Making inferences about muscle forces from clinical observations

The analysis of movement dysfunction often requires that inferences be made about the muscle forces which occur during motor task performance. Physiotherapists probably use a range of different models of analysis to make inferences about such forces. These models differ in the degree to which they invoke simplifying assumptions about the non-muscle forces acting on body segments. In some circumstances even the most simple models of analysis will enable reasonable inferences to be made about muscle forces, but in other situations it may be very difficult to make reasonable inferences about muscle forces from clinical observations alone.

Key words: Biomechanics; Gait; Muscles

The observation and analysis of motor task performance is a fundamental component of the assessment of movement dysfunction. Observation and analysis provide a starting point for the remainder of the physical examination by generating hypotheses about the potential causes of a movement problem. Moreover, in complex movement disorders, an analysis based on observations of task performance can sometimes provide the only real clues to the nature of the movement problem.

While the observation and analysis of motor task performance provide a key role in assessment of people with movement disorders, there has been very little explicit discussion in physiotherapy literature about precisely what should be observed or how those observations should be analysed. This paper will raise some issues relating to the analysis of motor task performance. Specifically, the paper will examine the processes by which inferences can be made about the muscle forces which occur during the performance of motor tasks.

Analysis of motor performance

The term analysis is sometimes used to mean the process of describing kinematic deviations from normal task performance (i.e., the observable characteristics of task performance such as the displacements, velocities and accelerations of body parts). It could be argued that simply describing kinematic deviations does not constitute analysis. The term analysis may be better used to refer to the processes by which inferences are made about the causes of movement dysfunction. The process of analysis involves making hypotheses about why the observed kinematic deviations occurred, in terms that are amenable to physiotherapy intervention. Typically the kinematic deviation is attributed to the inappropriate activation of muscles, the decreased ability of muscles to generate tension, the decreased length or extensibility of soft tissues, or the presence of pain in particular structures. The conclusion of an analysis may be, for example, that a particular person’s inability to grasp a cup is a result of their inability to sufficiently activate their thumb abductor muscles, or that a person’s inability to walk quickly is the result of soft tissue adaptations which have reduced the amount of motion available at the knee.

Analysis almost always involves making inferences about which muscles are and are not producing force during task performance. This is because the forces produced by muscles partly determine the accelerations of body segments which occur during performance of a task. Therefore, understanding how muscle forces are acting on the body is important when making judgements about why the body moves in the way that it does. At a more practical level, many physiotherapy treatments are directed at individual muscles or muscle groups. Thus it is important to identify muscles or muscle groups which are not generating tension in the way that is required for effective task performance.
The forces acting on a multi-segmented system

The body can be thought to consist of a number of rigid segments joined by frictionless pins. The forces acting on each body segment (in this case, the leg) are shown in Figure 1. The forces include a weight force (W), which acts downwards from the segment’s centre of mass; the joint reaction force (JRF) and ground reaction force (GRF) which arise as a result of the interaction of the segment with an adjacent body segment or with the ground; and a muscle moment (M) produced either by active muscle contraction or from the passive tension developed in stretched muscles or other soft tissues (Miller and Nelson 1973, Winter 1990). Figure 2 shows how muscle forces produce a turning effect, or moment, on body segments.

Reaction forces are forces that result when any two bodies (in this case any two segments or a segment and the ground) interact, and they are the means by which the movement of one body segment influences other body segments. The reaction forces are composed both of forces produced by the weight forces of other body segments and forces which arise as a result of the accelerations of other body segments (ie the inertial or motion-dependent forces of other segments). The component of the reaction force which is due to the weight forces of other body segments always acts in a vertical direction, but the motion-dependent component can act in any direction (depending on the direction of the accelerations of the accelerating body segments).

When a body segment rotates, even if it is rotating at a constant angular velocity, it undergoes an acceleration towards the axis about which it rotates. As a result, it can be said to experience an outward motion-dependent force which pushes it away from the segment about which it rotates. (A useful illustration is provided by the example of a ball on a string being swung in circles. The acceleration of the ball associated with its circular motion produces a force which pulls outward on the string.) This motion-dependent force will be transmitted to every other segment in the body. Rotations of body segments are always accompanied by motion-dependent forces which act on all other body segments. The rotatory effect of these motion-dependent forces will, however, be greatest on segments that are aligned perpendicularly to the moving segment, and zero on segments that are parallel to it.

The rotary effects of motion-dependent forces are clearly demonstrated by the action of standing up from sitting, illustrated in Figure 3a. As the trunk rotates forward early in the performance of the task, it generates a force that acts along the line of the trunk in the direction of the head, and this force is transmitted to

Figure 1.
The forces which act on body segments. W, weight force; JRF, joint reaction force; GRF, ground reaction force; M, net muscle moment.
When a muscle generates tension it produces a force at one of its attachments ($F_m$). The force applied by the muscle to its other attachment ($-F_m$) is transmitted to the first segment through the intervening joint. Together these forces tend to rotate the segment. (b) The two forces can be replaced by a mechanically equivalent muscle moment ($M$).

The magnitude of the motion-dependent component of the reaction forces acting on a particular segment depends on a number of factors. These are the magnitude of the accelerations of the body segments, the relative orientation of the segments, the relative mass of the segments, and the location of the centre of mass of the segments (Hoy and Zernicke 1986, Plagenhoef 1971, Putnam 1983 and Zajac and Gordon 1989). A number of recent studies have shown that, at least during the performance of some motor tasks, motion-dependent forces can constitute a dominant component of the joint reaction forces, and they can profoundly influence the muscle forces needed to produce the motions required of body segments (Ulrich 1989, Zajac and Gordon 1989, Zernicke et al 1991).

In summary, the forces acting on every segment in a multisegmental system will tend to rotate some segments more than others. Furthermore, when rotating body segments undergo angular accelerations (i.e., when they speed up or slow down their rotations) they exert an additional force, this time tangential to the arc of rotation. These forces also act to influence the motion of all body segments. To use the example of standing up, early in standing up, the trunk accelerates forward and then it rapidly decelerates at about the point at which the thighs lift off the seat (Rodosky et al 1989). The deceleration of the trunk produces a force that is perpendicular to the trunk and directed forward, and this force is transmitted to all other body segments (see Figure 3b). The force will have little effect on the rotations of the thigh (it will tend primarily to translate the thigh forward) but it will tend to rotate the leg anti-clockwise.

These examples illustrate how muscles can influence the motion of body segments other than those segments to which they attach. In fact, whenever muscles rotate body segments, they produce motion-dependent forces which are transferred to all other body segments as reaction forces. In the examples above, the moment-dependent forces attributable to the accelerations of the trunk act to accelerate, and ultimately displace, the leg and thigh in an anti-clockwise direction, and in this way they assist in the initiation of displacements which are necessary for successful standing up.
The system are:
(a) the weight of that segment;
(b) forces produced by muscles and other soft tissues which span the joints at either end of the segment; and
(c) reaction forces (joint reaction forces and ground reaction forces) due to:
- the weight of other segments
- motion-dependent forces produced by the motion of other segments.

Models for making inferences about muscle forces

The task for physiotherapists wanting to make inferences about the forces produced by muscles during task performance is a daunting one. Even when it is only necessary to make inferences about whether or not a particular muscle group is producing force (i.e., even if there is no need to know about how much force a particular muscle group is generating) the task is difficult. This is because of the lack of visual clues about the size and direction of the many forces acting on each segment.

By making simplifying assumptions about the forces acting on body segments, it is possible to circumscribe both the features of the movements which need to be observed and the complexity of the analysis. These simplifying assumptions constitute a model of analysis. No doubt physiotherapists use a variety of models for analysis, and these models probably vary greatly in their sophistication. In the ensuing parts of this paper, two models of analysis that are broadly representative of the models physiotherapists implicitly use in clinical practice will be discussed and their strengths and weaknesses considered.

Model 1: In the first model, all of the segments at one end of the joint of interest are thought of as one combined segment, and the combined segment is considered to be isolated from the rest of the body. The

Figure 3.
Early in standing up, motion-dependent forces ($F_i$) associated with (a), the rotation (or angular velocity, $\omega$), and (b) the angular acceleration ($\alpha$) of the trunk act on all other body segments.
Figure 4.
Application of two models to determine (a) the muscle group generating tension at the shoulder when taking a cup to the mouth; (b) the muscle group generating tension at the hip in the early part of standing up; and (c) the muscle group generating tension at the knee in the early swing phase of walking. $\alpha$, angular acceleration; $W$, weight force; $M$, the (inferred) net muscle moment.

Orientation of the combined segment in space is given by a line passing between the joint and the perceived centre of mass of the combined segment. The combined segment is assumed to be fixed in space at the joint of interest, and is therefore only able to rotate about this point. Only two moments are considered to act on the segment – a moment produced by the weight force, which always acts to rotate the free end of the combined segment downwards, and a muscle moment. As it is assumed that no accelerations are occurring, the two moments are considered to be equal in magnitude and opposite in direction. Therefore, if the weight moment is acting to pull the joint into extension, the inference is made that the muscle moment must be flexor, and if the weight moment is flexor, it is inferred that the muscle moment must be extensor. The following two examples illustrate how such a model might be used in practice.

Example 1: Making inferences about shoulder muscle forces that arise as a cup is taken to the mouth (Figure 4a): The arm, forearm and hand are considered to be a single combined segment hinged at the shoulder, and the orientation of this segment is determined by the estimated position of its centre of mass. The segment is free to rotate about the shoulder, but the shoulder is fixed in space. Because of the orientation of the combined segment, the weight moment acts to accelerate the segment anti-clockwise. As it is assumed that no accelerations are occurring, the weight moment and muscle moment must be equal and opposite, so the inference is made that a net flexor moment must be acting at the shoulder and that the shoulder flexor muscles must be generating tension.

Example 2: Making inferences about hip muscle forces that occur when standing up is initiated (Figure 4b): The trunk, head and arms are considered to be a single segment, hinged at the hip, and the hip is fixed in space. The segment is inclined
slightly backwards, because the centre of mass of the trunk is behind the hips in this early part of standing up. The moment due to the weight of the combined segment is small because the centre of mass of the segment is almost directly over the hip joint, but it acts to accelerate the trunk segment clockwise. The weight moment and the muscle moment are assumed to be in equilibrium, and so it is inferred that a net flexor moment must be acting at the hip, and that the hip flexor muscles must be generating tension.

Although this model of analysis is quite simple, and although it may often produce reasonable inferences about which muscle groups are generating tension, it clearly involves making some significant simplifying assumptions. Perhaps least tenable is the assumption that the body segments do not undergo significant accelerations. When this assumption is not valid (ie, when significant accelerations do occur) the model may generate unreasonable inferences about muscle forces. For example, if the person in Figure 4a were to slam their cup back down on the table they probably would be using their shoulder extensor muscles to accelerate their arm anti-clockwise, but the model would still predict that the shoulder flexor muscles were generating tension. This illustrates that this first model of analysis can generate incorrect inferences about muscle moments when substantial accelerations are taking place.

**Model 2**: The second model is marginally more complicated but it makes fewer simplifying assumptions. This model differs from the first model in that the moments are not necessarily assumed to be in equilibrium; the combined segment is allowed to experience angular accelerations. The angular acceleration of the segment is determined by the sum of the weight moment and the muscle moment. This means that any difference between the observed accelerations of the segment and the accelerations that would be expected to occur due to weight moments alone must be attributed to muscles.

The application of this second model can be illustrated using the same examples as before. In Figure 4a, in which the person is taking a cup to their mouth, the arm initially undergoes a clockwise acceleration. This acceleration cannot be attributed to the weight moment, because the weight moment acts to rotate the arm anti-clockwise (ie in the absence of any muscle forces the arm would tend to fall in a direction that is opposite to the observed acceleration). As the only other moments acting on the segment, the assumption is made that the arm flexor muscle moment must be acting to accelerate the arm clockwise. In Figure 4b, the trunk undergoes an anti-clockwise acceleration as the person begins standing up. Again, the acceleration of the trunk can be produced by muscles only because the weight moment is acting to rotate the trunk clockwise. Even when the trunk rotates past the vertical position, the weight moment of the trunk is initially insufficient to produce the observed anti-clockwise acceleration. The inference is made, therefore, that a flexor muscle moment must be acting at the hip to accelerate the trunk anti-clockwise.

It is important to note that it is the accelerations of body parts, and not their velocities (ie not the direction or rate of their movements), that should be considered when making inferences about muscle moments. In fact, when information about the accelerations of body parts is used to make inferences about muscle forces, the results are sometimes counter-intuitive. Consider an analysis of the muscles acting at the knee during the early part of swing phase of walking (Figure 4c). Intuition might suggest that, because the knee is flexing, and because gravity is acting on the leg in a way that resists flexion, knee flexor muscles must be generating tension. The critical observation is, however, not that the knee is flexing, but that it is flexing at a decreasing velocity. That is, the leg is accelerating clockwise. The clockwise acceleration of the leg is probably produced largely by gravity, and so there is little need for a muscle moment at the knee. This explains the common finding of a number of biomechanical studies of a negligible knee muscle moment or even a knee extensor muscle moment at the beginning of the swing phase of normal walking, particularly at fast walking speeds (Cavanagh and Gregor 1975, Winter 1987).

Model 2 is likely to generate reasonable inferences about muscle moments when it is used to analyse tasks which do not involve large accelerations of body parts other than the combined segment. In examples 1 and 2 (Figures 4a and 4b), the conclusions drawn are almost certainly correct – it is very likely that the person will indeed be producing a net flexor moment at the shoulder as they reach for the cup, and a net hip flexor moment as the trunk moves forward at the start of standing up.

However, this second model of analysis still ignores inter-segmental dynamics. That is, it assumes that body segments other than the combined segment experience negligible accelerations. When other body segments experience substantial accelerations, as is particularly likely to occur in rapid movements such as throwing or running, the assumption of no motion-dependent forces which is made by this model (and model 1) can lead to significant errors. Therefore, it is generally not appropriate to use these models of analysis for analysing the performance of tasks which involve large accelerations.

The major limitation of the second model of analysis is that it requires physiotherapists to estimate the magnitude of segmental accelerations, and compare the estimated accelerations with those expected to occur under the influence of gravity alone. To a degree, it would seem straightforward enough to observe increases or decreases in the velocity of motion of body segments and, insofar as this is the case, it is possible to infer the presence of accelerations. But it may be extremely difficult to
determine, on the basis of observations alone, whether the accelerations of groups of body segments are greater or less than those that would be expected to occur under the influence of gravity alone. This is particularly likely to hold when the combined segment consists of several segments which are accelerating in different directions, or when the acceleration of the combined segment is close to that which would be expected to occur under the influence of gravity alone. Under these circumstances, it is likely that inferences about muscle forces will be in error.

The preceding discussion detailed how it might be possible to make inferences about the direction of the muscle moments acting at joints, with the implication that making such inferences would enable physiotherapists to make decisions about when specific muscle groups are generating force. But the muscle moments about which the discussion has centred are not always related to muscle forces in a simple way. In reality, while a flexor muscle moment will always be associated with force production by the flexor muscles (or by stretched non-muscle tissues on the flexor aspect of the joint), the absence of a flexor muscle torque will not always be accompanied by the absence of flexor muscle forces. This is because the muscle moment is the sum of the moments produced by the muscles and other soft tissues which span both aspects of the joint. When the muscles on only one aspect of the joint are producing force, the muscle moments will faithfully reflect the forces produced by muscles, that is, flexor muscle moments will be accompanied by force development in the flexor muscles and not by force development in the extensor muscles. When, however, co-contraction occurs, the muscle moments will not faithfully reflect the muscle forces and flexor muscle moments will be accompanied by force development in both the flexor and extensor muscles.

Recent research suggests that some degree of co-contraction of agonist and antagonist muscle groups is a common feature of normal movement (Crago et al. 1990, Crisco and Panjabi 1990, Gielen et al. 1990). Probably co-contraction enables the motor control system to regulate the stiffness (Hogan 1985) and stability (Crisco and Panjabi 1990) of series of body segments. Moreover, co-contraction is a common feature of disordered movement (Knutsson 1981, Knutsson and Richards 1979). The ubiquity of co-contraction means that care needs to be taken when assuming, on the basis of inferences made about muscle moments, that a particular group of muscles is not producing force.

**Conclusions**

The process of making inferences about muscle forces from clinical observations requires that physiotherapists make simplifying assumptions about the non-muscle forces acting on body segments. When the accelerations of body segments are negligible, it may be possible to make reasonable inferences about muscle moments acting at a particular joint using models of analysis which assume the absence of segmental accelerations. However, when significant accelerations of body segments occur, more sophisticated models of analysis must be used if reasonable inferences about muscle moments are to be made. The successful application of these more sophisticated models requires that physiotherapists be able to make estimates of the accelerations of groups of body segments from their observations, a task which can be very difficult. When intersegmental dynamics dominate task kinematics it probably is not possible to make reasonable inferences about muscle moments from clinical observations alone. In these circumstances, physiotherapists must utilise findings from studies on the biomechanics of disordered movement in order to make meaningful analyses.

Muscle moments will reflect the forces produced by muscles except when co-contraction occurs. In the presence of muscle co-contraction it may be invalid to infer, on the basis of clinical observation alone, that a particular muscle group is not producing force.

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**References**


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