Redefining the Role of Muscle Groups during Gait:
Dynamic Compensations for Common Musculoskeletal Impairments

Principles Governing the Function of Muscle Groups during Normal Gait
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Compensatory Gait Strategies by Patients with Musculoskeletal Impairments
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Objectives

At the conclusion of this activity, participants will be able to:

1. Describe the often misunderstood function of lower extremity muscles in the closed kinetic chain during gait.
2. Identify some of the closed kinetic chain compensations available to patients with musculoskeletal impairments.
3. Apply these principles to develop more appropriate treatment plans for patients with musculoskeletal impairments.

Analysis of human movement can be divided into kinematics, the measurement of movement, and kinetics the measurement of the control of movement. Kinematic measurements traditionally used in clinical gait analysis include joint angles and velocities. Kinetic measures used in gait analysis include net joint moments and powers. (A net joint moment is the sum of all rotational forces produced by muscles and soft tissues crossing a joint. The net joint power is the scalar product of the net joint moment and the joint angular velocity and is an indication of how much energy muscles crossing a joint either add or remove from the body.)

These traditional methods are used to deduce the role of muscles during gait based on the position of the muscles in relationship to the joints they cross. For example, muscles crossing posterior to the knee joint are generally accepted as being knee flexors. However, when muscles contract in a closed kinetic chain they can often act in surprising ways. Zajac and Gordon (1989) used a musculoskeletal model to demonstrate that the gastrocnemius, a two joint muscle, may actually act as a knee extensor when a person is standing in a nearly erect position. Similar models (Kepple et. al. 1999) also indicate that there is significant redundancy in the control of the stance limb and that each muscle group has some ability to control motion at all other joints. This redundancy in musculoskeletal control can provide compensatory methods for controlling movement when there is a loss of function in one or more muscle groups.

In this workshop a simple computer simulation, based on the Zajac model, is developed and the resultant movement is analyzed by traditional means. This simulation demonstrates that traditional approaches for studying the role of muscle groups during human walking have two limitations:

- Inadequate explanation for the sources of the observed joint movements.
- Errors in determining the type of muscle contraction

To avoid these limitations, the mechanical equations that govern the relationship between muscle forces and the resulting movement are formulated starting with the Newton/Euler equations:

$$S\ \mathbf{F} = m\mathbf{a}$$
$$S\ t = I\ ?$$

The first equation states that the sum of all muscle and joint forces (**F**) that act on the segment will be equal to the product of the segment mass (m) and the translation acceleration (**a**) of an anatomical segment. The second equation states the sum of all net joint moments (t**)** acting on the segment will be equal to the product of the segment rotational inertia (I) and the angular acceleration of an anatomical segment (**?**).

Because muscles contracting across a joint generate moments equal to the product of the muscle force and the perpendicular distance to the joint center, these two equations can be coupled. By coupling the equations we can simplify them and obtain a single more powerful equation that directly relates the muscle forces to the resultant movement. This new equation allows us to determine the following principals that determine how muscles control human movement:

1. A moment at a joint will act to accelerate all of the joints of the body.
2. The magnitude of the accelerations created by a joint moment will be a function of both the magnitude of the moment and the positions of the segments.
3. The accelerations created by a joint moment are independent of the velocity of the joint. Thus, the accelerations created by a given joint moment are independent of type of contraction (eccentric vs. concentric.)

From these principles, it is clear that there is significant redundancy in controlling the motion of the stance limb and that each muscle group has some ability to control motion at all other joints. These principles also explain, in part, the ability of persons with muscle weakness to compensate via the use of alternative control strategies.

A series of clinical cases of patients with knee extensor weakness nicely demonstrates these principles. During the initial double limb support phase of gait, knee extension must occur to prevent limb collapse during weight acceptance. Normally, this knee extension is produced and maintained by the knee extensor muscles. However, a patient with knee extensor weakness must use an alternate strategy to control the knee joint and prevent limb collapse during gait. Advanced gait analysis of several patients with knee extensor weakness reveal a variety of compensations available to achieve this goal.

Patient #1 was a 16 year old male previously diagnosed with osteosarcoma of the distal left femur. At the time of gait analysis, he was one year post limb salvage surgery which included placement of an endoprosthetic knee that was covered with a gastrocnemius muscle flap. Primary impairments included muscle weakness in the left knee extensors (3+/5 on manual muscle test [MMT]) and left ankle plantar flexors (unable to rise up on toes in left single limb stance). He was able to walk independently without assistive devices. Results of gait analysis with traditional methods revealed the following:

walking speed: 0.65 statures/second
double limb support duration: 18% of the gait cycle
left knee function: The left knee was maintained in a few degrees of flexion throughout most of stance phase. Left knee extensor moments fluctuated about zero, but no evidence of left knee collapse was observed.
left hip function: Left hip extensor moments and power generation in early stance phase were nearly double in magnitude and duration as compared to normal gait.
left ankle function: Left ankle plantar flexor moments were decreased in magnitude approximately 50%.

Advanced gait analysis results revealed that the left hip extensor moment was the primary source of left knee extension acceleration, and therefore knee stability, during early stance phase. Reduced left ankle plantar flexor moments did not assist knee extension, probably due to weakness associated with the surgical procedure.

Patient #2 was a 29 year old male previously diagnosed with a soft tissue sarcoma near the right superior pubic ramus. At the time of gait analysis, he was 5 months post surgical resection of the tumor. Primary impairments included weakness in the right knee extensors (MMT 2/5), right hip flexors (MMT 2/5) and right hip adductors (MMT 3/5). He walked independently without assistive devices, but did report occasional problems with right knee instability during walking. Results of gait analysis with traditional methods revealed the following:

walking speed: 0.54 statures/second
double limb support duration: 15% of the gait cycle
right knee function: The right knee was maintained near full extension throughout most of stance phase. Right knee extensor moments were near zero during early stance phase, followed by a large flexor moment.
right hip function: Right hip extensor moments and powers were similar to normal gait.
right ankle function: Right ankle plantar flexor moments increased much earlier in stance phase than is typical of normal gait.

Advanced gait analysis results revealed that the right ankle plantar flexor moments provided the largest source of right knee extension acceleration. Only a small additional contribution to right knee extension was provided by the right hip extensors. The patient may have elected not to use the hip compensation secondary to possible discomfort following surgery. However, the knee appeared to be at risk for collapse in very early stance phase during the time the hip extensor compensation would typically be used, and before the ankle plantar flexor compensation could be fully recruited.

Patient #3 was a 54 year old male diagnosed with amyotrophic lateral sclerosis. Primary impairments included wide spread muscle weakness. In general, strength was 2/5 on MMT in the left lower extremity and 4/5 in the right lower extremity. He walked without assistive devices, but reported a history of falls. Results of gait analysis with traditional methods revealed the following:

walking speed: 0.42 statures/second
double limb support duration: 34% of the gait cycle

left knee function: The left knee was flexed at initial contact and then rapidly hyperextended. Left knee extensor moments were near zero during early stance phase, followed by a large flexor moment.

left hip function: Left hip extensor moments were prolonged as compared to normal gait.

left ankle function: Left ankle plantar flexor moments were reduced as compared to normal gait.

Advanced gait analysis results revealed that the patient used the right (contralateral) ankle plantar flexor moment as the primary source of left knee extension acceleration. The left hip extensors and ankle plantar flexors provided only a very small source of left knee extension, since these muscle groups also were very weak. The patient utilized the right ankle plantar flexors to extend the left knee by prolonging right foot flat and terminal right double limb support. However, this resulted in a walking speed that was much slower than speeds associated with the compensatory patterns of the first two patients.

The patient case examples demonstrate the variety of strategies available to compensate for a deficit in a single muscle group during one portion of the gait cycle. These strategies are available because each muscle group has the ability to accelerate all the joints of the lower extremity, including joints not crossed by the muscle. All compensations do not appear to be equally effective, based on measures such as walking speed or frequency of falls. Advanced gait analysis techniques facilitate identification of the compensatory strategies used by patients on an individual basis. Through additional research, these results can then be used in rehabilitation treatment to assist in training patients to use the most effective compensatory strategies possible for any given set of physical impairments in order to maximize functional outcome.

References

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