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ABSTRACT

This is a collection of significant papers by leading authorities, compiled by the American Association of Health, Physical Education, and Recreation's Kinesiology Committee of the Physical Education Division. The following papers are included in this collection: "Supporting Biomechanics Subject Matter in the Undergraduate Curriculum"; "Laboratory Exercises in Biomechanics for Undergraduate Students"; "Preaxial and Postaxial Neuromuscular Relationships in the Upper Extremity: A Method of Teaching Muscle Innervation"; "Biomechanical Analysis of Human Motion"; "Moment of Inertia of the Human Body"; and "Assessment of Forearm Position upon Upperarm and Shoulder Girdle Strength Performance." (JA)

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Supporting Biomechanics Subject Matter in the Undergraduate Curriculum

PROGRAMS OFFERING the opportunity to specialize in the emerging subject matter area known as *biomechanics* have begun to materialize at the graduate level in the United States. An increasing number of university physical education departments are establishing within their faculty, teaching posts which carry the responsibilities of developing courses and programs in biomechanics as well as supervising graduate theses. One might be tempted to call this notable trend a "Biomechanics Bloom," for it is real and is beginning to demonstrate its influence quite broadly. It is interesting to note that this development is almost certain to carry with it the gradual establishment of introductory biomechanics courses at the undergraduate level, a phenomenon which has shown itself to be operative in many other disciplines in the past.

Although this downward drift of subject matter content is to be expected, there is little likelihood of widespread development of degree programs in biomechanics at the undergraduate level in the immediate future. It would be possible to cite a number of reasons to support such a contention, but it is enough to say at this point that the twin requisites of qualified faculty and costly facilities to support such programs are simply beyond the resources of presently constituted departments of physical education.

Traditionally, physical education undergraduate majors have been introduced to matters akin to biomechanics through required *kinesiology* courses. The content and scope of these courses have and still do vary widely from school to school. So much so, that it is not uncommon to find entering graduate students virtually bereft of experiences dealing with the scientific foundations of motion study which would allow them unfettered passage into graduate courses in biomechanics without repeating the undergraduate kinesiology course or courses at the new institution.

It is to be expected that among the missing ingredients of such kinesiology courses were matters primarily mechanical and mathematical in nature. It is to be expected also that undergraduate kinesiology courses will gradually evolve to the point where more and more biomechanics subject matter will be included on an introductory but rigorous level in addition to the staple, applied anatomy. In this way, those who feel it unwise to relinquish the venerated term, kinesiology, can make a number of simple adjustments in their traditional kinesiology offerings which can improve the scope of the study of human motion under their tutelage and, at the same time, set the stage for subsequent course work under the heading of biomechanics.

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[1] This article was presented to the Kinesiology Committee Section meeting, National AAHPER Convention. Minneapolis, Minn., Spring. 1973.

The combination of kinesiology and biomechanics subject matter then could be construed to represent a very important arm of the broader subject matter of physical education, and those of us who have strong feelings about retaining kinesiology as a workable and descriptive term in the undergraduate curriculum would be served. For instance, this subject matter arm could carry a name which is a contraction of the two terms to become *kinesiomechanics.* Since writers often become enamored with terms of their own invention, kinesiomechanics will be used hereafter to represent the undergraduate subject matter combination within which separate emphases on kinesiology and biomechanics may be pursued as courses.

Discussions of the desirable contents of beginning biomechanics courses for the undergraduate course are inevitable. However, it is not the purpose of the present discussion to deal with course content except on the broadest of levels. The purpose at present is to deal with those matters which act to undergird the development and operation of undergraduate courses, inviting our attention to discussions of: (1) program considerations, (2) facilities and equipment support, (3) supporting organizations, and (4) faculty.

That which follows should be received with the understanding that the first undergraduate course in biomechanics is conceived as following a prerequisite kinesiology course which is structured as noted in the preceding paragraph. Furthermore, this discourse is, by no means, an exhaustive coverage of all the elements involved in establishing a new subject matter area. What it can be, is a simple discussion of everyday matters which may assist instructors in the tasks of launching new courses in biomechanics and, hopefully, encouragement for those with such aspirations to make the efforts necessary to the success of those courses.

PROGRAM CONSIDERATIONS

Like human beings, programs developed by them tend to show many of the same characteristics of aging. A tendency which is seen now and again in physical education teacher training curricula is that of inordinate clutter. Requirements which at one time were logical and defensible, remain in the curriculum although evidence for their being retained as requirements is meager. They may be kept more as a matter of administrative convenience, with each requirement bolstered by its advocates who lobby for continued inclusion of their pet. Nearly all of our physical education programs require a solid block of professional education courses which are designed to meet state certification requirements for public school teachers.

Concurrently, pressures build to introduce new subject matter which has developed from recent scholarly thrusts in our discipline. Short of adding extra semesters to encompass the growth, the outcomes of these stresses are programs which can be and often are: (1) rigid as to elective flexibility, (2) deficient in providing for innovative curriculum options, and (3) outmoded for their time.

Under such circumstances, students often find it difficult to schedule anything beyond their major programs and find that practically every minute of their student careers is controlled by requirements of one sort or another. It is possible to find well-known major programs in the United States which require the undertaking of 17 credit hours per semester in order that the degree and teaching credential can be obtained within a 4-yr. course of study, accumulating as many as 136 credit hours in doing so.

We, as physical educators, appear to demonstrate a propensity for collection which is not mitigated by a very clear understanding of space and time limitations. Fortunately, we are generally open to trying new things, but often the necessary awareness of the arithmetic of additions and subtractions comes as a surprise. Clutter is, indeed, one result of such faulty arithmetic and is seen to run counter to the needs of an environment which encourages the development of new subject matter areas such as biomechanics.

In common with many other emerging interests within physical education, biomechanics courses at the undergraduate level would, at first, be expected to serve an elective tenure. However, as noted earlier, for elective courses to be patronized, it is necessary to have clutter-free programs. Such programs come about by design and serious efforts in the service of elective flexibility and are likely to carry with them a heaping spoonful of painful experiences when some faculty members find that their specialties have been transplanted to elective status if the surgery is not skillful.

Yet, it is probably in the best interests of both faculty and students to require of all students only those courses which constitute undeniably the elemental parts of our discipline. Those which remain more peripheral must settle for being offered periodically as electives. Fortunately, those courses which demonstrate real substance and are continually well-taught, will survive and thus serve the needs of the department and students alike. Consequently, one of the prime program requisites to establishing undergraduate courses in biomechanics is to support the development of greater elective flexibility. It may just come to pass at some future time that biomechanics will have achieved a status which could justify its inclusion as a requirement for all students.

The needs of today's students with their more diversified interests and backgrounds, and the rapid expansion of knowledge in the field of physical education are placing increasing responsibilities on college and university departments to meet the challenge of preparing students with a more advanced knowledge of their discipline. One means of achieving this end is to develop curriculum options to serve the emerging and broader demands of that growing group of individuals who do not see their future in public school teaching but are, nevertheless, intensely interested in understanding the multifaceted place of motor performance in the daily existence of mankind.

A basic question underlying this sort of development deals with whether or not programs should be limited to the task of preparing students for a specific employment. In the past, public school teaching has usually been the sole, clearly identified place of future employment. With the demand for teachers now on the decline, placement is far from guaranteed, and graduating seniors are being forced to investigate other means of earning a living. This state of affairs is being recognized earlier by succeeding students, which tends to focus their attentions favorably toward curriculum options which, if available, can provide more-than-adequate credentials for competing for employment in a variety of areas in our society.

Although numerous sites of satisfying vocations could be listed here, it would seem advisable to see the prime function of non-teaching programs in physical education as providing an *education* which will allow the graduate sufficient background to pursue whatever courses meet his/her interests. This aim is, therefore, not unlike that espoused by many other college departments (i.e., English, foreign languages, history, fine arts, etc.) who welcome students, not on the assumption of guaranteeing some specific future employment, but on the basis of a mutual and abiding interest in the subject matter involved. Herein lies a stimulating means of securing a place for undergraduate biomechanics course work, for it is within this sort of educational climate that the introduction of new and influential practices may take root. It is certainly not beyond credibility to suggest that a first course in biomechanics might be included as a requirement of all students within such an undergraduate curriculum option.

With the development of new program options comes the opportunity to investigate briefly an assumption which has been with us so long a time that it has become practically axiomatic. That is, specialization within the subject matter domain of physical education cannot profitably take place other than at the graduate level. For example, if a student should develop an intense interest in the kinesiomechanics arm of our broader subject matter as a result of experience with human anatomy and kinesiology early in his undergraduate career, very few avenues will be found available to him to advance his knowledge in that area until after graduation.

Serious attention to the matter of *expecting* students to specialize to some extent, a very natural urge for most of us, in established areas of their interest within our field is a concept whose time appears to have arrived, particularly within nonteaching curriculum options. Certainly one of the areas which can be singled out for additional student emphasis is kinesiomechanics. Students selecting this path would be encouraged to elect courses outside of their department as well as from within to enrich their backgrounds further. In this way the problem of staying current with the advancing knowledge in certain, selected areas could be efficaciously pursued along with attending to the more general knowledge of the other areas provided by single courses in the curriculum.

If students were expected to identify and then pursue to additional depth, let us say, two concentrations (perhaps kinesiomechanics and exercise physiology might serve as an expected combination) from a group of those established by the department, a list of courses which were deemed appropriate to support those concentrations could be prepared to aid students in making correct choices in light of their backgrounds. For a student whose background was noticeably weak in mathematics, a rather common occurrence within physical education students, suitable courses leading to adequate working knowledge of such areas as analytic geometry and calculus could be prescribed. Similarly, if additional work in mechanics seemed appropriate where an adequate mathematics background was in evidence, courses selected from physics and engineering departments might be counseled. In such a program, the stimuli for offering additional in-house experiences for interested students would be high, and courses such as biomechanics could run parallel to those taken outside the department.

In most physical education degree programs, but particularly in those where different curriculum options are not available, it is most important to initiate and offer "Independent Studies" courses where interested students can work on a one-to-one basis with a faculty member in an area such as biomechanics where no formal course exists. Courses with this sort of purpose are found under different names in different institutions. It is not important what name the course has been given, but to provide a vehicle where experiences beyond that available from established courses in the catalog may be pursued. Under the auspices of these offerings, many valuable experiences can be made available that cannot be included in regular classes because of the large number of students serviced. Even with these desirable possibilities available, it is surprising how few students take advantage of these one-to-one services.

The problem probably hinges upon three contributory circumstances. First, special studies offerings are seldom advertised very adequately on a department level. Second, when known to exist, requirements clutter often interferes with the students electing the courses. Third, faculty members interested in supervising these experiences do not offer enough encouragement to those students whom they feel could handle such situations to advantage. It is our good fortune that these experiences materially benefit faculty members by providing new ideas, methods, and approaches for present or proposed courses. Thus, one means of developing an ongoing program and interest in the study of human motion topics is to encourage your able students to try their hands at independent studies and urge them to plan their schedules in advance to provide the time for them later.

Most colleges have, within their course numbering systems, a means for trying out new course offerings without first going through the tangled procedures which place a new course in the catalog with an official title and course number. These may be designated generally as "Special Problems" or "Seminars" where faculty members may offer and students may elect to study matters which are of special interest or just coming into prominence. On occasion, the subject of these trial courses may even be centered around a faculty member's personal research programs which may have accumulated a considerable cache of interesting findings to be compared and integrated with materials from the literature. When that research has been focused upon kinesiomechanics studies, it is natural that it could contribute well to a trial course in biomechanics. If, upon one or more trials of the course, it is clear that department and student needs are being served, the course can then be submitted formally for regular course status with a permanent catalog number designation. It is through procedures such as these that major curricula make great strides to avoid becoming outmoded, as well as encouraging the development of new courses in emerging subject matter areas such as biomechanics.

To summarize briefly regarding program considerations, it would appear helpful to recommend working toward or encouraging:

1. A reduction in the magnitude of requirements clutter, particularly in our present teacher training programs.
2. The development of broad elective flexibility in present programs as well as proposed programs.
3. The development of nonteaching curriculum options in programs, where none exist at present, so that an increase in subject matter depth may be offered.
4. The investigation of the possibilities of requiring students to specialize to some extent in nonteaching curriculum options.
5. The initiation and use of "Independent Studies" courses to enrich the usually limited offerings available in kinesiomechanics.
6. The development and use of trial courses which could, if proved effective on such a trial basis, become regular course offerings in the program.

FACILITIES AND EQUIPMENT SUPPORT

Few would argue against the value of including laboratory experiences in an undergraduate biomechanics offering. There is no avoiding the fact that biomechanics courses which include a substantial helping of laboratory demonstrations and experiments will be costly to initiate if certain facilities and equipment are not available at the outset. Further, if each student enrolled is expected to complete an investigative project of some sort as a course requirement, the cost of being adequately equipped will be higher still. So it becomes necessary to make some decisions as to what might be advantageously employed and to establish a general understanding of priorities in the acquisition of equipment for existing facilities.

An assumption underlying the discussions which follow is that the means of demonstrating and experimenting with biomechanics phenomena in a first course would be achieved best through the use of graphical methods of data acquisition, analysis, and presentation. It is quite likely that some important pieces of equipment are already available in most physical education department laboratories and if they are not, simple beginnings usually may be undertaken through the assistance of other departments within the college or university which deal with similar matters.

Examples of such are the departments of: (1) mechanical, civil, and electrical engineering; (2) physics, (3) dramatic arts and communications; (4) educational technology; (5) industrial education; and (6) audiovisual services. When it becomes clear that certain important support facilities and equipment are not going to be obtained by your department for some time to come, step out and get acquainted with your colleagues in other departments and work out arrangements to use their facilities on a temporary basis. You will be pleasantly surprised to find how receptive they can be to the needs of someone such as yourself in organizing a first course in biomechanics. So, make acquaintances and see what is available for your use.

Devices for the simple demonstration of mechanics phenomena, those that have become so familiar to us from beginning physics courses, are not difficult to obtain and put to use. However, a distinct problem in biomechanics situations is that of demonstrating these same phenomena unambiguously with human beings acting as the subjects under scrutiny. Because of the complexity of human movement functions, the process of capturing elements of a complicated task for immediate as well as subsequent study under convenient circumstances is of utmost importance and it is clear that devices ancillary to our own observational faculties are necessary. Those which are deemed within the reach of present physical education departments are listed below, and it will be seen that each is essentially a graphic process. Please note that they are listed in order of greatest value without regard to cost. They are: (1) Photographic, (2) Electromyographic, (3) Kinetographic,[2] and (4) Goniographic.

Insofar as one can predict general usage, the first priority with respect to equipment and facilities support is to provide the means of obtaining photographic records of transient events. The permanent records produced by a photo system may be conveniently stored and then utilized later in a manner which can provide for adequate data reduction, both qualitative and quantitative. Since some means of recording serial events (and thus provide a time base) is mandatory to biomechanics study, the use of *cinematography* is called for. Facilities to support even the most basic of cinematographic work depend upon two factors, namely, adequate lighting and sufficient space to accommodate the photographed act and the optical requirements of the system in use.

If the work is to be done indoors, sufficient light is a decided problem and artificial lighting, both horizontal and from above, must be provided in quantities far larger than most people imagine, particularly when large spaces such as gymnasiums are involved. It is of some importance to point out how common it is to find that existing electrical wiring capacities are not able to cope with the demands of indoor lighting over extended periods, and the inevitable searches must begin to find and replace blown fuses or to reactuate tripped circuit breakers. The message carried by this common occurrence is to know your facilities well and make plans to circumvent these perplexing and time-consuming difficulties. When filming outdoors, lighting problems are seldom insurmountable.

After the latent photographic record has been processed, at least two pieces of data reduction equipment are mandatory and it would be ideal if these could have their own area for use by students, undisturbed by the other activities of a laboratory. The first serves to support qualitative analysis in addition to everyday classroom teaching uses. It is a sturdy motion picture projector which provides both single-frame operation as well as motion projection. With this device, the more superficial but still important features of the photographed act may be studied over and over until they can be described with high accuracy. The second device is a film reader of some sort (they may be had in a wide range of sophistication) which allows convenient extraction of quantitative coordinate and time data from single-frame images. From these kinematic elements, numerous other mechanical quantities may be derived.

If suitable camera gear is not available, the equipment, film, and a photographer can usually be obtained to serve your temporary needs from the audiovisual services department of your college. With some care paid to informing the photographer of your special requirements, satisfactory records may be obtained, both for classroom use as well as for student projects. One cautionary note is essential here. These services may not be entirely gratuitous, and it is wise to investigate all costs and the procedures for interdepartmental billing that are used so that requests for adequate monetary support can be settled well in advance. Better still, ask for a sum of support funds to cover all course

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[2] This term has been taken from Morton, D. J., *The Human Foot*, (New York: The Hafner Publishing Co., 1964) p. 154. in which the term, *kinetograph*, was used as the name of a device for recording foot imprints during standing and ambulation. As used here, kinetographic processes of data acquisition refer to the use of force registering devices, the most sophisticated of which are force platforms.

costs as a part of the department's yearly budget and be sure to plan for the inevitable increase in costs of services and supplies as your course develops in complexity.

Next in importance is the ability to monitor and record action potentials from active muscles of the body during some event, either dynamic or static in nature. Hence electromyography is called for with a minimum capacity for monitoring two different muscles simultaneously at the outset, and a building capacity for at least four channels totally for future use. If limited to monitoring but one muscle at a time, much of the informative interplay between muscles is made most difficult to obtain. If it can be managed, purchase equipment that provides for *integrated* as well as *direct* recording modes of operation. In this way, both quantitative and qualitative analytical needs can be handled conveniently.

In the beginning, it should be satisfactory to limit the use of electrode types to the surface kind, and consequently, to the monitoring of superficial musculatures. After proficiency has been gained using surface techniques, an investment in and use of "indwelling," electrodes could be attempted after first investigating the medical and liability restrictions involved. Then, the movement contributions of deeper and smaller muscles can be demonstrated and studied. In addition, it would be wise to plan to include an oscilloscope to assist in the search for and demonstration of electrical artifacts and for some means of transducing the muscle action potentials into audible sounds through a loudspeaker.

One of the truly valuable advantages of electromyography in laboratory situations is its ability to have interpretable information at hand immediately. Because of this immediate record of monitored events, it serves the needs of laboratory demonstrations in a way that few other systems provide. For example, an original set of circumstances can be included in a demonstration and before the monitored act is performed, hypotheses may be advanced regarding expected outcomes. After studying the recorded evidence, additional hypotheses can be offered as to what should occur when a variable is added. This, too, can be tested immediately, leading to more tests under other circumstances, and so on.

When electromyography is combined with cinematography to record a movement event over a common time base, a synergistic effect is obtained where the total information obtained is greater than the sum of the individual system outputs. The combination of qualitative and quantitative features provided with such a combined system is literally overwhelming, to the point where a single recorded event can provide demonstration material of nearly endless biomechanical phenomena.

Kinetographic gear is usually one of the most commonly encountered equipment types found in physical education laboratories. Because of their use in conjunction with concerns of exercise physiology and kinesiology courses and studies, devices such as weight scales, dynamometers, cable tensiometers, and even more elaborate instruments to measure strength parameters utilizing strain gauges and load cells are often found in plentiful supply. These may be put to advantageous use in biomechanics situations when the direct measurement of applied forces is preferred to derivation. Under controlled conditions, forces exerted volitionally through our musculoskeletal lever systems and registered on devices such as the cable tensiometer, can serve nicely to study the changing effects of lever arm lengths, muscle lengths, and joint positions. When combined with simultaneous electromyographic monitoring of muscle actions, we again find outcomes which contribute more than would be expected to an understanding of the intricacies of anatomical mechanics.

The force plate of platform, a complicated instrument which can register concurrent force magnitudes in more than one dimension, is gaining advocates rapidly even though it is not inexpensive. It may be put to excellent use in verifying force magnitudes derived through cinematographic methods or in conjunction with cinematography to establish forces with the exact positions where they occurred. It is unlikely that instruments of this sort will be broadly available as the result of a simple purchase although they have immense value in the study of human movement. When they are obtained, they are usually fabricated on a special design basis from a small "development" company or by some to the large mechanical and electronic shops serving large engineering or science departments at major universities.

A search for one already in use on your campus, particularly within engineering departments, might well be profitable; if not for continuous use purposes, perhaps for periodic demonstration purposes. Again, step out and see what your institution has to offer. In any case, it would be wise to keep instruments of this sort in mind and gradually move toward developing the capacity to utilize them as an adjunct to your undergraduate biomechanics offerings, especially in those departments where graduate work in biomechanics is already established. For an introductory source of information concerning the force platform and its uses, readers are referred to Payne.[3]

Goniographic techniques for angular measurement of joint positions and movement have been in use for quite a long time. More recently, provision for continuous recording by electrical means have resulted in the *electrogoniometer* (elgon). As has been the case with other specialized devices found in physical education laboratories, in-house fabrication to meet specific needs has been common. Consequently, the ability to undertake goniographic investigations and demonstrations is not inordinately costly to implement. For those who are unfamiliar with this instrument, attention is directed to the first issue of this publication.[4]

Just as the force platform may be used with and to check the accuracy of cinematographic determinations, the same holds true for the combination of goniographic and cinematographic methods of measuring joint movement over a common time base. Also, in common with the other kinds of equipment discussed previously, goniographic methods place the investigative emphasis directly upon the use of human subjects, a circumstance which can too often be overlooked with the result that the "mechanics" in biomechanics can be emphasized to a degree where the "bio" is neglected.

SUPPORTING ORGANIZATIONS

The intent of this section is quite simple and can be attended to without undue laboring. The faculty member who finds himself or herself the only person with an intense interest and background in a subject matter area within a department, can lead a rather lonely existence inasmuch as there may be no others with whom special interests may be discussed. It has been a common tactic for physical education departments across the nation to employ one faculty member to serve the department as their resident *expert* in kinesiomechanics matters. Others may be asked to teach sections in undergraduate kinesiology so that the required number of major students may be served; but on most occasions, these faculty members have other specialties and duties which consume their interests and time. Consequently, the opportunity to exchange ideas, practices, methods, and new developments with others of similar interests are relished whenever they materialize while attending such gatherings as conferences, clinics, and workshops. It would .be most beneficial if this kind of stimulating interaction could occur more often than on a once yearly basis. Hence, the thrust of this discussion is to encourage the organization and development of common interest groups which can meet regularly to discuss kinesiomechanics topics.

Since the author has been involved recently in that kind of task, the incorporation

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[3] A. H. Payne, "The Use of Force Platforms in the Study of Physical Activities," *The University of Birmingham Review*, Autumn, 1966, Birmingham, England.

[4] Marlene J. Adrian, "An Introduction to Electrogoniometry," *Kinesiology Review*, 1968.

of a specific organization as a case in point appears to be justified. Figure 1, presents the mark or emblem of the Maryland Kinesiological Society, a new, common interest organization which has developed spontaneously as the result of the interaction of diversely placed faculty members within the University of Maryland. At present, members of the Society come from the faculties of the departments of anatomy and physiology of the School of Dentistry, anatomy and physical therapy of the School of Medicine, and physical education, as well as from the United States Public Health Service in Baltimore, Maryland.

Recently, invitations to attend monthly meetings have been extended to interested colleagues in other state and private colleges from the relatively small state of Maryland. Therefore, what was in the beginning an organization populated primarily by faculty members of one institution, now is in the process of expanding to embrace a larger number of interested specialists throughout the state.

Organizations of this sort need not be structured only along state lines. In large states such as Texas or California, smaller, regional groups would be more advisable for monthly meetings while statewide gatherings could be set up on a once yearly basis. Whatever the organizational structure turns out to be, the opportunities provided to share ideas is the true goal and our experience has been one of growing enthusiasm. Agendas for forthcoming meetings are prepared and distributed in advance, which announce reports and presentations from members concerning their research projects and findings, discussions of proposed projects and the usual soliciting of assistance in the planning of projects and courses to be taught.

Figure 1. Emblem of the Maryland Kinesiological Society.

For example, one recent meeting included an interesting and candid evaluative report of a Biomechanics Workshop course given at a midwestern university which was attended by a member. The following month, a slide presentation by another member, entitled "Application of Neuromuscular Function to Determine Occlusion and Rest by Visualizing Masticatory Muscle Potentials," generated a lively discussion. Because the meeting place was located in the facility where the research had taken place, demonstrations of some of the procedures were also presented.

Plans are afoot to invite prominent individuals outside our membership to speak of their studies and findings which relate to the purposes of the gatherings. In addition, it has been most gratifying to be able to invite students to attend these meetings and to find that they thoroughly enjoy the experience and hope to be invited again. Efforts are in the planning stage to cultivate additional memberships from the disciplines of engineering and orthopedics. Consequently, it seems reasonable to say that the time and efforts required to organize such groups are well worth the investment since the opportunities to "go to the well" for scholarly and professional refreshment are just cause for such an undertaking in support of the developing subject matter area of kinesiomechanics.

FACULTY

Although this discussion category is the most important of them all, it was left for last to provide for extra emphasis. For, if adequately prepared faculty members are not available to handle present and proposed courses in biomechanics and kinesiology, little of what has preceded this final category will be very useful. It is the view of this writer that at present there is a dearth of properly trained people to handle biomechanics courses within the present pool of undergraduate kinesiology teachers in our colleges and universities. Far too often, courses of this sort are serviced by the expedient known as "pressing into service of the ill-prepared." This situation needs to be remedied, and it is hoped that the following discussion will aid in identifying some areas where positive changes may be accomplished as well as identifying some means for doing so, short of resigning one's position and returning to full time graduate student status in biomechanics.

Among the areas of weakness which are often found in the backgrounds of many of the ill-prepared is that of an insufficient understanding of mathematics. Mathematics acts as the common language of the sciences and provides the means of going beyond the qualitative into the quantitative. Most of those who are limited in this manner are compelled to confine their treatment of biomechanics topics to coverages which may be described as bounded by intuition. Beyond these mathematical limitations, and related to them, are additional background deficiencies in basic physics and mechanics, anatomy which includes the dissection of human cadavers, comfortable acquaintanceships with technological hardware and the principles of its operation, and finally, knowledge of the research and professional literature involved with these matters. It is easy to see how several of these deficiencies can be related to one another.

For those readers who may consider the foregoing as a case of overstatement, the following anecdote may be useful. One member of this writer's summer term, undergraduate kinesiology course identified himself as a graduate student who had chosen this area of study to be one of several in which he hoped to be examined prior to admittance to candidacy for the Doctor of Philosophy degree. His interest and progress while pursuing the course of study indicated an aptitude commensurate with his intent. However, during an impromptu discussion with the student, he let it be known that although he had never before completed a single undergraduate course in the kinesiomechancis area, he was employed by a state college department of physical education and was their resident instructor of kinesiology for their undergraduate majors. The prevalence of such circumstances could be the cause of much argument, but it is likely that an occurrence of this sort is not nearly as improbable as we might prefer to imagine.

Another area of faculty concern which bears upon these discussions is that it appears that only a small number from the present pool of kinesiology teachers is demonstrating evidence of research productivity in the form of published reports. Consistent output seems to emanate from a few individuals who may, by the good fortunes of their employment, find it both personally stimulating as well as professionally rewarding to be productive in the scholarly pursuits of research endeavors and the public dissemination of their findings. The rather consistent publication of the results of student projects such as graduate theses is not to be confused with what has just been stated.

What *is* important is that faculty with avowed interests in teaching kinesiomechanics subject matter should see, as a natural adjunct to that kind of employment, the responsibility to contribute new knowledge to the area of their dedication. For there is no more exciting and satisfying experience in teaching than to be able to say to a class—". . . now, let us see how the results of some recent work of mine bears upon the topics we have just been discussing." "By the way, this project is not yet completed, and I was hoping to find several students interested in lending a hand two or three afternoons a week." The reactions to such invitations are usually most responsive and very productive in boosting the interests of many of your students because they are searching for involvement beyond the realm of the classroom.

To identify problems is valuable, while to offer suggested means for remedying those problems is helpful. The concluding paragraphs are involved with suggestions for improving present circumstances, dealing mainly with encouragements to: (1) begin a program of studying basic areas in backgrounds where important gaps are in evidence, (2) ask for help when it becomes necessary, and (3) get busy with research projects in areas of your interest.

All of us are cognizant of gaps in our educational backgrounds that we would dearly prefer to be filled, if only the time and means would present themselves. It is not reasonable to expect such means to come about spontaneously. They materialize because they are made to happen on the basis of careful planning and identification of the desired course of action. It makes little difference whether the study of mathematics and mechanics, for example, is pursued independently or in formal institutional settings. The important consideration is the strength of the will to improve the power of your background. If it is preferable to study analytical geometry and review algebra independently, purchase suitable books and materials and dig into it until the need for expert consultation becomes necessary. When this occurs, seek help from within your institution; possibly in the form of periodic tutoring from a colleague in another department or from the person whose office is just down the hall from your own in your department who has a command of such matters. There is no better time than the present to get started.

Lastly, on your way to your office on the first day of the new semester, stop in for a visit with your department Chairman and make it clear, diplomatically that is, that you are in the process of formulating the means of logically studying a kinesiomechanics phenomenon which has needed attention for some time. Further, let it be understood without equivocation that you expect certain adjustments to transpire in order that your project may begin and be carried through to its reasonable conclusion—that being the identification of and plans for attacking related matters that surely must come to light as a result of the original study, and the publication of the original results. You are probably in for a surprise to find your plans accepted as reasonable and desirable along with a promise to facilitate them. With this outcome residing firmly in your mind, and knowing that one of the most difficult tasks is in just getting started, it will be comforting to realize that most worthwhile endeavors take a while to mature and that the optimistic declaration of unknown origin that is becoming popular among busy, productive people can help you as well. That is --"Inch by inch, it's a cinch."

DORIS I. MILLER

Laboratory Exercises in Biomechanics for Undergraduate Students

WHENEVER POSSIBLE, laboratory experiments in undergraduate biomechanics courses should afford the student an opportunity to apply the laws of mechanics to actual situations in sport. Such applications not only provide meaningful experiences, but also reinforce the student's knowledge of the fundamental principles and increase his understanding of the related concepts. The two laboratory exercises presented here are examples of an attempt to achieve these objectives.

KINEMATICS AND KINETICS OF A CURLING ROCK AFTER DELIVERY

The sport of curling, specifically the motion of the rock after delivery, provides an appropriate vehicle for the experimental determination of linear and angular position, velocity, and acceleration as functions of time; the relationship between linear and angular velocity; as well as kinetic friction and coefficient of friction. When the curler releases the rock (Figure 1), he imparts to it both a linear and a rotary motion. In the case of a draw shot, the granite curling stone travels about 100 ft before coming to rest in the "rings" or "house" at the opposite end of the rink (Figure 2). During this 15- to 20-sec interval, the rock completes up to three or four turns which can be readily observed by watching the motion of the handle.

As it slides down the ice, the rock is under the influence of two external forces (Figure 3). Its weight (W), which may vary from 40 to 44 lb, acts vertically downward. The ground reaction force (R) is expressed as the vector sum of the normal component (N) directed upward at right angles to the ice surface and the kinetic friction component (Fr_k) acting along the ice surface to oppose the motion. Air resistance can be considered negligible in this situation. As the rock decreases in speed and approaches a condition of rest, the friction experienced by the edge on the outside of the turn may be smaller than that encountered by the inside edge. This unbalance in the friction force with the inside edge approaching a static condition while the outside continues to slide has been suggested as the reason why the rock "curls" or deviates from its initial linear path (2, 3).

The laboratory exercise designed to study these phenomena involves large groups of students and requires a minimum of equipment (Table 1). It has proven to be a particularly enjoyable experience for the students and yet, at the same time, stresses a number of fundamental mechanical principles. The following outline is distributed to the students before the laboratory.

Doris I. Miller is an assistant professor in the School of Physical and Health Education at the University of Washington, Seattle, Washington. The article is based upon a presentation given at the AAHPER National Convention in Minneapolis, Minnesota, April 13, 1973.

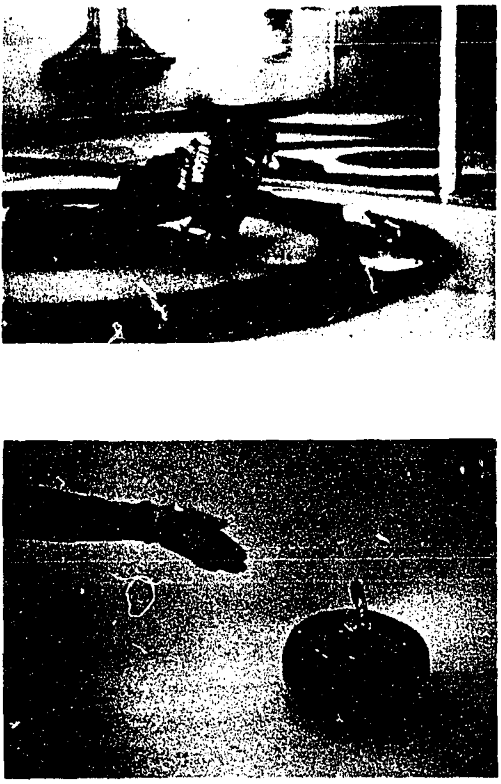

Figure 1. The curling delivery.

Laboratory outline

Introduction. The purpose of this laboratory is to investigate the kinematics and kinetics of a curling rock in a draw shot from the time the rock is delivered until it comes to rest in the "house." The linear position, velocity, and acceleration and the angular position and velocity of the rock will be determined as functions of time. The kinetic friction force and the kinetic coefficient of friction will be calculated. Attempts will also be made to relate the theory of an "unbalanced friction force" to the curl of the rock.

Application. Each group should have 15 to 20 members including one fairly consistent curler who will serve as the subject. The subject should select a particular draw shot and repeat it 3 times. The rock should *not* be swept.

The information to be recorded for each trial is listed on the laboratory record form (Table 2). The items marked with an asterisk (*) must be obtained during the actual trial while the other variables can be determined later. Specifically, the following information must be recorded:

1. The time for the rock to travel from:

(a) Release on the hog line

(b) The hog line to the center of the rink (the latter must be marked since no center line exists on the rink).

(c) The center to the hog line

(d) The hog to the tee line or until the rock comes to rest.

(e) The tee line until the rock comes to rest (if applicable).

2. The distance covered by the rock between the designated lines. Since the rock may not be traveling parallel to the

TABLE 1. EQUIPMENT REQUIRED FOR THE CURLING LABORATORY

Number	Item	Comments
2–4/group	Regulation curling rocks	
8–10/group	Stop watches	Fewer are required if split timers are available
8–10/group	Red poker chips	To indicate the location of the rock at designated distances
8–10/group	Blue poker chips	To indicate the initiation and completion of each half turn of the rock
1/group	100-ft measuring tape	
1	Weigh scale	An inexpensive bathroom scale will serve the purpose
1	Thermometer	One may be located in the curling rink. This is not an essential item

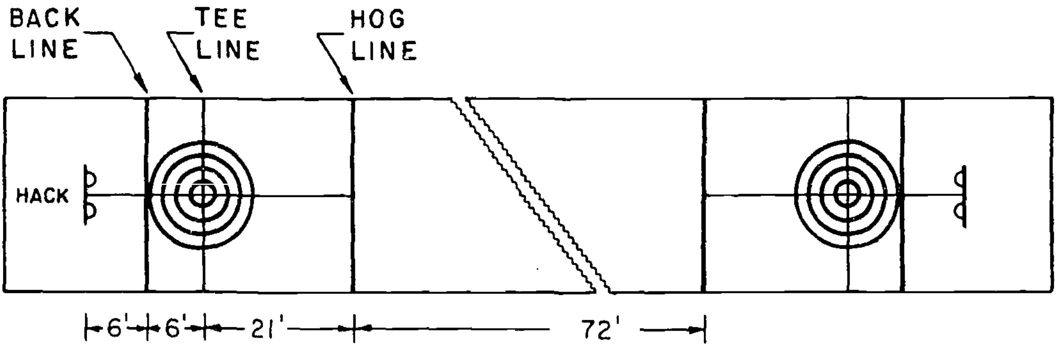

Figure 2. Diagram of curling rink.

restraining boards, it is important to place a marker at the point where it crosses a given line and then to measure the distance between the markers.

3. The time required for each half turn of the rock. Start when the handle is parallel to the length of the rink after release. Also note the location of each half turn on the rink by placing markers on the ice at the beginning and end of each half turn.

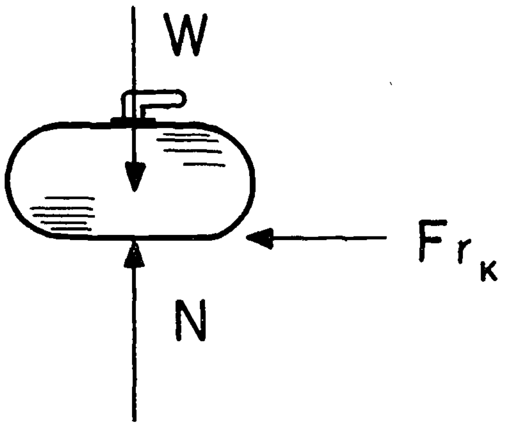

Figure 3. Kinetics of a curling rock.

$$\Sigma F_h = m a_h \qquad \Sigma F_v = m a_v$$

$$-Fr_k = \frac{W}{g} a_h \qquad N - W = 0$$

$$N = W$$

$$Fr_k = \mu_k N$$

$$\mu_k = \frac{Fr_k}{N}$$

4. The place at which the rock begins to curl.

5. The weight and radius of the rock.

Calculations. Determine the following:

1. The linear velocity and linear acceleration of the center of the rock during the distance intervals specified in Part 1. of the previous section. Plot linear position-time, velocity-time, and acceleration-time graphs. (Remember that distance and time intervals are not equal). Include the information from all three trials on each graph.

2. The angular velocity of the rock. Plot angular position-time and velocity-time graphs. Include the information from all three trials on each graph.

3. The linear velocity of the inside and outside edges of the rock each time the handle is perpendicular to the length of the rink (Figure 4). Assume that V_a, V_i, and V_o, the linear velocities of the center of gravity, inside and outside edges of the rock, respectively, are acting in the same direction. The value of V_a must be obtained from the linear velocity-time graph at the time corresponding to the midpoint of the half-turn being considered. (Do not forget that in all linear-angular velocity relationships, the angular velocity must be expressed in radians per second.)

4. The normal and tangential (friction) components of the ground reaction force acting upon the rock. To do this, first construct a free body diagram of the rock as it moves along the ice. Consider the rock as a particle. Then apply the force-mass-acceleration relationship (Newton's second law).

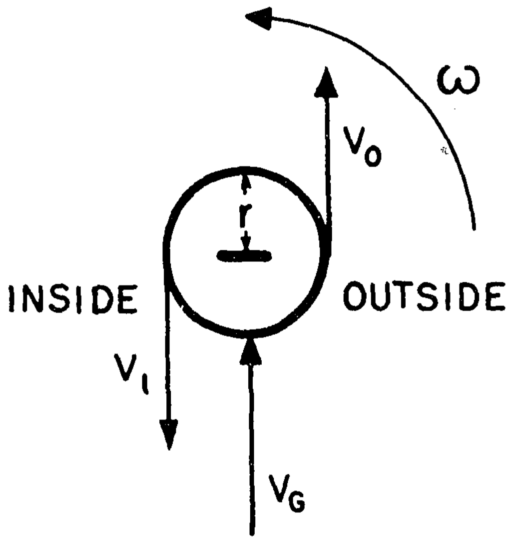

Figure 4. Linear-angular velocity relationship.

$$V_O = V_G + r\omega$$
$$V_I = V_G - r\omega$$

$$\Sigma F = m a$$

Draw a friction-velocity graph with velocity plotted along the horizontal axis.

5. The kinetic coefficient of friction from the relationship.

$$Fr_k = \mu_k N$$

Discussion of results. When interpreting the results of this laboratory, the following questions should be considered. Was the subject consistent in his performance? What are possible sources of error in obtaining the results? What is the relationship between the linear velocity of the rock and the friction force? How do the results compare with those obtained by Harrington (2) and McMillan (3)?

Comments

Examples of the type of position, velocity, and acceleration relationships commonly found in this laboratory are presented in Figures 5 and 6. The coefficient of kinetic friction can be expected to be in the .01 to .04 range. Theoretically, the kinetic friction should be independent of velocity until the rock slows considerably and approaches the condition of rest. At this time, it should become larger as it nears the higher static friction value. This increase, however, is difficult to show in the experimental results because of the gross nature of the measurements.

Since considerable flexibility is afforded by this laboratory, the instructor may want to limit the calculations to linear velocity and acceleration or he may choose to follow the instructions as presented. On the other hand, he may decide to go beyond these basic principles and use the information collected in the laboratory as the basis for considering the inherent error in the differentiation of experimental data and methods of curve fitting.

FLUCTUATIONS IN THE GROUND REACTION FORCE DURING JUMPING TAKE-OFFS[1]

The concept that the ground reaction force fluctuates above and below body weight in response to changes in the acceleration of the performer's mass center is difficult for most students to fully comprehend. The purpose of this laboratory, therefore, is to focus upon this problem in an attempt to increase the student's understanding of the basic principles involved. It actually consists of three exercises which may be presented either as a series or independently at the discretion of the instructor. For the sake of simplicity, most of the analysis is limited to the vertical components of the force and motion. The influence of air resistance is disregarded.

Theoretical calculations

The students are first given a chart (Table 3) listing the vertical coordinates of the mass

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[1] A detailed discussion of this concept is presented in Miller and Nelson (4:53-61).

TABLE 2. CURLING LABORATORY RECORD

Subject* .... Skill Level* .... Temperature* ....

Shot Attempted* .... Pebble Conditions* ....

Rock Weight* .... lb Mass .... slugs Radius* .... ft

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Linear velocity of center of rock	Trial 1	Trial 2	Trial 3
1. Release to hog line			
*a. Distance			
*b. Time			
c. Velocity			
2. Hog line to center			
*a. Distance			
*b. Time			
c. Velocity			
3. Center to hog line			
*a. Distance			
*b. Time			
c. Velocity			
4. Hog line to tee line			
*a. Distance			
*b. Time			
c. Velocity			
5. Tee line to rest			
*a. Distance			
*b. Time			
c. Velocity			

Linear acceleration of center of rock, kinetic friction force, and coefficient of friction

1. -2. a. Change in velocity
    - b. Change in time
    - c. Acceleration
    - d. Kinetic friction force
    - e. Coefficient of friction

(Repeat the same information for intervals 2. 3., 3. 4., and 4. 5.)

Angular velocity

1. First half turn
    - *a. Time
    - b. Angular velocity
    - *c. Location

(Repeat the same information for each subsequent half turn.)

Linear velocity of inside and outside edges of the rock

1. First half turn
    - a. Angular velocity
    - b. Linear velocity of center
    - c. Linear velocity of outside
    - d. Linear velocity of inside

(Repeat the same information for each subsequent half turn.)

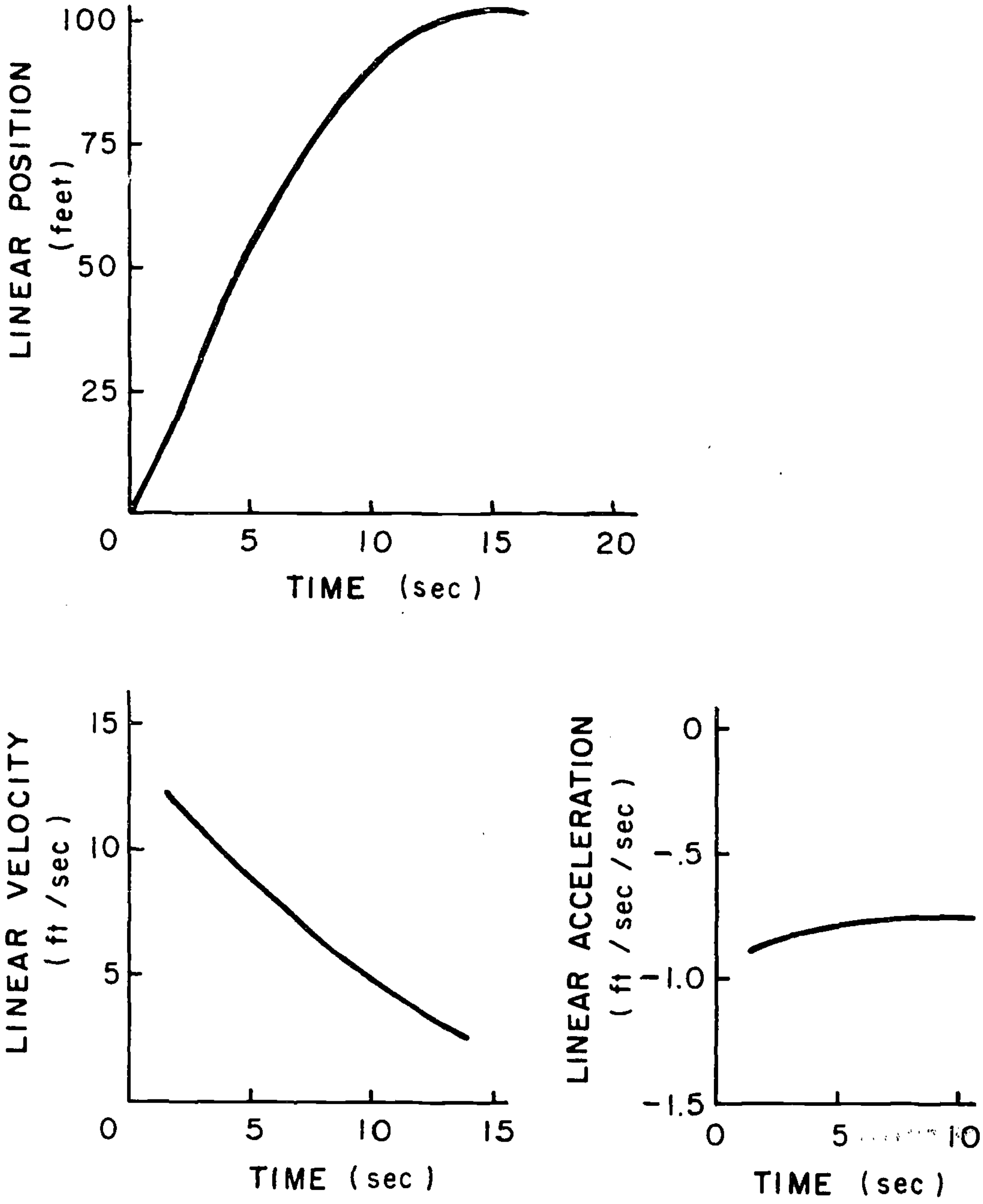

Figure 5. Linear kinematics of a curling rock after delivery.

TABLE 3. CALCULATION CHART[a]

From the time and vertical coordinates of the mass center of a 144-lb jumper, calculate the vertical displacement, velocity, change in velocity, acceleration and ground reaction force component. To facilitate calculations, assume the acceleration due to gravity to be −32.00 ft/sec/sec. Using a single graph with a common zero line, plot the vertical position, velocity and acceleration of the mass center; ground reaction force component; and body weight as functions of time.

Time (sec)	Position (ft)	Displacement (ft)	Velocity (ft/sec)	Change in velocity (ft/sec)	Acceleration (ft/sec)	Reaction force (lb)
0.00	3.40					
0.05	3.39					
0.10	3.37					
0.15	3.34					
0.20	3.29					
0.25	3.21					
0.30	3.07					
0.35	2.90					
0.40	2.71					
0.45	2.55					
0.50	2.43					
0.55	2.36					
0.60	2.36					
0.65	2.45					
0.70	2.67					
0.75	3.03					
0.80	3.55					
0.85	4.15					
0.90	4.72					
0.95	5.21					
1.00	5.62					

[a] Miller and Nelson (4:56)

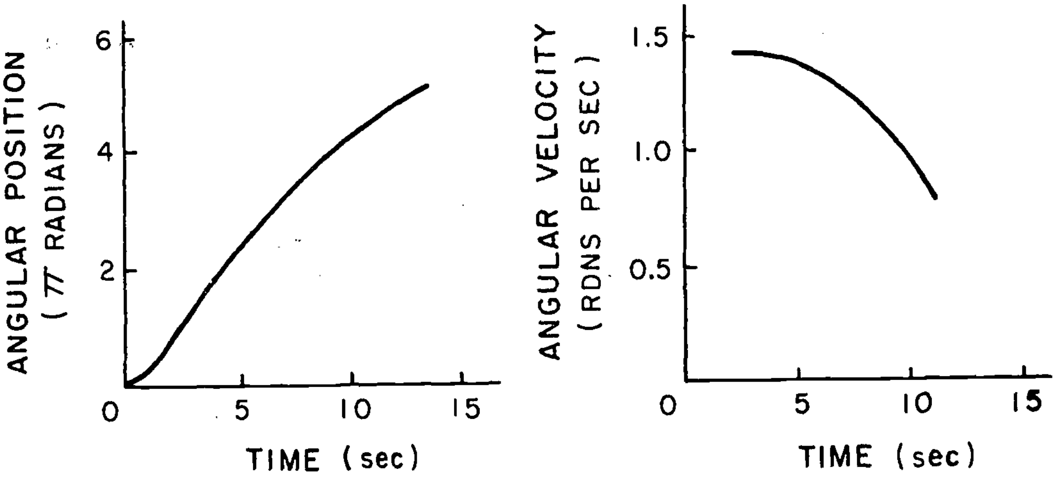

Figure 6. Angular kinematics of a curling rock after delivery.

center of an athlete during a standing jump take-off. These data, modeled after a study on vertical jumping reported by Gerrish (1), are used to determine the vertical components of position, velocity, acceleration, and ground reaction force as functions of time. All of these parameters along with body weight are plotted on a single graph with a common zero line (Figure 7) and interpretations are made. The students are directed to pay special attention to the maxima and minima of the curves as well to the points at which the curves intersect the zero line. For example, a careful examination of Figure 7 should indicate the following:

1. While the body is moving downward, the velocity remains negative; while the body is moving upward, the velocity is positive.
2. A negative acceleration corresponds with a decreasing velocity and a positive acceleration with an increasing velocity.
3. When the acceleration is equal to zero, the velocity is at its minimum or maximum and the ground reaction force is equal to body weight.
4. The jumper can be moving downward and yet experiencing upward or positive acceleration.
5. The vertical component of the ground reaction will always exceed body weight when the acceleration of the jumper's mass center is positive (upward) and will fall below body weight when the acceleration is negative. This fact should be verified by an examination of the free body diagram and the equations of motion (Figure 8).
6. Once free in the air, the jumper's velocity continues to decrease, his acceleration is a consatnt −32 ft/sec/sec (the acceleration due to gravity) and the ground reaction force is zero.

Experimental data

The second portion of the laboratory is devoted to collecting experimental data to illustrate the same principles. The equipment required for this phase includes a Polaroid Graph-Check Sequence Camera, a timing display, a weigh scale with a dial indicator, and some object of known length which can be used for converting film dimensions to actual distances. A piece of masking tape is placed on the hip of the subject to *approximate* the location of the center of gravity. The subject stands on the scale to have his body weight recorded. He then performs a movement of a nonexplosive nature such as descending to or ascending from a crouch position. This action is photographed by the Graph-Check Camera which is fastened securely to a tripod and aligned to an angle to the face of the scale so that the subject's head does not obstruct the view of the dial indicator (Figure 9). The plane containing the mark on the hip of the subject and the conversion object must be at right angles to the optical axis of the camera to avoid perspective error in estimating the linear position of the hip.

From the Polaroid picture which contains a sequence of eight images of the action, the students can read the vertical component of the ground reaction directly from the scale, the vertical position of the hip marker approximating the mass center location, and the time intervals. These data along with the resulting velocity and acceleration can be plotted on a graph similar to the one shown in Figure 7. It is readily admitted that the scale is by no means as accurate as a force platform and is not suitable for investigating explosive types of movements. The sequence of pictures, in conjunction with the scale readings, however, provides first-hand evidence of the fluctuations of the ground reaction force above and below body weight in response to the acceleration of the center of gravity of the body.

Linear impulse-momentum relationships

The theme of this laboratory can be extended to include a consideration of linear impulse and momentum related to jumping performance. The first point to be made is that forces acting over a time interval cause a change in momentum. The force-time curves of the long jump take-off presented by Ramey (7) can be used to illustrate this concept. They can be enlarged by an audio-

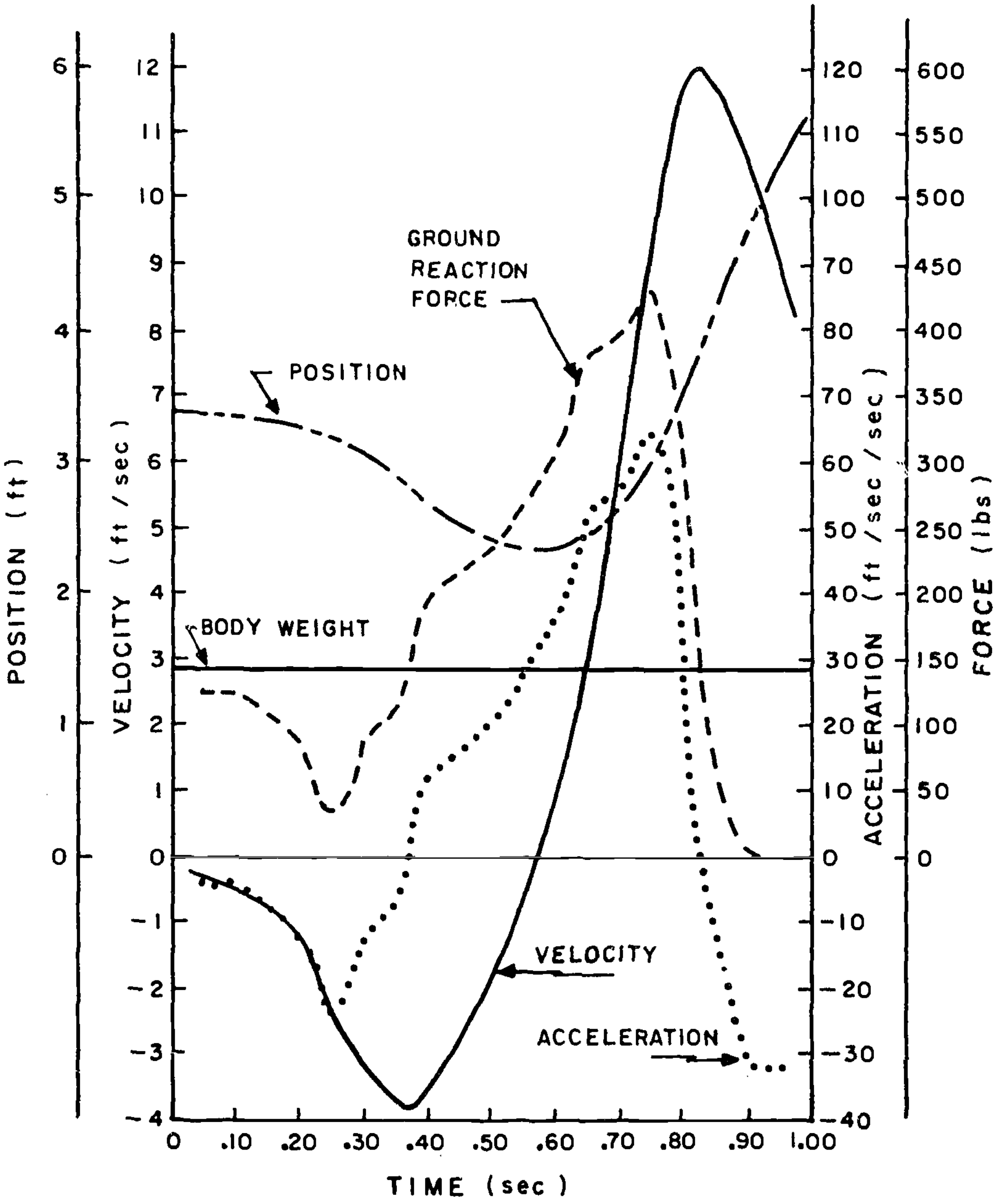

Figure 7. Vertical kinetics and kinematics of a standing jump take-off.

visual department and transferred to a spirit master so that dittoed copies of the curves are available for each student.

While the long jumper is in contact with the board, two external forces act upon him: his body weight and the reaction of the ground. The latter is expressed in terms of a horizontal and a vertical component, R_x and R_y, respectively. The impulses which these forces generate in the horizontal and vertical directions must be treated separately since they are vectors (*Figure* 10).

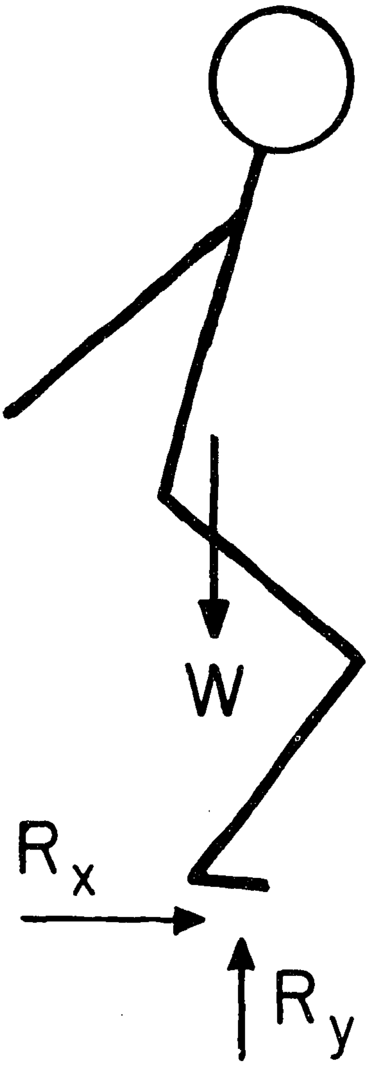

Figure 8. Free body diagram and equations of motion.

$$\Sigma F_x = m\,a_x$$
$$R_x = m\,a_x$$
$$\Sigma F_y = m\,a_y$$
$$R_y - W = m\,a_y$$
$$R_y = W + \frac{W}{g}\,a_y$$

Impulse is represented by $\int F\,dt$ in which F is the vector sum of all the external forces acting upon the body. Thus, in the vertical direction, $F_y = R_y - W$ while in the horizontal direction, $F_x = R_x$. The integral simply specifies the area beneath the force-time curve. In the case of a force such as the ground reaction which fluctuates with time, this curve is irregular. The area beneath it, however, can be approximated by dividing it into small rectangles or squares of known area and then summing these composite areas. If the curve is traced onto graph paper, this task can be accomplished with reasonable accuracy. Since the body weight is constant, the impulse of the weight is simply equal to the area of the rectangle with a base equivalent to the time the jumper is in contact with the board and height equal to his body weight.

From force-time curves recorded during a jump take-off, information on the performer's weight and his velocity at the beginning of the take-off, the horizontal and vertical components of the velocity of his mass center at the instant of projection can be determined. An example of the necessary calculations is shown in Figure 10.

When interpreting the significance of the force-time relationships, the students should consider: the influence of body weight; the implications of spending less time in contact with the take-off board (characteristic of good performers); and how the acceleration of the individual segments contributes to the acceleration of the mass center of the total body. References (5), (6), (7), and (8) are recommended reading for this laboratory and will help to provide an in-depth understanding of the application of linear-impulse momentum concepts to situations in sport.

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Figure 9. Sequence photograph.

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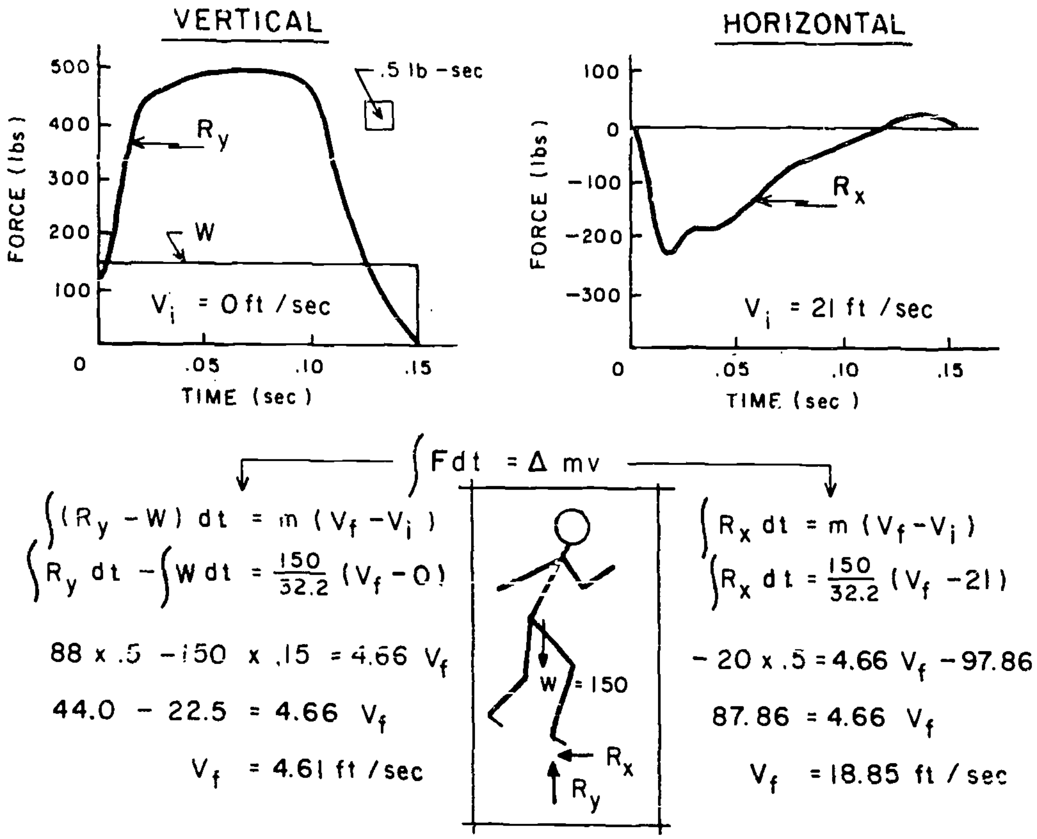

$$\int F\,dt = \Delta mv$$

$$\int (R_y - W)\,dt = m(V_f - V_i)$$

$$\int R_y\,dt - \int W\,dt = \frac{150}{32.2}(V_f - 0)$$

$$88 \times .5 - 150 \times .15 = 4.66\,V_f$$

$$44.0 - 22.5 = 4.66\,V_f$$

$$V_f = 4.61 \text{ ft/sec}$$

$$\int R_x\,dt = m(V_f - V_i)$$

$$\int R_x\,dt = \frac{150}{32.2}(V_f - 21)$$

$$-20 \times .5 = 4.66\,V_f - 97.86$$

$$87.86 = 4.66\,V_f$$

$$V_f = 18.85 \text{ ft/sec}$$

Figure 10. Linear impulse-momentum relationships during a long jump take-off.

DONALD J. HOBART
JOSEPH R. VORRO

Preaxial and Postaxial Neuromuscular Relationships in the Upper Extremity: A Method of Teaching Muscle Innervation

KINESIOLOGY STUDENTS normally are required to learn osteology and muscle actions and attachments in their study of the human organism. They are also asked later, to combine their knowledge of anatomy with mechanics to study various human movements. Consequently, a good comprehensive knowledge of the human body is needed so that kinesiological analysis can become a useful classroom tool. It is reasonable to assume then that in order to make their knowledge of anatomy lasting and useful, general principles must be taught wherever possible.

The purpose of this article is to present a general embryological principle of muscle innervation and to offer a plan to teach the specific innervation of the upper extremity. The use of this plan generally eliminates the need for detailed memorization of specific innervations and aids in future recall of general muscle actions. Thus, this method offers a different and possibly more effective method of organizing and studying the basic musculature.

In order for this plan to be an effective tool certain basic ideas must be presented and understood. The embryological basis is presented first, then a discussion of the typical spinal nerve and its relationship to the brachial plexus, and finally a set of statements presented according to osteological relationships, movement relationships, and exceptions.

EMBRYOLOGY

In the developing human embryo, limb buds emerge laterally from the trunk. Within these buds a bony axis is formed, thus, separating the developing muscles into anterior and posterior compartments (Figure 1). Later, these muscles become the flexors (anterior muscles) and the extensors (posterior muscles) of the limb. With time, the innervating nerves enter the limb also as anterior and posterior branches; the anterior nerves innervate the anterior muscles and the posterior nerves innervate the posterior muscles. Once this neuromuscular relationship is established, it is maintained into adult life.

Since the anterior or flexor muscles are located in front of (i.e., 'pre') the skeletal axis they are generally labeled as preaxial muscles and are innervated by preaxial (anterior) nerves. The posterior or extensor muscles are behind the skeletal axis (i.e., 'post') and are generally labeled as postaxial muscles. The innervating posterior nerves are also called postaxial nerves.

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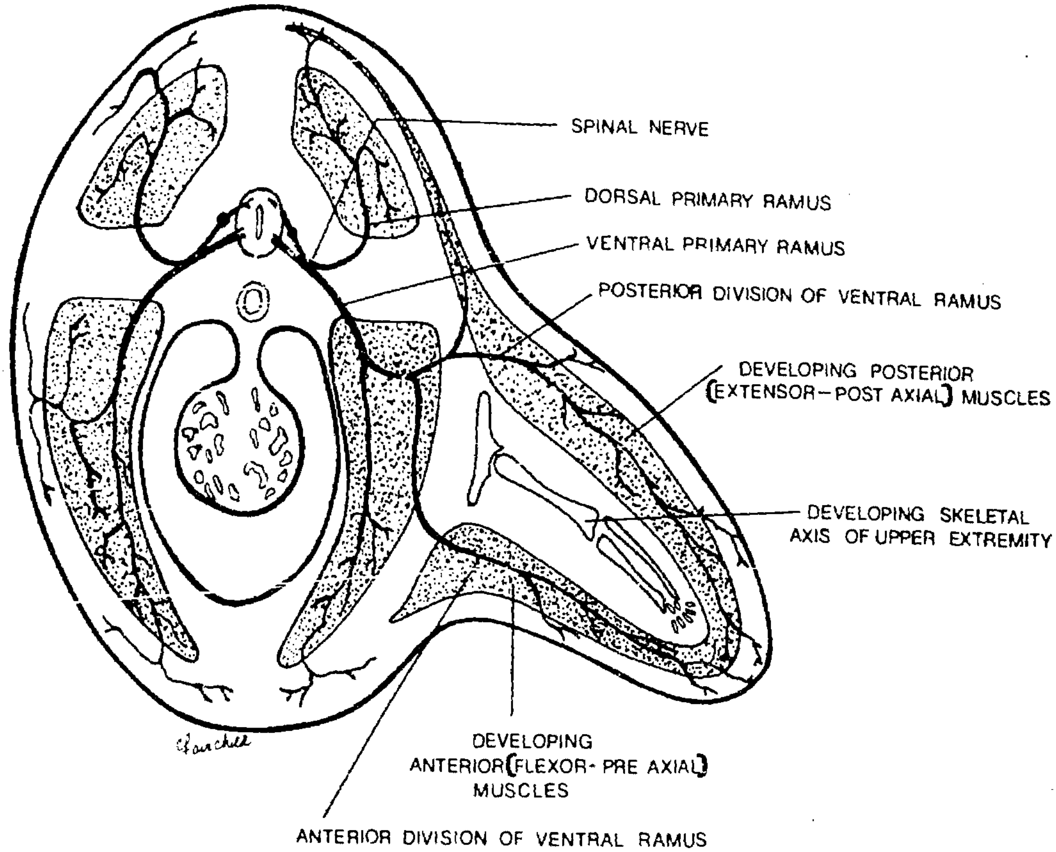

Figure 1. A cross section of the developing human limb-bud.

Postnatally the limb remains divided into anterior and posterior compartments (Figure 2). In the arm these compartments are separated by the humerus and the lateral and medial intermuscular septa. The anterior compartment contains the biceps, brachialis, and coracobrachialis, flexors at the shoulder and elbow joints, while the posterior compartment houses the triceps, an extensor. In the forearm the radius, ulna, interosseous membrane, and the lateral and medial intermuscular septa form the dividing line between the flexors at the wrist, M-P[1], and I-P[2] joints in the anterior compartment and the extensors at the wrist, M-P and I-P joints in the posterior compartment (Figure 2) (4).

TYPICAL SPINAL NERVE

The preaxial and postaxial nerves are branches of one of the 31 typical spinal nerves emanating from the various spinal cord levels. There are 8 cervical, 12 thoracic, 5 lumbar, 5 sacral, and 1 coccygeal nerves, each composed of a dorsal root which receives all of the sensory or afferent impulses, and a ventral root which transmits motor or efferent neurons. The two roots combine to form the mixed (sensory and motor) trunk of the spinal nerve. This part of the nerve is very short and divides into a dorsal and ventral primary ramus almost as soon as it emerges from the intervertebral foramen (Figure 3). The dorsal primary ramus immediately penetrates into the musculature of the back and supplies motor in-

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[1] Metacarpophalangeal joint.

[2] Interphalangeal joint.

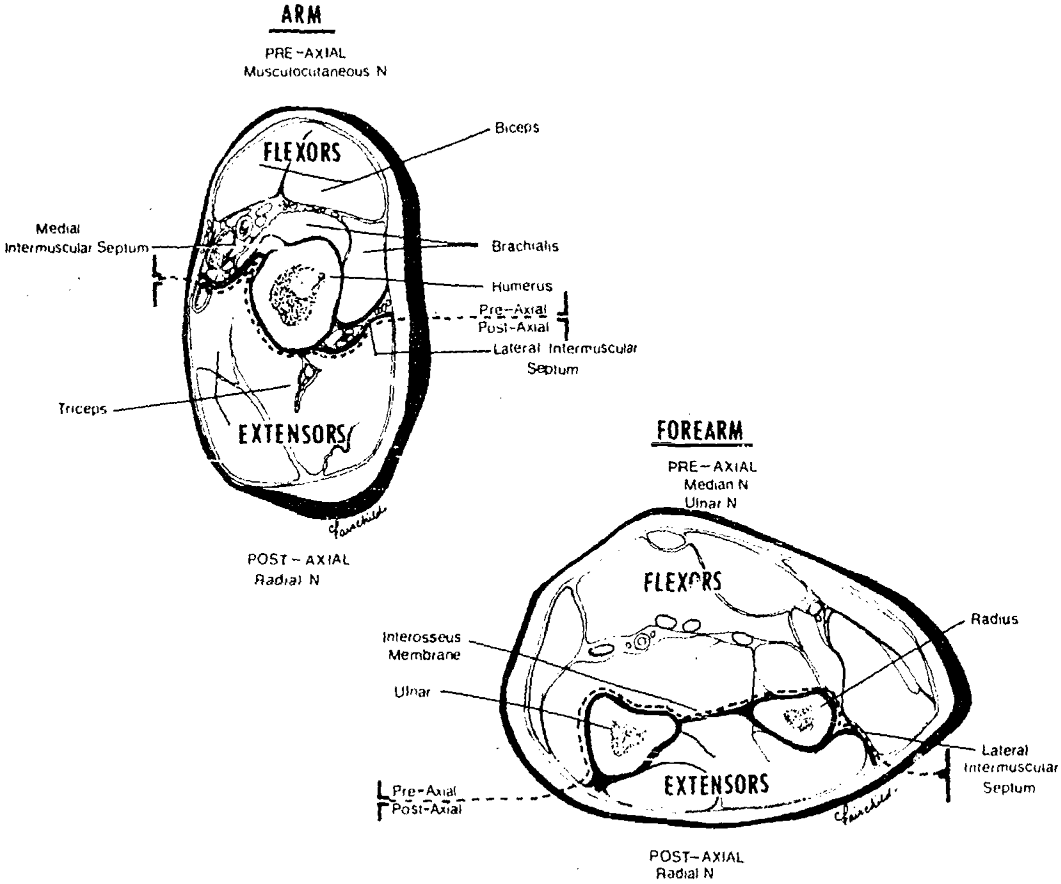

Figure 2. Cross sections of the arm and forearm showing the flexor and extensor compartments.

nervation and cutaneous sensation to this region. The ventral primary ramus on the other hand provides motor and sensory innervation to the lateral and anterior regions of the torso (1, 2, 3, 4).

At certain levels of the spinal cord, the ventral primary ramus of one level will combine with the ventral primary ramus of one or more other levels to form plexuses. These plexuses are areas for the intercommunication of the ventral primary rami. The resulting terminal branches may then carry neurons from various spinal cord levels. Several plexuses of this type are found along the spinal cord, i.e., cervical plexus, brachial plexus, lumbar plexus, and sacral plexus, each providing the innervation for a specific area of the body. The discussion here will be limited to the brachial plexus.

BRACHIAL PLEXUS

The brachial plexus is formed from the ventral primary rami of the last four cervical spinal nerves (C5, C6, C7, C8) and the first thoracic spinal nerve (T1). The ventral rami from C5 to C6 combine to form the superior trunk after posterior fibers have branched from C5 to become the dorsal scapular nerve and the long thoracic nerve (which also received contributions from C6 and C7). Additionally, two small nerves originate from the superior trunk. One, the suprascapular nerve, is composed of posterior fibers, and the other, the nerve to the subclavius, is composed of anterior fibers. The middle trunk is created by the ventral primary ramus of C7 alone, while the

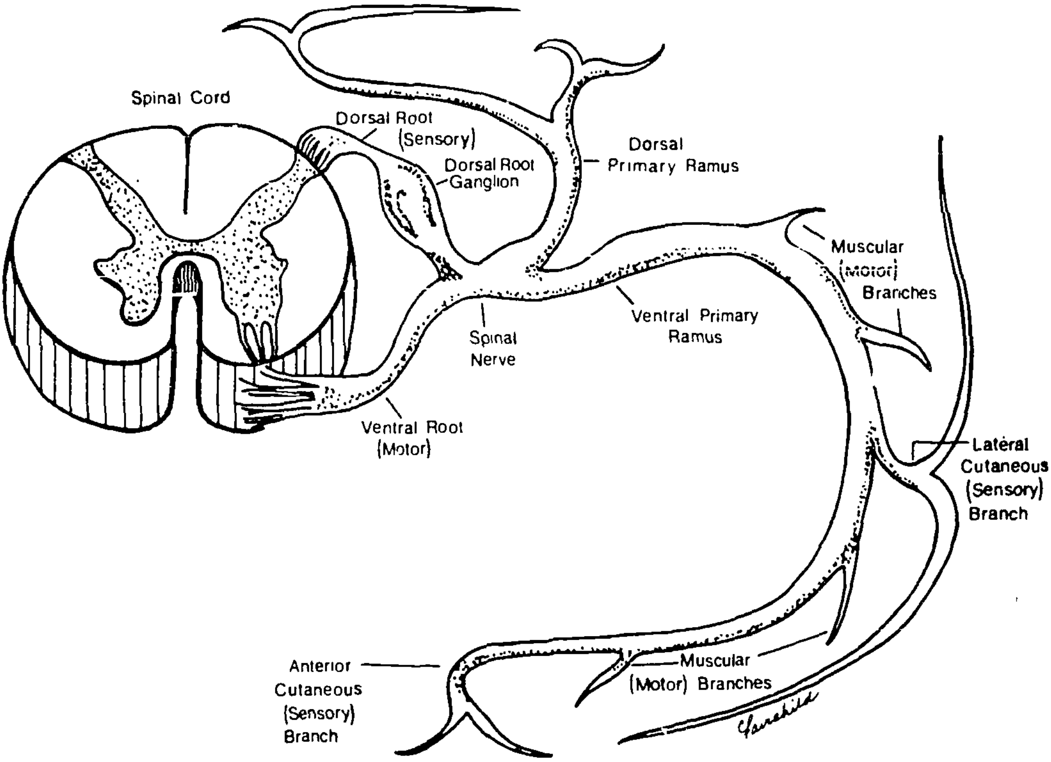

Figure 3. Typical spinal nerve.

inferior trunk is formed from a combination of C8 and T1.

Each of the three trunks then divide into anterior and posterior divisions. All of the posterior divisions combine to form the posterior cord. Thus, all branches originating from this cord will contain only posterior fibers. The anterior divisions from the superior and middle trunks join to make the lateral cord while the anterior division of the inferior trunk becomes the medial cord. Thus, all remaining branches from the lateral and medial cords will contain only anterior fibers. Five small nerves are derived from the cords at this point in the plexus. The lateral and medial pectoral nerves branch from the lateral and medial cords, respectively, while the upper and lower subscapular nerves and the thoracodorsal nerve (middle subscapular) originate from the posterior cord.

After giving off these branches the cords continue distally to approximately the inferolateral border of the pectoralis minor where they divide, intermingle, and unite again to form the terminal nerves of the plexus. The lateral and medial cords divide with one half of each combining to form the median nerve. The remaining part of the lateral cord continues as the musculocutaneous nerve, while the continuation of the medial cord is the ulnar nerve. The two terminal branches of the posterior cord are the axillary and radial nerves (Figure 4).

The important aspect of the brachial plexus, from the standpoint of this discussion, is the division of its terminal branches

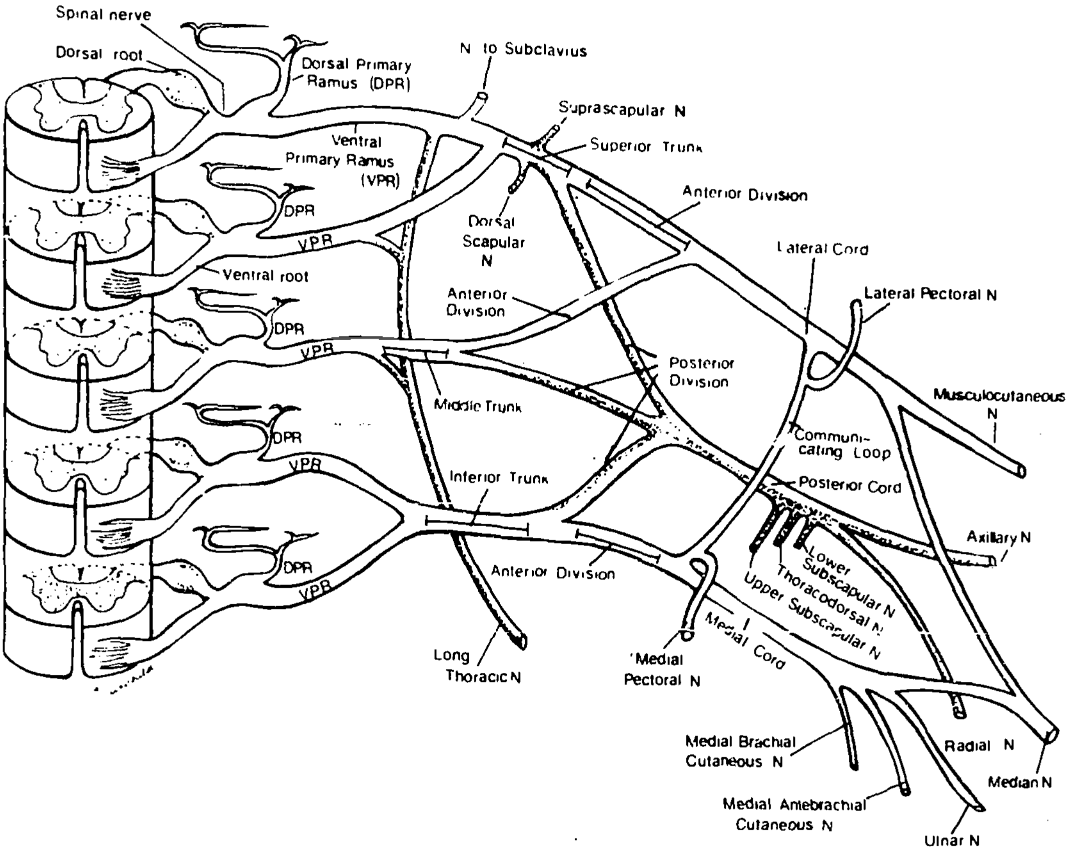

Figure 4. The brachial plexus. The shaded area indicates postaxial nerves.

into preaxial and postaxial groups. This division is summarized below:

Preaxial	*Postaxial*
1. Nerve to subclavius	1. Dorsal scapular nerve
2. Medical pectoral nerve	2. Suprascapular nerve
3. Lateral pectoral nerve	3. Lower subscapular nerve
4. Musculocutaneous nerve	4. Thoracodorsal nerve
5. Median nerve	5. Upper subscapular nerve
6. Ulnar nerve	6. Axillary nerve
	7. Radial nerve
	8. Long thoracic nerve

PRE- AND POSTAXIAL RELATIONSHIPS

Within the preceding sections, important facts have been discussed: (1) the musculature of the developing limb-bud is divided into a flexor (anterior) and an extensor (posterior) compartment by the limb skeleton, (2) the developing flexor muscles are innervated by the anterior divisions of the ventral primary rami while the extensor muscles receive their innervation from the posterior divisions, (3) these neuromuscular relationships are maintained throughout development, and (4) the brachial plexus is composed of five ventral primary rami, which divide into anterior and posterior divisions, intermingle, and eventually unite to form the terminal preaxial and postaxial nerves of the plexus.

Through the application of the above facts, it is possible to develop a set of general statements that can be used to define the specific innervation of the muscles of the upper extremity. This can be accomplished by: (1) pointing out how osteology can be used, (2) a discussion of movements other than flexion and extension, (3) presenting a functional breakdown of the terminal nerves of the brachial plexus, and (4) noting the exceptions.

Osteology. Observation of embryological development has revealed that in the upper extremity the clavicle has exclusively preaxial muscles attached to it and the scapula (excluding the coracoid process) has only postaxial muscle attachments. Thus, these bones can be considered preaxial and postaxial, respectively. The remaining bones of the upper extremity have both preaxial and postaxial muscles attaching to them (1, 3, 4).

The coracoid process of the scapula developed as an anterior bone and consequently has preaxial muscle attachments. It maintains its preaxial status although it later became attached to the body of the scapula. The clavicle is also a preaxial bone with preaxial muscle attachments. Muscles originating from the coracoid process and the clavicle; the pectoralis minor, biceps brachii, coracobrachialis, pectoralis major, and subclavius, are all preaxial muscles. Those muscles attaching to the scapula proper: the rhomboid major and minor, supraspinatus, infraspinatus, subscapularis, serratus anterior, deltoid, triceps, latissimus dorsi, teres major and teres minor, are all postaxial muscles. This information may be summerized in three statements:

Statement 1. Muscles attaching to the coracoid process of the scapula are preaxial muscles.

Statement 2. Muscles attaching to the scapula proper are postaxial muscles.

Statement 3. Muscles attaching to the clavicle are preaxial muscles.

The order of the above statements must be maintained to permit the student to determine the hierarchy of muscle attachments. For instance, is the biceps brachii a preaxial or postaxial muscle? The answer would be preaxial, as the coracoid process origin overrides the scapular origin. Similarly, the deltoid muscle is considered a postaxial muscle as its scapular origin takes preference over its clavicular origin.

Movements. It has been determined that movements other than flexion and extension are related to preaxial or postaxial organization. These additional movements are presented below and except where noted apply to the glenohumeral, elbow, wrist, M–P, and I–P joints. Each muscle that has one of these movements as their prime action will fall into the appropriate preaxial or postaxial category.

Preaxial:

1. Flexion (with the exception of the brachioradialis)
2. Adduction
3. Pronation
4. Abduction at the M–P joints
5. Opposition of the thumb

Postaxial:

1. Extension
2. Abduction
3. Supination
4. Rotation of the humerus

Statement 4. Muscles that have postaxial movements as their prime action are innervated by postaxial nerves.

Statement 5. Muscles that have preaxial movements as their prime action are innervated by preaxial nerves.

Now that the osteological and motion relations to the preaxial and postaxial concept have been examined, the terminal branches of the brachial plexus can be discussed and a functional classification of the above nerves outlined (see Tables 1 and 2):

Exceptions. Within any system of classification there exists exceptions and this system is no different. The exceptions include: (1) The brachioradialis is an elbow flexor (preaxial movement) but is innervated by the radial nerve which is postaxial, (2) The trapezius is innervated by a cranial nerve (XI, accessory nerve) which does not fit into this classification.

TABLE 1. OUTLINE OF THE BRANCHES OF THE TRUNKS AND CORDS OF THE BRACHIAL PLEXUS

Postaxial nerves and muscles
1. Dorsal scapular—Rhomboid major and minor
2. Suprascapular—Supraspinatus and infraspinatus
3. Long thoracic—Serratus anterior
4. Upper subscapular—Subscapularis
5. Thoracodorsal—Latissumus dorsi
6. Lower Subscapular—Subscapularis and teres major

Preaxial nerves and muscles
1. Nerve to subclavius—Subclavius
2. Lateral pectoral—Pectoralis major
3. Medial pectoral—Pectoralis major and minor

SUMMARY

The innervation of the upper extremity can be summarized by 9 statements which, when applied in order, can be used to determine the specific innervation of each muscle:

1. Muscles attaching to the coracoid process are preaxial.
2. Muscles attaching to the scapular proper are postaxial.
3. Muscles attaching to the clavicle are preaxial.
4. Since in the area of the shoulder the number of muscles innervated by each nerve is minimal, no general concepts can be drawn. However, the three statements listed below should help to avoid rote memorization of the innervation of each muscle:

a. Postaxial nerves associated with the scapula are: dorsal scapular, suprascapular, long thoracic, upper and lower subscapular nerves.

b. Postaxial nerves associated with shoulder movements are the axillary, long thoracic and thoracodorsal nerves.

c. Preaxial nerves associated with shoulder movements are pectoral nerves, nerve to subclavius, and musculocutaneous nerves.

5. Preaxial muscles are flexors, adductors, and pronators.
6. Postaxial muscles are extensors, abductors, supinators, and humeral rotators.
7. Muscles located in the hand are preaxial.
8. Preaxial muscles located in the forearm and hand are innervated by the median or ulnar nerve. Except for 1½ muscles, the median nerve innervates all of the preaxial forearm muscles as well as five muscles located in the hand (the thenar muscles and the two lateral lumbricals). The ulnar nerve innervates 1½ preaxial muscles in the forearm (flexor carpi ulnaris and the medial two heads of the flexor digitorum profundus) and all muscles located in the hand not innervated by the median nerve.
9. Postaxial muscles located in the arm and forearm are innervated by the radial nerve.

As an aid in using the above statements to determine the specific innervation of a muscle the following steps are offered:

1. Does the muscle attach to the scapular or clavicle? If not, continue.
2. Where is the muscle generally located: Anterior thoracic wall, arm, forearm, or hand?
3. What is the prime action of the muscle? Is it a preaxial or postaxial movement? If it is located in the forearm and is preaxial, is it the flexor carpi ulnaris or the flexor digitorum profundus? If it is located in the hand, is it a thenar muscle or the 1st or 2nd lumbrical?

With the answers to these questions and a good understanding of the above statements, the student should be able to determine the specific innervation of any muscle in the upper extremity.

ACKNOWLEDGMENT. The authors wish to thank Carol Fairchild for her excellent art work in the preparation of this manuscript.

TABLE 2. OUTLINE OF THE TERMINAL BRANCHES OF THE BRACHIAL PLEXUS AND THE MUSCLES THEY INNERVATE

Axillary nerve: Postaxial, innervates an abductor of the shoulder joint and a humeral rotator:

1. Deltoid
2. Teres minor

Radial nerve: Postaxial, innervates extensors of the elbow, wrist, M-P, I-P joints, supinator of the forearm, and an abductor of the thumb (it innervates no muscles located in the hand):

1. Triceps
2. Anconeous
3. Supinator
4. Extensor carpi radialis longus
5. Extensor carpi radialis brevis
6. Extensor carpi ulnaris
7. Extensor digitorum
8. Extensor indicis
9. Extensor digiti minimi
10. Extensor pollicis longus
11. Extensor pollicis brevis
12. Abductor pollicis longus
13. Brachioradialis—Exception

Musculocutaneous nerve: Preaxial, innervates flexors of the shoulder and elbow joints:

1. Coracobrachialis
2. Biceps brachii
3. Brachialis

Median nerve: Preaxial, innervates flexors of the wrist, M-P, and I-P joints, pronators of the forearm and thumb opposers:

1. Palmaris longus
2. Flexor digitorum superficialis
3. Flexor digitorum profundus (the two heads that insert in the second and third digits)
4. Flexor pollicis longus
5. Pronator teres
6. Pronator quadratus
7. Flexor carpi radialis
8. First and second lumbricales
9. Flexor pollicis brevis
10. Abductor pollicis brevis
11. Opponens pollicis

Ulnar nerve: Preaxial, innervates 1½ flexors at wrist joint; abductor, adductor and flexor of last four M-P and I-P joints; and adductor of thumb:

1. Flexor carpi ulnaris
2. Flexor digitorum profundus (two heads that insert in the fourth and fifth digits)
3. Third and fourth lumbricales
4. Dorsal interossei
5. Palmar interossei
6. Adductor pollicis
7. Opponens digiti minimi

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JAMES G. ANDREWS

Biomechanical Analysis of Human Motion

BIOMECHANICS IS A scientific discipline concerned with the application and extension of the principles and methodology of mechanics, to the analysis of biological systems. In the general biomechanical analysis of any human motor activity, we seek to relate observable configurations or motions of the body, to the forces which must be acting in order to maintain those configurations or produce those motions.

The development of valid and useful force-motion relationships requires that the body be represented by a simple yet realistic mechanical model. Subsequent investigations of the force-motion equations describing the behavior of that model are of considerable practical interest, not only to physical educators, coaches, and activity participants, but also to physicians, surgeons, physical therapists, and the handicapped and disabled. These investigations should lead to a better understanding of how physical activities are actually accomplished and should help to establish how to teach and train people to perform them more effectively and efficiently.

MODELING

Human body segments, with the exception of the hands and feet, may often be realistically idealized as rigid bodies for the purposes of a biomechanical analysis. The bony internal structure of any anatomical segment conforms closely to the idealization of a rigid body. The surrounding tissues, although deformable, usually undergo relatively small changes in size and/or shape during segment motion. These factors, coupled with the mathematical simplicity associated with the dynamic analysis of rigid as opposed to deformable bodies, have been used to justify the representation of body segments as rigid bodies for the purpose of performing biochemical analyses.

The human body may therefore be regarded as a mechanical system composed of N rigid bodies B_i $(i = 1, 2, \ldots, N)$ interconnected by anatomical joints. The characteristics of these joints vary from one location to another in the body, and the precise mechanical nature of most normal human joints is unknown. Consequently, in order to model these joints properly, we are normally forced to represent them as smooth but slightly loose ball-and-socket joints. The assumption of joint smoothness appears reasonable, particularly for normal subjects where an adequate supply of synovial fluid furnishes an excellent lubricating film between articular surfaces that have no discontinuities. For subjects with abnormal (e.g., arthritic) joints, however, such an idealization must be used with caution.

The concept of letting slightly loose ball-and-socket joints represent the anatomical joints between body segments is a useful one. Most normal human joints appear to exhibit some degree of looseness and allow for some small amount of general, three-dimensional rotational motion. By utilizing a mechanical ball-and-socket joint model, where the ball center is allowed to displace slightly relative

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to the socket center, we allow not only for all three possible rotational degrees of freedom, but also for all three possible translational degrees of freedom.

ANALYSIS

Each body segment B_i, if idealized as a rigid body, will move in accordance with the principles of Newtonian (nonrelativistic) mechanics. These principles specify that the motion of B_i in an inertial reference frame R is governed by two vector equations. These equations are the translational equation, referred to as the principle of the motion of the mass center, or center of gravity, G_i of B_i in R, i.e.,

$$\mathbf{F}_i = m_i \mathbf{a}^{G_i} \tag{1}$$

and the rotational equation, referred to as the principle of angular momentum of B_i about G_i in R, i.e.,

$$\mathbf{M}^{G_i} = \dot{\mathbf{H}}^{G_i} \tag{2}$$

In equation (1), $\mathbf{F}_i$ is the resultant external force acting on B_i, m_i represents the mass of B_i, and $\mathbf{a}^{G_i}$ denotes the acceleration of G_i in R. In equation (2), $\mathbf{M}^{G_i}$ is the resultant moment about G_i of all external forces and couples acting on B_i, and $\dot{\mathbf{H}}^{G_i}$ is the time-derivative of $\dot{\mathbf{H}}^{G_i}$, the angular momentum of B_i about G_i in R. (Symbols set in italic, such as m_i, represent scalar quantities, whereas, symbols set in boldface, such as $\mathbf{F}_i$, denote vector quantities.)

SIMPLIFICATIONS FOR PLANE MOTION

Many human motor activities are essentially two-dimensional, with all points in the body moving in planes that are fixed in R and parallel to each other. Normal gait, for example, is essentially planar in nature, and the body segments are often regarded as moving in the midsagittal plane. If we idealize body segments as rigid laminas, and consider their two-dimensional motion in an (x, y)-plane fixed in R, then the two vector equations of motion (1) and (2) reduce to the three scalar equations

$$F_{x_i} = m_i a_x^{G_i} \tag{3}$$

$$F_{y_i} = m_i a_y^{G_i} \tag{4}$$

$$M_z^{G_i} = I_z^{G_i} \alpha^{B_i} \tag{5}$$

On the left-hand sides of equations (3) and (4), F_{x_i} and F_{y_i} represent the x and y components of $\mathbf{F}_i$, respectively; in (5), $M_z^{G_i}$ denotes the z component of $\mathbf{M}^{G_i}$. On the right-hand sides of (3) and (4), $a_x^{G_i}$ and $a_y^{G_i}$ are the x and y components of a^{G_i}, respectively, while m_i denotes the mass of B_i, in (5), $I_z^{G_i}$ represents the moment of inertia of B_i about a z-axis through G_i, and α^{B_i} denotes the scalar angular acceleration of B_i in R.

FORCE AND MOMENT FACTORS

The left-hand sides of the equations governing the motion of B_i in R contain the force and moment factors. The resultant external force $\mathbf{F}_i$ acting on B_i is the vector sum of all external force distributions acting on B_i. The resultant moment acting on B_i about G_i, $\mathbf{M}^{G_i}$, is the vector sum of all moments about G_i due to each individual external force distribution acting on B_i.

The external force distributions contributing to $\mathbf{F}_i$ and $\mathbf{M}^{G_i}$ may be classified into two broad categories. The first category (I) includes all remotely applied force distributions such as the distributed weight force. It can be shown that the system of parallel distributed weight forces acting on B_i influences the equilibrium or motion of that rigid body in exactly the same way as (i.e., is equipollent to) a single force $\mathbf{W}_i$, the weight force, acting downward at the center of gravity or mass center point G_i and B_i. The magnitude of this resultant weight force, as well as the approximate location of point G_i where it may be regarded as acting, can be estimated with reasonable accuracy using the techniques and data recommended by Hay (1).

The second broad category (II) of external force distributions acting on B_i includes all directly applied force distributions arising due to contact of the segment with the external environment. This category may be conveniently divided into (a) those contact force distributions acting at the proximal and distal joints due to the presence of adjacent body segments (e.g., the compressive effects of the neighboring cartilage and bony structures, and the tensile effects of the muscles and ligaments, etc., which are theoretically separated when each body segment is isolated by passing an imaginary sectioning surface through the proximal and distal joints); and (b) those other contact force distributions acting on the body segment (e.g., the effects of segment contact with an external object such as the ground or a piece of equipment, and the effects of contact with other body segments on the surface area between the proximal and distal joints).

It can be shown that any general force distribution is equipollent to the resultant force of that distribution applied at an arbitrary point Q_i, plus a single couple with moment equal to the resultant moment of that force distribution about Q_i. In performing a biomechanical analysis of a typical body segment during any human motor activity, we normally make a sketch of that segment called a free body diagram or *FBD* (Figure 1). This sketch shows all external force distributions acting on B_i.

For the sake of simplicity, however, instead of showing the weight as a distributed (category I) force, we normally show only the equipollent resultant weight force $\mathbf{W}_i$ acting downward at the center of gravity, G_i. Similarly, instead of showing the complicated force distributions at the proximal and distal joints (category IIa), we normally show only the equipollent resultant force and moment corresponding to these distributions, arbitrarily referred to or acting at the joint center point (P_i for proximal, and D_i for distal, respectively). Finally, instead of showing the sometimes equally complex force distributions acting on the segment surface between the proximal and distal joints (category IIb), we normally show only the equipollent resultant force and the resultant moment corresponding to these distributions, acting at some arbitrary but appropriately located point Q_i.

Category IIa force distributions are transmitted by internal anatomical structures in the neighborhood of the body joints, and it is presently impossible to measure these forces directly and accurately in live human subjects. Category IIb force distributions, on the other hand, can be directly and accurately measured using force plates and other appropriately instrumented pieces of experimental equipment.

It is indeed unfortunate that category IIa force distributions cannot be measured directly and reliably, because these forces are of major interest to us if we wish to thoroughly understand a particular motor activity and devise and develop suitable methods for training and strengthening people to perform it more efficiently and effectively. The equipollent resultant force and moment at any body joint, since they depend directly on the individual force distributions in the various anatomical structures, are thus also impossible to reliably measure at present. These resultants may be determined indirectly, however, if all other terms in the equations of motion are known. This indirect approach to the determination of the resultants of all category IIa force distributions is characteristic of the biomechanical analysis of human motor activities, and it has been referred to as the indirect dynamics problem of biomechanics (2). Additional comments on this general method, and an example problem illustrating its use, are included in the last two sections of this paper.

INERTIA FACTORS

The inertia factors m_i and $I_z^{G_i}$ which affect the two-dimensional motion of B_i in R appear on the right-hand sides of equations (3), (4), and (5). The mass m_i is a scalar measure of the body's resistance to accelerated translational motion (i.e., motion of B_i such that no rotation takes place relative to R). Mass is related to body weight W_i by

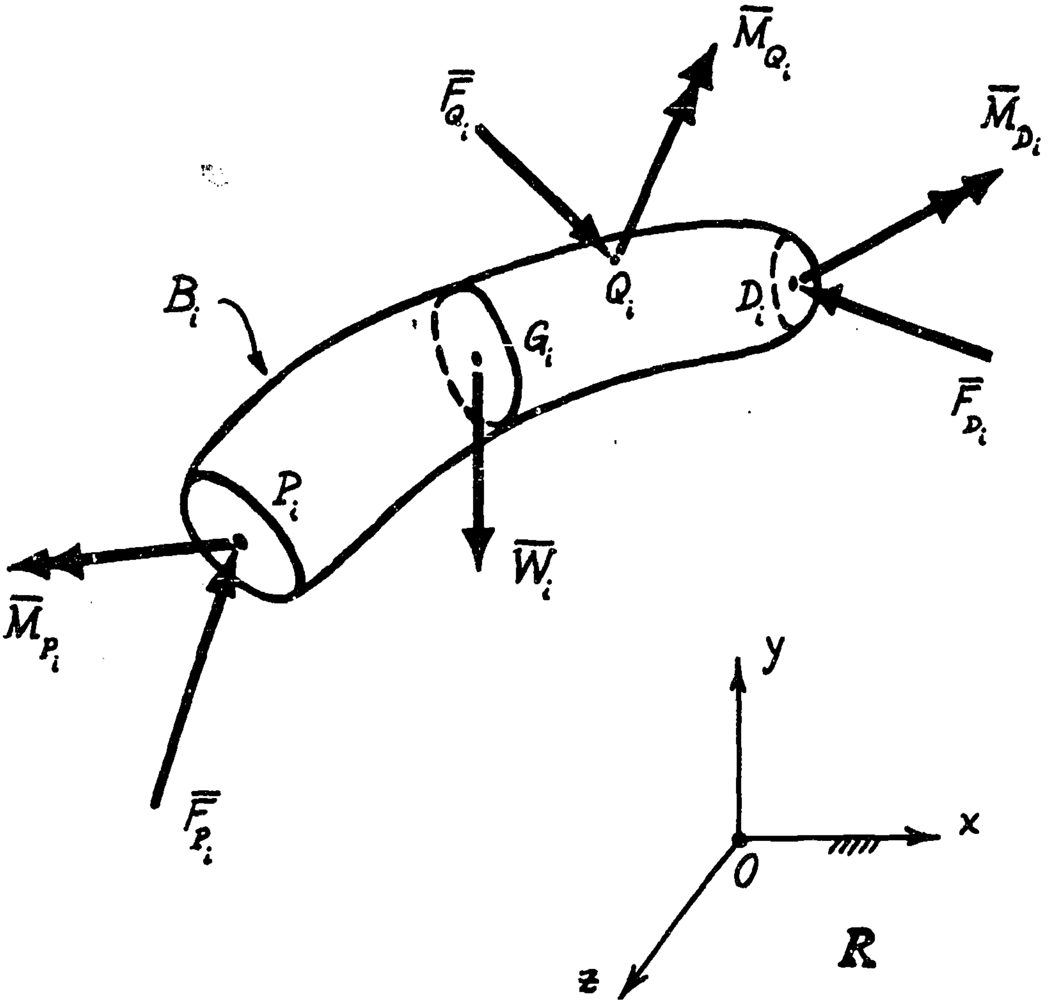

Figure 1. Free body diagram (FBD).

g, the local acceleration due to gravity (g is approximately equal to 9.8 mps^{-2}, or to 32.2 fps^{-2}), through Newton's second law. For a freely falling body subjected to only the weight force acting downward in the positive y-direction, equation (4) becomes

$$W_i = m_i g \qquad (6)$$

The moment of inertia term $I_z^{G_i}$ is a measure of the body's resistance to accelerated rotational motion. Moment of inertia is a point property of the body B_i (indicated by the superscript letter G_i), and it is also associated with an axis through that point (indicated by the subscript letter z). Thus, $I_z^{G_i}$ is the moment of inertia of body B_i about a z-axis through G_i. We can always express $I_z^{G_i}$ as the product of the mass m_i of B_i and the square of a characteristic length $k_z^{G_i}$, where $k_z^{G_i}$ is called the radius of gyration for B_i about a z-axis through G_i. Thus, we have that

$$I_z^{G_i} = m_i(k_z^{G_i})^2 \qquad (7)$$

In order to determine appropriate values for m_i and $I_z^{G_i}$ for any particular body segment of a live human subject, we again must

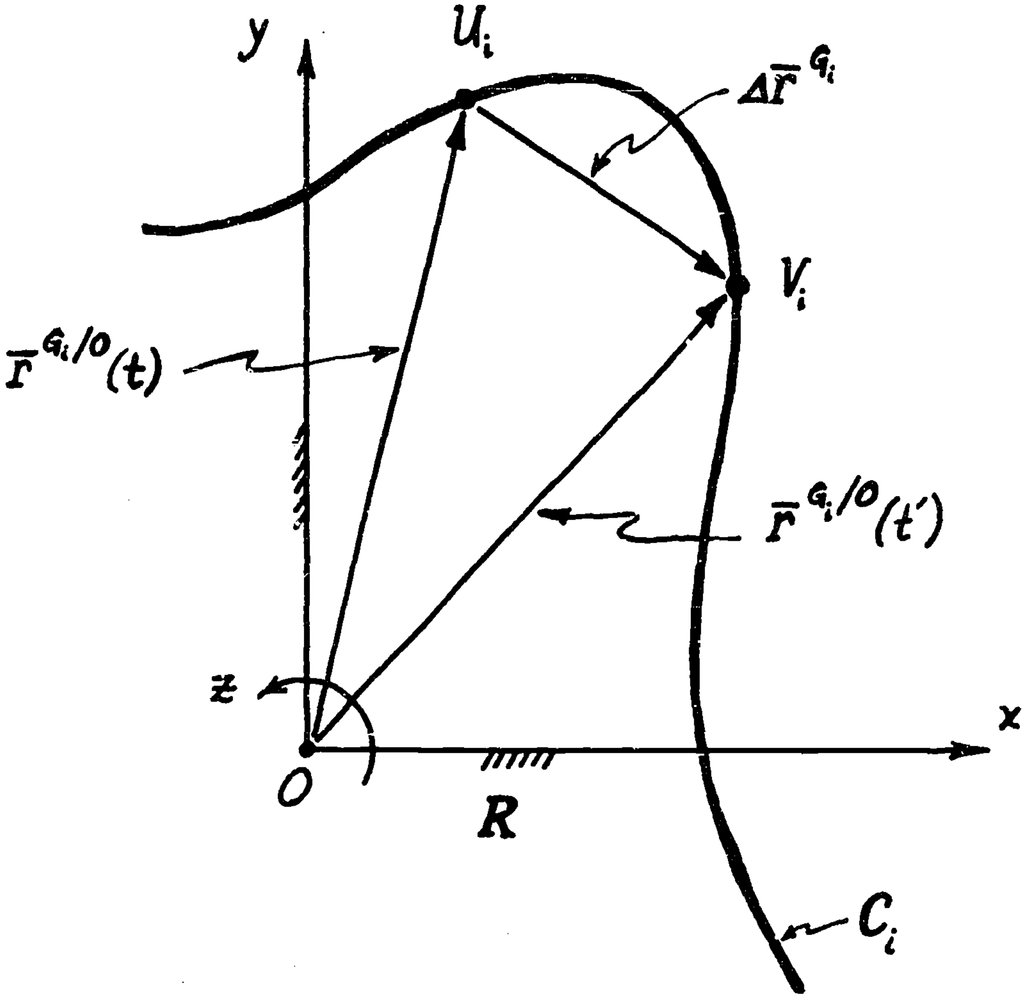

Figure 2. Location of G_i at time t and at time t′.

use anthropometric measurements and data and procedures that yield at best only approximate values. Segment mass values can be determined using equation (6) if the weight force $\mathbf{W}_i$ is estimated with reasonable accuracy as recommended by Hay (1), and if the local value of g is known. The situation regarding the determination of reasonably accurate moment of inertia (or radius of gyration) values is considerably less satisfactory. For a review and critique of the data and procedures currently available, see the survey article by Hay (3).

KINEMATIC FACTORS

The acceleration components of point G_i in R appear as right-hand side terms in equations (3) and (4), and in order to develop an understanding of these terms, it is useful to review the basic definitions in two-dimensional particle kinematics. Let point G_i move on a curve C_i fixed in the (x, y)-plane of the inertial reference frame $R{:}Oxyz$ with origin O. At time t, G_i is at point U_i on C_i; at a later time $t' \equiv t + \Delta t$, G_i is at point V_i on C_i (Figure 2).

The vector locating G_i relative to O at time t is denoted by $\mathbf{r}^{G_i/O}(t)$, and the vector locating G_i relative to O at time t' is denoted by $\mathbf{r}^{G_i/O}(t')$. We define the *displacement* of G_i in R during the time-interval $\Delta t \equiv t' - t$ by the symbol $\Delta\mathbf{r}^{G_i}$, where

$$\Delta \mathbf{r}^{G_i} \equiv \mathbf{r}^{G_i/O}(t') - \mathbf{r}^{G_i/O}(t) \tag{8}$$

The *average velocity* of G_i in R during Δt is denoted by $\mathbf{v}^{G_i}_{\text{avg}}$, where

$$\mathbf{v}^{G_i}_{\text{avg}} \equiv \Delta \mathbf{r}^{G_i}/\Delta t \tag{9}$$

The *velocity* of G_i in R at time t, denoted by $\mathbf{v}^{G_i}(t)$, is defined in terms of a limit as Δt gets very small, or as t' approaches t:

$$\mathbf{v}^{G_i}(t) \equiv \underset{\Delta t \to 0}{\text{limit}} \left(\mathbf{v}^{G_i}_{\text{avg}}\right) \tag{10}$$

The direction of $\mathbf{v}^{G_i}(t)$ is tangent to the curve C_i at U_i since the direction of $\Delta\mathbf{r}^{G_i}$, as Δt approaches zero, gets closer and closer to that tangent line.

The *average acceleration* of G_i in R during Δt is denoted by $\mathbf{a}^{G_i}_{\text{avg}}$, where

$$\mathbf{a}^{G_i}_{\text{avg}} \equiv [\mathbf{v}^{G_i}(t') - \mathbf{v}^{G_i}(t)]/\Delta t \tag{11}$$

The *acceleration* of G_i in R at time t, denoted by $\mathbf{a}^{G_i}(t)$, is also defined in terms of a limit as Δt gets very small:

$$\mathbf{a}^{G_i}(t) \equiv \underset{\Delta t \to 0}{\text{limit}} \left(\mathbf{a}^{G_i}_{\text{avg}}\right) \tag{12}$$

If we take movies of a particular human motor activity and identify the anatomical joint center points in each film frame, then we can locate the center of gravity of each individual body segment in each film frame by using appropriate center of gravity location data. If the developed pictures show the base reference frame R in the background, then we can locate each segment's center of gravity G_i in R at each instant of time t when a film frame is exposed. These position vectors $\mathbf{r}^{G_i/O}(t)$ can then be used to obtain the frame to frame displacement vectors $\Delta\mathbf{r}^{G_i}$, which can in turn be used to determine average velocity values $\mathbf{v}^{G_i}_{\text{avg}}$ If the number of film frames exposed per second is large enough so that the points G_i do not move too much from one frame to the next, then we can use the calculated average velocity values as approximate values for the actual velocities. These approximate velocity values can then be used to generate average acceleration vectors, which in turn can be used to approximate the actual acceleration values. In this way, we can experimentally measure the location history of the approximately located center of gravity points for each body segment, and deduce approximate values for $a_x^{G_i}$ and $a_y^{G_i}$ during the time period when we wish to study the motion of the various body segments B_i in R.

The scalar angular acceleration of B_i in R, α^{B_i}, appears as a right-hand side term in equation (5). In order to assure a proper understanding of this quantity, it is useful to review the basic definition in two-dimensional rigid body rotational motion. Let the rigid lamina B_i move in the (x, y)-plane of the inertial reference frame $R{:}Oxyz$ with origin O. Let points P_i and D_i be fixed in B_i, and let B_i move in R so that at time t, B_i is in configuration I, and at a later time $t' \equiv t + \Delta t$, B_i is in configuration II (Figure 3).

The *scalar angular displacement* of B_i in R during Δt is denoted by $\Delta\theta$, where

$$\Delta\theta \equiv \theta_2 - \theta_1 \tag{13}$$

The *average scalar angular* velocity of B_i in R during Δt is denoted by $\omega^{B_i}_{\text{avg}}$, where

$$\omega^{B_i}_{\text{avg}} \equiv \Delta\theta/\Delta t \tag{14}$$

The *scalar angular velocity* of B_i in R at time t, denoted by $\omega^{B_i}(t)$, is defined in terms of a limit as Δt becomes very small:

$$\omega^{B_i}(t) \equiv \underset{\Delta t \to 0}{\text{limit}} \left(\omega^{B_i}_{\text{avg}}\right) \tag{15}$$

The *average scalar angular acceleration* of B_i in R during Δt is denoted by $\alpha^{B_i}_{\text{avg}}$, where

$$\alpha^{B_i}_{\text{avg}} \equiv [\omega^{B_i}(t') - \omega^{B_i}(t)]/\Delta t \tag{16}$$

The *scalar angular acceleration* of B_i in R at time t, denoted by $\alpha^{B_i}(t)$, is defined by a limit as Δt becomes very small:

$$\alpha^{B_i}(t) \equiv \underset{\Delta t \to 0}{\text{limit}} \left(\alpha^{B_i}_{\text{avg}}\right) \tag{17}$$

If we take movies and identify two characteristic points (P_i and D_i) on each seg-

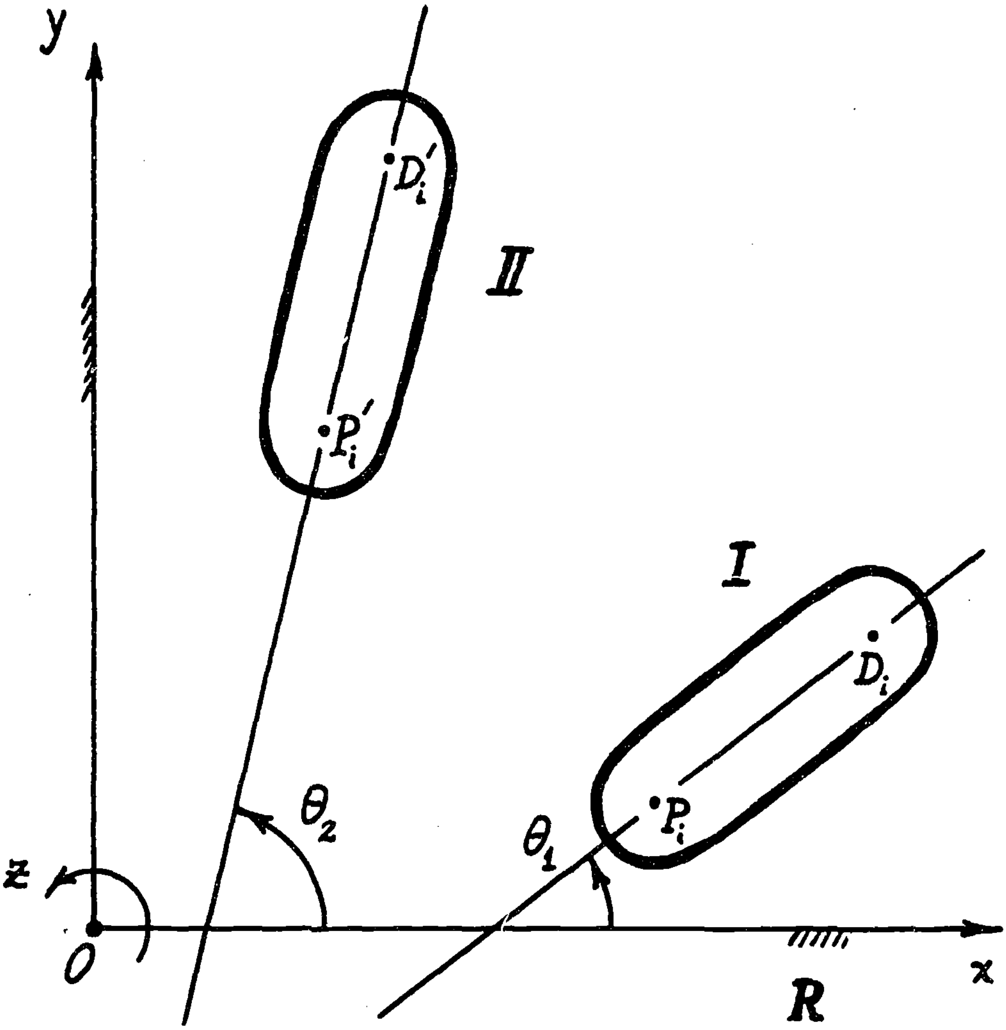

Figure 3. Location of B_i at time t and at time t'.

ment in each film frame, then we can measure the angle between the straight line segment P_iD_i and any fixed line (e.g., the x-axis of R) in each film frame. For sufficiently fast frame rates, we can use the average scalar angular velocity $\omega^{B_i}_{\text{avg}}$, to approximate the actual scalar angular velocity $\omega^{B_i}(t)$. Similarly, we can obtain the average scalar angular acceleration, $\alpha^{B_i}_{\text{avg}}$, and use it to approximate the actual scalar angular acceleration $\alpha^{B_i}(t)$. In this manner, we can determine approximate values for the scalar angular acceleration of B_i in R throughout the time period when we wish to study the motion of the various body segments.

SOLUTION PROCEDURE

In performing a biomechanical analysis of any human motor activity, we normally wish to determine the unknown category IIa force distribution resultants which act on the individual body segments in the neighborhood of the joints to maintain or change the joint configuration. These resultants cannot be measured directly in live human subjects with present-day technology, and they must therefore be calculated indirectly if they are to be determined at all. The procedure normally used to determine these unknown resultants is to solve for them using the equations governing the motion of the system elements. Equations (3), (4), and (5) describe the two-dimensional motion of a typical rigid body segment B_i moving in the (x,y)-plane of the inertial reference frame R. Although these three scalar equations are differential equations, they are valid at any instant of time t, and they can therefore be used to determine instantaneous values of the unknown category IIa force and moment resultants if all other terms in these equations are known.

In order to adequately describe the general solution procedure, let us expand the left-hand sides of equations (3), (4), and (5), using the two-dimensional *FBD* for a typical body segment B_i shown in Figure 4. We obtain

$$F_{P_ix} + F_{D_ix} + F_{Q_ix} = m_i a_x^{G_i} \qquad (18)$$

$$F_{P_iy} + F_{D_iy} + F_{Q_iy} - W_i = m_i a_y^{G_i} \qquad (19)$$

$$M_{P_iz} + M_{D_iz} + M_{Q_iz} + l_1F_{D_iy} - l_2F_{D_ix} + l_3F_{Q_iy} - l_4F_{Q_ix} + l_5F_{P_ix} - l_6F_{P_iy} = I_z^{G_i}\alpha^{B_i} \qquad (20)$$

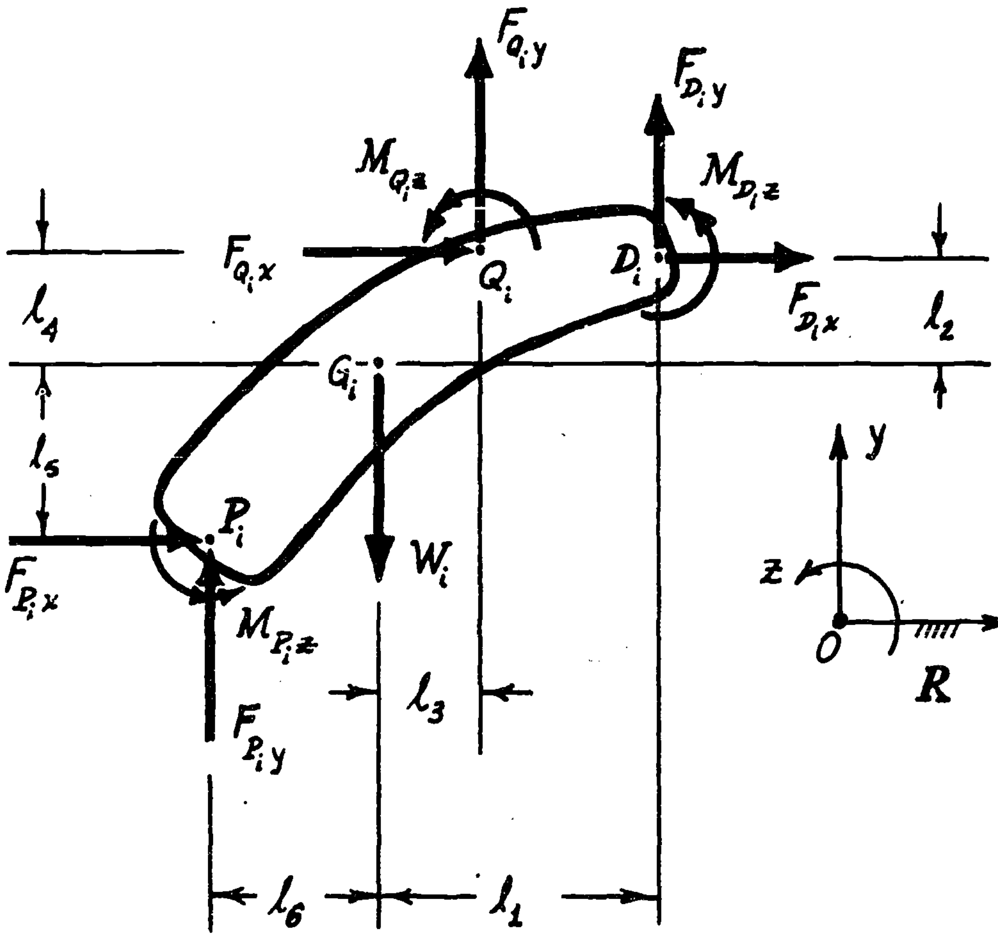

Figure 4. Two-dimensional free body diagram for a typical body segment B_i.

Using movies of the motor activity, we locate points P_i and D_i in each body segment at each instant of time t when a film frame is exposed. Using anthropometric measurements and suitable data and procedures, we also determine approximate values of segment weight, mass, center of gravity location, and moment of inertia. From this information, we can then deduce approximate values for $a_x^{G_i}$, $a_y^{G_i}$ and α^{B_i} as functions of time t, and thereby evaluate the right-hand sides of equations (18), (19), and (20) completely.

By devising suitable instrumentation (force plates, etc.), we can also determine the category IIb force distribution resultants (F_{Q_ix}, F_{Q_iy}, and M_{Q_iz}) and the points Q_i where they act on B_i. We therefore know some of the terms appearing on the left-hand sides of equations (18), (19), and (20).

The only unknowns that remain in the three scalar equations of motion are the x and y components of the proximal and distal joint resultant forces (F_{P_ix}, F_{P_iy} *and* F_{D_ix}, F_{D_iy}, respectively), and the z components of the proximal and distal joint resultant moments (M_{P_iz} and M_{D_iz}, respectively). In order to solve for these six scalar unknowns, we begin by considering the extremity (arm, leg, head) that either contains or is closest to the body segment or joint of interest. We initially focus our attention on the most distal of the body segments in that extremity, since, for this most distal segment (B_N), the resultant joint force and moment at the distal joint are both known. If these three scalars (F_{D_Nx}, F_{D_Ny}, and M_{D_Nz}) are not each identically equal to zero, then B_N is loaded at D_N by some external category IIb force distribution whose resultants can be measured experimentally. Consequently, for B_N, equations (18) and (19) each contain only one scalar unknown (F_{P_Nx} and F_{P_Ny}, respectively) which can therefore be determined directly. If we substitute these calculated values for F_{P_Nx} and F_{P_Ny} into equation (20), then this equation contains only one unknown (M_{P_Nz}) which can therefore be determined directly.

We then proceed to the adjacent and next most distal body segment (B_{N-1}), and use Newton's third law of action and reaction to determine the resultant force and moment acting on the distal joint of B_{N-1} due to the presence of B_N. Newton's third law implies that the category IIa force and moment resultants acting on the distal joint of B_{N-1} due to B_N must be equal in magnitude but opposite in direction to the corresponding resultants acting on the same (proximal) joint of B_N due to the presence of B_{N-1}. Hence, for segment B_{N-1}, we obtain a situation similar to the one we had for B_N, where we now know the resultants of the force distribution acting on the distal joint of B_{N-1}. We therefore proceed as for segment B_N, using the associated three scalar equations of motion to calculate the two unknown force components and the unknown moment component acting on B_{N-1} at the proximal joint P_{N-1}. We repeat this process, moving proximally from one body segment to the next, until we have solved for all unknown category IIa force and moment resultants acting on all intermediate body segments at the anatomical joints.

EXAMPLE PROBLEM

In order to illustrate the general procedure used in the biomechanical analysis of human motor activities, we shall briefly consider the essentially two-dimensional activity of running on a straightaway. For the sake of convenience, let us suppose that we wish to determine the forces transmitted by the anatomical structures in the neighborhood of the knee joint during foot contact with the ground.

We begin the associated biomechanical analysis by considering the most distal body segment in the extremity (leg) which contacts the ground and contains the region of interest. This segment is the foot enclosed in a shoe which we decide to model as a single rigid body (B_2). The foot plus shoe segment B_2 is isolated from the adjacent lower leg segment B_1 by an imaginary sectioning plane passing through the ankle joint A. The *FBD* of B_2, at the typical instant of time during segment contact with the ground, is shown in Figure 5. The ground reaction force distribution (category IIb) acting on B_2 has been replaced by a simple equipollent force-couple system consisting of the resultant force components F_{Qx} and F_{Qy} acting at point Q, and the resultant component M_{Qz}. The distributed weight force has been replaced by the resultant weight force $\mathbf{W}_2$ acting downward in the negative y direction at the center of gravity, G_2. The complex category IIa force distribution acting on B_2 at A has been replaced by a simple equipollent force-couple system consisting of the resultant force components F_{Ax} and F_{Ay} acting at A, together with the resultant couple M_{Az}.

The three scalar equations of motion corresponding to equations (18), (19), and (20) now take the form

$$F_{Ax} + F_{Qy} = \frac{W_2}{g} a_x^{G_2} \qquad (21)$$

$$F_{Qy} - F_{Ay} - W_2 = \frac{W_2}{g} a_y^{G_2} \qquad (22)$$

$$M_{Az} + M_{Qz} + S_3 F_{Qx} - S_1 F_{Qy} \\ - S_2 F_{Ay} - S_4 F_{Ax} = I_z^{G_2} \alpha^{B_2} \qquad (23)$$

Using an instrumented force plate, we can determine the horizontal and vertical components of the ground reaction force (F_{Qx} and F_{Qy}, respectively), and the moment component M_{Qz} about an arbitrary point Q in the contact region. By attaching two markers to B_2 at points A and H, and by identifying these points in each film frame, we can measure the angle between the line segment AH and the fixed x axis, and use this varying angle to determine α^{B_2}. If point G_2 can be approximately located relative to

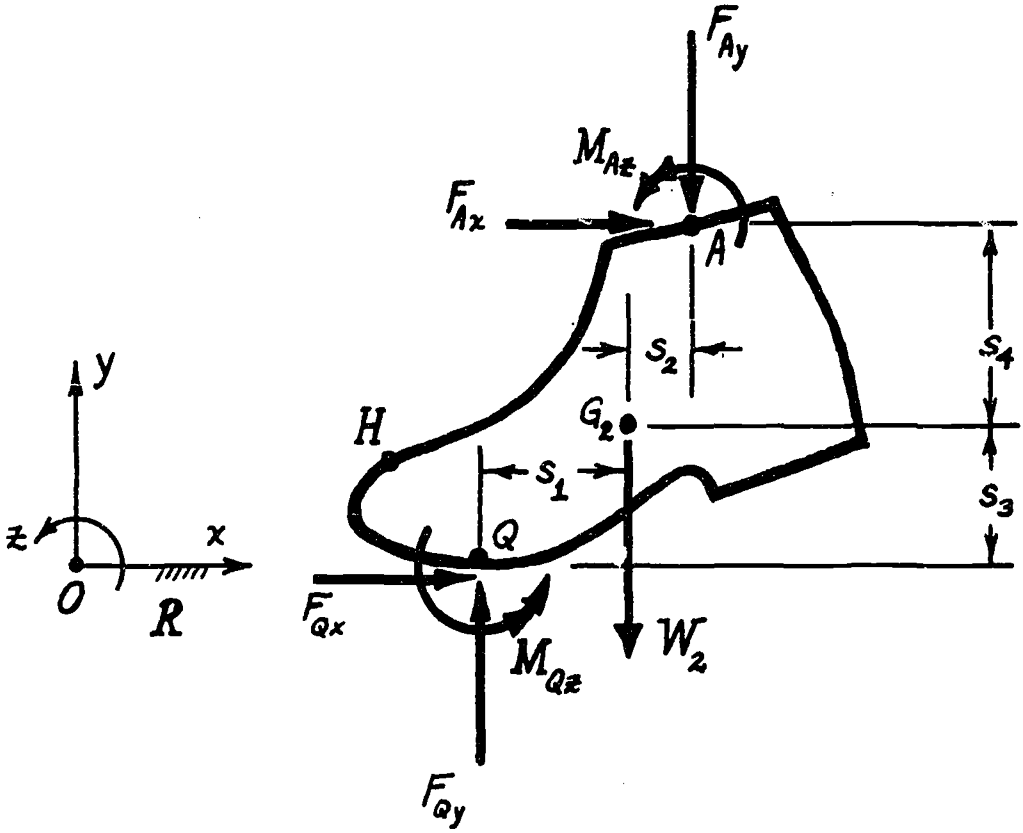

Figure 5. Free body diagram of B_2 during segment contact with the ground.

points A and H in each film frame, then we can also deduce values for $a_x^{G_2}$ and $a_y^{G_2}$. Finally, if we can obtain a reasonably accurate value for $I_z^{G_2}$, then we can solve equation (21) for F_{Ax}, solve equation (22) for F_{Ay}, and then substitute these values into equation (23) and solve it for M_{Az}.

We now proceed to the adjacent and next most distal body segment, the lower leg (B_1), and analyze it in a similar manner. The force and moment resultants acting on B_1 at A ($-F_{Ax}$; $-F_{Ay}$; $-M_{Az}$) are now known from the previous analysis of the foot plus shoe segment B_2. The three scalar equations governing the motion of B_1 in R can therefore be used to solve for the desired unknown force and moment resultants acting on B_1 at the knee, due to the presence of the neighboring thigh segment.

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JAMES G. HAY

Moment of Inertia of the Human Body

INFORMATION CONCERNING the inertial characteristics of the human body—the mass, center of gravity location, and moment of inertia or radius of gyration—is a necessary prerequisite to the conduct of detailed quantitative analyses of human motion.

Although numerous attempts have been made to obtain appropriate data concerning the mass and center of gravity location of the human body and each of its various segments (10), relatively few efforts have been directed toward obtaining appropriate data for the corresponding moments of inertia or radii of gyration.

The purposes of this paper are: (1) to review the work of the major contributors to knowledge in the area of moment of inertia determination; and (2) to suggest guidelines which might be followed in deciding which method or set of available results should be used in a given analysis of human motion.

Several methods of determining the moment of inertia (or the radius of gyration) have been proposed but only two of these—referred to here as the *compound pendulum* and the *mathematical modeling* methods—have been used with any frequency.

COMPOUND PENDULUM METHOD

Basically, this method consists of suspending the body from some fixed point, setting it in motion by shifting it a few degrees from its equilibrium position, and determining the period of oscillation (i.e., the time taken for the body to swing from the limit of its motion in one direction to its limit in the other direction, and back again). The moment of inertia is then obtained using the following equation (based upon the behavior of a body which experiences such simple harmonic motion):

$$I_0 = \frac{WhT^2}{4\pi^2}$$

where I_0 = the moment of inertia of the body about an axis through the point of suspension, O; W = the weight of the body; h = the distance from the center of gravity to point O; and T = the period of oscillation.

Two other equations:

$$I_0 = mk^2$$

where m = the mass of the body and k = the radius of gyration relative to the axis through O, and:

$$I_0 = I_{cg} + mh^2$$

where I_{cg} = the moment of inertia of the body relative to an axis through its center of gravity and parallel to the axis through O, are then used to obtain, respectively, k and I_{cg}.

Fischer (8) and Dempster (5) used the compound pendulum method to determine the moments of inertia of selected segments of cadavers.

Fischer dissected a small cadaver [150.0 cm (59.3 in.), 44.057 kg (97.1 lb)], inserted parallel steel rods, one at each end of each segment, suspended each segment from

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each rod in turn and determined the periods of oscillation. From the data thus obtained and previously obtained data on segment mass and center of gravity location, he then computed the moment of inertia and radius of gyration of each segment relative to a transverse axis through its center of gravity. [Note: Fischer also reported values for these same parameters relative to a longitudinal axis through the center of gravity of each segment. However, the manner in which he arrived at these values is not clear.]

Dempster followed a very similar procedure using eight, white, male cadavers of "medium build" (Table 1). Each segment in turn was supported on knife-edges fixed to the ends of a .5-in. pipe placed transversely through the proximal end of the segment. (In the case of the head, neck, and trunk segment, the rod was placed through the centers of the acetabula.) "The body was then allowed to swing freely on the knife edges through an arc of approximately 5°. . . Ten measurements, each of 10 periods of oscillation, were taken with a stop watch; from these an average period was determined and recorded" (5, pp 50-51). The results obtained by Dempster are presented in Tables 2 and 3.

Santschi, DuBois, and Omoto (14) used two large, compound pendulums, to determine the principal moments of inertia of the living human body in eight different positions (Figure 1). Sixty-six males, selected on the basis of stature and weight to represent the Air Force population stature and weight characteristics as described by Hertzberg, Daniels, and Churchill (11) were used as subjects. The procedure involved strapping the subject into the first pendulum in the required position, setting the pendulum to oscillate through ± 1° and determining the period of oscillation. ("At least two 10-

TABLE 1. CADAVERS USED IN DEMPSTER'S STUDY

No.	Somatotype[a] (Sheldon system)	Age[b] yr	Supine height[b] cm (in.)	Weight[b] (kg) lb	Cause of death	Embalmed
14815	4-5-2 1/2	67	168.9 (66.5)	(51.2) 113	Unknown	yes
15059	3-5-3	52	159.8 (62.9)	(58.3) 128.5	Cerebral hemorrhage	no
15062	4-2-4	75	169.6 (66.8)	(58.3) 128.5	General arteriosclerosis	no
15095	4-3-4	83	135.3 (53.3)	(49.5) 109.25	Unknown	no
15097	4-5-3	73	176.4 (69.4)	(72.3) 159.5	Esophageal carcinoma	no
15168	3-3-4	61	186.6 (73.5)	(71.2) 157	Coronary thrombosis	no
15250	3-3-4	—	180.3 (71.0)	(60.3) 133	Acute coronary occlusion	no
15251	4-4-2	—	158.5 (62.4)	(55.8) 123	Chronic myocarditis	no

[a] Determined from front, left side, and rear view photographs of suspended cadaver.

[b] With regard to the physical characteristics of his subjects, Dempster observed that "all the available cadaver material represented individuals of the older segment of the population. The specimens were smaller then either the average white male population or the military populations of special interest, and the weights were below those of average young individuals. Physically, however, the subjects were representative specimens for their age level" (5, p. 47).

TABLE 2. MOMENTS OF INERTIA OF SEGMENTS ABOUT TRANSVERSE AXES THROUGH THEIR CENTERS OF GRAVITY

(after Dempster)

Moments of inertia in gm-cm^2 × 10^6

Cadaver number	Entire upper extremity	Arm	Forearm and hand	Forearm	Hand	Entire lower extremity	Thigh	Leg and foot	Leg	Foot
Left side										
14815	1.10	.122	.187	.059	.005	4.90	0.26	0.82	.321	.021
15059	0.78	.118	—	.051	.004	5.70	0.64	0.73	.330	.025
15062	0.96	.115	.155	.043	.005	6.05	0.82	0.55	.308	.029
15095	0.79	.079	.128	.035	.005	4.60	0.65	0.73	.260	.026
15097	0.98	.222	.287	.055	.009	9.10	1.14	1.58	.650	.037
15168	1.42	.191	.188	.072	.002	10.00	3.29	1.66	.560	.043
15250	1.35	.155	.218	.074	.003	9.80	1.22	1.29	.560	.035
15251	1.02	.112	.146	.050	.003	5.60	0.61	0.94	.340	.033
Right side										
14815	0.90	.190	.220	.058	.007	4.60	0.21	0.81	.307	.018
15059	0.78	.130	.137	.041	.005	6.70	0.70	0.85	.340	.025
15062	0.99	.102	.180	.055	.004	5.67	0.76	0.86	.298	.028
15095	0.58	.062	.128	.059	.003	5.20	0.69	0.75	.275	.013
15097	1.10	.220	.298	.072	.011	9.20	1.27	1.65	.620	.040
15168	1.40	.145	.197	.061	.003	8.60	3.12	1.64	.620	.038
15250	1.57	.166	.232	.068	.004	9.50	1.44	1.40	.620	.035
15251	0.91	.120	.152	.054	.003	5.20	0.61	0.96	.360	.032

TABLE 3. MOMENTS OF INERTIA OF TRUNK SEGMENTS ABOUT TRANSVERSE AXES THROUGH THEIR CENTERS OF GRAVITY

(after Dempster)

Moments of inertia in gm-cm^2 × 10^{-6}

Cadaver number	Trunk minus limbs	Trunk minus shoulders	Shoulders		Head and neck	Thorax	Abdomino-pelvic region
			Left	Right			
15059	15.5	14.0	0.355	0.378	0.22	0.45	—
15062	23.7	15.9	0.500	0.324	—	—	—
15095	13.4	13.0	0.417	0.421	—	—	—
15097	22.1	21.0	0.800	0.700	0.31	1.19	3.24
15168	24.3	23.1	0.520	0.800	0.23	2.18	9.70
15250	14.9	16.4	0.425	0.425	0.32	0.96	2.44
15251	14.9	14.0	0.480	0.420	0.39	0.99	1.96

cycle-period averages were taken . . . to ensure that reproducibility was achieved"). The "suspension axis" of the pendulum was then changed and the process repeated. Finally, the subject was strapped into the second pendulum in the same position and the entire process repeated.

The moments of inertia relative to the three principal axes of the body were then computed (Table 4). A multiple regression analysis of moment of inertia vs. stature and weight was conducted for all positions and principal axes. In all but three instances the multiple correlation coefficients exceeded 0.9

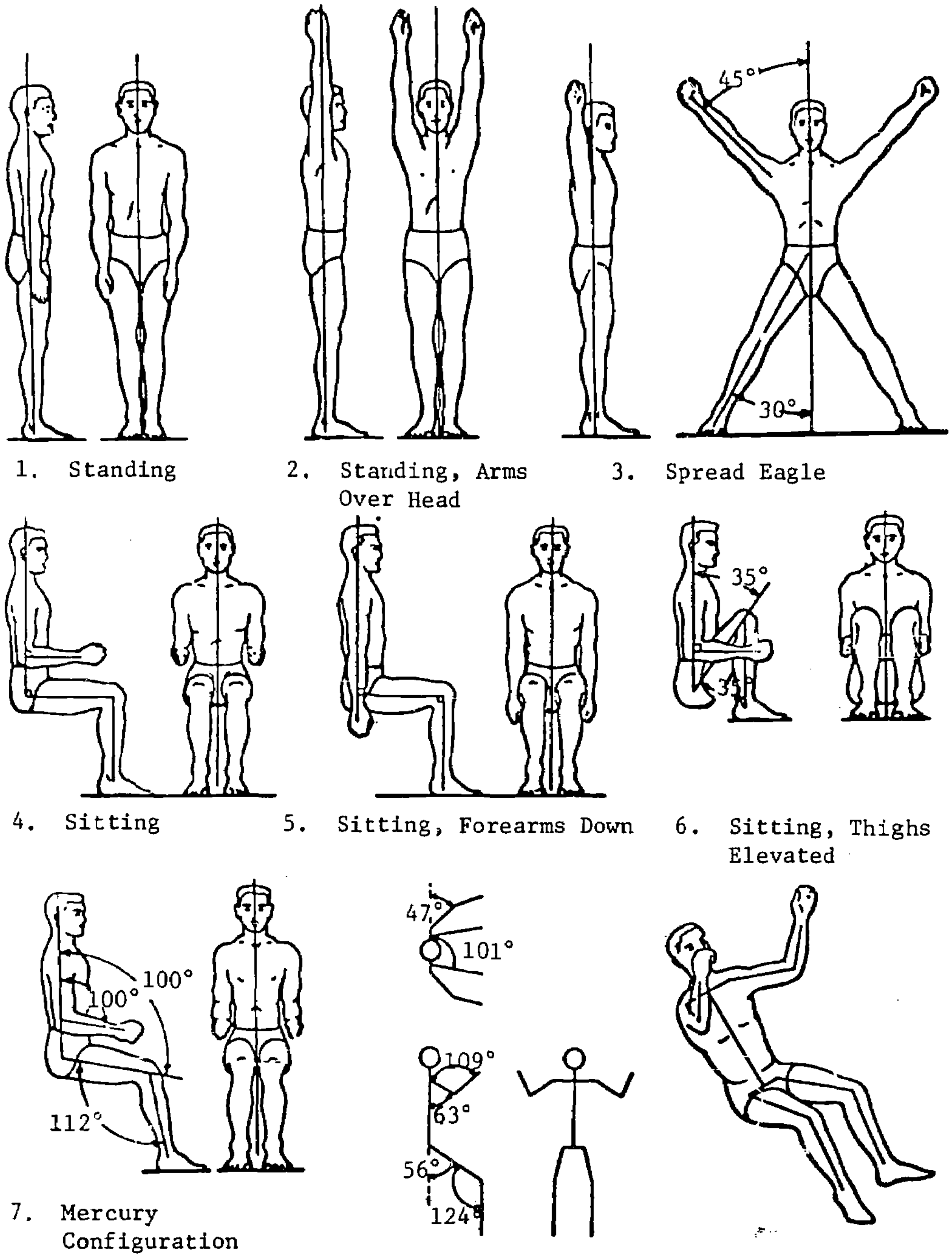

Figure 1. Body positions used in Santschi et al. study.

(Table 5). Santschi *et al.* concluded, therefore, that: "These large values of *R* indicate a very strong dependence of moment of inertia on stature and weight, which combined with the relatively small values of standard error of estimate and the large sample size, demonstrate the usefulness of the regression equation as a predictive tool."

TABLE 4. ARITHMETIC MEANS AND STANDARD DEVIATIONS OF SAMPLE MOMENTS OF INERTIA (after Santschi *et al.*)

		Moment of inertia (lb-in.-sec.^{2})	
	Axis[a]	Mean	SD
1. Standing	x	115.0	19.3
	y	103.0	17.9
	z	11.3	2.2
2. Standing, arms over head	x	152.0	26.1
	y	137.0	25.3
	z	11.1	1.9
3. Spread eagle	x	151.0	27.1
	y	114.0	21.3
	z	36.6	7.9
4. Sitting	x	61.1	10.3
	y	66.6	11.6
	z	33.5	5.8
5. Sitting, forearms down	x	62.4	9.7
	y	68.1	12.0
	z	33.8	5.9
6. Sitting, thighs elevated	x	39.1	6.0
	y	38.0	5.8
	z	26.3	5.1
7. Mercury configuration	x	65.8	10.3
	y	75.2	14.0
	z	34.2	5.6
8. Relaxed (weightless)	x	92.2	13.3
	y	88.2	13.3
	z	35.9	5.4

[a] The z-axis if formed by the intersection of the sagittal plane and the frontal plane; the y-axis, by the intersection of the frontal and transverse planes; and, the x-axis, by the intersection of the sagittal and transverse planes.

Drillis and Contini (6) outlined several methods which might be used to determine the moment of inertia of a human body and/or its individual segments. These methods were also discussed in earlier articles by Contini, Drillis, and Bluestein (4) and Drillis, Contini, and Bluestein (7) and in a subsequent article by Contini (3). Among these was one which they eventually used to gather data on the moments of inertia of the limb segments of 20 adult males aged 20–40 yr. [Note: Although the authors refer to a test sample of 20 subjects (6, p. 15), results are reported for only 12 subjects (6, p. 49 *et seq.*)]

In this method, castings of plaster of Paris or dental stone were made of the limb segments of each subject. These were then made to oscillate about a fixed suspension point and the period of oscillation determined. This period was then corrected on the basis of the relative weights of the actual segment and the cast replica and the moment of inertia of the segment was computed. The mean values obtained are presented in Table 6. [Note: Drillis and Contini reported these results in "gr^2" (6, p. 86). However, since they compared their values directly with those of Dempster, it is assumed that Drillis and Contini intended that the same gm-cm^2 unit used by Dempster be reported for their own results.] Table 6 also contains mean values for the radii of gyration expressed as a function of segment length, for eight subjects.

These data on radii of gyration have also been reported by Contini (3), who, in addition, reported average values for radii of gyration for various populations—normals, amputees, and hemiplegics, both male and female. However, whether these values were obtained using the casting-compound-pendulum method or, more simply, by measuring segment lengths and using ratios previously determined (see Table 6) is not clearly stated.

MATHEMATICAL MODELING METHOD

In this method, each segment of the body is represented as a regular geometric solid of known mass and its moments of inertia (and/or radii of gyration) are determined using the appropriate computational techniques.

Amar (1), one of the first to use this approach, considered the trunk as a cylinder and the limbs as frustra of cones and computed segmental moments of inertia for an adult male of 65 kg (143 lb).

Kulwicki, Schlei, and Vergamini (12)

TABLE 5. CORRELATION OF MOMENT OF INERTIA WITH STATURE AND WEIGHT
(after Santschi *et al.*)

	Axis	R_{I-sw}	SE	I_o Regression equations[a]		
1. Standing	x	0.98	4.18	−232.0	+3.77S	+0.512W
	y	0.96	5.27	−212.0	+3.43S	+0.460W
	z	0.93	0.84	−0.604	−0.098S	+0.112W
2. Standing, arms over head	x	0.98	5.63	−328.0	+5.36S	+0.652W
	y	0.96	6.89	−332.0	+5.34S	+0.589W
	z	0.89	0.87	1.4	−0.085S	+0.094W
3. Spread eagle	x	0.98	4.90	−353.0	+5.63S	+0.677W
	y	0.96	6.24	−270.0	+4.30S	+0.516W
	z	0.93	2.82	−101.0	+1.52S	+0.191W
4. Sitting	x	0.92	4.01	−91.6	+1.43S	+0.322W
	y	0.92	4.51	−135.0	+2.26S	+0.268W
	z	0.97	1.45	−52.8	+0.76S	+0.201W
5. Sitting, forearms down	x	0.91	3.98	−78.7	+1.29S	+0.309W
	y	0.92	4.67	−127.0	+2.05S	+0.321W
	z	0.97	1.36	−53.7	+0.765S	+0.206W
6. Sitting, thighs elevated	x	0.89	2.79	−33.8	+0.543S	+0.212W
	y	0.77	3.66	−22.2	+0.434S	+0.180W
	z	0.92	2.00	−30.4	+0.328S	+0.204W
7. Mercury configuration	x	0.93	3.75	−94.3	+1.57S	+0.308W
	y	0.94	4.96	−175.0	+2.85S	+0.318W
	z	0.96	1.64	−45.0	+0.668S	+0.197W
8. Relaxed (weightless)	x	0.96	3.71	−106.0	+1.77S	+0.452W
	y	0.94	4.54	−139.0	+2.43S	+0.352W
	z	0.96	1.54	−47.2	+0.776S	+0.176W

[a] I_o and SE in lb-in.-sec^2
S in in.
W in lb

developed a model consisting of six right circular cylinders (two arms, two legs, torso, and head) in order to evaluate the effectiveness of certain movements in producing rotation while in a weightless state. The linear dimensions of the model were based on the 50th percentile data of Hertzberg, Daniels, and Churchill (11) and the mass of each segment was based on the corresponding mean for Dempster's (5) cadavers. The principal moments of inertia were computed using the standard equations:

$$I_c = 1/2\, mr^2$$

where I_c = the moment of inertia about the segment's long axis, m = the segment mass, and r = the radius of the segment, and

$$I_o = \frac{1}{12} m\,(3r^2 + l^2)$$

TABLE 6. SEGMENT MOMENTS OF INERTIA AND RADII OF GYRATION OF SEGMENTS ABOUT TRANSVERSE AXES THROUGH THEIR CENTERS OF GRAVITY
(after Drillis and Contini)

Segment	Moment of inertia (gm-cm^2 × 10^{-6})	Radius of gyration Segment length
Entire upper extremity	1.33	0.24
Upper arm	0.138	0.26
Forearm and hand	0.247	0.25
Forearm	0.073	—
Hand	0.0059	—
Entire lower extremity	7.49	0.24
Thigh	0.895	0.23
Shank and foot	1.120	0.29
Shank	0.495	0.27
Foot	0.020	—

where I_a = the moment of inertia about the segments frontal or transverse axis and l = the length of the segment. The results of these computations are shown in Table 7.

Whitsett (16) developed a 14-segment model of the human body for the purpose of predicting "man's mechanical behavior in some selected conditions associated with weightlessness." The 14 segments and the geometric solids used to represent these segments are shown in Figure 2. The linear dimensions of the model were based on the 50th percentile data of Hertzberg *et al.* (11); the masses of the limb segments were determined using the regression equations developed by Barter (2); the center of mass locations for the limb segments and the average density for all segments—the latter used, among other things, for obtaining values for the masses of the head and torso —were based on Dempster's work with cadavers (5). The principal moments of inertia of each segment were computed using the standard equations for the corresponding geometric solid (Table 8). These data were then used to determine the principal moments of inertia of the whole body for three selected positions.

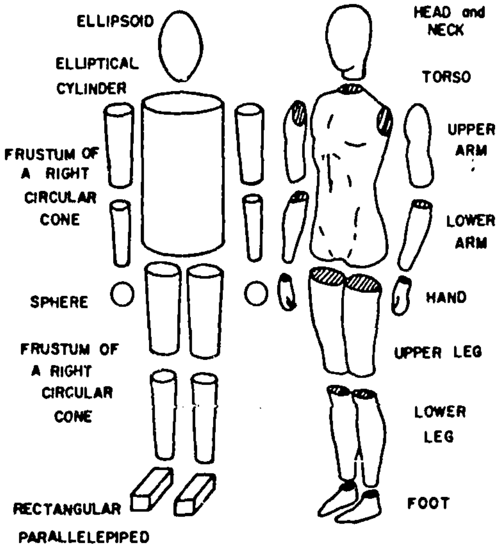

Figure 2. Whitsett's 14-segment model.

TABLE 7. PRINCIPAL MOMENTS OF INERTIA
(after Kulwicki *et al.*)

Segment	Moments of inertia (slugs-ft^2) Longitudinal axis	 Transverse and frontal axis[a]
Head	.012	0.043
Torso	.324	1.118
Arm	.002	0.086
Leg	.017	0.512

[a] Since the segments were symmetrical about their long axes, the computed moments of inertia for the transverse and frontal axes were identical.

Hanavan (9) designed a 15-segment model (Figure 3) in order to predict the inertial properties of the human body in any fixed body position. The dimensions and properties of the segments were calculated using a total of 25 anthropometric measurements taken on the individual subject. The weights of the segments were computed using the regression equations derived by Barter (2).

To determine the validity of his model, Hanavan used anthropometric raw data obtained by Santschi *et al.* (14) and computed the principal moments of inertia of each of their 66 subjects for each of the first seven positions shown in Figure 1. He then compared the results obtained in this manner with those obtained experimentally, by Santschi *et al.* For frontal and transverse axes, one half of the predicted values (i.e., the values obtained using the model) generally fell within 10 percent of the experimental values. Markedly greater errors were obtained in computing the moments of inertia relative to the longitudinal axis—one half of the predicted values generally fell within 20 percent of the experimental data. Hanavan attributed these greater percentage errors to the fact that the moment of inertia relative to the longitudinal axis is generally of a much smaller magnitude than the other

TABLE 8. PRINCIPAL MOMENTS OF INERTIA OF BODY SEGMENTS
(after Whitsett)

Segment	Moments of inertia (slugs-ft^2) Frontal axis	Transverse axis	Longitudinal axis
Head	0.0183	0.0183	0.0124
Torso	1.0000	0.9300	0.2300
Upper arm	0.0157	0.0157	0.0018
Lower arm	0.0056	0.0056	0.0008
Hand	0.0004	0.0004	0.0004
Upper leg	0.0776	0.0776	0.0154
Lower leg	0.0372	0.0372	0.0037
Foot	0.0028	0.0028	0.0006

principal moments of inertia and thus "a small numerical error becomes a much larger percentage error."

Finally, Hanavan used his mathematical model to develop a design guide which could be used to establish preliminary design specifications requiring knowledge of the inertial properties of the human body in selected body positions. For this purpose he used the anthropometric dimensions for five composite subjects (5th, 25th, 50th, 75th, and 95th percentile) obtained in the survey of Air Force Personnel conducted by Hertzberg *et al.* (11) and 31 different body positions which could be assumed in a full pressure suit. The inertial properties of these five composite subjects were computed for each of the 31 body positions.

OTHER METHODS

A number of other methods have been used to determine the moments of inertia of the human body and/or its component parts.

Liu, Laborde, and Van Buskirk (13) used a torsional pendulum—a device which twists back and forth after being released from a torsional stress initially imposed upon it—to determine the principal moments of inertia of serial transverse sections of the trunk of a male cadaver. The principal moments of inertia for each of the 24 transverse sections (each of which contained roughly one vertebra) are shown in Table 9.

Weinbach (15) described a method for determining the moment of inertia of an erect human body about a transverse axis through the soles of the feet. This method involved the construction of a "volume contour map" based on data gathered from front and side view photographs of the subject (or from anthropometric measures taken directly from the subject) and the determination of the area under one of the derived curves making up the "map." The moment of inertia concerned was then computed using the relationship:

$$I = \frac{H^5}{h^3} A \text{ cu decm-mm}^2$$

where H = the actual height of the subject (in cm), h = the height of the subject as

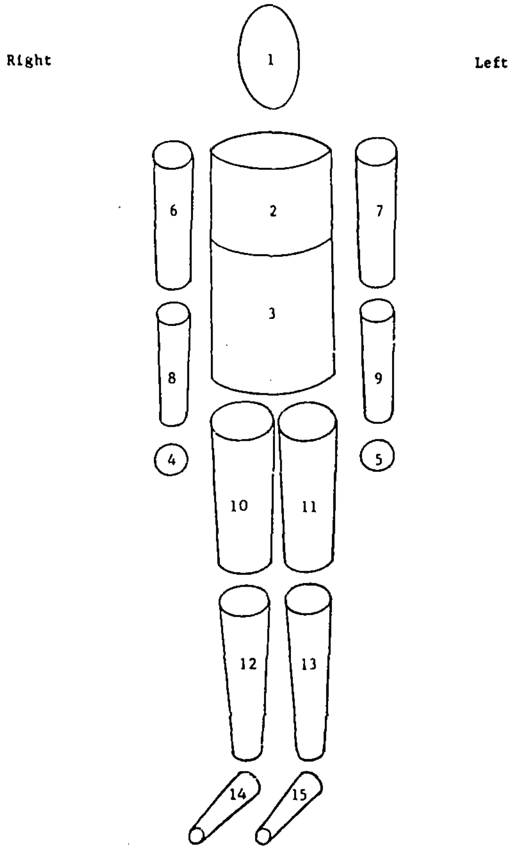

Figure 3. Hanavan's 15-segment model.

TABLE 9. PRINCIPAL MOMENTS OF INERTIA OF TRUNK SEGMENTS (after Liu *et al.*)

Level	Mass (lb-sec^2/in)	Moment of inertia (lb-sec^2-in.)		
		Frontal axis	Transverse axis	Longitudinal axis
C 1	.00182	.0047	.0055	.0097
C 2	.00162	.0037	.0047	.0070
C 3	.00089	.0029	.0023	.0038
C 4	.00117	.0013	.0033	.0050
C 5	.00154	.0053	.0043	.0127
C 6	.00129	.0018	.0047	.0086
C 7	.00348[a]	.0311[a]	.0089[a]	.0385[a]
T 1	.00348[a]	.0311[a]	.0089[a]	.0385[a]
T 2	.00558	.0516	.0175	.0758
T 3	.00558	.0472	.0222	.0764
T 4	.00478	.0508	.0212	.0716
T 5	.00720	.0789	.0295	.115
T 6	.00669	.0762	.0428	.115
T 7	.00890	.0987	.0618	.148
T 8	.00623	.0666	.0428	.105
T 9	.00704	.0784	.0494	.115
T10	.00573[a]	.0636[a]	.0482[a]	.107[a]
T11	.00573[a]	.0636[a]	.0482[a]	.107[a]
T12	.00856	.0837	.0637	.144
L 1	.0113	.122	.0626	.174
L 2	.0100	.0998	.0542	.147
L 3	.0119	.124	.0542	.162
L 4	.0101	.108	.0408	.141
L 5	.0125	.133	.0588	.181
Pelvis	.0354	.383	.454	.476

[a] Averaged with adjacent slice due to bad cut.

depicted (in mm), and A = the area under the derived curve (in sq mm).

DISCUSSION

Which of the available methods or sets of data should be used in a given investigation depends on a number of factors including the nature of the proposed investigation, the axes about which moments of inertia are required, and the characteristics of the subjects involved.

In some instances the appropriate choice from among the available methods or sets of data is fairly obvious. For example, if an investigation requires the determination of one or more of the principal moments of inertia of a subject (or subjects) in any of the positions depicted in Figure 1, the logical procedure is to obtain the required measures of height and weight and use these in conjunction with the appropriate regression equation(s) in Table 5.

However, where an investigation calls for the determination of moments of inertia of a body in orientations other than those considered by Santschi *et al.* a choice must be made between (a) using the segmental data of Dempster (5), Drillis and Contini (6), Hanavan (9), or Whitsett (16),[1] and (b)

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[1] The data of Kulwicki *et al.* (12) is probably too gross for most applications and is excluded from this list for that reason.

undertaking a study similar to that of Santschi *et al.* in order to determine the required values. Since the latter of these two alternatives constitutes an undertaking of considerable magnitude, it would seem logical to ensure that the possibilities afforded by the first alternative had been quite exhausted before seriously considering the second.

The nature of the segmental data available from the four sources listed above varies in two important respects:

1. Only two (Hanavan and Whitsett) provide segmental moments of inertia relative to all three principal axes. The other two sources contain data for segmental moments of inertia relative to the transverse axis only—a fact which severely restricts the uses to which these latter data can be put. [Note: If it is only the moments of inertia relative to the transverse axes that are required, data from the studies of Dempster and Hanavan are probably to be preferred to those reported by Drillis and Contini, Contini (both of which reports were incomplete at critical points) and Whitsett (whose model took no account of individual differences in physique).]
2. The characteristics of the subjects on whom segmental data has been gathered, or upon whose dimensions the mathematical models have been based vary considerably. Thus, since Santschi *et al.* have demonstrated that the principal moments of inertia are greatly influenced by the physical dimensions of the individual, it would seem reasonable to suggest:

a. If Dempster's cadaver data is to be used, the data gathered on the cadaver whose stature and weight most nearly approximates that of the subject concerned would be the most appropriate.

b. If a mathematical model is to be used to derive the required segmental data and the subjects involved are available for the purpose of obtaining anthropometric measurements, the model of Hanavan would probably be more appropriate than that of Whitsett because it is based on the physical dimensions of individual subjects rather than on mean values.

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JOHN PISCOPO

Assessment of Forearm Positions upon Upperarm and Shoulder Girdle Strength Performance

FLEXION AND EXTENSION of the elbow joint in the sagittal plane, well illustrated by pull-ups or chinning, continues to predominate as a popular exercise for testing upperarm and shoulder girdle strength. Flexing the elbow against resistance primarily entails strong contractions of the biceps brachii, brachialis, and brachioradialis. Along with sit-ups, pull-ups are usually an integral element in standardized physical fitness tests (2, 6, 7, 9, 13). Most physical educators agree that isotonic movements of elbow flexion and extension are fundamental motions in manipulating objects, and, perhaps more important, essential for controlling neuromuscular coordination and body weight.

Germane to the performance of pull-ups is the position of the hands. Various kinesiologists have reported the effects of forearm position on elbow flexion efficiency; however, differences in opinion continue (4, 10, 11, 12, 14). Is the pronated grasp superior to the supinated grip? What advantage does the semipronated forearm have over the pronated or supinated position? Two investigators describe the midpoint (semipronated) position as the most efficient method for mechanical and electromyographical standpoints (4, 12). Other researchers recommend the supinated grasp (3, 6, 14, 15). One researcher suggests that little justification exists for requiring any certain position of the hands while chinning (8).

Recent studies have been conducted exploring hand positions and elbow flexion. A synthesis of these investigations appears to discredit the pronated (palms forward) hand grasp as an efficient method of pull-up performance for boys, and the flexed-arm hang for girls (3, 15). Notwithstanding, certain physical fitness tests continue to specify the pronated grasp as a prescribed manner in executing the pull-up (2, 9).

Electromyographical analysis and performance testing reveal significant findings which question the rationale of the pronated hand position as an acceptable technique in performing the traditional pull-up exercise.

ELECTROMYOGRAPHICAL ASPECTS

Studies by Basmajian (4) point out the fine isotonic flexion interplay among the biceps brachii, brachialis, and brachioradialis, and suggest that a wide range of individual patterns of myographic activity exists in elbow flexion. It is significant to note that the biceps brachii is generally active during flexion of the supine forearm under all conditions as well as in the semiprone forearm when a load of 2 lb is lifted (4). However, action potentials with the forearm prone reveal little, if any, role in flexion of the elbow. This phenomenon may be partially explained by the change in the line of puii from pronated to supinated in the chinning action (Figures 1a and 1b). Rasch and Burke (10)

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describe the inability of the biceps to record strong electromyographic potentials due to the wrapping of the tendon of the biceps more than half-way around the bone (radius) with contraction of the muscle tending to unwrap itself and thus supinate the hand. Wells (14) concludes that the pronated forearm pull-up cannot be justified from a kinesiological viewpoint, since the biceps brachii is least active with the hand in pronation.

The forearm position does not appear to lessen the brachialis and brachioradialis contraction. Basmajian (4) states that the brachialis is a flexor of the supine, semiprone and pronated forearm in slow and quick movements and designates this muscle as the "workhorse" among the elbow flexors. Electromyographically, the brachioradialis records greater action potentials in the semiprone and prone positions than with the supine hand grasp. Although these prime elbow flexors differ in their flexor activity in various forearm positions, all three muscles act maximally when a weight is lifted during flexion of a semiprone forearm (4). It should be noted that the above postulations are based on lifting weights with the hand, and not the traditional pull-up of lifting body weight on a chinning bar.

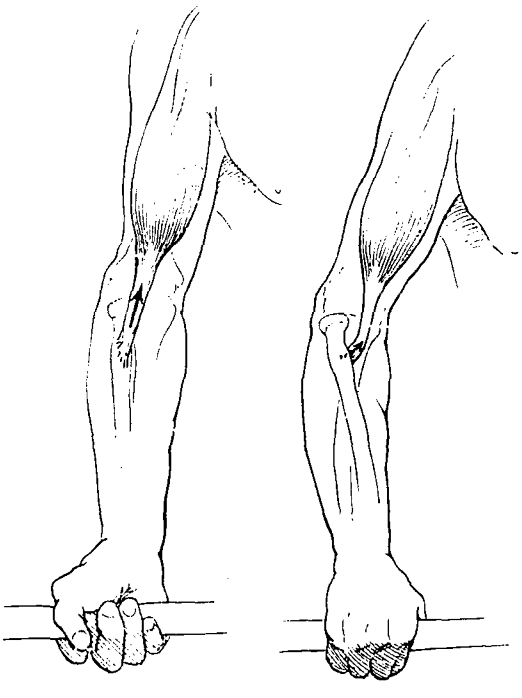

Figure 1. (a) Supinated forearm (direct line of pull); (b) Pronated forearm (twisting line of pull).

MECHANICAL ASPECTS

The elbow articulation is a typical uniaxial ginglymus (hinge) with an average 146° range of motion (1). Figure 2 illustrates elbow flexion as an internal lever of the third class. The prime flexors originate from the tip of the corocoid process and glenoid fossa of the scapula (short and long heads of biceps), lower two-thirds on front of the humerus (brachialis) and lower two-thirds of the outer condyloid ridge of the humerus (brachioradialis). Insertion of these powerful flexors attach to: (a) the medial aspect of the radial tuberosity (biceps); (b) the lower part of the coronoid process and tuberosity of the ulna (brachialis); and (c) the lateral side of the radius above the styloid process (brachioradialis) (5).

Mechanically, elbow flexion is a classic example of the body's structure demonstrating a long resistance arm and short force arm arrangement (Figure 2). Short force arms (distance from joint to muscle insertion) and a long resistance arm (distance from joint to point of resistance) simply require more muscular strength to produce movement. The internal skeletal and musclar arrangement does not favor muscular advantages in the pull-up action of chinning. The biceps brachii is not only a flexor of the elbow but a prime supinator as well, and in this writer's view it is this factor which causes the position of the forearm to affect pulling efficiency in elbow flexion.

The insertion of the biceps on the tuberosity of the radius lies behind the longitudinal axis of the latter so that the tendon winds around the ulna border of the radius (11). It is this supinatory effect which prohibits the full mechanical advantage of the muscle's direct line of pull upon the biceps brachii when the forearm is pronated.

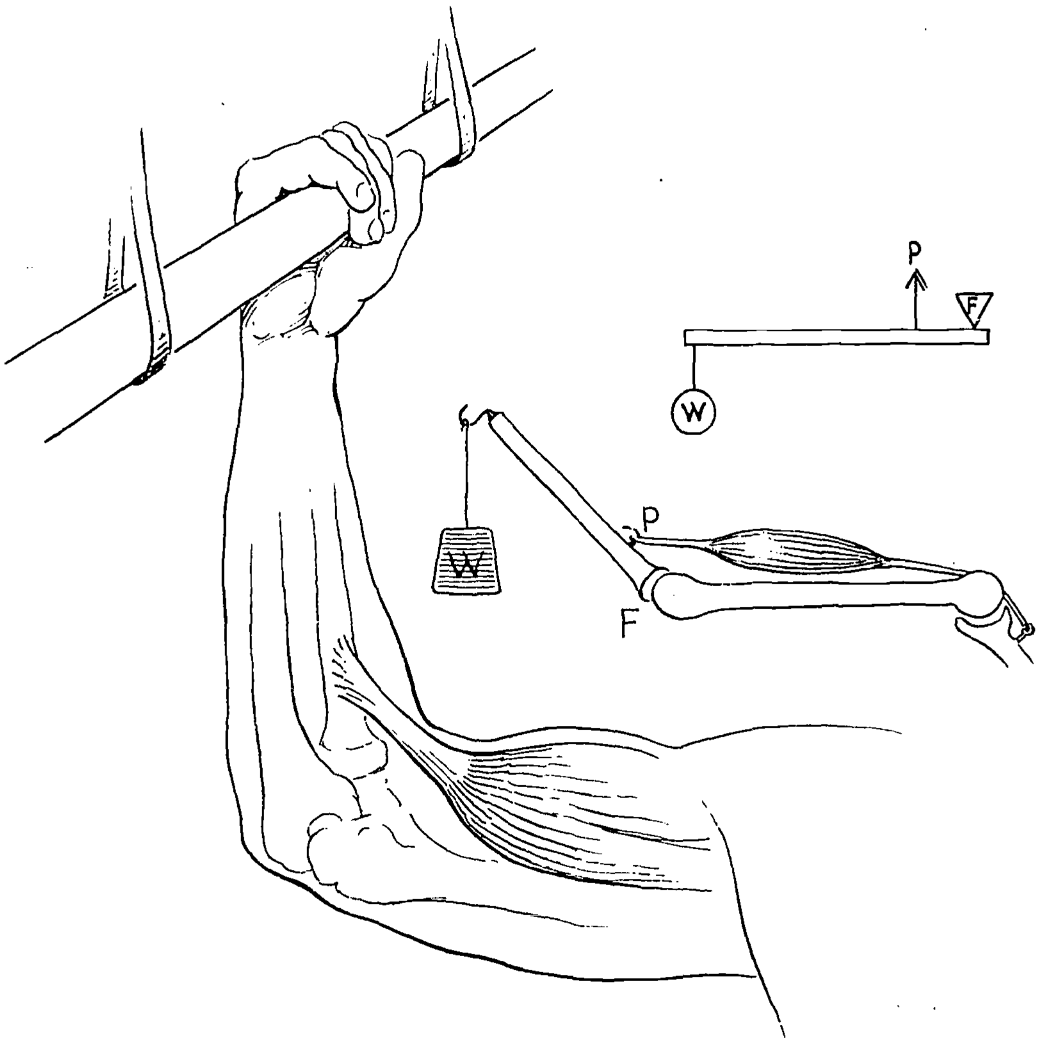

Figure 2. Flexion of the elbow joint (third class lever).

Figure 1b illustrates the twisting line of pull of the biceps when the elbow is flexed with a pronated hand.

Mechanically, the semiprone (one-half way between supination and pronation) is a compromise grasp. In this pull-up position (palms facing each other), the biceps tendon has started to wrap around the radius. Some rotational power is present and the biceps is not utilized to its fullest potential as compared with the supinated position, but its strength is greater than in the pronated position.

RECENT STUDIES AT SUNYAB

Two recent studies completed at the State University of New York at Buffalo, under the supervision of the writer, support the superiority of the supinated hand grasp over the pronated grip in the performance of pull-ups and flex-arm hang among elementary and junior high school boys and girls (3, 15). Williams (15) investigated the supinated, pronated, and semipronated forearm positions among 123 fifth and sixth grade boys using each of the three positions. Pronated and supinated grasps were performed in the traditional chin-up fashion on the horizontal bar. The semiprone grasp was executed on a modified horizontal ladder rigging, shown in Figure 3. Reliability coefficients of .93, .90, and .94 were established for each position, respectively, indicating high consistency scores.

Means of 4.02, 3.56, and 2.38, respectively, were calculated for the supinated, semipronated and pronated grasps. Mean scores for each group revealed that the supinated grasp was superior to the other grasps tested, while use of the pronated forearm was least productive in performance (15). Analysis of variance indicated that a significant difference among the three grips was significant at the .01 level of confidence (15). Although the semipronated grasp was not as efficient in pull-ups achieved when compared with the supinated grasp, Williams (15) suggests that this style should be investigated further because the traditional grasp had the advantage of familiarity among the subjects. Most students found the semipronated grip strange, and this variable may have elicited lower scores in the semipronated position as compared with the supinated grasp.

Ash (3) analyzed forearm grasps in a similar study among 151 ninth and tenth grade girls. The flexed-arm test (AAHPER method) was administered in each of the following forearm positions: pronated, supinated, and midpoint (semipronated). Reliability coefficients ranged from .84 to .89. Analysis of variance disclosed differences significant at the 1 percent level among the three positions. The *t* test was applied to the pronated and supinated grasps, with mean scores of 8.70 and 21.08 sec, respectively.

Figure 3. The semipronated position.

Results supported the performance superiority of supinated grasp as compared with the pronated position. Mean scores of 22.15 (midpoint) add 21.08 (supinated position) did not elicit a significant difference at the 1 percent level between these two grasps. This investigation is congruent with the Williams data, which reveal the inefficiency of the pronated grasp as compared with the supinated position. As in the Williams study, the midpoint grasp was new and unfamiliar to the girls tested. This factor may have influenced the results, lessening the scores with the semipronated grasp.

DISCUSSION AND IMPLICATIONS

Evidence appears to support the supinated forearm grasp as the most effective method of performing pull-ups. Mechanically and electromyographically, the biceps brachii, one of the most powerful elbow flexors, can exert its greatest force in the supinated position with the mechanical aspect favoring the nontwisting tendon advantage over the pronated forearm.

The pronated forearm position cannot be defended kinesiologically as an efficient grasp in performing pull-ups, yet certain arm and shoulder strength tests specify this style.

Some question still remains concerning the semipronated grasp. It is this writer's view that the newness and unfamiliarity of the midpoint grip does have the effect of decreasing the number of pull-ups performed; however, more research is needed at this time to analyze the semipronated forearm specifically as an effective position.

The correct hand grasp has important implications for physical educators and allied health specialists interested in human movement proficiency.

Individuals with low strength decrements may achieve greater pull-up performance through the improved mechanical efficiency of the supinated forearm by delaying the onset of fatigue.

Standardization of forearm grasps will allow measurement and evaluation specialists to compare pull-up norms validly.

Coaches and performers in such sports as gymnastics and swimming have a special interest in hand grasp where correct hand position is essential for maximum pulling power.

Corrective rehabilitation exercise therapists can apply the direct line of pull principle of the supinated hand for greater elbow flexion in restoring normal range of movement.

Bioengineers may well utilize kinesiological implications of forearm grasps in the design of hand tools, appliances, and prothestic instruments.

Tasks requiring elbow flexion are innumerable in human movement. Whatever the task may be, efficient body mechanics adds quality to everyday living as the individual moves in his/her work and recreational environment.

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