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Chapter 16

NORMAL GAIT

Alice Bonnefoy-Mazure* and Stéphane Armand
Willy Taillard Laboratory of Kinesiology,
Geneva University Hospitals and Geneva University, Switzerland

ABSTRACT

Walking is the first way of displacement for human and essential for daily life activities and social participation. The human gait can be analyzed from several points of view and specialties. The aim of this chapter is to describe from a simple manner the normal gait in term of gait cycle, acquisition and development of the gait, joint kinematics, kinetics of the lower limb, electromyography and arm movements.

Keywords: gait cycle, gait maturation, kinematics, kinetics, electromyography and arm movement

KEY POINTS

- Gait involves a large numbers of sub-systems such as skeletal, joint, muscular, neurologic, vestibular, visual, proprioceptif systems.
- The gait cycle is a period of time between any two nominally identical events in the gait process that serves as a reference in the studies and/or examinations of gait parameters.
- The gait maturation is a long process.
- Walking can be described with the support of spatio-temparal parameters, kinematics, kinetics and electromyography.

* Corresponding author: Alice Bonnefoy-Mazure PhD Willy Taillard Laboratory of Kinesiology, Geneva University Hospitals and Geneva University, Rue Gabrielle Perret-Gentil 4, 1205 Geneve, Switzerland; Email: alice.bonnefoymazure@hcuge.ch

16.1. INTRODUCTION

Walking is the most natural mode of locomotion in humans to travel independently and with an efficient manner. The gait can be defined as a movement consisting of a translation of the whole body permitted by a repetition of movements of body segments while keeping the balance. This repetition of movement involves the definition of a cycle.

16.2. THE GAIT CYCLE

The gait cycle could be defined as a period of time between any two nominally identical events in the gait process [1]. Generally, these two nominally identical events correspond to the instant where one foot strikes the ground and ends when the same foot strikes again the ground (called initial contact or IC). During the gait cycle, lower limb considered an alternate stance phase (foot in contact with the ground) and swing phase (foot without ground contact). A gait cycle is thus divided in a period of stance phase (about 60% of the cycle) and in a period of swing phase (about 40% of the cycle) of the lower limbs, right and left (Figure 1). It is possible to make a sub-division according to the stance and swing phase of the two lower limbs. When both members are in stance phase, this is a bipodal support (or double support) and when one of the two members is in stance phase while the other is in swing phase, this is a unipodal support (or single support).

More specifically, the stance phase can be divided into five functional sub-phases occurring in the following sequences: initial contact (IC), loading response (LR), midstance (MSt), terminal stance (TSt) and preswing (PSw) [2]. As the same way, the stance phase is divided into three functional sub-phases occurring in the following sequences: initial swing (ISw), mid-swing (MSw) and terminal swing (TSw). However, we prefer to keep a division according the events occurring during the gait cycle (i.e. first double support, single support, second double support, and swing phase) [3] that permits a more precise definition of the sub-phases and avoids confusion in the terms [4] (Figure 1).

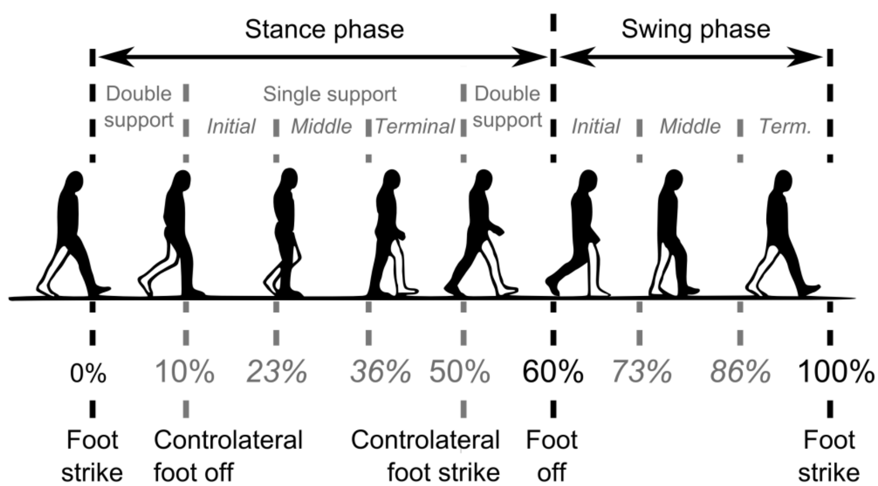

Figure 1. Common temporal divisions of the gait cycle.

Each sub-phases cited below, enables at the lower limbs to realize three functional tasks of the gait that are: weight acceptance, single-limb support and limb advancement [2].

This gait cycle divided into various phases serves as a reference in the studies or examinations of gait analysis. Graphics used for its interpretation are usually normalized to the duration of the gait cycle and the phases are expressed as a percentage thereof. Moreover, during the gait cycle, several gait characterizations can be done with the temporal measurements such as: gait speed, cadence, step length, stride length and step width.
The gait speed also known as walking speed, gait velocity, is generally defined as the rate of motion measured in meters per second and is a scalar quantity. Gait speed predicts the future health status and it is easy to measure and to interpret, that is why it is recommended as the “sixth vital sign” [5]. The cadence denotes the number of steps taken in a given time, generally steps per minutes. A natural or free cadence describes a self selected walking rhythm. The step length is defined as the longitudinal distance between for example the left and right heels of the feet when both are in contact with the ground. Stride length is the distance between two successive placements of the same foot. Finally, step width is as medio-lateral distance between the left and right foot, also measured when both feet are in contact with the ground.

16.3. Acquisition and Development of the Gait

The mean age for onset of independent walking differs between 11 and 14.5 months [6, 7]. Before this age, several steps are necessary to acquire the toddler gait [8]. Indeed, since the birth, baby learns to lift and to control his head, then, around three months, he is able to sit without support. After that, we observe that child is able to roll over and around nine months, he is able to pull himself to stand and then to walk with support. This first gait or primitive gait according around 12 months, is considered and defined as independent when child can perform a minimum of 5 steps [9]. During all this period, child is confronted to constantly growing and changing in term of neuro-musculo-skeletal system to evolve towards a mature and stable gait pattern.

Indeed, in term of gait patterns, the toddler’s gait pattern differs from adult gait, i.e. from mature gait. All studies concerning the gait maturation agree that the most important feature of toddler gait is a large amount of inter and intra-subject variability. In 1980, Sutherland and collaborators [6] realized a gait analysis on 186 children (age between one and seven years). This large study, described important differences in term of spatio-temporal parameters, joint kinematics, ground reaction forces and muscles activation patterns.

Indeed, in term of spatio-temporal parameters, it was observed, that toddlers have a lower average walking speed, higher cadence, shorter step length, wider support base and a more prolonged double support phase compared to a mature gait [10]. In term of kinematics, children fixe their arms in guard position, i.e. with arms in abduction, external rotation and elbows flexed (to maintain the stability); they position their feet in external rotation and they have no heel strike. During the stance phase, the hip and knee are not in complete extension but are simultaneous in flexion during the swing phase [11]. Concerning the kinetics of the toddler, some differences were observed with a dominance of hip and knee extending moments during the stance phase of the gait, with a sustained power production for the same joint [12-14]. In last, concerning the surface electromyography (EMG), a mature pattern of muscle recruitment and EMG activation during gait is achieved by an age of 6 to 8 years for healthy children [15]. Thus, differences between mature gait and toddler gait are characterized by: less co-contraction during stance phase and improved integration of descending and stretch-reflex activities in mature gait patterns.

16.4. KINEMATICS

Kinematics is the study of bodies in motion without considering the forces (internal and external forces) that cause the body movement (Figure 2).Thus, the kinematics analysis allows to observe and to describe the body movements during the gait. Kinematics includes the analysis of positions, angles, velocities and accelerations of the body segments and joints. Joint angles describe the angle between two adjacent segments in a specific plane. The three commons planes used in description of the gait kinematics are the sagittal plane for the flexion-extension movements; the frontal plane for the adduction-abduction movements and the transversal plane for the internal-external rotations. The most studied joints were the ankle-foot; knee, hip, pelvis and trunk joints in the sagittal plane.

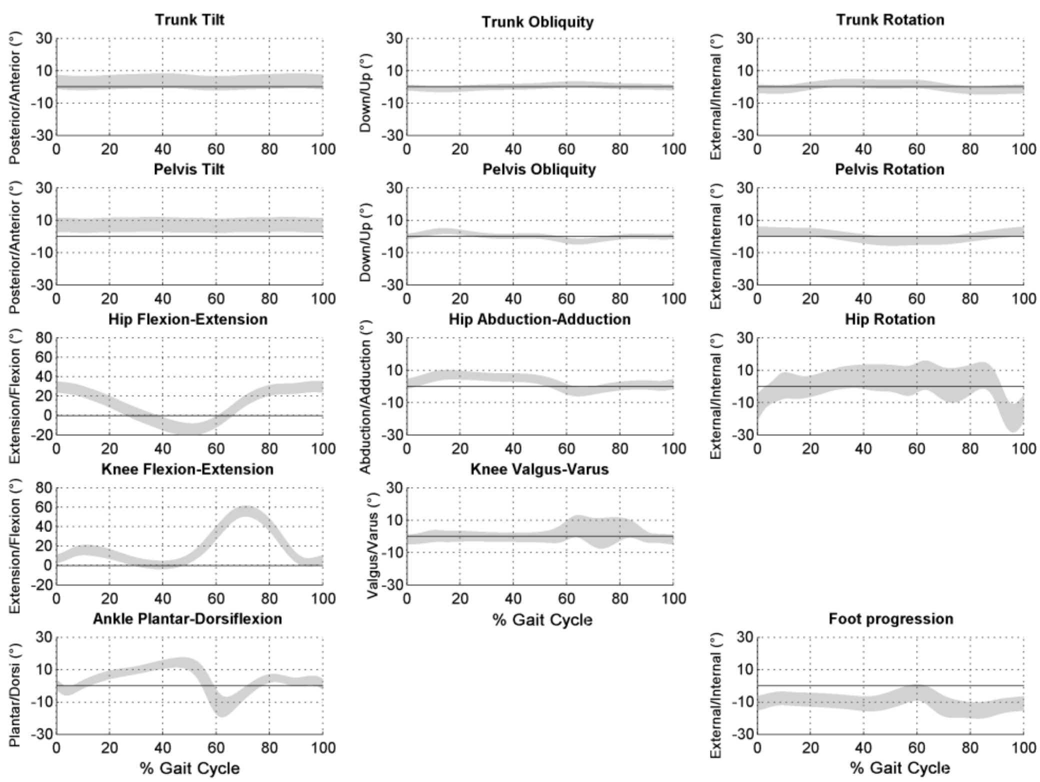

Figure 2. Example of normal kinematic curves (mean +/- one standard deviation) in the three dimensional planes at self-selected walking speed. First column corresponds to the sagittal plane. The second column corresponds to the frontal plane. The third column corresponds to the transversal plane. The vertical line corresponds to end of the stance phase of the gait cycle.

Ankle Joint and Foot Segment

The analysis of the ankle angle concerns the relative angle between the long axis of the shank and the long axis of the foot (axis from the calcaneum to the toe). Moreover, the foot and ankle form a dynamic link between the body and the ground.

The main role and function of the ankle and the foot during the stance phase of the gait is to produce a wheel-like rolling motion under the foot. This specific function is described in the literature in terms of three rockers [2]. The action these three functional rockers, namely named heel (first rocker), ankle (second rocker) and forefoot rockers (third rocker) are the progression of the leg over the supporting foot (Figure 3).

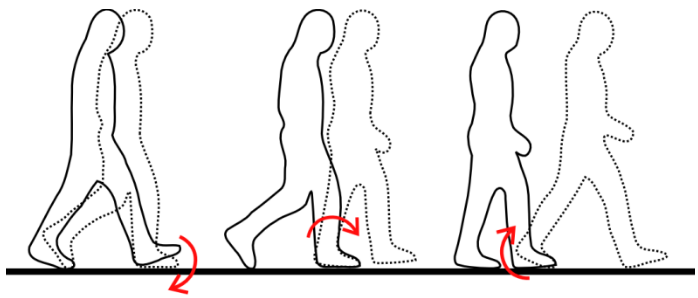

Figure 3. Illustration of the different foot rockers: heel rocker (or first rocker), ankle rocker (or second rocker) and forefoot rocker (third rocker).

The two first rockers correspond at deceleration rockers and begin at the initial contact of the gait cycle, and extend through the loading response. Thus, at the initial contact with the floor, the ankle is in neutral position to initiate the first rocker and to facilitate the progression of the limb. After this short period (2% of the gait cycle), the ankle is in plantar flexion (around 5°) in order to preserve the momentum generated by the fall of the body weight onto the stance limb. It is referred as the heel rocker. During the single support, the tibia advances from an 5° of plantar flexion to 15° of dorsiflexion, thus the heel and forefoot are in contact with the floor and are in stable foot-flat posture. This specific movement is called the ankle rocker or second rocker. Third and last rocker, named forefoot rocker, occurs during the second double support and corresponds to the heel rise. At this instant, only the forefoot is in contact with the floor. The ankle moves rapidly from 15° of dorsiflexion until 20-30° of plantarflexion. Thus the movement of the foot around the third rocker allows to maintain height of the center of mass and the propulsion of the body during the gait.

During the swing phase, at the beginning, the ankle is in plantarflexion and the tibia is behind the body (60% to 73% of the gait cycle i.e. the initial swing). The mid swing (73% to 86% of the gait cycle) corresponds to the period of the gait cycle where the ankle is in dorsiflexion to able to foot clearance while the terminal swing (86% to 100% of the gait cycle) enables the ankle to move in neutral position to prepare the initial contact with the floor.

To conclude in the sagittal plane, the movements of the ankle are important for normal coordinated gait and regulate the movement of the center of mass. It allows the foot to accommodate to different grounds, provides shock absorption and also acts as a rigid segment for propulsion of the body during the second double support. The range of motion of the ankle joint during the gait cycle is around 35° for a normal gait.

In the transverse plane, the foot progression angle corresponds at the angle between the long axis of the foot and the direction of progression. During the first double support and single support, the foot is in external rotation (around 10°). During the second double support, the foot has a movement toward internal rotation. During the swing phase, the foot has a movement toward external rotation. During all the gait cycle, the range of motion of foot angle progression is around 5°.

During the gait, pronation and supination normally occur in the foot. Indeed, the pronation is important for optimal movement and shock absorption. During the healthy gait, the pronation corresponds at the moment where the foot is in contact with the ground and begins to roll inward, everting slightly with arch flattens. The purpose of the pronation is to able the foot to adapt to the surface. After the pronation, the foot continues toward supination. This results in the foot turning slightly outward then changing from a flexible foot to a more rigid foot, so it can propel the foot and push off from the ground. During this phase the foot inverts slightly, and the arches become higher, thus enabling the foot to properly roll over the hallux.

Knee Joint

The analysis of the knee angle concerns the relative angle between the long axis of the thigh and the long axis of shank. Moreover, the knee has a wide range of function during the execution of gait, including limb stability during the stance phase, supporting body weight, deceleration and flexibility to allow limb movement in swing phase.

At the initial contact of the gait cycle, the knee is in full extension and just after, for the loading response (first double support), the knee is in flexion (around 15°) in order to absorb the shock of the weight transfer onto the limb and also to maintain stability. During the single support, the knee is fully extended to optimize the stance stability. During the second double support, there is a passive knee flexion (around 35°) due to the fact that the ankle moves. This passive movement prepares the limb to the swing phase. At the beginning of the swing phase, the knee is in flexion (around 60°) in order to allow the foot clearance and to allow the limb advancement. The mid swing corresponds at a passive knee extension movement corresponding at the limb advancement. Finally, at the terminal swing, the knee stays in extension to prepare the limb for the stance. To conclude in the sagittal plane, the knee movement plays a major role in order to maintain the stance stability and to allow the absorption shock. Moreover, the knee movement is intimately associated with the foot and ankle movements. The range of motion of the knee joint during the gait cycle is around 60° for a normal gait. In the frontal plane, the movement is negligible (varus or valgus movement) with a neutral position.

Hip Joint

The analysis of the hip angle concerns the relative angle between the long axis of the thigh and a perpendicular to the pelvic plane.

At the initial contact of the gait, the hip is flexed (around 35°) to allow a forward progression. During single support, the hip joint plays its role of stabilizer to support the limb loading and to maintain the pelvis and trunk position, while allowing advancement of the body. During this phase, the hip moves from a flexion position to an extension position (around 10°). At the second double support, the hip moves quickly from an extension motion to a flexion motion to allow the body advancement. During the initial and mid swing, the hip continues its flexion motion to attain its maximal flexion around 35°. During these periods, the limb is in forward progression, the foot is not in contact with the ground and the limb swing is a passive movement. The terminal swing enables the limb to position the initial contact. The hip prepares the limb for stance by stopping flexion. To conclude for the sagittal plane, the hip movement allows the forward progression of the limb and maintains the pelvis and the trunk. The range of motion of the hip joint during the gait cycle is around 40° for a normal gait.

In the frontal plane, it appears that the hip movements are linked with the pelvis movement. Indeed, when the pelvis is up, the hip is in adduction during the single support (positive value on the curve around 6°) and then during the second double support, the hip is in abduction (negative value on the curve, around 7°). During the swing phase, the hip moves in slight adduction. The range of motion of the hip is around 13°.

Concerning the hip rotation movements, at the loading response, the hip is in internal rotation and becomes in external rotation at the end of stance phase. At the end of the swing phase, the hip is in external rotation. During the gait cycle, the range of motion of the hip rotation is around 8°.

Pelvis Segment

The analysis of the pelvis angle concerns the inclination of pelvis plane with respect to the horizontal. The movement of the pelvis is minimal during the gait with a range of motion around 5°. Its inclination toward anteversion (pelvic tilt) is around 10° during the entire gait cycle. During the first double support, a posterior movement is observed followed by an anterior movement during the single support phase. During the second double support, a slight posterior movement is again observed. During the swing phase, the pelvis moves from a posterior position to an anterior position and then to a posterior position.

In the frontal plane, the pelvis obliquity, the range of motion is around 8°. During the first double support, the pelvis rises 4° (positive value on the curve pattern) and after it drops during single support to 7° (negative value on the curve pattern). After that, during the swing phase the pelvis rises again 8°. During the gait cycle, the pelvis is twice time in neutral position. In the transversal plane, the pelvis moves from internal to external rotation with a range of motion around 8-10° depending form the walking speed. The role of this movement is to assist the forward progression of the swing leg.

Trunk Segment

The analysis of the trunk angle concerns the forward inclination of the long axis of the torso. The trunk plays an important role in human locomotion. Indeed, the trunk represents more than 50% of the body weight and its kinematic maintains the dynamic stability in individuals. As for the pelvis kinematics, in the sagittal plane the trunk inclination is around 0° with a range of motion around 3°. Moreover, as the pelvis, the trunk moves between an anterior and posterior movement during the gait cycle.

In the frontal plane, the trunk position, i.e. the trunk obliquity, is around 0° and with a range of motion negligible.

In the transversal plane, the trunk has similar movement than the pelvis. The coordination of the movement between the pelvis and the trunk is depending of the walking speed. If the walking speed is low, the trunk rotation movements are in phase with the pelvis; if the walking speed is high, the trunk rotation movements is in anti-phase with the pelvis [2]. Moreover, the trunk plays a major role in postural control in order to allow successful execution of functional activities as the gait [16, 17].

Thus, the role of trunk movement is mainly to counterbalance the asymmetric kinematic of the lower limbs [18].

16.5. Kinetics

Kinetics is the study of forces that cause motion of the bodies. Thus the kinetics aims to characterize the forces that act upon the body and the body segments.

Generation of Ground Reaction Force

The ground reaction force (GRF) is an important force in walking. Indeed, the point of application of this force found underneath the contacting foot and it is direct opposite to the body weight. Thus the GRF influences the movement of the entire body during the gait and the analysis of the shape of the GRF can be derived on the whole-body motion.

During the stance phase of the normal gait, the GRF has a typical pattern with a double bump corresponding to two maxima surpassing body weight with an intermediate minimum inferior at the body weight. This specific pattern is often modeled in the literature as an inverted pendulum moving over a rigid supporting leg [19].

Thus, the generation of the ground force begins at the instant where the foot contacts the ground i.e. at the IC of the gait cycle. At this specific instant, the body weight is transferred very quickly on one leg. For this, the foot and the leg act together as shock absorber [2]. Consequently, the impact force is followed by a loading response. During this short period, the whole foot is in contact with the ground and the vertical GRF increases to attain the first maximum peak force (F1 on Figure 4). After this first peak, the vertical force diminishes corresponding at the mid stance phase (F2 on the Figure 4). Indeed during this phase, the opposite foot is in the mid swing phase, therefore the whole body weight is supported by the stance limb. The foot and the leg provide a stable platform to able the movement of the body, like an inverted pendulum [20]. When the heel lifts away from the ground, the GRF starts increasing once again. This ascending second peak (F3 on the Figure 4) of the GRF corresponds to the second double support. Finally, the GRF pattern starts descending to zero with the pre-swing phase and drops to zero when the foot leaves the ground (Figure 4).

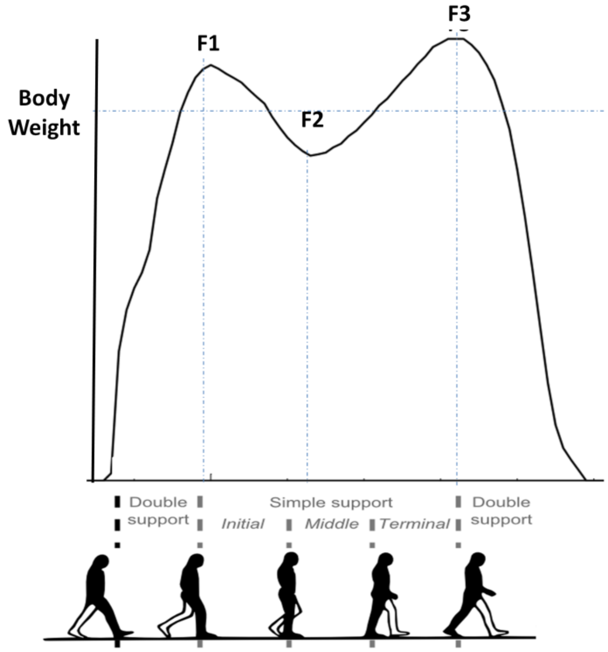

Figure 4. Example of the vertical ground reaction force recorded during the stance phase of the normal gait cycle.

Joint Kinetics or Joint Moments and Powers

If the GRF and the joint movements are measured and known (as well as the anthropometric data of the subject), it is then possible to calculate the net joint moments from a specific model named inverse dynamics.

The net joint moment (or torque or moment of force) corresponds at the net result of muscular and non-muscular forces (as tension from ligaments and joint capsule) acting around the joint and causing movement of the joint (Figure 5). Basically, the moment is the ability of a force to rotate a body about an axis. In classical mechanics, the moment of a force is the cross product of a force vector with its perpendicular distance from the axis (named lever-arm distance vector), which causes rotation about this axis. Thus, in the case of the human gait, for static and quasi-static position, the net joint moment increases if the GRF increases, or if the lever arm (distance between the joint center and the GRF) increases.

Moreover, the net joint internal moment (corresponding to the joint moment produced by muscle and soft tissue forces) gives an idea about which muscle group is dominant during the gait. But in all the cases, this parameter gives no information about the individual muscle forces. Indeed, it is not possible to measure the net tension or force in the muscles because there are not enough equations to calculate the large number of unknown i.e. the muscle forces.

This problem depends of another mathematical field of researcher corresponding at the optimization approach [21-25]. However, in order to have an idea of the muscles role during the gait, it is possible to have the electromyography data corresponding to the muscle activities.

Moreover, from the inverse dynamics, it is possible to calculate the power output corresponding at the rate of the energy delivered by muscles to move a joint. Thus the net joint power parameter is information of how much effort is needed to perform a specific movement, and about eccentric and concentric contraction (Figure 5).

For the net ankle moment pattern, there is a brief dorsi-flexor moment (negative value on the curve) to control the foot lowering. This moment is followed by a plantar flexor moment (positive value on the curve). At the end of the stance phase, there is a peak value for the plantar flexor moment limiting the ankle dorsi flexion movement around 10-15°. This moment decreases progressively through the remainder of stance. Concerning the ankle power pattern, it appears that there is a peak of absorptive power (negative value on the curve) at the IC, following by a low amplitude power absorption reflecting an eccentric action of the muscles.

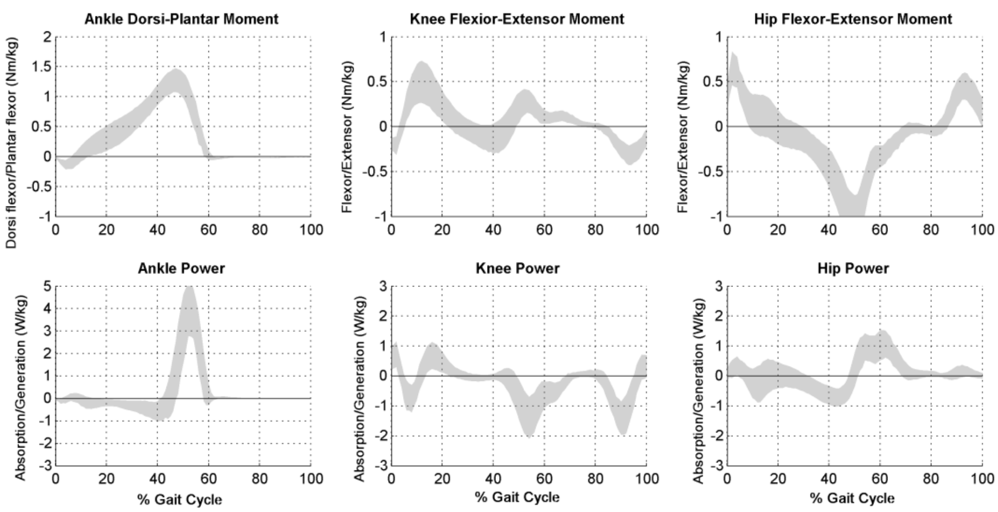

Figure 5. Example of normal kinetic curves in the sagittal plane at typical walking speed. First column corresponds to the ankle net joint moment and power. The second column corresponds to the knee net joint moment and power. The third column corresponds to the hip net joint moment and power.

At the end of the stance phase, a peak of positive power (generation of power) appears corresponding at the push-off in order to propulse the limb into the swing.

For the net knee moment pattern, it is generally observed three flexor moments (negative values on the curve) and two extensor moments (positive values on the curve). The first peak appears at the IC of the stance phase and it is a flexor moment in order to control the knee hyper extension. This first peak is followed very quick extensor moment to ensure stability of the knee during the loading response and to control the knee flexion movement. Then the flexor moment diminishes to become negative i.e. an extensor moment at the end of the single support. During the second double support, a small extensor moment appears to control the rapid knee flexion. During the mid swing and terminal swing phases, the knee extends and then the flexor moment increases to control the movement. Concerning the knee power pattern, it appears that at the first double support, the power is absorbed (negative values on the curve) linked to eccentric activity of muscles. During single support, a little peak of power generation is present to increase the knee extension. At the second double support, peak power absorption occurs as well as at the end of the terminal swing.

For the net hip moment pattern, an extensor moment (positive values on the curve) is present at the IC and decreases quickly during first double support. The hip moment is negative i.e. flexor during the single support and with a peak at the beginning of the second double support. After that, the flexor moment declines to become positive and then power is generated when the hip flexes rapidly. Concerning power, there is a period of power generation (positive values on the curve) at the end of stance phase which helps at the forward progression of the gait.

16.6. MUSCLE ACTIVITIES OF THE LOWER LIMBS DURING THE NORMAL GAIT

The human gait pattern is normally fluid and shows continuous movements. It is a natural and repetitive movement controlled by muscles. Thus, the muscles are the motors of the gait and accomplish a specific role during the gait cycle. When muscles are actively contracted under neural control, they produce an electric signal that can be recorded by electromyography.

The role of each muscle during gait is globally known but different interpretations of muscle activity can be done. Several causes may be raised: some muscles are biarticular and act directly on two joints; the action of a muscle in single support, double support or during swing is different due to opened or closed chain; the position of a joint changes the possible action of a muscle. Understanding precisely the role of each muscle during normal gait is still the object of researches. The following description is a simplified overview of muscle control of the lower-limbs during gait (Figure 6).

At the initial contact, the foot begins its contact with the floor; at this instant, the gluteus maximus and the biceps femoris help to control hip flexion movement whereas the tibialis anterior controls and slows down the foot movement.

During the first double support, seven main muscles are in action in order to control the ankle, knee and hip to maintain the equilibrium while allowing forward progression.

The rectus femoris has an extensor role in order to control and slows down the knee flexion. Moreover, it absorbs the shock occurring during the loading response. At the same time, the action of the hamstring is reduced (to flex the knee) whereas the gluteus maximus action is increased. Indeed, the gluteus maximus and hamstring have a concentric action and allows to accelerate the hip. Finally, the gluteus medius stabilizes the pelvis.

At the end of the stance phase, the tibialis anterior is just beginning its activity to prepare the initial swing phase.

During the initial swing phase, the swing leg leaves the ground and advances. To product this movement, three main muscle groups are in action. The hip flexor muscles i.e. the adductor longus, the sartorius, the iliacus and the gracilis muscles, have an ongoing activity to advance the thigh and to create, passively thank of inertia of the leg, the knee flexion. In addition, the biceps femoris muscle increases the knee flexion and tibialis anterior and extensor digitorum longus muscles lift the foot from its previously plantar flexed position in order to prepare foot clearance.

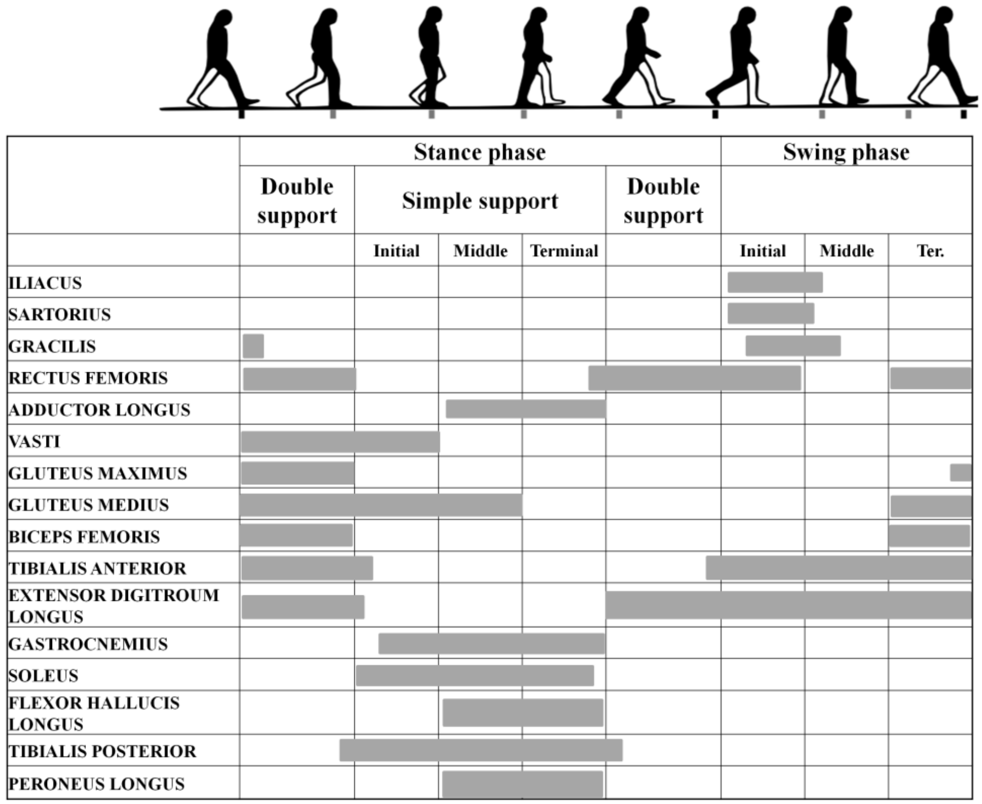

Figure 6. Representation of muscle activity during a gait cycle. The grey color indicates periods where the muscles are active during the gait cycle.

During the mid swing phase, thigh continues its advancement and there is a vertical alignment of the tibia with the foot. During this period, the muscle activity is limited. Iliacus, sartorius,rectus femoris and gracilis activity have ceased. The tibialis anterior supports and maintains the ankle position. The contro-lateral gluteus medius supports the pelvis position.

The terminal swing phase corresponds to the end of the gait cycle. This phase prepares the next stance phase. Three main muscles are in actions. The hamstring muscle have an action on the hip and knee joints to slow down the forward movement of the leg. The rectus femoris muscle extends the knee and the tibialis anterior positions the ankle joint to assure the contact with the ground.

16.7. The Role of the Arms during the Gait

Linked to the bipedal characteristics of the human walking, the movement the arms is a typical feature of human walking. Indeed, during walking the arms swing out of phase relative to the legs but there is no direct link with propulsion.

In several studies this arm swing movement is explained to minimize the body's angular momentum around the vertical axis and then to reduce energy expenditure [26-29].

In these studies, the arm movements are often seen as pendulum movement that move passively due to the thorax movements, gravity and inertia [30, 31].

However, a net joint moment of the shoulder is present during the gait [32], the arm swings are not passive and are driven by muscle activities [33]. Muscle activities keep the swing between legs and arms out of phase [29]. Finally, arm movement during gait is in part due to the muscle activities (deltoid, latissimus dorsi and trapezius muscles) and in another part due to passive dynamics as acceleration of the thorax, inertia and gravity [34]. The implication of arm swing during gait is to reduce energetic cost around 8% [26]. Moreover, it appears that the arm movements during gait facilitate the movements of the legs. Arms help to maintain or regain balance and equilibrium after a perturbation or risk of falling.

CONCLUSION

The gait is a daily activity of human beings, the most important and yet most banal. However, this activity is complex and involves a large numbers of sub-systems such as skeletal, joint, muscular, neurologic, vestibular, visual and proprioceptif systems.

To better understand the human locomotion is a question that arises for many research teams. This area of research, because of its richness and complexity, includes a large number of scientific specialties. Therefore, the aim of this chapter was to simply describe the normal gait pattern in terms of development, kinematic, kinetic and electromyography parameters.

However, this description stays basic because each sub-chapter could be a specific chapter and a field of research. Several domains of normal walking have not been addressed in this chapter, such as motor control, energy expenditure, information integration and influences from different conditions (e.g: walking inside, outside; walking and performing a cognitive task). In all the cases, before trying to understand and explain the abnormal or pathological gait, it is essential to have good knowledge of the great principles of the normal gait (more details could be found in reference books [2, 4, 35-39].

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