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BIOMECHANICS AS AN INTERDISCIPLINE

1.0 INTRODUCTION

The biomechanics of human movement can be defined as the interdiscipline that describes, analyzes, and assesses human movement. A wide variety of physical movements are involved—everything from the gait of the physically handicapped to the lifting of a load by a factory worker to the performance of a superior athlete. The physical and biological principles that apply are the same in all cases. What changes from case to case are the specific movement tasks and the level of detail that is being asked about the performance of each movement.

The list of professionals and semiprofessionals interested in applied aspects of human movement is quite long: orthopedic surgeons, athletic coaches, rehabilitation engineers, therapists, kinesiologists, prosthetists, psychiatrists, orthotists, sports equipment designers, and so on. At the basic level, the name given to the science dedicated to the broad area of human movement is kinesiology. It is an emerging discipline blending aspects of psychology, motor learning, and exercise physiology as well as biomechanics. Biomechanics, as an outgrowth of both life and physical sciences, is built on the basic body of knowledge of physics, chemistry, mathematics, physiology, and anatomy. It is amazing to note that the first real “biomechanicians” date back to Leonardo da Vinci, Galileo, Lagrange, Bernoulli, Euler, and Young. All these scientists had primary interests in the application of mechanics to biological problems.

and diagnosing the causes. If measurements can be made during the patient's movement, then data can be presented in a convenient manner to describe the movement quantitatively. Here the assessor's task is considerably simplified. He or she can now quantify changes, carry out simple analyses, and try to reach a more objective diagnosis. At the highest level of assessment, the observer can view biomechanical analyses that are extremely powerful in diagnosing the exact cause of the problem, compare these analyses with the normal population, and monitor their detailed changes with time.

The measurement and analysis techniques used in an athletic event could be identical to the techniques used to evaluate an amputee's gait. However, the assessment of the optimization of the energetics of the athlete is quite different from the assessment of the stability of the amputee. Athletes are looking for very detailed but minor changes that will improve their performance by a few percentage points, sufficient to move them from fourth to first place. Their training and exercise programs and reassessment normally continue over an extended period of time. The amputee, on the other hand, is looking for major improvements, probably related to safe walking, but not fine and detailed differences. This person is quite happy to be able to walk at less than maximum capability, although techniques are available to permit training and have the prosthesis readjusted until the amputee reaches some perceived maximum. In ergonomic studies, assessors are likely looking for maximum stresses in specific tissues during a given task, to thereby ascertain whether the tissue is working within safe limits. If not, they will analyze possible changes in the workplace or task in order to reduce the stress or fatigue.

1.1.1 Measurement, Description, and Monitoring

It is difficult to separate the two functions of measurement and description. However, for clarity the student should be aware that a given measurement device can have its data presented in a number of different ways. Conversely, a given description could have come from several different measurement devices.

Earlier biomechanical studies had the sole purpose of describing a given movement, and any assessments that were made resulted from visual inspection of the data. The description of the data can take many forms: pen recorder curves, plots of body coordinates, stick diagrams, or simple outcome measures such as gait velocity, load lifted, or height of a jump. A movie camera, by itself, is a measurement device, and the resulting plots form the description of the event in time and space. Figure 1.2 illustrates a system incorporating a cine camera and two different descriptive plots. The coordinates of key anatomical landmarks can be extracted and plotted at regular intervals in time. Time history plots of one or more coordinates are useful in describing detailed changes in a particular landmark. They also can reveal to the trained eye changes in velocity and acceleration. A total description in the plane of the movement is provided by the stick diagram, in which each body segment

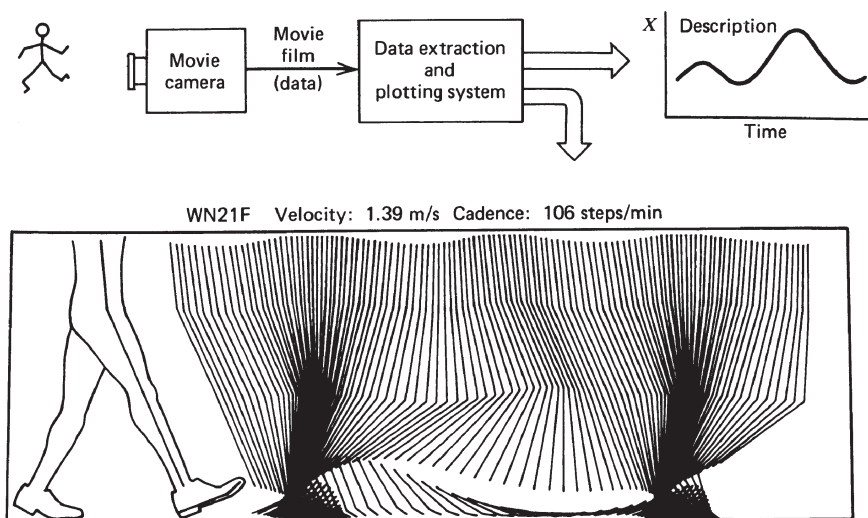


Figure 1.2 Flow of data from a camera system and plotting of data in two different forms, each yielding a different description of the same event.

is represented by a straight line or stick. Joining the sticks together gives the spatial orientation of all segments at any point in time. Repetition of this plot at equal intervals of time gives a pictorial and anatomical description of the dynamics of the movement. Here, trajectories, velocities, and accelerations can be visualized. To get some idea of the volume of the data present in a stick diagram, the student should note that one full page of coordinate data is required to make the complete plot for the description of the event. The coordinate data can be used directly for any desired analysis: reaction forces, muscle moments, energy changes, efficiency, and so on. Conversely, an assessment can occasionally be made directly from the description. A trained observer, for example, can scan a stick diagram and extract useful information that will give some directions for training or therapy, or give the researcher some insight into basic mechanisms of movement.

The term *monitor* needs to be introduced in conjunction with the term *describe*. To monitor means to note changes over time. Thus, a physical therapist will monitor the progress (or the lack of it) for each physically disabled person undergoing therapy. Only through accurate and reliable measurements will the therapist be able to monitor any improvement and thereby make inferences to the validity of the current therapy. What monitoring does not tell us is why an improvement is or is not taking place; it merely documents the change. All too many coaches or therapists document the changes with the inferred assumption that their intervention has been the cause. However, the scientific rationale behind such inferences is missing. Unless a detailed analysis is done, we cannot document the detailed motor-level changes that will reflect the results of therapy or training.

1.1.2 Analysis

The measurement system yields data that are suitable for analysis. This means that data have been calibrated and are as free as possible from noise and artifacts. *Analysis* can be defined as any mathematical operation that is performed on a set of data to present them in another form or to combine the data from several sources to produce a variable that is not directly measurable. From the analyzed data, information may be extracted to assist in the assessment stage. In some cases, the mathematical operation can be very simple, such as the processing of an electromyographic signal to yield an *envelope* signal (see Figure 1.3). The mathematical operation performed here can be described in two stages. The first is a full-wave *rectifier* (the electronic term for a circuit that gives the absolute value). The second stage is a low-pass

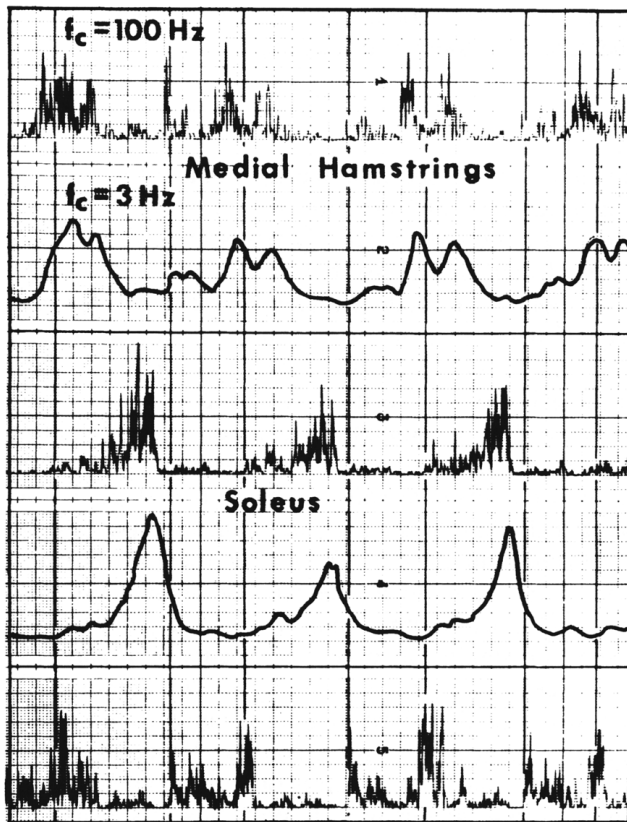


Figure 1.3 Processing of raw electromyogram (EMG) signals to present the variable in a different form. Traces 1 and 3 show the full-wave rectified EMG of the medial hamstrings and soleus muscles during walking. A cutoff frequency ($f_c = 100$ Hz) is indicated for the rectified signal because this is the bandwidth of the pen recorder. In traces 2 and 4, the linear envelope signal (low-pass filter with $f_c = 3$ Hz) is presented.

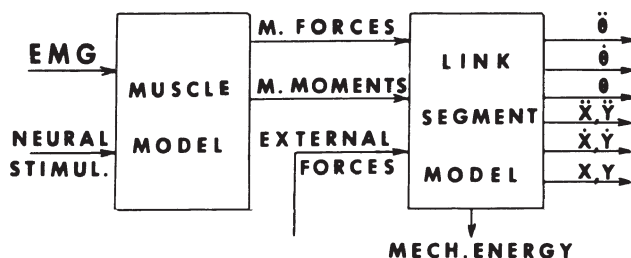


Figure 1.4 Schematic diagram to show the relationship between the neural, kinetic, and kinematic variables required to describe and analyze human movement.

filter (which mathematically has the same transfer function as that between a neural pulse and its resultant muscle twitch). A more complex biomechanical analysis could involve a link-segment model, and with appropriate kinematic, anthropometric, and kinetic output data, we can carry out analyses that could yield a multitude of significant time-course curves. Figure 1.4 depicts the relationships between some of these variables. The output of the movement is what we see. It can be described by a large number of kinematic variables: displacements, joint angles, velocities, and accelerations. If we have an accurate model of the human body in terms of anthropometric variables, we can develop a reliable link-segment model. With this model and accurate kinematic data, we can predict the net forces and muscle moments that caused the movement we just observed. Such an analysis technique is called an *inverse solution*. It is extremely valuable, as it allows us to estimate variables such as joint reaction forces and moments of force. Such variables are not measurable directly. In a similar manner, individual muscle forces might be predicted through the development of a mathematical model of a muscle, which could have neural drive, length, velocity, and cross-sectional area as inputs.

1.1.3 Assessment and Interpretation

The entire purpose of any assessment is to make a positive decision about a physical movement. An athletic coach might ask, "Is the mechanical energy of the movement better or worse than before the new training program was instigated, and why?" Or the orthopedic surgeon may wish to see the improvement in the knee muscle moments of a patient a month after surgery. Or a basic researcher may wish to interpret the motor changes resulting from certain perturbations and thereby verify or negate different theories of neural control. In all cases, if the questions asked yield no answers, it can be said that there was no information present in the analysis. The decision may be positive in that it may confirm that the coaching, surgery, or therapy has been correct and should continue exactly as before. Or, if this is an initial assessment, the decision may be to proceed with a definite plan based on

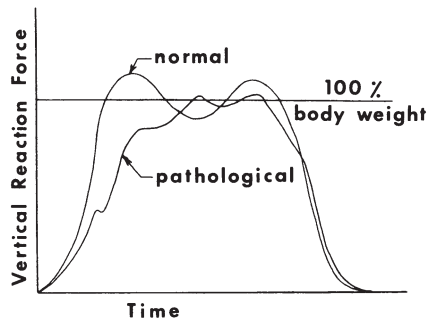


Figure 1.5 Example of a ground reaction force curve that has sometimes been used in the diagnostic assessment of pathological gait.

new information from the analysis. The information can also cause a negative decision, for example, to cancel a planned surgical procedure and to prescribe therapy instead.

Some biomechanical assessments involve a look at the description itself rather than some analyzed version of it. Commonly, ground reaction force curves from a force plate are examined. This electromechanical device gives an electrical signal that is proportional to the weight (force) of the body acting downward on it. Such patterns appear in Figure 1.5. A trained observer can detect pattern changes as a result of pathological gait and may come to some conclusions as to whether the patient is improving, but he or she will not be able to assess why. At best, this approach is speculative and yields little information regarding the underlying cause of the observed patterns.

1.2 BIOMECHANICS AND ITS RELATIONSHIP WITH PHYSIOLOGY AND ANATOMY

Because biomechanics is a recent entry on the research scene, it is important to identify its interaction with other areas of movement science: neurophysiology, exercise physiology, and anatomy. The neuromuscular system acts to control the release of metabolic energy for the purpose of generating controlled patterns of tension at the tendon. That tension waveform is a function of the physiological characteristics of the muscle (i.e., fiber type) and of its metabolic state (rested vs. fatigued). The tendon tension is generated in the presence of passive anatomical structures (ligaments, articulating surfaces, and skeletal structures). Figure 1.6 depicts the relationship between the sensory system, the neurological pathways, the muscles, the skeletal system, and the link-segment model that we analyze. The essential characteristic of this total system is that it is converging in nature. The structure of the neural system has many excitatory and inhibitory synaptic junctions, all summing their control on a final synaptic junction in the spinal cord to control individual motor units. The α motoneuron ①, which is often described as the

Neuro-musculo-skeletal integration

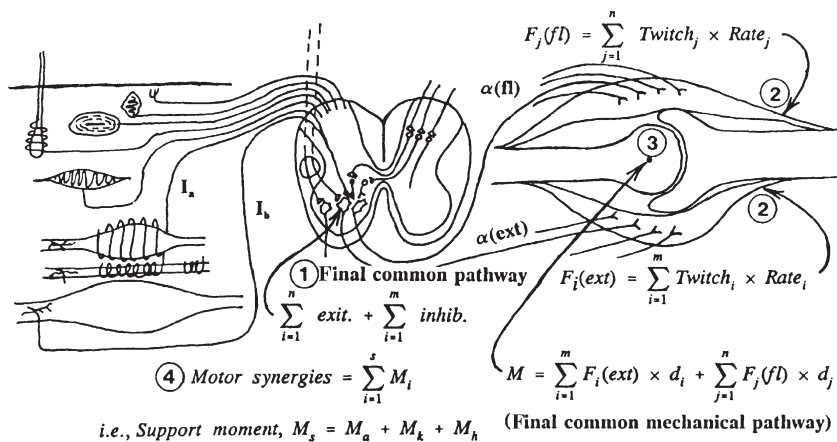


Figure 1.6 Four levels of integration in the neuromusculoskeletal system provide control of human movement. The first is the neural summation of all excitatory/inhibitory inputs to the α motoneuron ①. The second is the summation of all motor twitches from the recruitment of all active motor units within the muscle and is seen as a tendon force ②. The third is the algebraic summation of all agonist and antagonist muscle moments at the joint axis ③. Finally, integrations are evident in combined moments acting synergistically toward a common goal ④.

final common pathway, has its synapse on the motor end point of the muscle motor unit. A second level of convergence is the summation of all twitches from all active motor units at the level of the tendon ②. This summation results from the neural recruitment of motor units based on the size principle (cf. DeLuca et al., 1982; Henneman and Olson, 1965). The resultant tension is a temporal superposition of twitches of all active motor units, modulated by the length and velocity characteristics of the muscle. A third level of musculoskeletal integration at each joint center where the moment-of-force ③ is the algebraic summation of the force/moment products of all muscles crossing that joint plus the moments generated by the passive anatomical structures at the joint. The moments we routinely calculate include the net summation of all agonist and antagonist muscles crossing that joint, whether they are single- or double-joint muscles. In spite of the fact that this moment signal has mechanical units ($N \cdot m$), we must consider the moment signal as a neurological signal because it represents the final desired central nervous system (CNS) control. Finally, an intersegment integration may be present when the moments at two or more joints collaborate toward a common goal. This collaboration is called a synergy. One such synergy ④, referred to as the support moment, quantifies the integrated activity of all muscles of the lower limb in their defense against a gravity-induced collapse during walking (Winter, 1980, 1984).

Bernstein (1967) predicted that the CNS exerts control at the level of the joints or at the synergy level when he postulated the “principle of equal simplicity” because “it would be incredibly complex to control each and every muscle.” One of the by-products of these many levels of integration and convergence is that there is considerably more variability at the neural (EMG) level than at the motor level and more variability at the motor level than at the kinematic level. The resultant variability can frustrate researchers at the neural (EMG) level, but the positive aspect of this redundancy is that the neuromuscular system is, therefore, very adaptable (Winter, 1984). This adaptability is very meaningful in pathological gait as a compensation for motor or skeletal deficits. For example, a major adaptation took place in a patient who underwent a knee replacement because of osteoarthritic degeneration (Winter, 1989). For years prior to the surgery, this patient had refrained from using her quadriceps to support her during walking; the resultant increase in bone-on-bone forces induced pain in her arthritic knee joint. She compensated by using her hip extensors instead of her knee extensors and maintained a near-normal walking pattern; these altered patterns were retained by her CNS long after the painful arthritic knee was replaced. Therefore, this moment-of-force must be considered the final desired pattern of CNS control, or in the case of pathological movement, it must be interpreted either as a disturbed pattern or as a CNS adaptation to the disturbed patterns. This adaptability is discussed further in Chapter 5, on kinetics.

1.3 SCOPE OF THE TEXTBOOK

The best way to outline the scope of any scientific text is to describe the topics covered. In this text, the biomechanics of human movement has been defined as the mechanics and biophysics of the musculoskeletal system as it pertains to the performance of any movement skill. The neural system is also involved, but it is limited to electromyography and its relationship to the mechanics of the muscle. The variables that are used in the description and analysis of any movement can be categorized as follows: kinematics, kinetics, anthropometry, muscle mechanics, and electromyography. A summary of these variables and how they interrelate now follows.

1.3.1 Signal Processing

A major addition to this fourth edition is a chapter on signal processing. Some aspects of signal processing were contained in previous additions; it was decided that all aspects should be combined in one chapter and be given a more rigorous presentation. Why signal processing? Virtually all the variables we measure or analyze come to us in the time domain: EMG, forces, displacements, accelerations, energies, powers, moments, and so on. Thus, they are signals and must be treated like any other signal. We can analyze

their frequency content, digitize them, analog or digitally filter them, and correlate or average their waveforms. Based on their signal characteristics, we can make decisions as to sampling rate, minimum length of data files, and filter cutoff frequencies. Also, there are correlation and covariance techniques that allow us to explore more complex total limb and total body motor patterns.

1.3.2 Kinematics

Kinematic variables are involved in the description of the movement, independent of forces that cause that movement. They include linear and angular displacements, velocities, and accelerations. The displacement data are taken from any anatomical landmark: center of gravity of body segments, centers of rotation of joints, extremes of limb segments, or key anatomical prominences. The spatial reference system can be either relative or absolute. The former requires that all coordinates be reported relative to an anatomical coordinate system that changes from segment to segment. An absolute system means that the coordinates are referred to an external spatial reference system. The same applies to angular data. Relative angles mean joint angles; absolute angles are referred to the external spatial reference. For example, in a two-dimensional (2D) system, horizontal to the right is 0° , and counterclockwise is a positive angular displacement.

The basic kinematic concepts are taught on a 2D basis in one plane. All kinematic displacement and rotational variables are vectors. However, in any given direction or rotation, they are considered scalar signals and can be processed and analyzed as such. In three-dimensional (3D) analysis, we add an additional vector direction, but we now have three planes to analyze. Each segment in 3D analyses has its own axis system; thus, the 3D orientation of the planes for one segment is not necessarily the same as those for the adjacent segments.

1.3.3 Kinetics

The general term given to the forces that cause the movement is *kinetics*. Both internal and external forces are included. Internal forces come from muscle activity, ligaments, or the friction in the muscles and joints. External forces come from the ground or from external loads, from active bodies (e.g., those forces exerted by a tackler in football), or from passive sources (e.g., wind resistance). A wide variety of kinetic analyses can be done. The moments of force produced by muscles crossing a joint, the mechanical power flowing to or from those same muscles, and the energy changes of the body that result from this power flow are all considered part of kinetics. It is here that a major focus of the book is made, because it is in the kinetics that we can really get at the cause of the movement and, therefore, get some insight into the

mechanisms involved and into movement strategies and compensations of the neural system. A large part of the future of biomechanics lies in kinetic analyses, because the information present permits us to make very definitive assessments and interpretations.

As with the kinematics, all basic kinetic concepts will be covered in detail in 2D analyses. Three-dimensional analysis adds an additional force vector in the global reference system (GRS), but, because of the two additional planes, there are two additional moment vectors. The 3D analysis techniques are considerably more complex; however, within any of these three planes, the interpretation is the same as in 2D analyses.

1.3.4 Anthropometry

Many of the earlier anatomical studies involving body and limb measurements were not considered to be of interest of biomechanics. However, it is impossible to evolve a biomechanical model without data regarding masses of limb segments, location of mass centers, segment lengths, centers of rotation, angles of pull of muscles, mass and cross-sectional area of muscles, moments of inertia, and so on. The accuracy of any analysis depends as much on the quality and completeness of the anthropometric measures as on the kinematics and kinetics.

1.3.5 Muscle and Joint Biomechanics

One body of knowledge that is not included in any of the preceding categories is the mechanical characteristics of the muscle itself. How does its tension vary with length and with velocity? What are the passive characteristics of the muscle—mass, elasticity, and viscosity? What are the various characteristics of the joints? What are the advantages of double-joint muscles? What are the differences in muscle activity during lengthening versus shortening? How does the neural recruitment affect the muscle tension? What kind of mathematical models best fit a muscle? How can we calculate the center of rotation of a joint? The final assessment of the many movements cannot ignore the influence of active and passive characteristics of the muscle, nor can it disregard the passive role of the articulating surfaces in stabilizing joints and limiting ranges of movement.

1.3.6 Electromyography

The neural control of movement cannot be separated from the movement itself, and in the electromyogram (EMG) we have information regarding the final control signal of each muscle. The EMG is the primary signal to describe the input to the muscular system. It gives information regarding which muscle or muscles are responsible for a muscle moment or whether antagonistic

activity is taking place. Because of the relationship between a muscle's EMG and its tension, a number of biomechanical models have evolved. The EMG also has information regarding the recruitment of different types of muscle fibers and the fatigue state of the muscle.

1.3.7 Synthesis of Human Movement

Most biomechanical modeling involves the use of inverse solutions to predict variables such as reaction forces, moments of force, mechanical energy, and power, none of which is directly measurable in humans. The reverse of this analysis is called *synthesis*, which assumes a similar biomechanical model, and using assumed moments of force (or muscle forces) as forcing functions, the kinematics are predicted. The ultimate goal, once a valid model has been developed, is to ask the question, "What would happen if?" Only through such modeling are we able to make predictions that are impossible to create in vivo in a human experiment. The influence of abnormal motor patterns can be predicted, and the door is now open to determine optimal motor patterns. Although synthesis has a great potential payoff, the usefulness of such models to date has been very poor and has been limited to very simple movements. The major problem is that the models that have been proposed are not very valid; they lack the correct anthropometrics and degrees of freedom to make their predictions very useful. However, because of its potential payoff, it is important that students have an introduction to the process, in the hope that useful models will evolve as a result of what we learn from our minor successes and major mistakes.

1.3.8 Biomechanical Motor Synergies

With the increased technology, biomechanics has made great strides in analyzing more complex total body movements and, because of the considerable interactions between adjacent muscle groups, it is becoming necessary to identify motor synergies. In a new chapter, we use several techniques to identify two or more muscle groups acting synergistically toward a common goal.

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