APPROACHES TO OBTAINING THREE DIMENSIONAL INFORMATION ABOUT BIOLOGICAL SYSTEMS

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The fundamental purpose behind most biomechanical studies is to determine the loads imposed upon the body from external forces or to ascertain the forces produced by biological structures, particularly by the muscles. Almost all studies try in some way to measure or estimate these forces. There are essentially five approaches to measure or estimate the forces experienced by biological structures. These approaches are (1) to measure the external forces directly, (2) to measure the actual internal forces, (3) to estimate internal muscle forces from electromyographic signals, (4) to model mathematically the biological structures, or (5) to apply inverse dynamics methods (whereby internal forces and moments are computed from kinematic measurements). In the following discussion the strengths and weaknesses of each of these approaches for obtaining three-dimensional information about the human body will be explored.

External force measurements. The simplest way to obtain biologically produced forces is to measure them externally. One can construct a force transducer or purchase a commercially available **dynamometer** to record the forces that are produced at the contact points between the human body and the environment. The most common triaxial device is the **force platform**. Most biomechanics laboratories are now equipped with these instruments from Kistler Instrument Co. or AMTI. With these devices one can readily record patterns of ground reactions force under the feet during locomotor, jumping, or lifting activities. Unfortunately, despite being highly accurate and reliable, force platform data if not combined with other information tell little about the underlying mechanisms within the body.

In recent years, sophisticated uniaxial dynamometers, such as the KinCom and Cybex **isokinetic dynamometers**, have become available (although at exorbitant prices). Very few of these class of dynamometers, however, can handle triaxial motions. A notable exception is the Isostation B-200 triaxial trunk measuring system, presented in a previous paper. These systems can isolate particular joints to determine the strength requirements of certain motions or the maximum voluntary contraction forces of specific muscle groups. The major shortcoming with these devices is that they impose artificial motions or loadings to the subject by, for example, measuring moments of force under isokinetic (constant angular speed) conditions or forcing the subject to move about an artificial axis due to the machine's leverage system. In real-life one rarely contracts isokinetically or moves one joint in isolation from the other surrounding joints. It would be beneficial to know the forces produced when subjects perform their daily tasks in their normal working environment or when an elite athlete produces a world record on the athletic field.

Internal force measurements. The best way to obtain the actual forces produced by muscles or experienced by bones, etc., is to attach a transducer directly to the anatomical structure. In a previous presentation, bone pins were used to identify the motion of the skeletal system unaffected by external soft tissue movements. Other authors, such as my colleague Dr. Lamontagne, have applied **strain gauge transducers** directly to muscle tendons in an effort to gauge the true forces produced. The drawback with this approach is somewhat obvious. It is difficult and sometimes impossible to obtain "ethics" approval to undertake such studies let alone recruit sufficient subjects to make statistically valid statements about the differences among various testing conditions or subject groupings. Moreover, there are no commercially available sensors or research facilities to ease the technological difficulties associated with developing a reliable and accurate system. Furthermore, it is still beyond our technical expertise to instrument an entire limb, with all its muscles and bones, let alone an entire musculoskeletal system. Future microtechnology will eventually overcome these obstacles but for the present time obtaining the necessary information for evaluating human performance with this approach is impractical.

Predicting muscle forces from electromyography. This approach is probably the least accurate method of obtaining valid predictions of the forces produced by muscles and cannot by itself be used to predict bone-on-bone forces. New technologies have made it relatively easy to measure the EMG activity of many muscle groups "in the field" with little encumbrance of the subject. Microchip technology now permits the construction of small but powerful computer modules that can be carried on a subject's belt to collect and even process EMG data for later uploading and analysis by bigger computer systems. Such systems can be purchased for hundreds of dollars instead of the tens of thousands necessary for force platforms, isokinetic dynamometers, or automated imaging systems. Furthermore, the subject's are relatively free to perform their motor tasks unfettered by equipment.

The problem with EMG analysis is that the relationship between EMG levels and the forces produced by their associated muscles is not well defined and may never be due to the inherent environment from which the EMG arises. For instance, if one uses only indwelling electrodes then only a portion of the muscle's total activity is recorded. If this particular part is uncharacteristic of the whole then the predicted force will be misleading. If one employs surface electrodes, the global pickup will be affected by the activity of surrounding muscles or you may be unable to record the activity of the deeper muscles entirely. More importantly, EMG reflects only the state of the active component of the muscle. The passive, elastic, component will be totally ignored. Therefore, when muscles are performing eccentrically near their maximum length the EMG will underestimate the force being produced. Many other sources of error must also be accounted for before a valid picture of the contraction state of muscles can be derived from EMG recordings alone. These sources of error can only be accounted for by applying other forms of instrumentation, such as mentioned previously and following. Suffice to say that EMG recording alone is completely inadequate to quantify human performance but combined with other sources of data add a valuable dimension to the analyst's toolkit.

Mathematical models. It is difficult to consider mathematical models in isolation from the other approaches since these models must obtain their initial conditions and dynamic characteristics from data acquired by one or more of the other approaches. Some authors have built models and used data derived exclusively from published sources. In many cases data were derived from several unrelated publications making the models results somewhat questionable.

Several studies have tried to distribute the net moments of force produced at the joints amongst the various muscle protagonists by means of the reduction or optimization methods. The goal of the reduction method is to reduce an initially indeterminate problem to one that is determinate. The **reduction** method (e.g., Paul, 1965) requires the elimination of those quantities that render the system of equations indeterminate. This elimination process may of course be neglecting components that contribute significantly to the motion.

The **optimization** approach (e.g., Seireg and Arvikar, 1973,1975) was adopted by several researchers which distributed the joint moments amongst muscular protagonists. This approach used linear programming and required the optimization of an objective (or cost) function which is unknown *a priori*. The problem with the optimization approach is that the objective function is difficult to construct with enough imbedded physiological significance. Furthermore the solution is purely mathematical.

In view of these problems a more rigorous physiological hierarchical model was developed by Pierrynowski and Morrison (1985a,b). Though this model provided a physiological framework based on neurological, muscular and anatomical data to solve for individual forces in the human locomotor system it used data derived from published sources, rather than from the actual subject, and was not directly validated.

The main advantage of mathematical modelling is that there is relatively little added cost to working in three dimensions as opposed to two. There is no additional equipment cost and the added computer processing cost is no longer a factor. However, most models suffer from inadequate validity testing primarily because of the very reason why one elects to choose this method—to reduce cost. To properly validate these mathematical models you need to have criterion measurements of the system that you are modelling. In most cases, no such criteria are available.

Inverse dynamics. This approach has the advantage of being able to non-invasively analyze human motions. Subjects perform while an **imaging system** (film, video, or UV cameras) records their motion patterns. Often a force platform or transducer is needed to permit analysis of supported motions. The human body is then modelled as a system of interconnected rigid bodies. By knowing the external forces and estimating the inertial properties of each segment, Newton's Laws of Motion are applied to solve for the net forces and moments of force at each connection. Many laboratories have developed their own systems for executing the inverse dynamic equations in two dimensions. Unfortunately, there are very few researchers who have constructed the equations for three-dimensional analyses. Furthermore, it is difficult to obtain such systems commercially. It is possible to purchase computer programs for acquiring three-dimensional coordinates, in fact, automated imaging systems, such as, the WatSmart, Vicon, and Motion Analysis systems come already equipped with such capabilities. The more important step of computing the net forces and moments of force are left for the researcher to develop. Most biomechanics researchers do not have the mathematical sophistication necessary to produce such programs.

The main disadvantage of this approach is that it does not actually measure the forces produced by the real muscles and joint structures only the sum of all the forces and moments of force that act across a joint. You must then hypothesize as to which of the various physiological structures may have caused the computed net moments of force. There are also situations where the equations of motion are indeterminant. For example, when the limbs form a closed kinematic chain (golf swing, holding a load) or when there are more points of contact with the environment then there are force transducers (crutch walking, wrestling). As with many of the previous approaches few researchers have conducted studies to validate their results.

CONCLUSIONS

In the absence of a system for directly measuring the internal muscle forces and anatomical loadings what should we do to thoroughly investigate human movements. The answer is to apply two or more of the above mentioned approaches, simultaneously. For example, while you have your subject video taped running across the force platform have EMG electrodes attached to the major muscle groups. After you perform the inverse dynamics equations you can consult the EMG recordings to verify that the moments of force were reasonable and to identify which muscles were active to produce the resulting moments.

There are too few three-dimensional kinetic analyses of human performance. But until inexpensive systems with “user friendly” interfaces can be purchased, real progress into the complexities of human motion will be stalled. Researchers will spend too much of their valuable time on instrumentation and programming instead of on analysis and assessment. As more and more automated imaging systems become available we must develop software for providing kinetic as opposed to kinematic information about mechanics human motion. Otherwise, our analyses are little better than what a skilled coach or clinician can do with an experienced eye.

REFERENCES

Paul, J.P. (1965) Biomechanics and related bio-engineering topics. Oxford: Pergamon Press.

Pierrynowski, M.R. and Morrison, J.B. (1985a) A physiological model for the evaluation of muscular forces in human locomotion: theoretical aspects. Mathematical Biosciences, 75, 69-101.

Pierrynowski, M.R. and Morrison, J.B. (1985b) Estimating the muscle forces generated in the human lower extremity when walking: a physiological solution. Mathematical Biosciences, 75, 43-68.

Seireg, A. and Arvikar, R.J. (1973) A mathematical model for evaluation of forces in lower extremities of the musculo-skeletal system. Journal of Biomechanics, 6, 313-326.

Seireg, A. and Arvikar, R.J. (1975) The prediction of muscular load sharing and joint forces in the lower extremities during walking. Journal of Biomechanics, 8, 89-102.