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H M REYNOLDS, J MARCUS, J FREEMAN   F49620-78-C-0012
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System Anthropometry has laid the foundation for a three-dimensional anthropometry. A unique, dedicated laboratory has been built and is currently used in an investigation of the lumbar/pelvic/femur linkage system. Data have been analyzed describing the three-dimensional seated posture of 281 young female subjects. Through the use of a multivariate clustering procedure, two postures were identified: slouched and erect. Data have been collected and analyzed on the sacroiliac and hip joint motion in three-dimensional space.

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Thus, the basis for describing in three-dimensional space a fixed body posture and for obtaining data on joint mobility (the anatomical site at which a change of posture is made) has been established.

AFOSR-TR- 81-0086

Final Report

A FOUNDATION FOR SYSTEMS ANTHROPOMETRY

United States Air Force
Office of Scientific Research
Bolling AFB, D.C. 20332

AFOSR Contract #F49620-78-C-0012

Herbert M. Reynolds, Ph.D.
Principal Investigator

November 25, 1980

Prepared By

Department of Biomechanics
College of Osteopathic Medicine
Michigan State University
East Lansing, M.I. 48824

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1.0 Introduction

The application of mechanical concepts to the description of the human body and its capabilities developed into a scientific field of investigation during the late nineteenth and early twentieth centuries. The realization that the human body is subject to the Laws of Mechanics and the initial attempts to measure these properties of the body were strongly influenced by W. Braune, O. Fischer, R. Fick, J. Agar and W.T. Dempster. Early attempts at investigating the biomechanical properties of the human body were restricted to two-dimensional measurements and analyses. In general, the body has been studied in the sagittal profile since this plane represents the plane of body symmetry and many body activities occur in this plane.

As a result of the two-dimensional approach to measurement and analysis, the assumptions in the description of the dynamic human body have a degree of uncertainty in their results which reduces their effectiveness. For example, while using a two-dimensional model of a joint as an instantaneous joint center of rotation, Dempster located the hip joint center within a 1.2 to 1.5 inch ellipse for the seated position of the human body (1955). The imprecision in Dempster's joint descriptions rests in the limitation of describing a three-dimensional body with two-dimensional data. The two-dimensional planar model is limited to describing three of the six degrees of freedom in the hip joint which introduces uncertainty into the data. The human body is three-dimensional in both size and movement; the methodology by which three-dimensional data suitable for biomechanical analysis can be obtained and analyzed, is the focus of this research investigation.

The current research began at The University of Michigan, Highway Safety Research Institute in July 1976. The purpose of the research was initially to lay a foundation for a new three-dimensional anthropometric system suitable for computer-aided design and analysis. These data would, therefore, be capable of:

a) locating the human operator in three-dimensional space;

b) defining spatial relationships between various body segments (head, neck, upper and lower torso, arms, and legs); and,

c) describing voluntary motions between these body parts.

Thus, systems anthropometry is the measurement of man as a three-dimensional dynamic organism that has functional anatomical structures which move and have mass properties.

The research sponsored by the Air Force Office of Scientific Research has investigated how to quantify these movements as a system. First, the task was simply to establish a philosophical basis for a three-dimensional anthropometry; second, to examine a data collection methodology; third, to construct a laboratory capable of meeting the requirements of Systems Anthropometry; and fourth, to demonstrate data collection and analysis procedures from laboratory measurements on the lumbar/pelvic/femur linkage system. The remainder of this report will describe the tasks and a brief summary of research.

2.0 Tasks for Systems Anthropometry by Phase

2.1 Phase I Task.

The first task for Systems Anthropometry was to establish a foundation for three-dimensional anthropometry. Both dynamic and workspace models simulate the position and mobility of the whole human body. Three-dimensional measurement technologies have been developed for either investigations of relative motion or absolute position. When both types of data are required, measurement technologies are reduced to the use of radiographic techniques. This measurement technique images the absolute positions of the skeleton for quantitative analysis. The location of the skeleton provides these data since it represents the only system of rigid bodies suitable for three-dimensional analysis.

2.2 Phase II Task.

Research in Phase II centered upon development of a stereo-radiographic measurement system that could be used to investigate the lumbar/pelvic/femur linkage system. The investigation had two goals: 1) to define linkage landmarks that will be measured in future population studies, and 2) to develop a stereo-radiographic system described in Phase I. In particular, kinematic analysis of the lumbar/pelvic/linkage system uses anatomical and anthropometric landmarks located with a stereo-radiographic technique.

2.3 Phase III Task.

Based upon results in Phase II, the need for a dedicated stereo-radiographic laboratory was recognized. Consequently, the research program was moved to the Department of Biomechanics, College of Osteopathic Medicine, Michigan State University where the Systems Anthropometry Laboratory was constructed. The laboratory consists of three rooms: a stereo-radiographic laboratory, a darkroom, and a data analysis room. The stereo-radiographic laboratory has two x-ray tubes mounted on a "3-D Siemens" tube mount that expose film in a film cassette holder that moves in a vertical plane perpendicular to the tubes. After the film is exposed, it is processed in a darkroom with an automatic film processor. The film utilized in the experiments is 14" x 36" film. The data analysis room contains a minicomputer (General Automation 16/460), terminals (hardcopy, CRT, and graphics), x/y digitizer and an x/y digital plotter. These three rooms and their associated equipment are dedicated to Systems Anthropometry research which follows in Phase IV.

2.4 Phase IV Task.

An investigation of the lumbar/pelvic/femur linkage system in both the standing and sitting positions was outlined for Phase IV. The kinematic properties of the hip joint, sacro-iliac joint, and lumbo-sacral joint were investigated in fresh unembalmed cadavers in the laboratory. These data have been analyzed using a screw axis to describe the motion between positions.

3.0 Summary of Results

The following summary was presented in Cambridge, England at the NATO Symposium on Anthropometry and Biomechanics. It represents a summary of two of the major research activities in Systems Anthropometry: three-dimensional data analysis describing position and mobility of the human body.

3.1 Three-dimensional Anthropometry.

The basic variable in three-dimensional anthropometry is a location vector, its value determined with a mathematical frame of reference, such as a Cartesian coordinate axis system. Within such a framework, measurements of the body are made by locating points with a mechanical, electro-mechanical, or optical system from which three-dimensional coordinates can be derived. The data, therefore, are x-, y-, and z-coordinates in a fixed axis system located in relation to an environment, such as a laboratory, automobile, chair, etc. Three-dimensional anthropometry is the measurement of points on the human body in a well-defined vector space. Within the context of an investigation these points are either random targets closely spaced for a good estimate of body volume (Herron, 1976) or functional pointmarks that represent specific anatomical landmarks, for an accurate measure of body position and mobility (Reynolds and Hubbard, 1980). Only the latter approach will be described in the present paper.

Traditionally, anthropometric landmarks have provided repeatable endpoints of a measurement that represented an anatomical or clearance dimension. A pointmark is, on the other hand, a targeted point on a landmark. The location of a pointmark defines a vector in three-dimensional space and anatomical or clearance dimensions are calculated as point-to-point distances between two pointmarks. Because they can be measured with the body in any position, the use of pointmarks is a substantive addition to the science of anthropometry. With three pointmarks on each body link, an anatomical frame of reference (Reynolds and Hubbard, 1980) can be defined which will specify completely the spatial relationships between body links: the standardized posture required in traditional anthropometry has thus been superseded. If the same three pointmarks on each body segment are measured in different positions, the relative change in position can be used to describe the motion characteristics of a joint (Marcus, 1980). Therefore, three-dimensional anthropometry may be considered an appropriate method of describing the body as an open-link system whose posture is variable but quantifiable.

Posture may be described quantitatively either as a set of pointmark vectors for a given workspace or, more completely, as a set of anatomical coordinate frames whose relative positions are defined in three-dimensional space. Following are two examples: 1) a sample of living subjects seated in a hard-seat and 2) the hip and sacroiliac kinematics of one unembalmed cadaver. In both examples, the basic data set consists of three-dimensional coordinate locations of pointmark vectors: the foundation for a three-dimensional systems approach to the human machine is established.

3.2 Three-dimensional Seated Posture.

Although Europeans (Akerbloom, 1948; Grandjean, 1969) have studied seated posture extensively, most research investigations have encountered difficulty in quantifying the position of the body in various postures. In fact, a single posture has often been standardized when anthropometric data on the seated position are desired.

Past investigations of body posture have utilized graphical (Corlett, et al., 1979) or verbal (Branton and Grayson, 1967) methodologies. One of the most highly systematized methods of describing body position was developed in the field of dance where labanotation (Hutchinson, 1970) has been programmed (Smoliar and Tracton, 1978). A more elaborate system was perhaps developed by Roebuck (1968) for evaluating spacesuit mobility; however, none of these techniques for describing posture provide the capability of spatially relating the human machine to the geometry of the working environment. In order to quantify posture accurately so that it has a geometric basis, three-dimensional anthropometry shows promise as a potentially useful technique. Thus, extremely precise codification of the human machine may contribute to the solution of its "breakdown" problems.

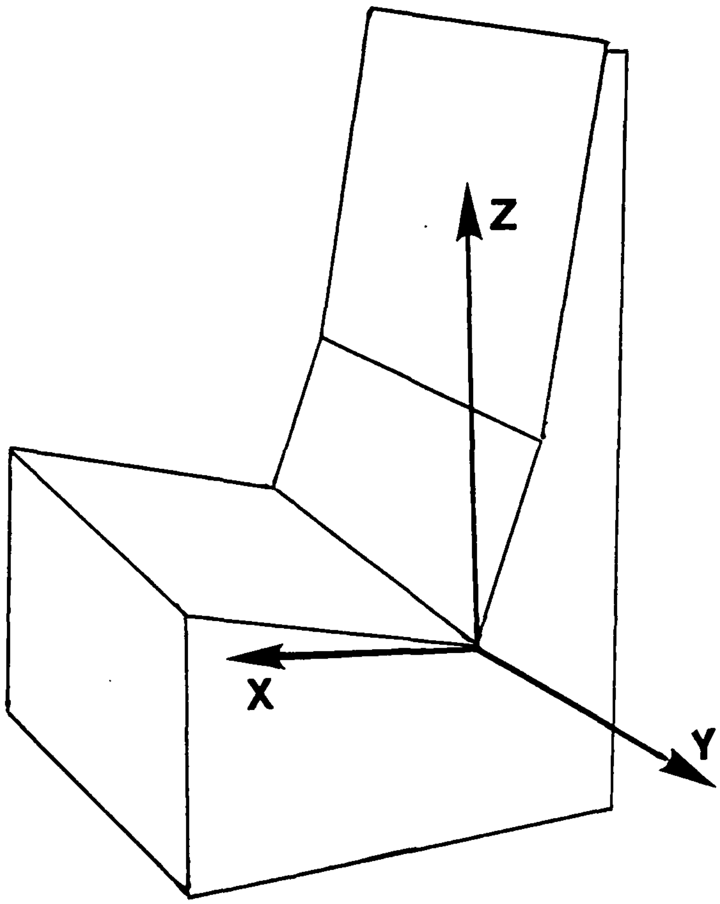

Figure 1. Hard-seat with three-dimensional axis system depicted.

for each subject. To remove the positioning effect, each subject's variable dataset was transformed into the new coordinate axis system, thus changing the origin to an anthropometrically comparable location.

Variability in the data was now reduced to differences in body size and posture. To determine if subjects assumed different postures, the data were clustered using the Michigan Interactive Data Analysis program at The University of Michigan Computing Center. Based upon the average Euclidean distance between the x- and z- coordinates for vertex and ectocanthus pointmarks, the clustering algorithm established two groups. Because it lies in the frontal plane and describes lateral body stability, which should be independent of body position, the y-coordinate was not used. Thus, within the range of possible postures in the hard-seat, a "slouched" and "erect" posture were identified in the three-dimensional data.

The two-dimensional location of each pointmark in the two clusters has been plotted in Figure 2 which depicts the sagittal projection (XY-plane) of the average values. The sagittal projection illustrates that the subjects have been divided into: 1) a "slouched" posture (Δ) with the head (vertex and ectocanthus) positioned away from the chair back and the pelvis (iliocristale and iliospinale) rotated back toward the chair; 2) an "erect" posture (o) with the head positioned back toward the chair and the pelvis rotated forward. The projection illustrates that those individuals with a "slouched" posture are taller with respect to the chair than those individuals with an "erect" posture.

Body posture has always been difficult to describe quantitatively. The basic problem results from the very complex human machine; that is, the open-chain linkage system has, by a conservative estimate, approximately 44 degrees of freedom, the sum of the degrees of freedom for each of the major joints of a body represented in typical computer man-models. Therefore, the variety of postures which an individual may assume and the variety of postures which a group of individuals may

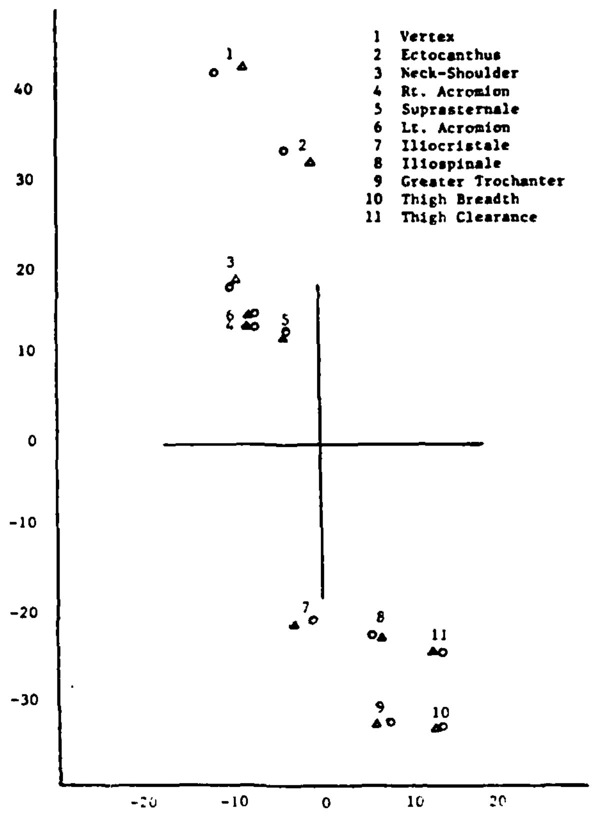

Figure 2. Two-dimensional plot of average values in centimeters for eleven pointmarks in the x-z plane (Δ = "slouched" posture; o = "erect" posture).

assume are, for all practical purposes, infinite. The foregoing example has however, demonstrated that 3-D anthropometry can quantify, with great precision, specific body positions within a sample group of body postures.

3.3 Three-dimensional Relative Motion of the Skeletal System.

The human machine moves by relative displacements of the skeletal linkage system. That is, motion of one link can be described relative to a fixed link by measuring in three-dimensional space the location of the moving link in two positions. When motion parameters of the skeletal linkage system are determined in three-dimensional space, an accurate model of body position and mobility can be developed. The assumptions involved in restricting the model to motions of the skeletal linkage system are as follows:

- -- the skeleton provides the primary basis of human body position;
- -- the skeleton provides the primary leverage system for muscle action;
- -- the skeleton defines the geometric shape of a joint within which joint mobility is constrained;
- -- the skeleton defines basic body size.

Within this conceptual framework, three-dimensional data have been obtained to investigate the kinematic properties of the human machine as a three-dimensional system composed of links connected at joints each with six degrees of freedom. A stereo-radiographic technique has been developed in the Systems Anthropometry Laboratory at Michigan State University to measure the three-dimensional locations of anatomical pointmarks on the skeletal linkage system. Current research in the Laboratory is focused on relative motions among the skeletal segments of the lumbar/pelvic/femur linkage system. Relative movement between the sacrum, hip bone and femur and their absolute position with respect to an inertial axis system have been obtained from an unembalmed cadaver, held in a standing position while the thigh was moved through paths of motion. A pair of stereo-radiographs was obtained of the pelvic/femur links for each discrete position along the paths of motion, beginning from the anatomical position and ending when the body became unstable in its upright-supporting harness. Pointmarks targeted on the film were digitized and outputted to a program that calculated the three-dimensional coordinates of each target relative to an inertial axis system, which is visible on each film.

Relative motion among the bones can be described by an angle about and a displacement along a single axis (Suh and Radcliffe, 1978). The instantaneous screw axis is defined by a translation "s" along the axis, a rotation "ϕ" about the axis, and direction cosines, "U_x, U_y, U_z" of the axis. Data in Tables 1 and 2 describe three screw axes for relative motion at the hip and sacroiliac joints. Each of the three bones was targeted with three pointmarks and an axis system calculated for each of the three bony segments. The left hip bone was mathematically held fixed in space and the data analyzed for relative motion of the femur (Table 1) and sacrum (Table 2).

These data provide limited evidence that the pelvis is not a rigid body: the sacrum appears to move as a function of femoral movement, although its motion is, for practical purposes, only rotation. Thus, for hip abduction, the sacrum rotates primarily in the x-y plane of the hip bone axis system; for hip abduction, primarily, in the x-z plane; and for the hip flexion, primarily, in the y-z plane.

The screw axis in Tables 1 and 2 have been located relative to an anatomical frame of reference. Anatomical axes systems constitute a change from traditional biomechanical engineering approaches since they are relative frames of reference based upon measured data. When an axis system is defined with measured data, errors in mensuration become evident and important. The effect of errors in the definition of an anatomically-based coordinate axis system has been investigated by Robbins (1977) and Marcus (1980). Robbins stated that the data can be no more accurate than the definition of the axis system itself and that the axis system

TABLE 1

Screw Axis Analysis for Hip Motion

Motion	s(cm)	ϕ (deg)	u_x	u_y	u_z
Abduction	-.07	24.0	.949	-.265	.171
Abducto-flexion	-.46	44.5	.742	-.407	.532
Flexion	1.44	55.6	.951	-.309	0.0

TABLE 2

Screw Axis Analysis for Sacroiliac Motion

Motion	s(cm)	ϕ (deg)	u_x	u_y	u_z
Abduction	.03	1.23	-.148	-.346	.926
Abducto-flexion	.13	1.20	.339	.917	0.22
Flexion	0.0	2.33	.985	.080	-.147

definition should be based on pointmarks as far apart as possible on the same rigid body. Marcus showed that the origin of the anatomical axis system should be equidistant from all of the pointmarks used to define it. Such requirements are not easily met; and the methods of determining an anatomical frame of reference which meets these stringent criteria is still under investigation.

3.4 Discussion and Conclusion.

Incorporated in all these data is a basic problem in the identification of pointmarks. Engineers have often accused anthropometrists of having "magic fingers"; and at present a substitute for careful palpatory location of pointmarks derived from comparative morphological anatomy does not seem to exist.

Pointmarks and their identification must be carefully investigated since they contribute to errors in data analysis: the absolute position and mobility of the body in three-dimensional space can only be as accurately defined as the pointmarks are accurately located. Population studies are possible only when variability in pointmark definition between subjects is minimized. All three-dimensional data analysis is made with algorithms that react sensitively to errors because the analysis used mathematical calculations that propagate and often magnify error. As a result, procedures must be developed that contain error in the raw data and minimize error propagation in the data analysis.

Despite the two examples presented here that show a clear advance in information obtained with three-dimensional, over two-dimensional, anthropometry, a current need remains to develop accurate and cost efficient means of three-dimensional measurements and analysis. With the advent of the digital computer, models have proliferated both for civilian and military applications, but the advances in modeling technique have often been made without concurrent advances in anthropometric databases. This trend clearly needs to be eliminated if we are to progress toward accurate predictive models of the human machine.

Three-dimensional anthropometry presents both basic and applied investigators with a tool for measuring geometric properties of the human body for dynamic models. These data are essential to the ergonomic maintenance, repair, and replacement of productive capacity for our human machine.

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5.0 Contract Accomplishments

1) Anatomical axes systems established in this research program have been used in jointly-sponsored NHTSA and AFAMRL research programs into the mass distribution of adult men and women.

2) Three-dimensional data on pelvic geometry have been used by the FAA and NHTSA to build representative pelves of a small female, average male and large male for anthropomorphic dummies.

3) Three-dimensional data on the pelvis have established hip joint locations for COMBIMAN at AFAMRL and for the Tri-Service "Standard Man" anthropomorphic dummy study.

4) A unique stereoradiographic laboratory dedicated to the aims of Systems Anthropometry has been constructed by AFOSR (35%) and Michigan State University's College of Osteopathic Medicine (65%) for $350,000 in 1977 dollars.

5) The analysis of three-dimensional Cartesian coordinates have provided for the first time a quantitative geometric basis for describing seated posture.

6) Through the use of three-dimensional pointmarks defining anatomical axes systems, screw axes describing relative motions between the hip bone and femur have been located relative to skeletal pointmarks at the hip joint.

7) A Master's Thesis by Jeff Marcus entitled "The Accuracy of Screw Axis Analysis Using Position Data from Anatomical Motion Studies" has been completed based upon research in the Systems Anthropometry Laboratory. This thesis has also been submitted to AFOSR as the Annual Report for Phase IV.

6.0 List of AFOSR - Sponsored Publications and Presentations.

1977 - A Foundation for Systems Anthropometry. (co-author) Interim Report to United States Air Force Office of Scientific Research, January 31. (UM-HSRI-77-7). 126 pp.

"The Use and Abuse of Height/Weight Tables for Personnel Selection Criteria." (co-author) Paper presented at 48th Annual Scientific Meeting of the Aerospace Medical Association, May 9-12, Las Vegas.

1978 - "Systems Anthropometry, or Where Has Dynamic Anthropometry Gone?" (author) Paper presented at 47th Annual Meeting of the American Association of Physical Anthropologists, April 12-15, Toronto. Abstract in AJPA, 48(3):428.

A Foundation for Systems Anthropometry. Phase II. (co-author) Annual Report to United States Air Force Office of Scientific Research, March 15. (UM-HSRI-78-11). 89 pp.

"Anatomical Frames of Reference and Biomechanics." (co-author) Paper presented at 22nd Annual Meeting of the Human Factors Society, pp. 607-610.

"Anthropometric Model of Total Body Volume for Males of Different Sizes." (co-author) Human Biology, 50(4):529-540.

1979 - "A Normative Mid-Size Adult Male Pelvis." (co-author) Paper presented at the 48th Annual Meeting of the American Association of Physical Anthropologists, Apeil 11-13, San Francisco.

"Three-Dimensional Skeletal Geometry of the Pelvic Girdle." (author) Paper presented at the 6th International Congress of the International Federation of Manual Medicine, April 18-22, Baden-Baden, West Germany.

"Der drei-dimensionale Aufbau Des Beckenrings." (author) In: Dr. Heinz-Dieter Neumann and Dr. Hanns-Dieter Wolff (eds.) Theoretische Fortschritte und pracktische Erfahrungen der Manuellen Medizin. Bühl: Konkordia.

A Foundation for Systems Anthropometry. Phase III. (author) Annual Report to United States Air Force Office of Scientific Research, March 27. 53 pp.

"Total Body Volume in Females: Validation of a Theoretical Model." (co-author) Human Biology, 51(4):499-505.

1980 - "Anatomical Frames of Reference and Biomechanics." (co-author) Human Factors, in press.

"Three-Dimensional Kinematics in the Pelvic Girdle." (author) Paper presented at American Osteopathic Association Research Conference Symposium "Functional Anatomy of Human Locomotion and Posture." March 13-15, Chicago.

"The Human Machine in Three-Dimensions - Implications for Measurement and Analysis." (author) Paper presented at NATO Symposium "Anthropometry and Biomechanics: Theory and Application." July 7-11, Queen's College, Cambridge, England.

"Three-Dimensional Kinematics in the Pelvic Girdle." (author) J.A.O.A., Vol. 80(4), in press.

1981 - "The Human Machine in Three-Dimensions - Implications for Measurement and Analysis." (author) In: "Proceedings of NATO Symposium on Anthropometry and Biomechanics. R. Easterly, E. Kroemer and D. Chaffin (eds.) Plenum Press Publications, Inc., in press.

Papers submitted or in preparation:

"Systems Anthropometry: Development of a Stereoradiographic Measurement System," J. Biomechanics.

"Sampling the Hamann-Todd Skeletal Collection to Represent the U.S. Civilian Population described by the Health Examination Survey, 1960-62." Am. J. Phys. Anthrop.

"Variability in Seated Posture of Young Females," Am. J. Phys. Anthrop.

"The Anatomical Location of Screw Axes Describing Hip Mobility," J. Biomechanics.

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