Simulations Using a Whole-body Biomechanical Model

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Abstract

Further developments on a dynamic biomechanical model are presented to assess musculoskeletal stresses and human responses. The model being developed is an extension of the Articulated Total Body (ATB) Model, originally developed by Calspan Corp. for the study of human dynamics during automobile crashes, later adopted to the U.S. Air Force to simulate the reactions of aircrew personnel to such forces typically encountered in various phases of flight operations. Further refinements were introduced by Freivalds and Kaleps (1984) to account for a human neuromusculature.

In this study, modelling of active neuromusculature was described and simulations of whole-body human motion were performed using the ATB Model. It indicated the potential of using a muscularized biomechanical model coupled with CAD capabilities to simulate human responses in a variety of industrial settings as well. This will serve as a basis of incorporating computer aided design methods into a muscularized biomechanical models.

Introduction

Since the interactions among the person, the equipment, the task, and the environment are complex and the efficient and safe operation of civilian and military systems requires that such systems be compatible with the user's capabilities, many researchers and engineers are concerned with the need for ergonomic models that describe the physical characteristics of people and their interactions. Such models should be representations of real systems designed to describe and predict their essential characteristics and performance.

There have been in the past numerous efforts to develop descriptive physical models of the human body. In the prospectus for the workshop held by the Committee on Human Factors of the National Research Council, three major classes of models were described: *anthropometric,* representations of static body geometry such as body dimensions, reach, position of the body, posture; *biomechanical,* representations of physical activities of the body in motion, using anthropometric data as inputs; and *interface,* specific combinations of anthropometric and biomechanical models for representations of human-machine interactions (NRC, 1988).

In most instances, the development of such models has not extended beyond the requirements to meet the specific application needs of the moment. Such specialized models may serve their specific purposes well but give little help in solving general human interaction problems outside their specific boundaries. For example, most biomechanical models used to estimate one's physical stresses are being used as stand-alone and lack the ability to predict his interactions with the environment, while interface models or biodynamic models fail to account for muscular activities such as loadings on muscles and bones and their responses (Jung, 1988). A more versatile model is thus needed to simulate human responses and capabilities in real situations. In this paper, the use of biodynamic computer-based models for the prediction of human body response to external stresses is discussed.

The development of biodynamic models has been very successful during the last two decades. The rapid growth in computer technology enabled us to solve analytical equations describing the complex and detailed mechanical structure of the human body. This is particulary true of the whole-body simulation models based on rigid body dynamics. Current models usually use Euler or Lagrange technique to formulate equations describing chains of coupled rigid bodies. The articulated, three-dimensional models of human body structure have been developed by numerous investigators. Among these are models by Fleck et al. (1974), Butler and

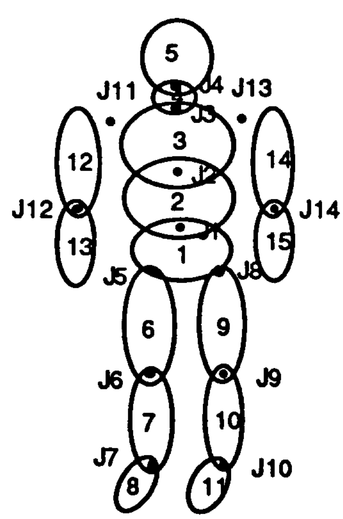
Fleck (1980), Freivalds and Kaleps (1984). These models are all based on rigid-body dynamics with Euler equation of motion and Lagrange type constraints. This type of models can be a useful tool for evaluating biomechanical stresses involved in a variety of jobs.

Basic Modelling

The model being developed is a modification of the Articulated Total Body (ATB) Model, originally developed by Calspan Corp. to simulate the automobile crash victim for the U.S. Department of Transportation. Later, the U.S. Air Force modified the model to simulate the forces and motions experienced by a human body in high-acceleration events such as ejection from aircraft. This model can also be adapted to less abrupt stresses as experienced by typical industrial workers.

The specific model configuration applied in this study used 15 body segments, consisting of the head, neck, upper torso, center torso, lower torso, upper arms, lower arms, upper legs, lower legs and feet. A schematic showing the segments and the numbering scheme for both segments and interconnecting joints is shown in Figure 1. The model possesses 14 joints and a total of 48 degrees of freedom.

Figure 2 shows the segment structure and linkage employed in the model. The center of mass of segment N is at R_N, defined with respect to an external inertial system. Principal axes of segment N are defined with respect to the inertial axes



Joint J connects Segment N(J) with Segment J+1

J = 1 2 3 4 5 6 7 8 9 10 11 12 13 14

N(J) = 1 2 3 4 1 6 7 1 9 10 3 12 3 14

Figure 1. Model Segment and Joint Scheme

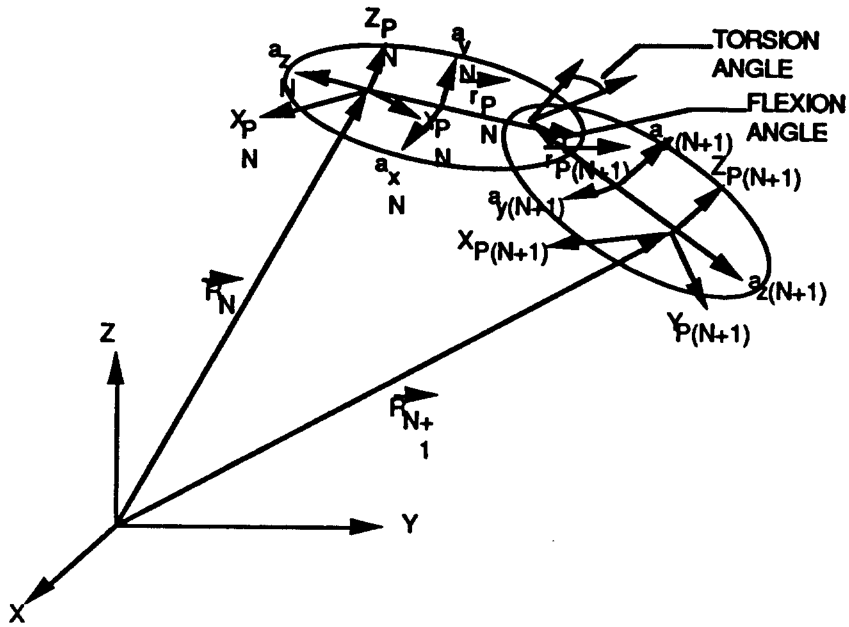


Figure 2. Basic Body Segment Property and Coupling Description

and used thereafter to reference all segment geometric properties. A geometric center of the segment is defined and ellipsoidal radii are specified to define a contact ellipsoidal surface for the segment. A coordinate system with a specified orientation is assigned to each joint within the segment, thus linking the adjacent segment N+1, with center of mass located at R_{N+1}.

To simulate a specific dynamic event, considerable body descriptive data should be supplied for model input. These data include principal moments of inertia, mass, contact surface ellipsoidal center and radii and joint locations for each segment, as well as segment interaction characteristics for segment-to-segment or configurational surface contacts. Properties of joints must be specified by identifying the type of joints and the torque properties across the joint as a function of relative adjacent segment rotational orientation. In addition, the external dynamic environment to which the body is to be exposed is defined.

Modelling of Active Neuromusculature

The ATB Model, although realistically reflecting human body structure, mass distribution, and tissue characteristics, presently has the serious limitation of only simulating events with passive internal responses. It means that the whole-body motion would be similar to that of an anthropometric dummy. Therefore, the modelling of active neuromusculature must be included to represent real motion and responses.

Both active and passive muscle models have been developed by a number of researchers in the area of biomechanics and muscle physiology (Hill et al., 1975; Fung, 1981; Hatze, 1981; McMahon, 1984). Hatze (1981) developed a simple lumped muscle model (refer to Figure 3). The tension observed when passively stretching the resting muscle is due to elastic structures which lie in parallel to the contractile proteins: the sheath of the individual fiber and all outer connective tissue sheaths. This set of parallel elastic elements consists of some which are to be considered in parallel with each sarcomere of each fiber (PS) and others which are only in parallel with the whole muscle (PE). Because these tissues move in fluid, appropriate damping elements (DE) also need to be included when stimulation takes place. The proteins of the contractile element (CE) produce active tension which, via elastic components such as tendons, is transferred to the end points of the muscle (SE). Also, the cross-bridge in a sarcomere possesses elastic property (BE). From the assumption that all the sarcomeres in a fiber and motor unit have similar morphological and histochemical profiles, a simpler lumped model to represent the whole muscle can be made as depicted in Figure 3.

Freivalds and Kaleps (1984) further simplified this lumped model. Since BE is a very stiff spring and SE is also rationalized to be a stiff spring as compared to PE, both could be eliminated so that four elements in parallel are left. Combining two parallel elastic components finally yields the simplified muscle model in Figure 4, and a muscle force expressed as

$$F = (f_{PE} + f_{CE} + f_{DE}) / F_{max}$$

where F_{max} is the maximum isometric tension of the muscle.

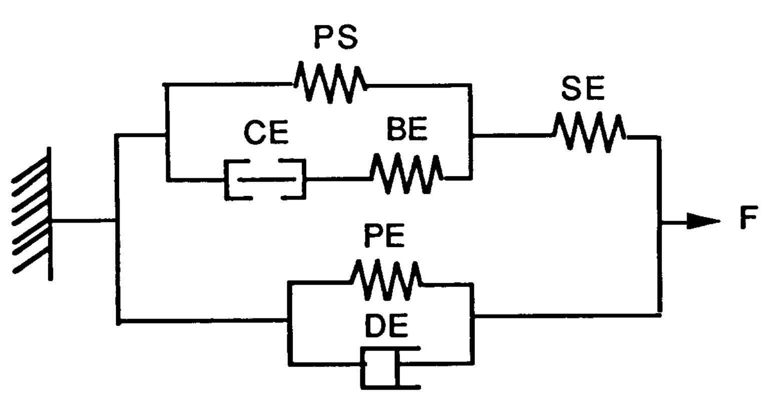


Figure 3. The Lumped Muscle Model by Hatze

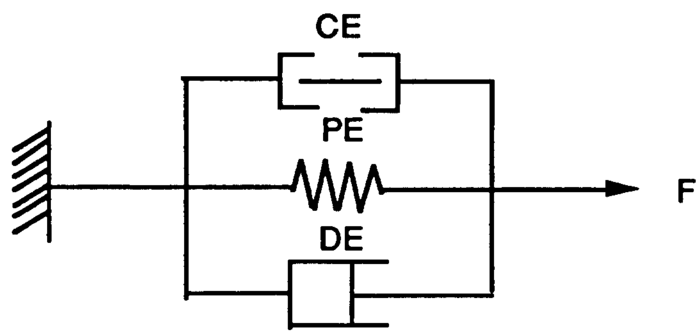


Figure 4. The Simplified Muscle Model

Mathematical representations for each element were derived from various experimental findings. For the parallel elastic element, Yamada (1970) conducted extensive tests on human satorius muscle and indicated an exponential stress-strain relationship:

$$f_{PE} = 0.0016296 \cdot \exp(7.6616\,\varepsilon - 1)$$

where f_{PE} is the force normalized with respect to the maximum isometric tension and ε is the strain:

$$\varepsilon = (L - L_o) / L_o$$

where L is the instantaneous muscle length and L_o is the resting length.

The damping element of the muscle can be expressed as a mechanical dashpot:

$$f_{DE} = 0.139\ \dot{\varepsilon}$$

where f_{DE} is the normalized force and $\dot{\varepsilon}$ is the muscle strain rate.

The contractile element is the only active component in the model. Its behavior is extremely complex and basically depends on three functions: the length-tension relationship (f_l), the force-velocity relationship (f_v), and the active state function (f_q).

$$f_{CE} = f_l \cdot f_v \cdot f_q$$

The length-tension relationship representing the degree of filamentary overlap can be expressed by the function by Gordon et al. (1986) and Hatze (1981) as

$$f_l(\varepsilon) = 0.32 + \exp(-1.112\,\varepsilon)\sin(3.722\,\varepsilon + 1.28)$$

The force-velocity relationship is also similarly determined:

$$f_v(\dot{\eta}) = 0.1433 \cdot [0.1073 + \exp\{-1.409\ \sinh(3.722\,\dot{\eta} + 1.6)\}]^{-1}$$

where $\dot{\eta}$ represents the normalized contractile element velocity

$$\dot{\eta} = \dot{\varepsilon} / \dot{\varepsilon}_{max}$$

with $\dot{\varepsilon}_{max}$ being the maximum shortening velocity of the contractile element.

The active state function f_q is defined by the relative amount of Ca^{++} bound to troponin. If the maximum number of potential interactive sites on the thin filament are exposed by the action of Ca^{++}, then $q(t) = 1$; while in a resting state $q(t) = 0.005$. The isometric tension developed by a muscle fiber can be expressed as

$$q(t) = \frac{0.005 + 82.63\, v^2 [1 - \exp(-mt)]^2}{1 + 82.63\, v^2 [1 - \exp(-mt)]^2}$$

where m is a constant dependent on the type of motor units (i.e., Type I or Type II motor unit) and v is the relative stimulation rate defined by

$$0 \leq v = \bar{\tau} / \tau \leq 1$$

where $\bar{\tau}$ is the maximum stimulation rate and τ is the instantaneous stimulation rate.

A graphical depiction of each relationship is shown in Figures 5-9, respectively. Also, the specific muscle characteristics such as orderly recruitment of motor units and muscle fatigue represented by the endurance time were included in the model.

Simulations of Whole-body Human Motion

As an example of a whole-body human motion, lifting a load was selected since lifting a load from the ground using a squat posture involves a very large set of muscles and thus provides a good perspective of the model. In addition to the typical leg and arm muscles, back muscles for the stabilization of the vertebral column and shoulder muscles for raising the arms are included.

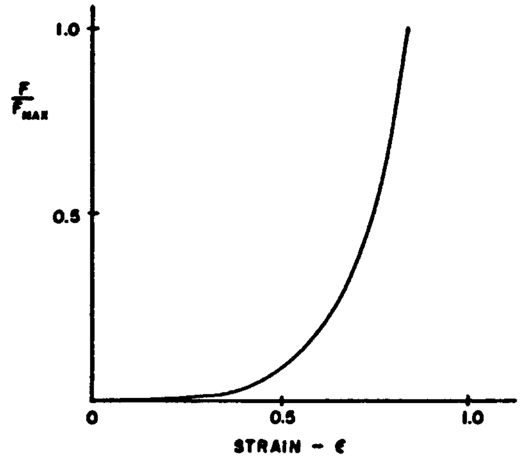


Figure 5. Passive Muscle Force - Strain Function

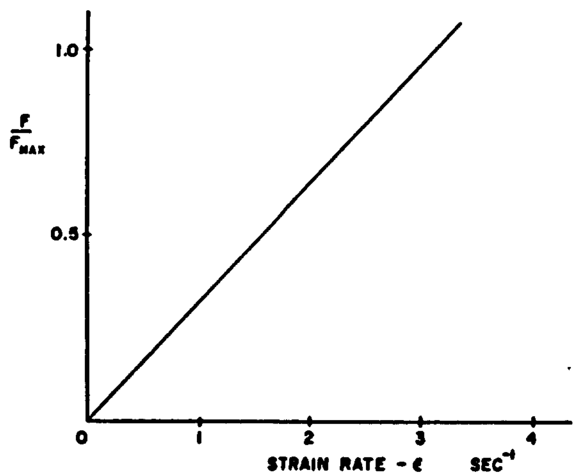


Figure 6. Passive Muscle Viscous Damping Forces

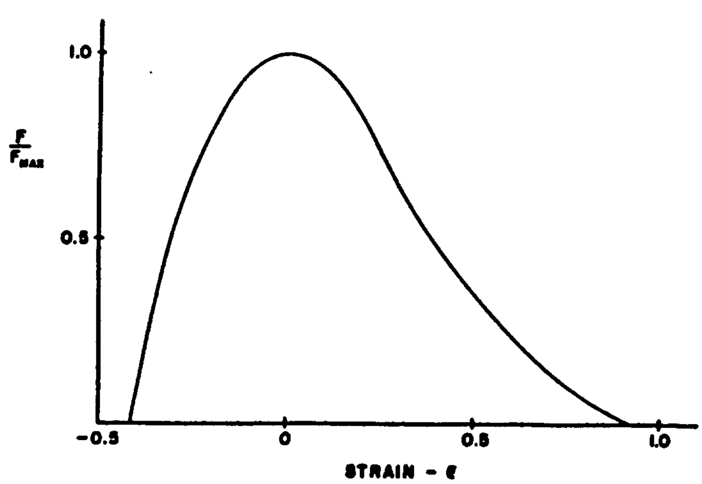


Figure 7. Muscle Length - Tension Relationship

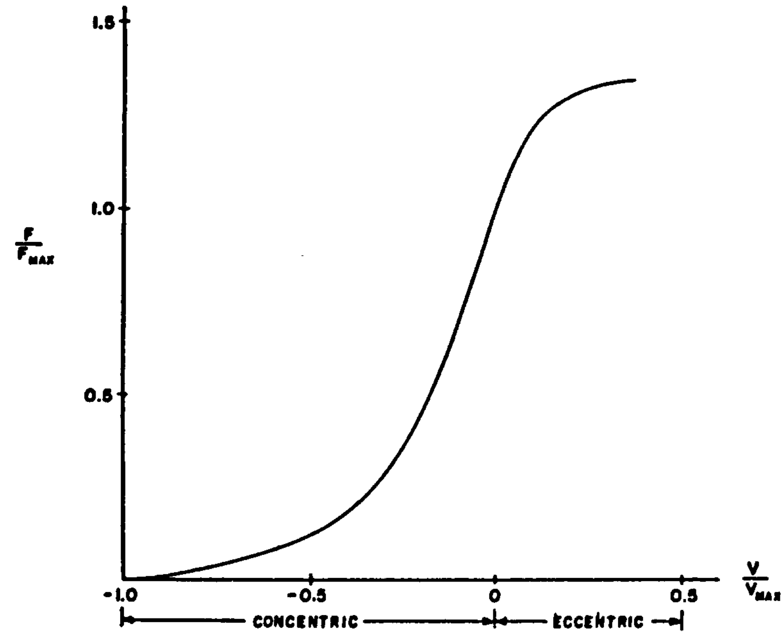


Figure 8. Muscle Force - Velocity Relationship

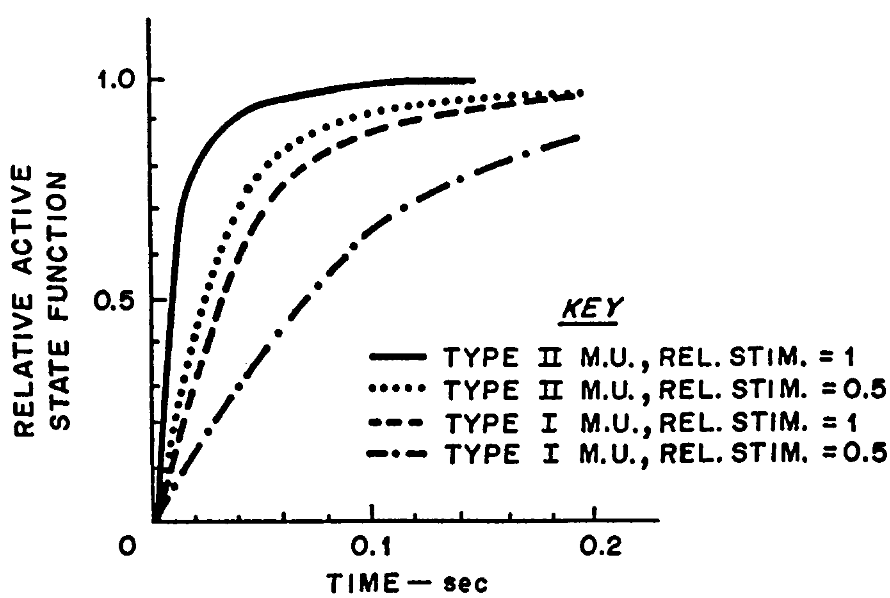


Figure 9. Relative Force Developed by Active State Function

A total of 32 muscles (16 on each side of the body) was utilized. These are as follows: leg - gastrocnemius, soleus, quadriceps; shoulder - latissimus dorsi; hip - glutens medius, glutens minimus, glutens maximus; back and trunk - iliocostalis lumborum, iliocostalis dorsi, longissimus dorsi, spinalis dorsi and multifidus.

An 11 lb. load was placed in each hand simulating a weightlifting motion. At time zero, all the muscles were activated. Figure 10 shows the results of 0 msec and 125 msec graphically. Here, the legs were properly extended, the back extended and arms lifted as expected.

Conclusion

The whole-body human motion involves a large set of muscles, each being activated differently and interacting to different joints and bones. It seems almost impossible to consider all the muscles involved in the dynamics of human motion. However, simulations performed using the ATB Model revealed fairly good representations of human body dynamics. This indicates the potential of a muscularized three-dimensional biomechanical model to simulate physical stresses and human responses in a variety of conditions met in industrial and military settings.

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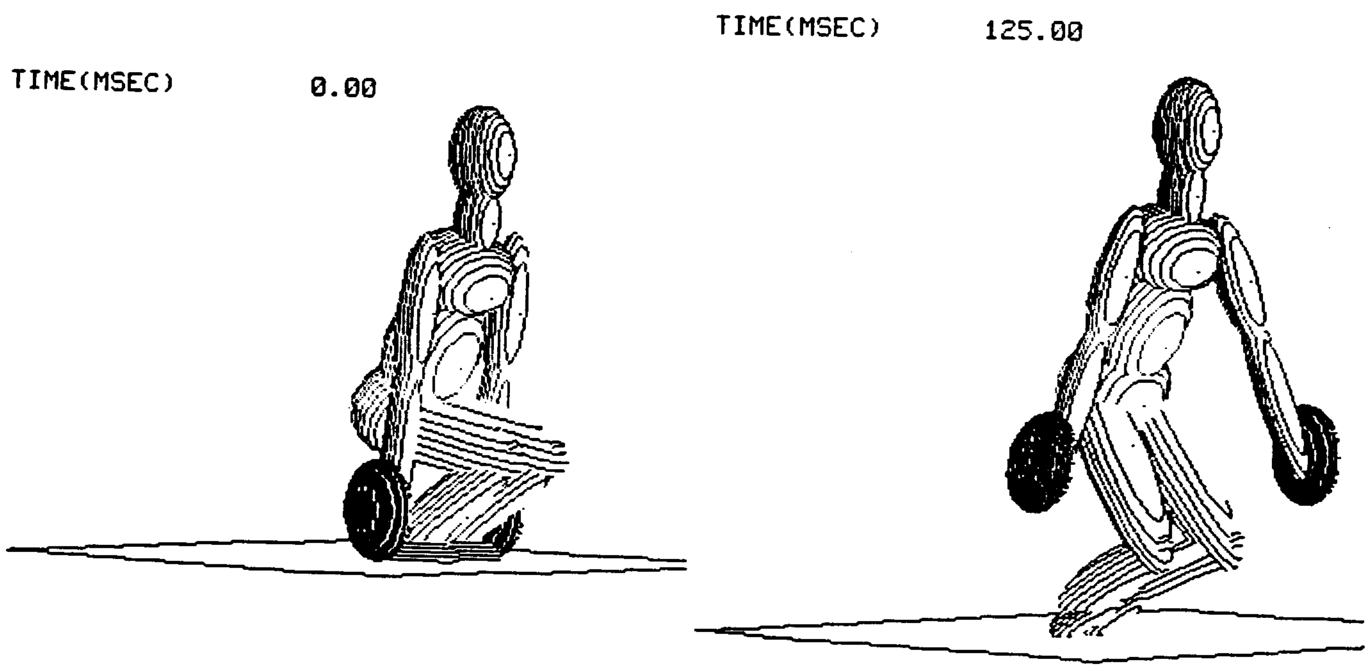

Figure 10. Simulation of Squat Lifting