The Clinical Use of Kinetics for Evaluation of Pathological Gait in Cerebral Palsy

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Until very recently, gait problems in children who had cerebral palsy had been treated empirically, and this empiricism had been based only on observation of the child’s gait and the clinical evaluation. However, in the more recent past, there have been efforts to approach gait disorders in cerebral palsy on a more scientific level, by assessment of the child preoperatively and postoperatively with use of computerized gait analysis.

Kinesiology, which is the study of gait, can be divided into two areas: kinematics and kinetics. Kinematics is the study of motion without regard to the forces that produce it. An example of this is the sagittal plane graph of knee motion (Fig. 1). Kinematics, therefore, gives a precise description of the motions that are occurring in a particular joint in all three planes during the gait cycle, but the measurements are essentially descriptive and do not provide any insight into the cause of the motion. Kinetics, on the other hand, deals with the forces that produce the motion. These measurements include joint moments and joint powers. In 1987, Winter described the way in which kinetics are calculated (a procedure known as inverse dynamics) and discussed some of the possible clinical uses for kinetics. Subsequently, Davis et al. and Ounpuu et al. developed clinical software that describes the moments and powers of each of the three major joints of the lower extremity in all three planes. Employment of these parameters for the assessment of normal and pathological gait led to the discovery that these measurements can provide a great deal of insight into the specific gait abnormalities associated with cerebral palsy.

Before proceeding with the discussion of the clinical use of kinetics, it is necessary to have insight into how kinetic information is calculated. The process is known as inverse dynamics. In addition, to understand inverse dynamics, some concepts from basic physics must first be understood: specifically, the relationship between force and motion as expressed by Newton’s second law. Newton’s second law states that, at every instant in time, the sum of the forces acting on a body is equal to the mass of the body multiplied by the acceleration of the body: \( \Sigma \text{force} = \text{mass} \times \text{acceleration} \). The scientific unit of force is the newton. One newton is the force that is needed to accelerate a mass of one kilogram at a rate of one meter per square second (1 N = 1 kg \( \times \) 1 m/sec\(^2\)). Scientists make a distinction between mass and weight. Mass, which is generally measured in kilograms, tells about the inertia of an object (that is, how difficult the object is to accelerate) since, from Newton’s second law, the force needed to produce a given acceleration is proportional to the mass. Weight,
The relationship between a child and an adult on a seesaw is exactly the same as that of the muscle and the ground-reaction force at each of the joints in the lower extremity. The pivot point (fulcrum) is always the center of the joint. \( M = \) weight of large subject, \( d = \) his distance from fulcrum, \( m = \) weight of small subject, and \( D = \) his distance from fulcrum. (Reprinted, with permission, from: Gage, J. R.: Gait Analysis in Cerebral Palsy, p. 80, London, MacKeith Press, 1991.)

On the other hand, is measured in newtons and refers to the force that gravity exerts on the object. On the surface of the earth, an object falling freely in a vacuum has an acceleration of 9.8 meters per second squared. Therefore, a mass of one kilogram has a weight of approximately 9.8 newtons.

If a force acts at a distance from a rotational axis, the moment of the force about the axis is given by the product of the force and the moment arm (also called the lever arm), where the moment arm is the shortest distance between the line of action of the force and the axis of rotation (Fig. 2). The force exerted by a muscle produces a moment about the axis of rotation of a joint that it crosses. Newton’s second law can also be applied to express the relationship between moments and angular accelerations. Specifically, the sum of all moments of force acting on a body is equal to the mass moment of inertia of the body multiplied by the angular acceleration of the body: \( \Sigma M = \text{mass moment of inertia} \times \text{angular acceleration} \), or \( \Sigma M = I \alpha \).

An additional concept that is used in inverse dynamics is described by Newton’s third law, which states that for every action there is an equal and an opposite reaction. Thus, if I push down on the floor with my foot, the floor pushes back with an equal force, known as the ground-reaction force. Ground-reaction forces and moments can be easily measured with use of a force-plate.

To illustrate how these concepts can be applied to the analysis of human movement, consider the sagittal view of the foot (Fig. 3). The ground-reaction force produces a moment around the ankle joint. The moment is referred to as the external joint moment. It is resisted by an internal joint moment produced by the muscles crossing the ankle; in this case, primarily the triceps surae. Both the internal muscle force and the external ground-reaction force act on the skeletal levers to produce rotation around the ankle joint. The internal muscle force is acting through the lever arm of the hindfoot, whereas the external ground-reaction force is acting through the lever arm provided by the forefoot. If these two moments are identical, there will be no motion around the ankle — that is, \( \Sigma M = 0 \), so the angular acceleration must also equal zero. However, if the internal muscle moment is slightly greater than the ground-reaction moment, the ankle will move into plantar flexion — that is, the angular acceleration will not be zero.

Inverse dynamics, as described by Winter, involves solving for the forces and moments that will produce observed motions. It requires information from three sources: ground-reaction forces and moments measured with use of a force-plate; positions, velocities, and accelerations of all segments of the lower limb; and anthropometric data. The three types of information are used in an iterative application of Newton’s second law in order to solve for the unknown forces and moments acting at the ankle, the knee, and the hip.

I will begin with the foot. The forces and moments acting on the foot are the known ground-reaction forces and moments (as measured with the force-platforms) and the unknown forces and moments acting at the ankle (for example, internal muscle forces). The accelerations of the foot are also known, and the mass and moment of inertia can be estimated from anthropometric data. If the equations are rearranged (Fig. 4), the unknown ankle forces and moments can be solved for.
With this insight into inverse dynamics, muscle function should be discussed next. Muscles provide all of the power needed for erect stance and propulsion, but they can function in only three ways: eccentric contraction, concentric contraction, and isometric contraction. Eccentric contraction, which is lengthening under tension, always implies shock absorption. Concentric contraction is shortening under tension; all accelerators work concentrically. Isometric contraction is muscle tension without a change in length; postural stabilizers work in this mode.

In gait analysis, it is very useful to have some estimate of muscle power. The kinetic concept that can be used to derive this estimate is joint power\(^*\). Joint power, measured in watts per kilogram, is the product obtained by multiplication of the joint moment of force by the angular velocity of the joint: joint power = joint moment \(\times\) angular velocity, or \(P = M\alpha\).

A positive value for joint power indicates that the muscle is shortening and producing an acceleration. A negative value indicates that the muscle is lengthening and producing a deceleration. If there is a moment but no power, the joint is being held motionless either by ligamentous forces or by isometric contraction of muscle (Fig. 5). Joint power is the single variable that best describes the concentric and eccentric phases of mechanical energy that muscles generate in order to accomplish movement. Since the power estimation is based on the concept of inverse dynamics, the estimates of power obtained by these methods are net power and, hence, do not provide any information about the power of specific muscles or muscle groups.

Once the forces and moments acting on the foot at the ankle joint have been solved for, the forces and moments acting on the shank at the ankle are also known (according to Newton's third law, these forces and moments are equal in magnitude but opposite in direction to the calculated forces acting on the foot).

Newton's second law can again be applied to determine the forces and moments acting on the shank at the knee. Similarly, the calculated knee forces and moments can be used to calculate the forces and moments acting on the thigh at the hip. In this manner, the internal joint moment can be determined for each joint in the lower limb.

**Fig. 4**

An illustration of how Newton's second law is used in the calculation of inverse dynamics. The weight (W) of the foot, the location of its center of mass, and its moment of inertia are estimated from anthropometric data. For simplicity, in this illustration, the center of mass is assumed to be located along the axis of the foot, as shown. \(M_d\), \(F_{yd}\), and \(F_{xd}\) represent ground-reaction forces and moments measured with a force-plate. Newton's second law (represented schematically by \(\Sigma F = ma\) and \(\Sigma M = I\alpha\)) allows the forces and moments to be related to the accelerations. The acceleration of the center of mass in the x and y directions (\(a_x\) and \(a_y\)), and the angular acceleration of the foot (\(\alpha\)), are also known quantities, derived from position measurements (\(F_{yd} - F_{yp} = ma_y, F_{xd} - F_{xp} = W = ma_y\), and \(M_d - M_y = I\alpha\)). The unknown forces and moments acting proximally at the ankle (\(M_p, F_{xp},\) and \(F_{yp}\)) can be calculated by rearranging the expressions for Newton's second law and solving for \(M_p, F_{xp},\) and \(F_{yp}\) (\(M_p = M_d - I\alpha, F_{xp} = F_{xd} - ma_x,\) and \(F_{yp} = F_{yp} - W - ma_y\)). Once these values are known, they can be used, along with anthropometric data and kinematic information for the shank, to calculate the forces and moments at the knee. Similarly, the calculated forces and moments at the knee can be used to calculate the forces and moments at the hip.

**Fig. 5**

Graph representing joint power at the ankle during normal gait. The numerical value for power is calculated by multiplication of the moment by the joint angular velocity. The sign convention is such that negative power indicates negative work — that is, the muscle is contracting eccentrically (\(A_1\) (hatched area)) and absorbing energy. Positive power indicates that the muscle is contracting concentrically (\(A_2\) (solid area)) and performing positive work — that is, producing an acceleration.
be purchased with most gait-analysis systems.

**Clinical Applications of Kinematics and Kinetics**

After an introduction to joint kinetics, kinematics and kinetics can be used to look at the function of the ankle joint in the sagittal plane. During normal walking, ankle function can best be described in terms of three rockers (Fig. 6). First rocker begins at initial contact of the heel with the ground and continues until the entire sole of the foot is in contact with the floor. First rocker is controlled by eccentric lengthening of the anterior tibial musculature. Its purpose is shock absorption — that is, deceleration of the inertia of the body at initial contact. Consequently, the terminology used at Rancho Los Amigos Medical Center refers to this portion of the gait cycle as loading response. Loading response constitutes about 10 per cent of the gait cycle.

Second rocker begins when the entire sole of the foot is in contact with the floor and ends when the heel rises off the floor. In the Rancho Los Amigos terminology, this portion of the gait cycle is known as mid-stance and constitutes about 35 per cent of the gait cycle. Second rocker, like first rocker, is eccentric. Second rocker is largely under the control of the soleus. Its purpose is to conserve energy by controlling the rate of forward progression of the shank and, by so doing, controlling the position of the ground-reaction force referable to the knee. If the ground-reaction force is maintained slightly in front of the knee, an extension moment can be generated against the posterior aspect of the capsule that, in turn, relieves the quadriceps of the responsibility of stabilizing the knee. Therefore, energy conservation is realized by contraction of the quadriceps ceasing at the end of loading response and maintenance of the stability of the knee throughout the remainder of stance phase via the ground-reaction force. Since the ground-reaction force is actually generated by the action of the ankle plantar flexors, this phenomenon is referred to as a plantar flexion-knee extension couple.

Third rocker begins when the heel leaves the ground. During the latter part of mid-stance, the gastrocnemius joins the soleus as an active plantar flexor. The combined force of these two muscles is enough to arrest the forward progression of the tibia (ankle dorsiflexion) and begin ankle plantar flexion. Thus, third rocker is concentric, and...
concentric muscle action, by definition, produces an acceleration. If it is assumed that the individual is walking at a constant speed, the purpose of third rocker is to maintain a steady state by producing an acceleration sufficient to recover the inertial energy lost by the two previous rockers. The period during which this rocker acts is known as terminal stance and constitutes approximately 15 per cent of the gait cycle.

In a graph of the kinematics and kinetics of the sagittal plane (Fig. 7), in which gait cycle is on the x axis and degrees of motion are on the y axis (the abscissa), the line at about 60 per cent of the gait cycle represents toe-off and hence separates stance from swing. First rocker ends at about 10 per cent of the gait cycle, second rocker ends at about 45 per cent of the gait cycle, and third rocker ends at toe-off. The foot then is pulled
Walking and running power graphs. The magnitude of the powers during running is much greater than during walking, but since the sequencing of their action, and not their magnitude, is of interest, they have been graphed to the same scale. Notice the sinusoidal nature of the hip and the knee power curves during running. (See text for explanation.)

back into dorsiflexion during swing. On a graph of joint moment measured in newton-meters per kilogram, the dorsiflexion moment is so small that it barely shows on the graph. The plantar flexion moment peaks early in third rocker and then rapidly falls to zero in the period of double support, so that by the time of toe-off, no substantial plantar-flexion moment remains. On a graph of joint power, eccentric muscle action (power absorption) is always negative and hence is below the zero line. Concentric power (acceleration) is above the zero line. The convention for numbering the power bursts is to use the initial for the joint followed by a sequential numbering of the bursts beginning at the onset of the gait cycle. With use of that convention, the graph

Fig. 10

Fig. 11

Preoperative (Fig. 11) and postoperative (Fig. 12) photographs of a child who had a severe right spastic hemiplegia preoperatively while walking.
shows that second rocker (A1) is purely eccentric and third rocker (A2) is purely concentric.

Kinetics may well prove to be the most useful measurement for gait analysis in that it provides information about the cause of a movement disorder, points to the source of power for movement, and provides some information about net energy consumption at individual joints. With use of moment graphs, the activity time of a particular muscle group can be estimated, as the period of electromyographic activity should be roughly equal to the period of the internal moment depicted on the moment graph. Inspection of power graphs allows a determination of the mode of action of a particular muscle group — that is, whether the action is eccentric, concentric, or isometric. Individual joints can also be looked at as torque generators, and integration of power curves enables the estimation of the magnitude of eccentric or concentric work done in joules per kilogram (Fig. 7). If a moment is present without any generation of power, the joint must obtain its stability either from ligaments — that is, the plantar flexion-knee extension couple — or by isometric contraction of muscle. With this background, this lecture will discuss how these concepts can be used to understand the dynamics of both normal and pathological gait.

The graphs that illustrate the kinematics and kinetics of normal gait in the sagittal plane will now be considered (Fig. 8). Now that the kinematics and kinetics of the ankle have been explained, the hip and knee kinematics should be fairly self-explanatory. There are two bursts of concentric power in the hip. The former corresponds to an extensor moment and the latter, to a flexor moment. This means that the hip extensors generate power during the first half of stance and the hip flexors generate power in pre-swing and in initial swing. These two power bursts, plus the large power burst at the ankle, provide the propulsive power for walking. Which muscle groups are supplying this power can be determined from the moment graphs. For example, the first burst of concentric power at the hip coincides with an extensor moment and the second burst, with a flexor moment. Therefore, the first burst of energy is concen-
Preoperative (dotted curve) and postoperative (solid curve) ankle sagittal-plane kinetics of the patient compared with normal data. Preoperatively, the ankle moment was biphasic and there was a double burst of power. Postoperatively, both the moment and the power curves closely approximated normal. (See text for explanation.)

The concentric and is provided by the hip extensors, whereas the second burst of energy is eccentric and represents energy absorption by the hip flexors. Similarly, at the ankle, the burst of concentric power coincides with a plantar flexion moment. Thus, the power needed for propulsion during walking comes primarily from the hip and the ankle. If the area under each of the curves is integrated, it can be determined that about 45 per cent of the power required for walking comes from the ankle plantar flexors; 30 per cent, from the hip extensors; and 20 per cent, from the hip flexors. It must be remembered that this power is being contributed bilaterally and that the timing is such that the power of the plantar flexion of the ankle of the trailing limb comes just slightly before the power of the hip extension of the front limb. Thus, the pushing power of the trailing limb is augmented by the pulling power of the front limb. Furthermore, the acceleration of the hip flexors, which, along with the plantar flexion burst, launches the trailing limb into swing phase, occurs concomitantly with the acceleration of the hip extensors on the front limb.

Overlaying of moment and power curves can provide additional information about normal walking, such as the way that the body controls the limbs, the support strategy for the lower limbs, and the power flow during the gait cycle. For example, overlaying of the graphs of the sagittal plane moments and powers of the hip, the knee, and the ankle reveals that there is a flow of power

By integration of the power curves, the work of the ankle plantar flexors during one gait cycle can be estimated in joules per kilogram. Preoperatively (dotted curve), the patient had an abnormal power burst in mid-stance; the abnormal burst was no longer present after the operation. The concentric energy was 0.26 joule per kilogram preoperatively compared with 0.21 joule per kilogram postoperatively. The eccentric energy was −0.31 joule per kilogram preoperatively compared with −0.10 joule per kilogram postoperatively. Since the patient was walking at approximately the same velocity preoperatively and postoperatively, the less work done in the postoperative period indicates that the ankle was functioning more efficiently.
that starts with the hip extensors, moves down to the knee extensors (quadriceps), and finally reaches the ankle plantar flexors (Fig. 9). The support strategy for the lower limb can be seen in this wave as these are all antigravity muscles, and this bipedal flow allows the limbs to support the trunk and to avoid collapse while still delivering the smooth flow of energy that is needed for propulsion during gait. This power flow is even more apparent if these graphs are overlaid for running because in running, there is a more distinct contribution of power from the knee (Fig. 10). The graphs also show the sinusoidal nature of the hip and knee curves during the swing phase of running. By inspection of the moment graphs to determine which muscle group is dominant and examination of the power graphs to determine whether the muscle is working eccentrically or concentrically, it can be determined that, during initial swing, there is an eccentric extensor moment at the knee and a concentric flexion moment at the hip. Whereas, in late swing, there is an eccentric flexion moment at the knee and a concentric extensor moment at the hip. What these graphs show is that there is a transfer of energy from the knee to the hip during both initial and terminal swing. The body uses the two-joint muscles to accomplish this. Hence, during initial swing, the rectus femoris is contracting eccentrically at the knee and concentrically at the hip, whereas, during terminal swing, the hamstrings are contracting eccentrically at the knee and concentrically at the hip. Since the contraction is eccentric at one end of the muscle and concentric at the other, the muscles probably remain relatively isometric with respect to net length. In both cases, however, these biarticular muscles essentially work as energy-transfer straps and act to harness the energy of the Shank and carry it proximally to the hip, where it can be used to augment hip flexion. Yack and Winter estimated that the energy transfer of the biarticular muscles reduces the energy cost of walking by about 22 per cent.

Illustrative Case Report

These tools will now be used to look at pathological gait in a child who had a severe right spastic hemiplegia secondary to an embolus of the middle cerebral artery, which occurred after a cardiac procedure. The preoperative photograph of the child walking showed that the knee was flexed to about 45 degrees in terminal swing and the foot was in mild equinus so that, at initial contact, there was a toe-toe gait on the right side as well as an extremely short step-length (Fig. 11).

The postoperative photograph showed nearly full knee extension; however, there was still mild equinus (Fig. 12). Thus, the patient was positioned to come down with a longer step-length than he had had preoperatively and with a foot-flat gait. The preoperative sagittal-plane kinematics of the hip, the knee, and the ankle (Fig. 13) showed that there was excessive lumbar lordosis and hip flexion. The knee was continuously flexed during stance with a restricted range of flexion-extension during swing. The pattern of ankle motion was interesting in that the range of motion was normal but the movement pattern was not. Maximum dorsiflexion was reached early in stance, followed by a biphasic thrust into equinus and a persistent foot drop in swing. Preoperative ankle kinematics (Fig. 14) revealed a biphasic moment and two distinct bursts of concentric power. Evaluation of the kinematics shows that the progressive dorsiflexion that normally occurs during second rocker was interrupted by a premature burst of power of the ankle plantar flexor. If the sagittal plane kinematics are examined, it is seen that, at initial contact, the knee was flexed approximately 45 degrees and the foot was in approximately 10 degrees of equinus. Thus, the fast-twitch, biarticular gastrocnemius was stretched from the moment of initial contact whereas, in normal gait, this muscle would not come under stretch until mid-stance. In addition, the muscle was spastic because, on clinical examination, ankle clonus on the hemiplegic side could be evoked easily. Finally, the monarticular soleus could have neither a static nor a dynamic contracture as the ankle allowed normal dorsiflexion.

Therefore, the most likely explanation for the double burst of power of the ankle plantar flexor was that the gastrocnemius displayed dynamic clonus during gait. In light of this information, length-
ening of the Achilles tendon would not have been reasonable because this procedure would have lengthened both the gastrocnemius and the soleus. Consequently, I elected to do a Strayer-type gastrocnemius recession to address the contracted gastrocnemius and, at the same time, to preserve soleus function. In the actual analysis of the gait of this child, I also used the sagittal and coronal plane kinematics and kinetics of the hip and the knee, which are not included here. With the use of gait analysis in conjunction with a clinical examination, the patient was classified as having a type-IV hemiplegia with associated femoral anteverision.

On the basis of these data, the child had a single-event operation on the hemiplegic side that consisted of an intertrochanteric derotational femoral osteotomy, an intramuscular psos tenotomy, lengthening of the medial hamstrings, the distal end of the rectus femoris to the intramuscular stump of the gracilis, and a Strayer-type recession of the gastrocnemius. Twelve months later, the patient had postoperative gait analysis (Figs. 13 and 14). Comparison of the graphs of the preoperative and postoperative kinematics with normal graphs revealed that there had been a reduction of lordosis and that the kinematics of the hip, the knee, and the ankle were all much closer to normal. Inspection of the kinetics of the ankle showed that the postoperative plantar-flexor moment had also normalized and that there was only a single burst of power that was equal to or slightly greater in magnitude than the second preoperative burst.

Integration of the preoperative and postoperative power curves for the patient (Fig. 15) gives an estimation of the work done at the ankle during a single gait cycle in joules per kilogram of body weight. Both concentric and eccentric work were reduced postoperatively. Preoperatively, the concentric work was evenly distributed between the two power bursts. The timing of the second burst was such that it contributed to forward propulsion, but the first burst was simply wasted work. Postoperatively, all of the concentric work contributed to propulsion. Since the primary goal of an operation is to make walking more energy-efficient, this type of information is very useful in the assessment of postoperative outcomes as it provides very specific information about the effect of operative treatment.

Finally, it is useful to compare the overlaid moments and powers of a normal profile (Fig. 9) with the postoperative moments and powers of the patient (Fig. 16). Even in the hemiplegic limb, there was a progression of extension moments that began at the hip and traveled down the limb to the ankle. Although the flow in the hemiplegic limb was not quite as smooth, it was otherwise not unlike that in the normal limb. The power bursts, on the other hand, were much more abnormal in that they were not as acutely timed or as smooth, and there were large bursts of eccentric energy, particularly at the knee, that were clearly abnormal. If this information is combined with preoperative and postoperative linear measurements (stride length, cadence, velocity, and so on) and energy costs (milliliters of oxygen used per kilogram of body weight per meter traveled), the effectiveness of the operative intervention can be assessed very critically.

Before the development of kinetics, only descriptive information could be gathered with regard to gait. With this tool, information about cause can begin to be acquired. With use of the data acquired from these new methods of investigation, important advances in the treatment of cerebral palsy have already begun.

References