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The Use Of Biomechanics in the Study of Movement in Microgravity

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Introduction

As biomechanists interested in the adaptability of the human body to microgravity conditions, it appears that our job is not only to make sure that the astronauts can function adequately in space but also that they can function upon their return to Earth. This is especially significant since many of the projects now being designed at NASA concern themselves with humans performing for up to 3 years in microgravity. While the Extended Duration Orbiter flights may last 30 to 60 days, future flights to Mars using current propulsion technology may last from 2 to 3 years. It is for this range of time that the adaptation process must be studied.

Specifically, biomechanists interested in space travel realize that human performance capabilities will change as a result of exposure to microgravity. The role of the biomechanist then is to first understand the nature of the changes realized by the body. These changes include adaptation by the musculoskeletal system, the nervous system, cardiorespiratory system, and the cardiovascular system. As biomechanists, it is also our role to take part in the development of countermeasure programs that involve some form of regular exercise. Exercise countermeasure programs should include a variety of modalities with full knowledge of the loads imposed on the body by these modalities. Any exercise programs that are to be conducted by the astronauts during space travel must consider the fact that the musculoskeletal and neuromuscular systems degrade as a function of flight duration. Additionally, we must understand that the central nervous system modifies its output in the control of the human body during space flight and most importantly, we must prepare the astronauts for their return to one g.

The science of biomechanics is interrelated with many other scientific disciplines that must integrate their objectives to develop exercise programs to counter the effects of microgravity (Figure 1).

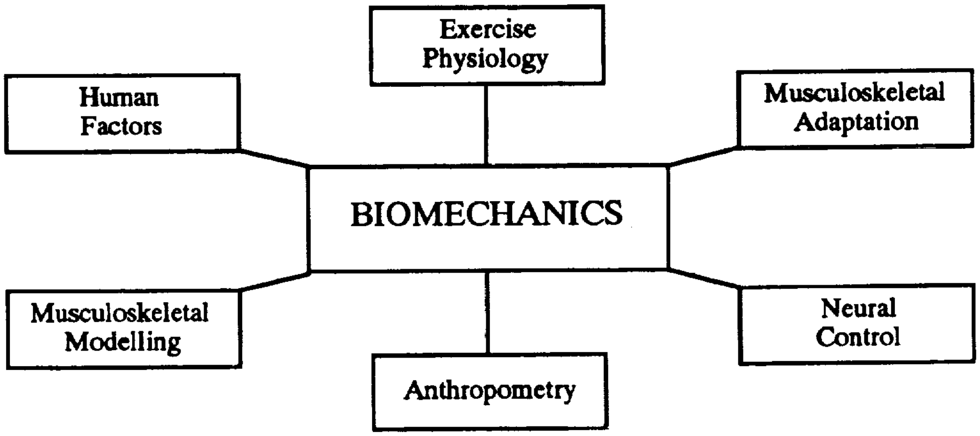

Figure 1. *Interaction between biomechanics and other scientific disciplines in the study of movement in microgravity.*

anthropometry, human factors engineering, and musculoskeletal modeling. Interrelationships with musculoskeletal adaptation include the understanding that the musculoskeletal system degrades as a function of space-flight duration. The adaptation of bone to space flight, as documented by Zernicke *et al.* [9], includes skeletal degeneration and the observation of a negative calcium balance. Weight-bearing bones appear to be more sensitive to the effects of microgravity with mechanical strength and stiffness reported to be markedly reduced as a result of exposure to microgravity. In addition, there are certain geometric alterations in bone that are related to their mechanical properties and there is an ongoing debate regarding in-flight vs. ground-based models in the study of bone loss.

Regarding the adaptation of skeletal muscle to microgravity, we must first review the various factors that affect the muscle's ability to produce force. These factors include: (1) velocity of contraction, (2) the type of contraction, (3) muscle length, (4) muscle architecture, (5) muscle fiber type, and (6) the activation history of the muscle. As a result of several research projects, it appears that antigravity extensors are most affected by exposure to microgravity [3]. Force production in lower extremity extensors such as the vasti muscles, tricep surae muscles, and gluteus maximus are markedly lower. It appears that lower extremity flexors, such as the hamstrings and tibialis anterior, and upper extremity flexors and extensors are less affected. Ground-based hindlimb suspension models and evidence from research on animals during space flight indicate that slow muscle atrophies more than fast muscle, and that slow motor units may increase their speed of shortening [3]. These latter two observations are consistent with general observations made using disuse models in which slow fibers appear to be more affected than fast, and that slow fibers increase their contraction velocity. In summary, the musculoskeletal system appears to be markedly affected as a result of exposure to microgravity.

With the interface of biomechanics and neural control, our attention focuses on sensorimotor integration. In review, we know there are certain muscle fiber types that are recruited in certain ways as a function of the Size Principle [6] and that any electrical signal seen from the muscle (i.e., the electromyogram) typically precedes the initiation of force production in that same muscle [7]. Consequently, there is an orderly process to the recruitment of certain muscle types and there is a delay between the excitation of that muscle and the actual mechanical output observed as muscle force. These output parameters appear tightly coupled to sensory input and the various feedback systems employed for motor control. Regarding motor control, the losses observed to date have been in motor coordination, sensorimotor integration, and losses in the vestibulo-ocular system. These result in disorientation in the astronauts, loss of balance and stability, and impairment of sensory motor integration that may subsequently affect their ability to control the vehicle (i.e., Space Shuttle). Theories on central motor programs apply to this particular area, and use of biofeedback in understanding the impairment experienced by the astronauts and, subsequently, in training them to overcome these impairments, involves the coordination and integration of biomechanical principles and neural control.

The integration of biomechanics and anthropometry focuses in the field of human factors engineering. If, indeed, skeletal muscle and bone mass losses do approach 10 to 20 percent, one must consider the effect of these tissue losses on actual body segment parameters (i.e., mass and moments of inertia of the body segments involved). Any changes in these body segment parameters have an ultimate consequence on musculoskeletal modeling in which the mass and mass moment parameters are required for input to equations of motion. There has been a great deal of work done on work-space design in the Space Shuttle environment as well as in space suit design (i.e., reach envelops) the mechanical interface of the human with the vehicle, and tools designed to enhance work output. Biomechanics play a significant role here since one must first understand the requirements imposed on the astronauts and the need to develop specific technology so that the astronauts can carry out the various jobs required of them in microgravity.

The final link with biomechanics involves the field of musculoskeletal modeling. Musculoskeletal modeling includes: (1) principles in inverse dynamics, (2) the use of optimization algorithms, and (3) the use of forward solutions methods in which force may be directly predicted from electromyography (EMG). These various types of modeling procedures are used in movement analysis in one g and can, of course, be applied in movement in microgravity if proper mechanical conditions are taken into account (i.e., loss of gravitational acceleration). The ultimate goal of individuals in biomechanics as they interface with scientist's musculoskeletal modeling, of course, is to develop predictive models of human kinetics and dynamics in microgravity [2].

It seems, then, that the role of biomechanics in the study of human performance in microgravity involves interface with a variety of other scientific disciplines. It is the integration of the techniques used in these various disciplines that must be coordinated in the study of human movement in microgravity. We must first realize the effects of microgravity on the musculoskeletal, neuromuscular, cardiovascular, and cardiorespiratory systems. Our objective is to then develop countermeasure techniques that will enable the astronauts to perform in microgravity and return to the one-g environment. The use of predictive models to understand human performance in microgravity requires knowledge of the degrading system losses (i.e., the effects of the microgravity on bone and muscle) as well as knowledge of the loads imposed on the human body exercising in microgravity. While biomechanics will play a role in, first, monitoring these forces and describing the loads imposed during various tasks in microgravity, any countermeasure program using principles in biomechanics must include information on the magnitude of the losses in the musculoskeletal system. Any exercise program designed to counter the effects of microgravity must: (1) employ principles in biomechanics to study the magnitude of loss in the musculoskeletal system, (2) understand the nature of the loads imposed on the body, and (3) recognize the need to monitor the system losses and develop the potential for one learning to accommodate and adapt to the effects of microgravity.

Certainly, locomotion (i.e., walking) imposes the highest loads on the lower extremity extensors that are the muscles most affected by microgravity. It is conceded that the musculoskeletal system will degrade. Results from the most recent experiments indicate this loss will proceed despite the use of exercise programs. Consequently, the development of countermeasures to the effects of microgravity must include knowledge of these losses and must be flexible enough to change exercise regimens in light of these losses for the health and safety of the astronauts.

The procedures that I am going to describe in the remainder of this manuscript are procedures, in principle, that can be applied to any exercise regimen used in microgravity. While I will use cycling as an example, principles employed here could easily be used for activities such as running, walking, rowing, or jumping. The first principle concerns the identification of loads imposed on the human body by the environment. Identification of the orientation and magnitude of ground reaction forces or any external reaction force in the environment is requisite to our understanding of exercise as a potential countermeasure to microgravity. In walking, we would want to understand the orientation and magnitude of the ground reaction force as one proceeds through the stance phase of locomotion. During cycling, we would want to understand the orientation and magnitude of the pedal reaction force on both the right and left lower extremities. It is clear in both cases that the orientation and magnitude of this force changes as one proceeds through the stance phase of locomotion as well as through the power phase of cycling (from top dead center to bottom dead center in the pedaling cycle). Cycling offers a more constrained environment in which the trajectory of the lower extremities is more repeatable than during locomotion and can be controlled with respect to the magnitude of the external forces imposed. The cycling task need not include a bicycle but may include any seated position in which the astronaut will sit and pedal any circular coupling system similar to a bicycle chain drive system. This cyclic alternation of the right and left lower extremity can be controlled with respect to range of motion, speed and load imposed. One can envision a series of isometric contractions at various crank angles or a continuous motion in which the velocity of the crank is held constant and the load varied during the cycling pattern. Certainly, in this controlled environment, the forces imposed on the lower extremity are, in general, considerably lower than those imposed during locomotion, but at some point in an exercise regimen involving cycling, walking, and rowing, these lower forces may be desirable.

When using any exercise regimen in microgravity, one must know how the human system performs at one g. Information related to the cycling task shows that the pedal reaction force varies from a minimum value at top dead center to a maximum at approximately 100 degrees of the pedaling cycle [4]. The magnitude of this pedal reaction force then declines as one proceeds down to bottom dead center. The magnitude of the joint reaction forces, while much lower than those during walking, do change as a function of the pedal reaction force. Additionally, the muscle moment patterns indicate there is a large hip extensor moment during the power phase that approaches zero as the cyclist proceeds through recovery (i.e.,
cycle). The knee moment appears to be extensor during the early part of the power phase and then changes to a flexor moment in the second quadrant ranging from 90 to 180 degrees of the pedaling cycle. This flexor moment continues, although of lower magnitude, through early recovery. It then switches to an extensor moment as the cyclist proceeds through the fourth quadrant up to top, dead center. The ankle shows a continuous plantar flexor moment that is almost a mirror image of the resultant pedal reaction force.

It appears that the tricep surae muscles are predominantly responsible for this particular muscle moment at the ankle. Using optimization algorithms designed to calculate the magnitude and direction of the muscle moments at hip, knee, and ankle in microgravity, we can see that the muscle moment actually increases in magnitude and is similar in direction as one proceeds from one g to microgravity (Figure 2).

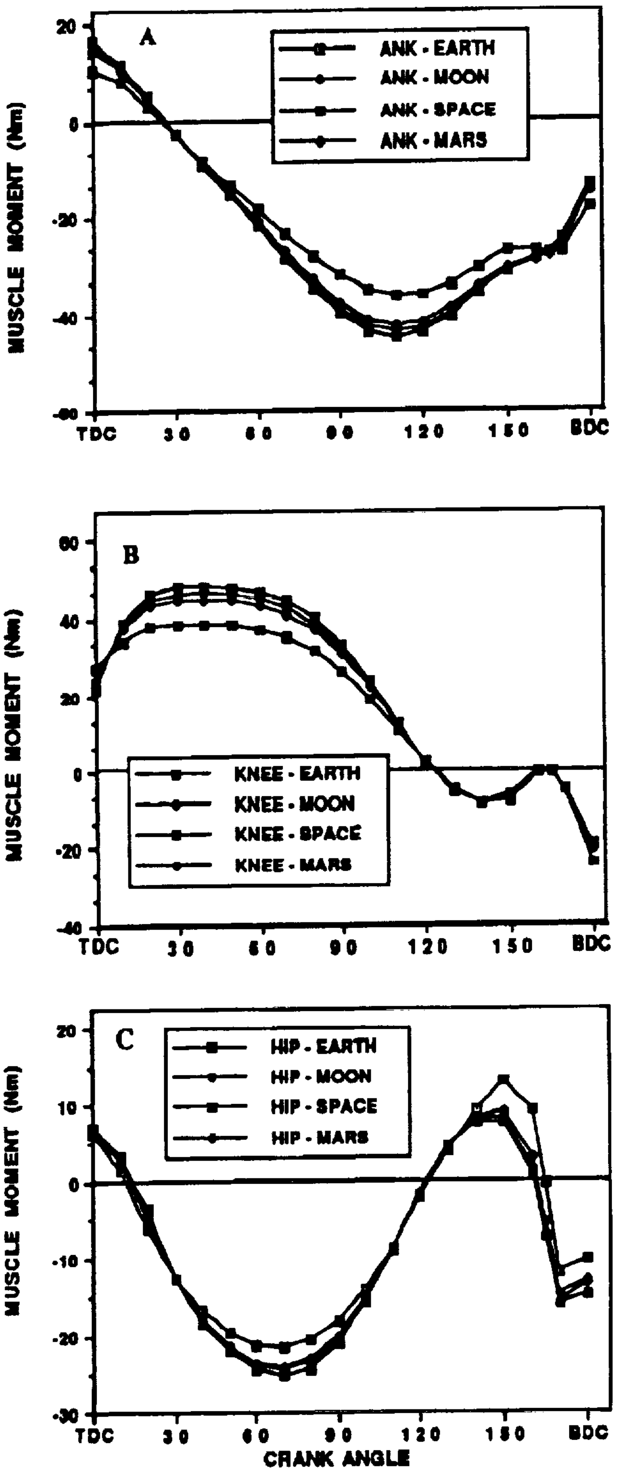

Figure 2. *Muscle moments during the power phase of cycling (0 to 180 degrees) at the ankle (A), knee (B) and hip (C) simulated using the gravitational fields of the Earth (one g), Moon (0.16 g), Mars (0.38 g) and in space (zero g).*

when they move from ground-based models to microgravity above the surface of the Earth. Since the muscle moment increases as one moves from one g to microgravity, further information is needed as to the exact role played by the muscles during the cycling task in an exercise regimen in microgravity.

The motor program of lower extremity musculature indicates that the single joint extensors are relatively immutable during the cycling task [8]. That is, from subject to subject, the single joint, hip extensors, knee extensors, and ankle extensors show a relatively constant activation pattern during the pedaling cycle. It is currently felt that the single joint extensors provide the power to the lower extremity and, subsequently, to the bicycle. This is quite similar to the loads imposed on the lower extremity extensors during the walking cycle in which the ground reaction force during stance imposes heavy loads on single joint hip, knee and ankle extensors. Cycling, to some degree, is similar. Since the single joint, lower extremity extensors are most affected by microgravity, one might ask the question as to which exercise is most useful in attenuating this loss of musculature and force production capability. While walking may stress the lower extremity extensors more than cycling, the loads imposed on the lower extremity also affect other tissues (i.e., bone). If these tissues respond differently to the various loads, then I feel we must be ready to show some flexibility in a countermeasure program so that loads imposed on the lower extremity can be sustained by the degrading muscle and bone. One might further ask the question, if the lower extremity extensors are immutable during cycling in one g, does this hold true in microgravity? Certainly, the flexors are less affected by microgravity, and the rider may shift to the flexors and pull up on the crank since gravity assisted propulsion no longer exists.

Exercise regimens, such as walking and cycling, can also be used to study musculoskeletal mechanics. The use of cycling in The Human Biomechanics Laboratory at UCLA has been extensive in the study of the human musculoskeletal system. We have current information that shows the actual force production of the tricep surae complex during the cycling task in response to three separate power outputs [5]. The information gained on parameters such as muscle force, muscle EMG patterns, muscle length changes, velocity of muscle action, and joint moments as well as joint moment arms, is useful input to predictive models of the musculoskeletal system. In our laboratory, the cycling task has been used to study lower extremity function and can be used to study musculoskeletal function in microgravity. With knowledge of losses of muscle and bone, one can, from the information that we have recorded, develop predictive models for performance in microgravity. For example, using the cycling task, we can develop an optimization algorithm to predict function in the lower extremity. This algorithm can be modified by changing inputs as a result of changes in tissue from exposure to microgravity. The changes in input parameters to this model, with knowledge of requirements of imposed external loads, can prove useful in our understanding of human performance in microgravity. The development of such a model may, of course, be extrapolated to other tasks such as walking and rowing in which external loads are imposed on the body and tissue changes are similar.

One final use of biomechanics concerns its interface with neural control and motor learning. We have developed some techniques in our laboratory in which selected aspects of the cycling task can be used as feedback to the subject to enhance their performance [1]. This feedback is critical for updating the individual regarding the status of their motor output. Any task, whether it be rowing, walking, jumping, cycling, or possibly just a single joint movement, can employ feedback techniques to update the astronauts on their motor function capabilities. This type of information could be very useful in monitoring the capabilities of the astronauts as a result of extended duration orbits. We have studied the effects of feedback during single as well as continuous motor tasks, and more information is being collected regarding the way in which the human body processes information during a continuous task. The nature of this feedback can enhance performance and be used as a monitoring device for astronaut function in microgravity. One could envision that knowledge of the forces required for an emergency egress, once the Shuttle lands on Earth and returns the astronauts to a one-g environment, could serve as an acceptable baseline for continued function in microgravity. These loads would be the lowest acceptable limits tolerated by the degrading musculoskeletal system that would determine whether the flight continued. If we could continuously update the astronauts through some form of exercise regimen and use some motor tasks to provide information about their status, then we can best serve the safety and the continued progress of the crew.

In summary, biomechanics can be employed in the study of human performance in microgravity. Principles in biomechanics include integration with a variety of other fields to first identify the magnitude of change in the human body as a result of prolonged exposure to microgravity as well as in the design of flexible and adaptable exercise regimens that could be used as countermeasures to the effects of microgravity. Principles in biomechanics as they relate to motor control can give astronauts necessary feedback regarding the status of their motor function and can serve as a diagnostic tool to indicate to the astronaut when they are reaching the lowest acceptable limits for emergency egress upon return to one g. While cycling was the example used in this particular discussion, certainly the principles employed in understanding this task and the possible use of this task as an exercise countermeasure, can be applied to any other type of exercise regimen whether it be locomotion, jumping, rowing, or single joint, flexion/extension actions.

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