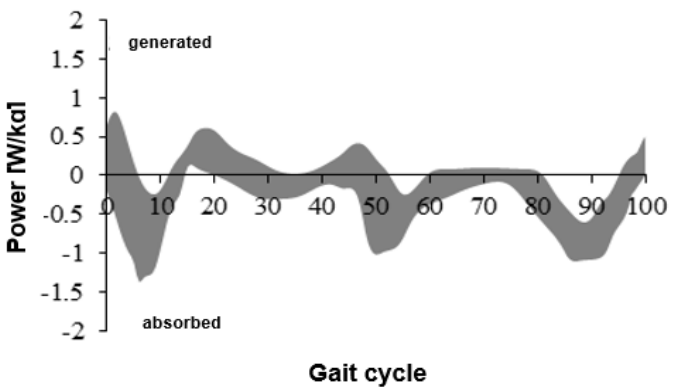

Fig. 54 Power in the knee joint [[33], [8], [17]]

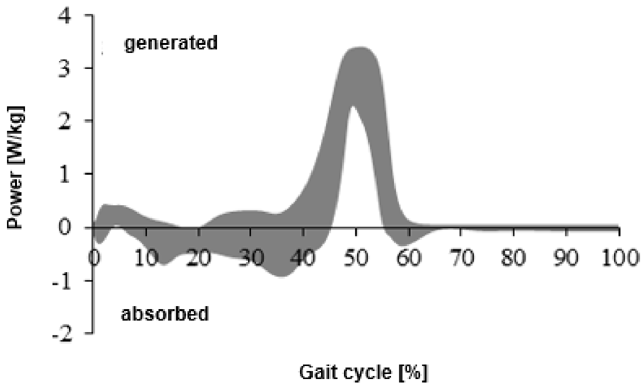

Fig. 55 Power in the ankle joint [[33], [8], [17]]

10. Muscle work during walking

To determine muscle work during gait, surface EMG is most commonly used. The potential difference between two electrodes located along the muscle fibers is obtained directly as the result of the measurement. The measured potential difference results from the fact of appearing and movement of action potential. Due to the method of measurement consisting in sticking electrodes to the skin, it is possible to collectively measure the electrical activity of the entire muscle or muscles group [[14]].

The combined analysis of the measured EMG signals together with the course of angles and ground reactions allows the determination of the type of muscle work - isometric, concentric or eccentric work.

During walking, EMG measurement is usually performed for the following muscles [[33]]:

- anterior tibial muscle,
- gastrocnemius muscle,
- soleus muscle,
- rectus femoris muscle,
- vastus femoris muscle,
- gluteus maximus muscle.

The measurement results presented in the following figures (Fig. 56 - Fig. 62) show that the analysed muscles show the most activity during the support phase, in particular in the double-support phase, when the body decelerates and accelerates.

COURSES OF CHANGES OF PARTICULAR MUSCLES ACTIVITY IN TIME

The following charts show the changes over time of the seven muscles in relation to the percentages of the gait cycle.

When analyzing the presented graphs, first of all, one should pay attention to two elements:

- high activity of muscles stabilizing the hip and knee joint at the beginning of the support phase, when the body decelerates
- high activity of the plantar flexor muscles of the foot during the propulsive phase, when the body accelerates to the next step.

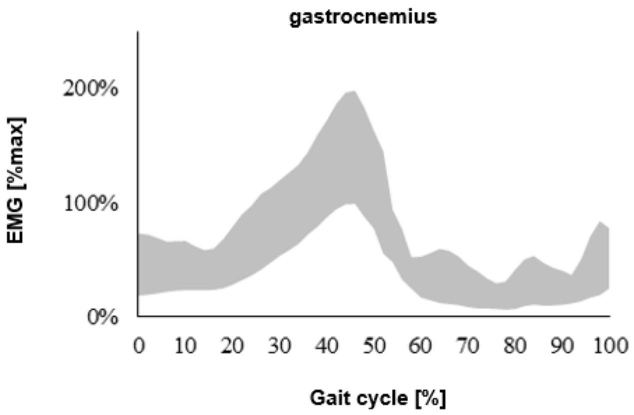

Fig. 56 Activity of gastrocnemius muscle during the normal gait cycle [[33], [21],[36]]

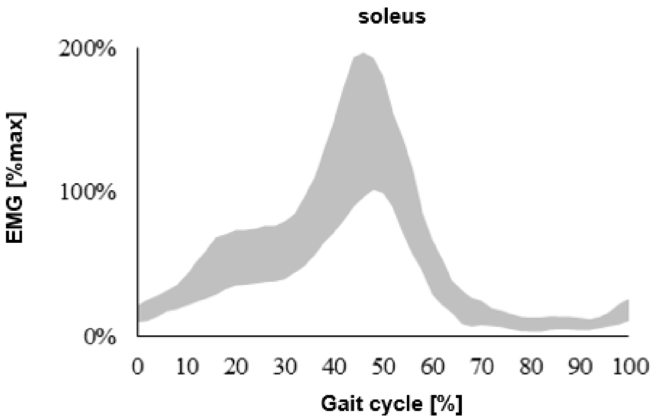

Fig. 57 Course of soleus muscle activity during the normal gait cycle [[33], [21],[36]]

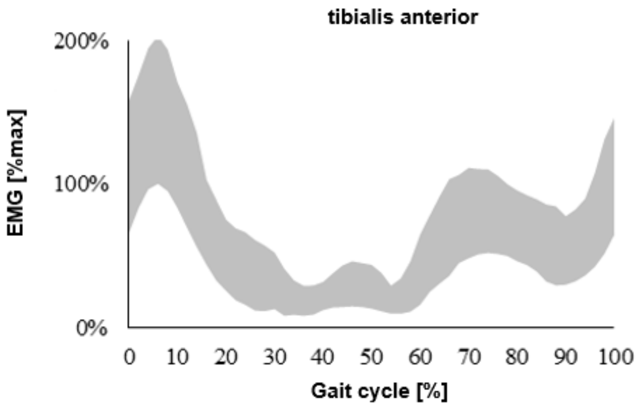

Fig. 58 Activity of the anterior tibial muscle during the normal gait cycle [[33], [21],[36]]

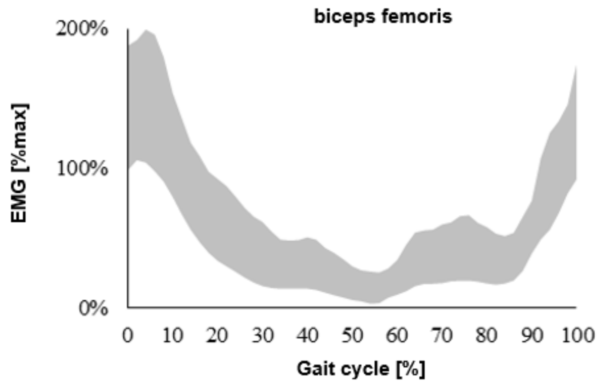

Fig. 59 The course of biceps femoris muscle activity during a normal gait cycle [[33], [21],[36]]

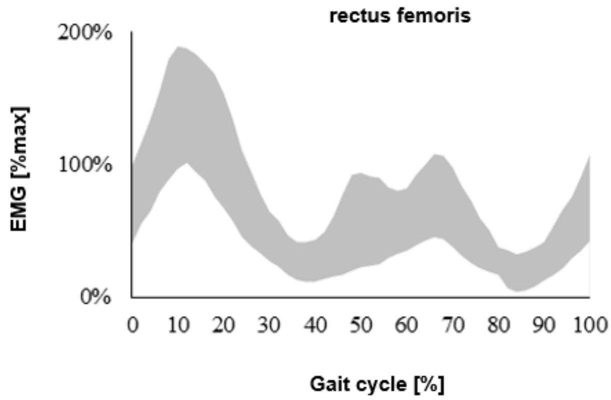

Fig. 60 The course of rectus femoris muscle activity during the normal gait cycle [[33], [21],[36]]

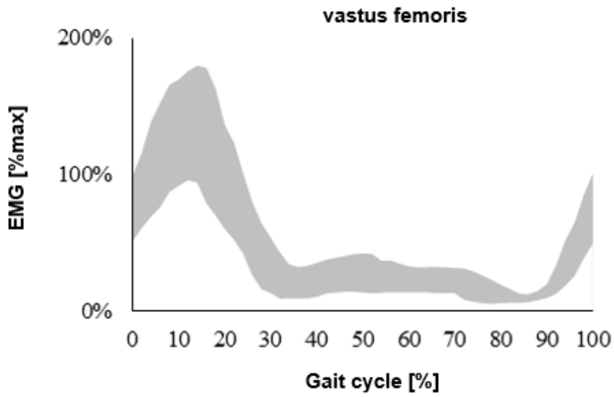

Fig. 61 The course of activity of the vastus femoris muscle during the normal gait cycle [[33], [21],[36]]

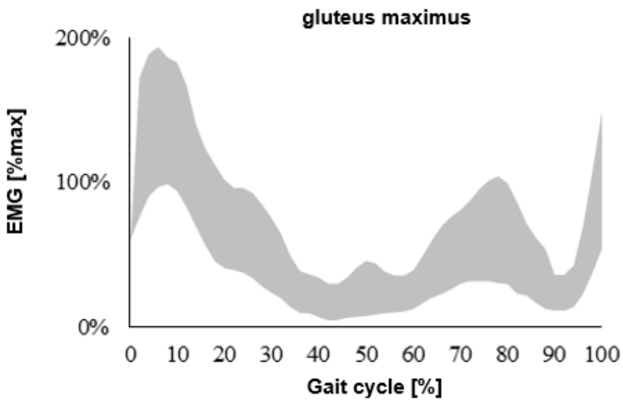

Fig. 62 Activity of the gluteus maximus muscle during the normal gait cycle [[33], [21],[36]]

ON/OFF ANALYSIS OF MUSCLE WORK

Another way of analysing muscle work is on / off analysis, i.e. determining when a given muscle starts working and when it ends, i.e. in what phase of the movement the muscle is active. A healthy muscle under normal working conditions only turns on when necessary and turns off when its work becomes unnecessary. Detection of muscle activity in the movement phase when in case of healthy person this muscle does not work, may indicate some abnormalities, such as, for example, pain, increased tension (e.g. due to spasticity), joint instability or it can result from stress or poor motor coordination. Improper muscle work may also indicate the existence of compensatory. This information can be very important, enabling the patient to be properly diagnosed and then treated [[6], [14]].

An important benefit of analysis of this type is the lack of the need to normalize the received signal, which is necessary when analysing courses of electrical potential over time. It should be remembered, however, that incorrect definition of the threshold for the onset of muscle activity may result in misinterpretation of the results for example, incorrect neuromuscular coordination diagnosis [[6], [14]].

The next charts show the correct work of the muscles responsible for the stabilization of individual lower limb joints.

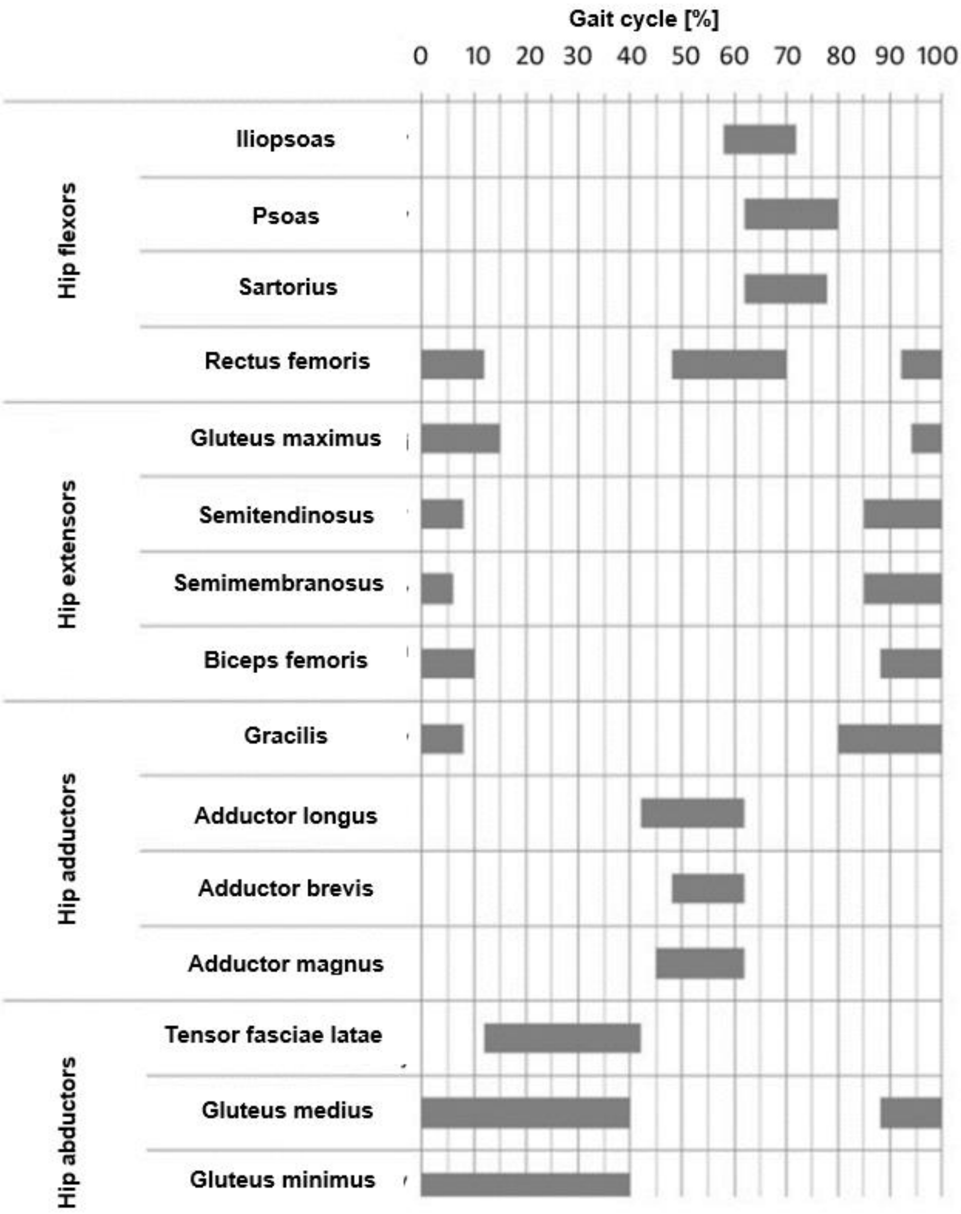

Fig. 63 Muscle activity in the hip joint during the normal gait cycle [[9], [32], [33], [35], [36]]

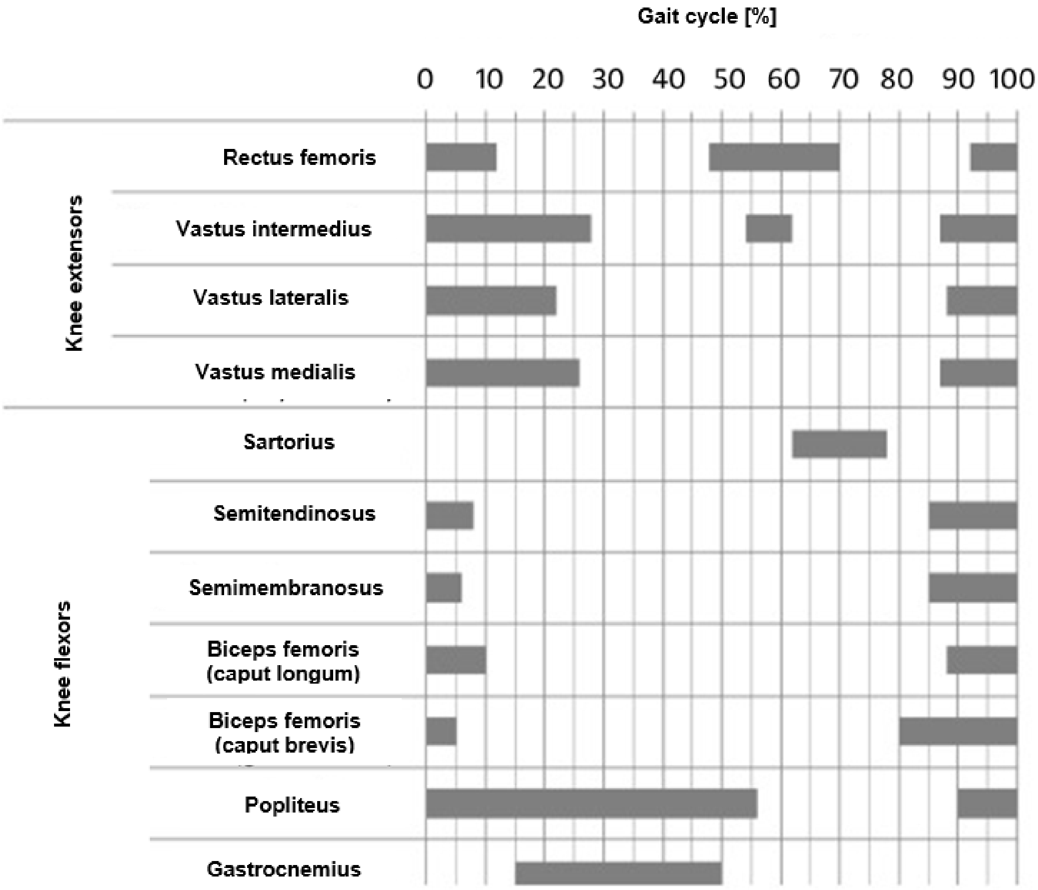

Fig. 64 Muscle activity in the knee joint during the normal gait cycle [[9], [32], [33], [35], [36]]

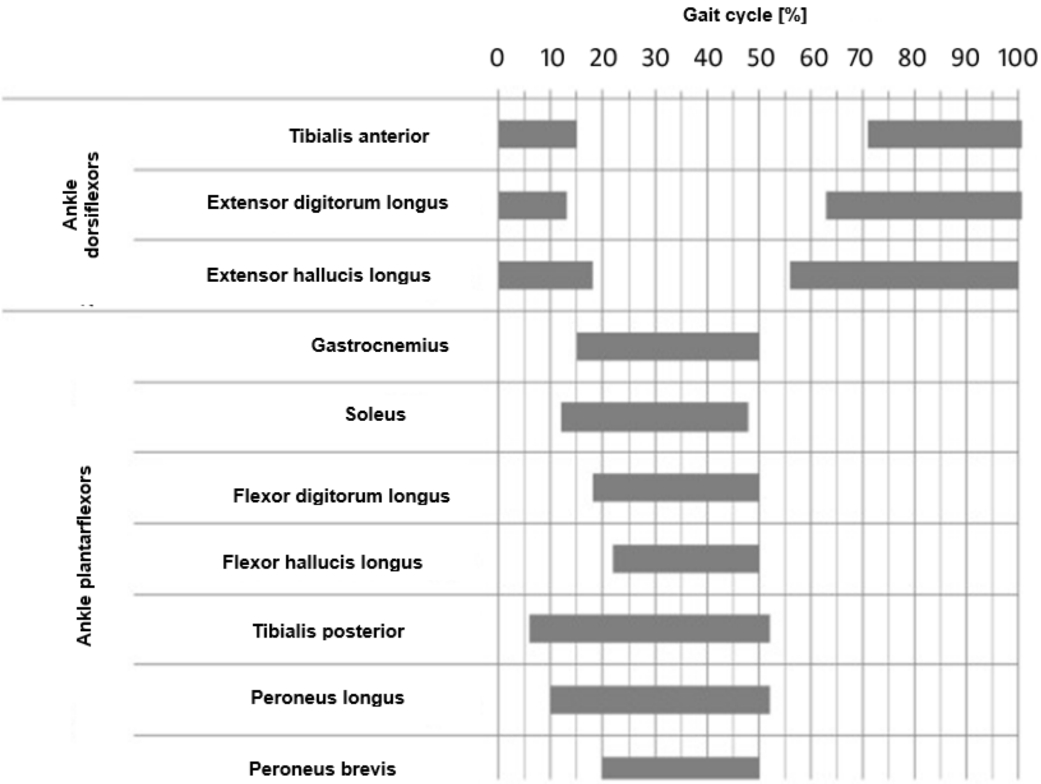

Fig. 65 Muscle activity in the ankle joint during the normal gait cycle [[9], [32], [33], [35], [36]]

11. Key ideas

- Knowledge of gait biomechanics is necessary to evaluate the human musculoskeletal system.

- For the description of gait biomechanics, parameters obtained from observation and measurements done by means of specialized equipment are used.

- When assessing gait, one should simultaneously base on determined kinematic and dynamic values as well as on measurements of muscle functions. Only the use of all these elements gives a full picture of biomechanics of gait, which in turn enables the correct assessment of possible disorders.

12. Bibliography

[1] Assi A, Ghanem I., Lavaste F., Skalli W.: Gait analysis in children and uncertainty assessment for Davis protocol and Gillette Gait Index, Gait & Posture 2009,vol. 30, Issue 1, s. 22–26

[2] Auvinet B., Berrut G., Touzard C., Moutel L., Collet N., Chaleil D., Barrey E.: Reference data for normal subject obtained with an accelerometric device. Gai&Posture, 2002, 16 (2), 124-134

[3] Baker R. The history of gait analysis before the advent of modern computers. Gait&Posture, 2007, 26, 331-342

[4] Benedetti M.G., Catani F., Leardini A., Pignotti E., Giannini S.: Data management in gait analysis for clinical applications. Clinical Biomechanics, 1998, 13 (3), 204-215

[5] Błaszczyk J.W.: Biomechanika kliniczna, Wydawnictwo Lekarskie PZWL, Warszawa 2004.

[6] Bober T.: Biomechanika chodu i biegu, Studia i monografie AWF we Wrocławiu, zeszyt nr 8, Wrocław 1985

[7] Cho S.H., Park J.M., Kwon O.Y.: Gender differences in three dimensional gait analysis from 98 heslthy Korean adults. Clinical Biomechanics, 2004, 19 (2), 145-152

[8] Davis R.B., Ounpuu S., DeLuca P.A.: Analysis of gait. Biomechanics. Principles and application, CRC Press, 2008

[9] De Lisa J.A. (ed): Gait Analysis in the science of rehabilitation. Monograph, 002, 1998

[10] Dec J.B., Saunders M., Inman V.T., Eberhart H.D.: The major determinants in normal and pathological gait. Journao of Bone and Joint Surgery. 1953, 35,543-558

[11] Dega W.: Ortopedia i rehabilitacja, Wydawnictwo PZWL, Warszawa 2006.

[12] Dusing S., Thorpe D.: A normative sample of temporal and spatial gait parameters in children using the GAITRite electronic walkay. Gait&Posture, 2007, 25, 135–139.

[13] Kadaba M.P., Ramarkrishnan H.K., Wootten M.E.: Measurement of lower extremity kinematics during level walking. Journal of Orthopaedic Research, 1989, 8, 383-392 27

[14] Konrad P.: The ABC or EMG. A practical Introduction to Kinesiological Electromyography. Noraxon INC. USA, Version 1.0, April 2005

[15] Kwolka A.: Rehabilitacja medyczna, Wydawnictwo Medyczne Urban & Partner, Wrocław 2001

[16] Leardini A., Sawacha Z. i in.: A new anatomiacally based protocol for gait analysis in children. Gait & Posture, 2007, 26, 560-571

[17] Michnik R., Jurkojć J., Guzik A., Tejszerska D.: Analysis of loads of the lower limb during gait, carried out with the use of the mathematical model, made for patients during rehabilitation progress. Eccomas Conference Multibody Dynamics 2007, Milano

[18] Michnik R., Jurkojć J., Jureczko P., Guzik A., Tejszerska D.: Analisys of gait kinematics of patient after total hip or knee replacement. Journal of Vibroengineering, 2006, 8 (3).

[19] Michnik R., Kopyta I., Jochymczyk-Woźniak K.: Wykorzystanie metod inżynierskich w analizie chodu dzieci z mózgowym porażeniem dziecięcym. Monografia. Wydawnictwo Politechniki Śląskiej, Gliwice, 2016

[20] Morecki A., Ramotowski W.: Problemy biocybernetyki i inżynierii biomedycznej, tom 5, Wydawnictwa Komunikacji i Łączności, Warszawa 1990

[21] Neptune R.R., Sasaki K.: Ankle plantar flexor force production is an important determinant of the referred walk-to-run transition speed. Journal of Experimental Biology, 2005, 208, 799-808

[22] Öberg T., Karsznia A., Oberg K.: Joint angle parameters in gait: Reference data for normal subjects 10-79 years of age. Journal of Rehabilitation Research and Development, 1994, 31 (3), 199-213

[23] Öberg T., Karsznic A., Öberg K.: Basic gait parameters: Reference data for normal subjects, 10-79 years of age. Journal of Rehabilitation Research and Development, 1993, 30 (2), 210-223

[24] Pierce R., Orendurff M., Sienko Thomas S.: Gait parameters norms for children ages 6-14. Gait & Posture, 2002, 16, Suppl. 1, 53-54.

[25] Romei R., Galli M., Motta F., Schwartz M., Crivellini M.: Use of the normalcy index for the evaluation of gait pathology. Gait & Posture, 2004, 19 (1), 85-90

[26] Ryu T., Soon Choi H., Choi H., Chung M.H. .: A comparison of gait characteristics between Korean and Western people for establishing Korean gait reference data. International Journal of Industrial Ergonomics, 2006, 36, 1023–1030

[27] Schutte L.M. i in.: An index for quantifying deviations from normal gait. Gait&Posture 2000, 11, 25-31

[28] Śnieżek A., Mężyk A., Michnik R.: Analiza dynamiki chodu prawidłowego. Aktualne problemy biomechaniki, 2007, 1

[29] Staszkiewicz R., Ruchlewicz T., Nosiadek L.: Zmiany wybranych parametrów chodu w zależności od prędkości. Acta of Bioengineering and Biomechanics, 1999, 1 (1)

[30] Syczewska M: Diagnostyka rehabilitacyjna narządu ruchu dziecka, Standardy Medyczne 2003, tom 5, Nr 9, s. 1254 – 1264

[31] Syczewska M, Dembowska-Baginska B., Perek-Polnik M., Perek D.: Functional status of children after treatment for a malignant tumor of the CNS: a preliminary report, Gait & Posture 2006, vol. 23, s. 206–210

[32] Syczewska M., Lebiodowska M., Kalinowska M.: Analiza chodu w praktyce klinicznej, [W:] Biocybernetyka i inżynieria biomedyczna 2000, Pod red. Macieja Nałęcza, Tom 5, Biomechanika i inżynieria rehabilitacyjna, Red. Romuald Będziński [i in.], Akademicka Oficyna Wydawnicza EXIT, Warszawa 2004

[33] Tejszerska D., Świtoński E.: Biomechanika inżynierska, Wydawnictwo Politechniki Śląskiej, Gliwice 2004

[34] Valderrabano V., Nigg B.M., Vinzenz von Tscharner, Darren J. Stefanyshyn D.J., Goepfert B., Hintermann B.: Gait analysis in ankle osteoarthritis and total ankle replacement. Clinical Biomechanics, 2007, 22, 894-904

[35] Vaughan Ch. L., Davis B.L., O'Connor J.C.: Dynamics of human gait. Kiboho Publisher, Cape Town, 1999

[36] Winter D.A., Biomechanics of human movement. John Wiley&Sons, New York, 1979

[37] https://brain.fuw.edu.pl/edu/index.php/Pracownia_Sygna%C5%82%C3%B3w_Biologicznych/Zajecia_9

[38] https://pl.pinterest.com/pin/420242208980082843/#

[39] https://www.imaging-resource.com/news/2012/11/27/eadweard-muybridge-the-photographic-pioneer-who-froze-time-and-nature