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Linear Acceleration of Impact Type

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

LINEAR ACCELERATION OF IMPACT TYPE

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THEORETICAL MECHANICS FOR EXPRESSING IMPACT ACCELERATIVE RESPONSE OF HUMAN BEINGS

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SUMMARY

The theoretical requirements for expressing the kinematics of human impact acceleration experimentation are presented. Two basic coordinate systems necessary for expression of the kinematic information are identified as: 1) the body reference frame, defined in terms of the experimental subject's anatomy; 2) the laboratory reference frame, selected by the experimenter as required for each experiment. A general set of rules for deriving these coordinate systems is described. Necessary variables and parameters are defined in terms of the general set of rules. The resulting descriptions are compared with definitions in a previous AGARD publication and in a previous publication for use in prolonged acceleration.

I. INTRODUCTION

A combined U. S. Navy, U. S. Army project (Determination of Human Dynamic Response to Impact Acceleration) was initiated in 1966. Under the experimental protocol of this project, 236 human runs were conducted on the WHAM II accelerator at Wayne State University (1). The experimental design and the preliminary results were reported at the Twelfth and Thirteenth Stapp Car Crash Conferences (2,3). One of the immediate technical goals was to measure precisely the complete two-dimensional kinematic response of the human head and neck to $-G_x$ impact acceleration. Another technical goal of the two-dimensional experiments was to develop the techniques that could ultimately be used for more complex three-dimensional experimentation.

It is the purpose of this paper to examine the theoretical mechanics in order to derive the coordinate systems necessary to describe the kinematic measurement of impact acceleration experiments in three dimensions. Also, pertinent kinematic variables and computational parameters will be defined in terms of the derived coordinate systems.

II. THEORETICAL ANALYSIS

A. General Requirement for Complete Description of Kinematic Measurements of Human Response to Impact Acceleration.

There are certain salient characteristics of impact acceleration experiments which any method of description of the experimental measurements must be able to accommodate. These characteristics are:

1. Short duration of the impact acceleration pulse. Impact acceleration is defined as that acceleration occurring for one second or less.

2. High angular and linear acceleration levels.

3. Trajectories of body components that cannot be predicted with precision prior to the experiment.

4. Lack of experimentally established criteria pertaining to the spatial resolution requirements to ultimately describe mechanisms of injury.

5. Possibility that the angular and linear displacements, velocities, accelerations, and rates of onset of acceleration may be implicated in mechanisms of impact acceleration injury.

6. Possibility that kinematic measurements at one portion of the experimental subject's anatomy must be routinely transformed to other portions of the anatomy for analysis of experimental results.

The theoretical approach selected to accommodate these characteristics is to make sufficient measurements such that the kinematic response of the subject is completely determined. The sufficiency of the measurements relies on one major presumption; i.e., that certain critical components of the anatomy can be observed directly or indirectly and treated with rigid-body simulation techniques throughout the dynamic event. Rigid-body simulation techniques permit reduction of observable kinematic variables to a description of two principal coordinate frames, which are the laboratory-reference frame and the body-reference frame. Selected components of the bony skeleton that respond without fracture or substantial deformation can be treated as body-reference frames and should permit this descriptive approach.

With rigid-body simulation techniques, the characteristics of impact acceleration experiments as they relate to kinematic response can be completely described by the measurement or derivation of a limited set of kinematic variables.

The description of the time history of these kinematic variables throughout the impact event, therefore, is a major general requirement for impact acceleration experiments. The variables are those sufficient to describe unconstrained rigid-body motion with three degrees of freedom of angular displacement, velocity, and acceleration and three degrees of freedom of linear displacement, velocity, and acceleration. The pertinent variables to be described are listed with appropriate symbols in Table I.

Table I. Kinematic Variables of Interest in Impact Acceleration Experiments Using Rigid-Body Simulation Techniques

$\vec{D}$	Linear Displacement Vector
$\vec{V}$	Linear Velocity Vector
$\vec{A}$	Linear Acceleration Vector
$\hat{\theta}$	Angular Displacement Operator
$\vec{\omega}$	Angular Velocity Vector
$\vec{\alpha}$	Angular Acceleration Vector

It should be noted that in Table I, no unique symbols for rates of onset of angular or linear acceleration are listed since they usually are not measured directly. When needed, the rate of onset of linear acceleration (jerk) is often represented as $\frac{d\vec{A}}{dt}$, and rate of onset of angular acceleration as $\frac{d\vec{\alpha}}{dt}$. It should also be noted that the quantities in Table I are vectors except for the angular displacement operator. The angular displacement operator in three dimensions cannot be described as a vector or any geometrical angle but requires, as a minimum, a three-step operation of successive rotations.

B. Specific Requirements for Complete Kinematic Description of Measurements of Human Response to Impact Acceleration.

The general requirement was the determination of a limited set of kinematic variables. The specific requirements arise from the need to express each of these variables completely and unambiguously in terms of precisely defined coordinate systems of the two general types used for rigid-body simulations. Also, any computational procedures and parameters required to describe the unconstrained motion must also be uniquely and unambiguously defined in the selected coordinate systems.

Since the description of linear and angular displacement assures the ability to describe all the other variables, this should be considered first. The description of linear displacement is quite straightforward. This requires simply a statement of the coordinates of a body point of interest relative to a reference-coordinate system. This operation simply tracks the origin of the body-coordinate system relative to the reference-coordinate system. Rotation in three dimensions requires more elaborate description. The orientation of each body axis of interest relative to a reference coordinate system must be precisely known throughout the time duration of the experiment. The problem describing rotation in three dimensions has been dealt with extensively in classical mechanics (4,5). There are many alternate possible approaches to the problem from which three have been chosen. The first involves the use of direction cosines that relate each axis of the body-coordinate system to each axis of the reference system. The second involves the use of three Euler angles that describe the three successive rotations of the body system relative to the reference system. The third involves a set of parameters called quaternions. Therefore, it is necessary to : 1) define and explain a set of rules for forming a coordinate system, 2) define the variables from Table I in the coordinate system, and 3) define parameters and operations required for linear and angular displacement.

C. Analytical Result.

The simplest approach is to adopt the least number of rules sufficient to derive any coordinate system and then add sufficient definitions of variables and computational parameters in terms of the derived coordinate system to meet the requirements for use in impact acceleration experiments. Many of the coordinate systems adapted for flight dynamics or physiological acceleration are for special purposes and defined in terms of the subject matter of the application (6,7). They have not been concerned with the general requirement for a method of defining a coordinate system independent of subject matter or structure. The minimum rules for coordinate system definition which were identified and selected are:

1. Select an origin.

2. Select the first and second axis of the system, which can be identified, respectively, by the subscripts "i" and "j" and are at right angles to each other.

3. Define the third axis and all operations and parameters within the coordinate system by use of a right-hand rule.

The first two parts of the rules are illustrated in Figure 1 and the third in Figure 2. The approach of using a left-handed rule was arbitrarily excluded.

This set of rules discussed for impact acceleration requirements can be systematically applied, leading to the following definitions:

1. The third axis is defined by the cross product $\vec{\mu}_i \times \vec{\mu}_j = \vec{\mu}_k$, where the subscript "k" identifies the third axis. The result is illustrated in Figure 2.

2. Linear accelerations are described by $\vec{a}_i$, $\vec{a}_j$, $\vec{a}_k$, shown in Figure 3.

3. Angular accelerations are described by the vectors $\vec{\alpha}_i$, $\vec{\alpha}_j$, $\vec{\alpha}_k$, where the α's are counterclockwise around the indicated axis in accordance with the right-hand rule, as shown in Figure 4.

4. The definition of angular and linear velocity is the same as for angular and linear acceleration, with an appropriate change of symbols from $\vec{A}$ to $\vec{V}$ and $\vec{\alpha}$ to $\vec{\omega}$.

5. Linear displacement is defined by the three coordinates of the body origin in terms of the reference origin.

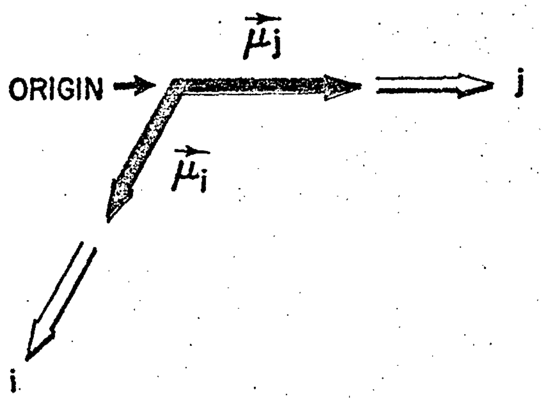

Figure 1. Selection of Origin and First and Second Axes.

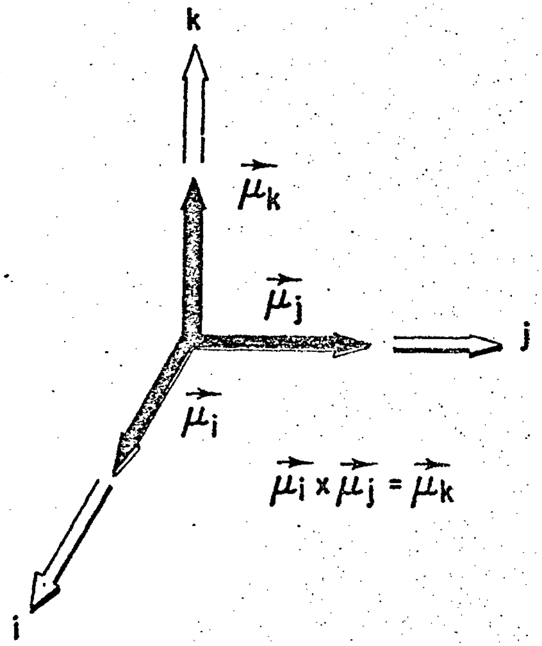

Figure 2. Definition of Third Axis (k).

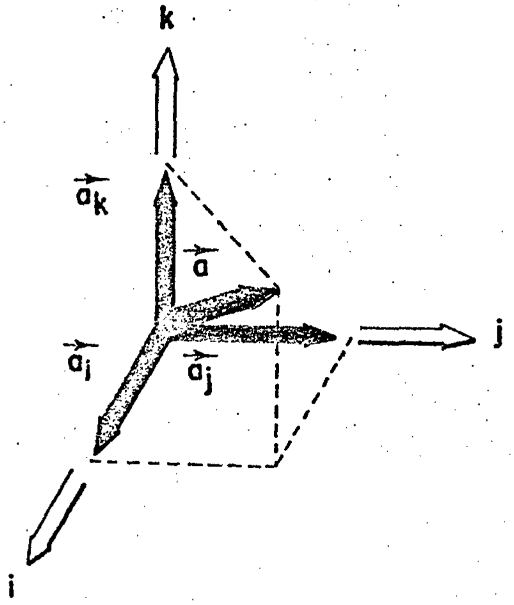

Figure 3. Illustration of Linear Acceleration.

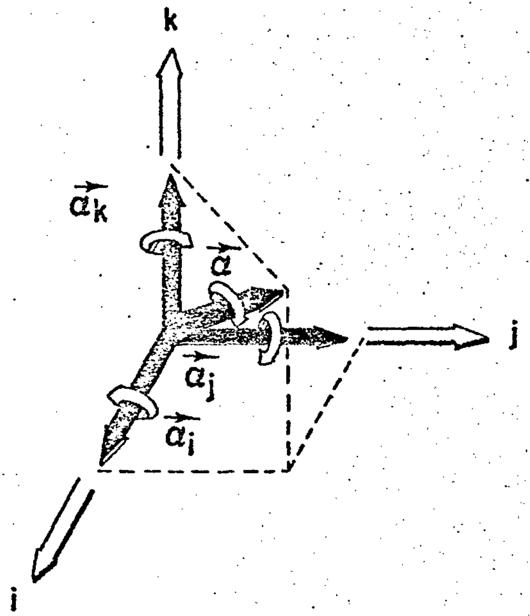

Figure 4. Illustration of Angular Acceleration.

6. Description of the angular displacement is accomplished by definition of the following three sets of parameters:

a. Direction cosines are found by the nine possible scalar products that are used to describe the orientation of each of three body axes (unprimed set, Figure 5) relative to each of the three reference system axes (primed set, Figure 5). The scalar products are formed from the unit vectors illustrated in Figure 5.

b. Euler angles are defined in order about the first, second, and third axes in accordance with a right-hand rule. The successive rotations are labeled E_i, E_j, E_k and shown in Figure 6. It should be noted that there are twelve possible definitions of Euler angles. They are divided into two types. The first type is defined sequentially around each of three successive axes; there are six possibilities, depending on the order of the axes. The second type is defined as a rotation around an original axis, then around a derived axis, and finally around the original which has been rotated; again there are six possibilities. The selected definition is of the first type, using the i, j, k order.

c. The quaternion definition chosen is a set of four real numbers that can be used to express the orientation of a body-coordinate system relative to a reference-coordinate system. The numbers arise from a particular computation that will transform the expression of a vector in a one-coordinate system to an expression in any other coordinate system. They can be expressed as ϵ_o, ϵ_i, ϵ_j, and ϵ_k and can be illustrated geometrically. This is due to the fact recognized by Euler that there is an instantaneous spin axis in the body about which the body-coordinate system can be rotated that can be used to describe the rotation with respect to any reference frame. The unit vector $\vec{\mu}_s$ which identifies the spin axis, the direction cosines of the unit vector $\vec{\mu}_s$, and the relation to a vector representation of the quaternion parameters $\vec{\epsilon}_i$, $\vec{\epsilon}_j$, and $\vec{\epsilon}_k$ are illustrated in Figure 7. From this figure it is also possible to represent the remaining quaternion ϵ_o, as a component of $\vec{\mu}_s$

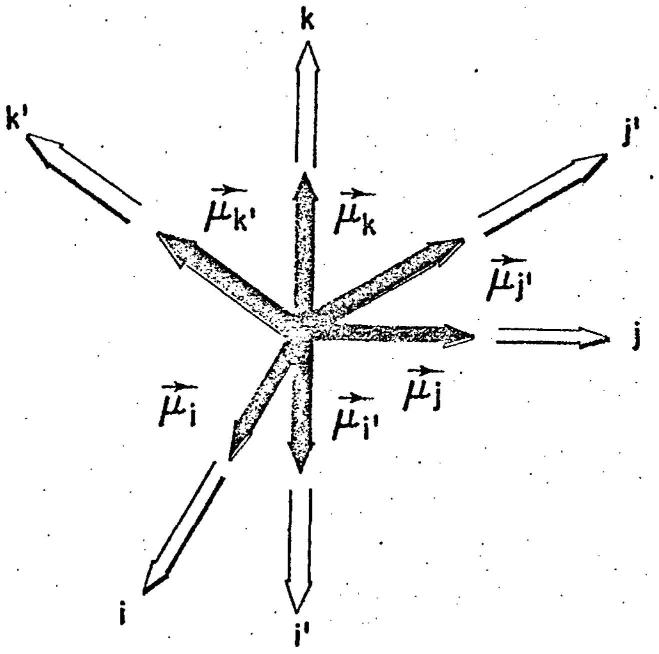

Figure 5. Unit Vectors for Computation of Direction Cosines.

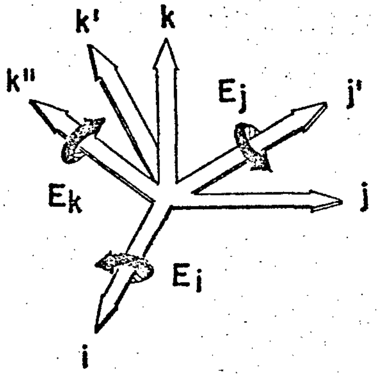

Figure 6. Euler Angles.

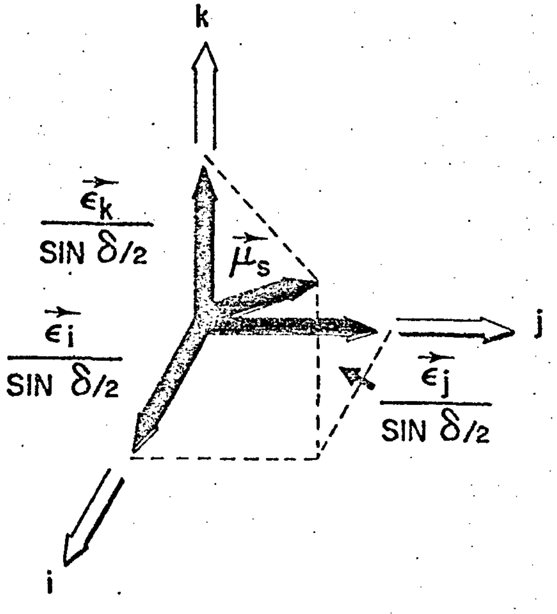

Figure 7. Spin Axis Determination in Terms of Quaternions.

with amplitude cos [illegible]. These quaternions are described in references (8) and (9). Another definition of quaternions is given in reference [illegible] which uses a four-vector representation that is a generalized form of a complex variable representation of a vector. This quaternion definition is not considered necessary, but it could readily be defined in terms of the derived coordinate system.

The coordinate system derivation rules and the variables and parameters defined in terms of a derived coordinate system are sufficient to express the kinematic variables of three-dimensional impact acceleration research. The inclusion of three independent methods of three-dimensional coordinate transformations associated with angular displacement was intentionally redundant. The first method that uses nine direction cosines is a straightforward way of executing coordinate transformations. However, they are not independent; therefore, there is considerable redundancy. The second method uses the least number of parameters possible to execute the coordinate transformation. These parameters are the three Euler angles. If the origin and first two axes are appropriately attached to a body, each Euler angle can be uniquely identified as roll, pitch, or yaw. This is a major advantage for the graphical expression of the experimental results. The difficulty with Euler angles in computation is that when one of the angles approaches ± 90°, the rate of change of the other two approaches infinity, introducing a point of singularity into the computation. Quaternion parameters as explained in references (8) and (9) avoid this problem by introducing four parameters with which there are no associated singularities. The parameters are related by the constraint $\epsilon_o^2 + \epsilon_i^2 + \epsilon_j^2 + \epsilon_k^2 = 1$. Since there are important advantages to each method for expressing experimental results, each has been retained and described.

III. DISCUSSION

The set of coordinate system derivation rules and the variables, parameters, and operations defined in terms of the derived coordinate system have been developed without any specific reference to the geometry of the subjects or systems generally studied in impact acceleration experiments. Therefore, there has been no discussion of the relationship of these definitions to preferred anatomical or physiological coordinate systems. The possibility of such relationship can be examined by establishing which of the commonly used or agreed-upon coordinate systems in the general area of acceleration research, if any, can meet the requirements of the proposed approach.

AGARD in Principles of Biodynamics has described several coordinate systems under the general headings of vehicle coordinate systems and human coordinate systems (7). Two human coordinate systems are described. The first is called Direction of applied force or resulting acceleration and is reproduced in Figure 8. The directions of forward, rightward, and upward are related to the anterior, right, and cephalad directions of the man. If taken in the order mentioned, they constitute a left-handed coordinate system. Also, angular rotation has not been defined for this system. The second is called Direction of heart rotation relative to skeletal frame and is reproduced in Figure 9. In essence, this is a reactive system that is used to describe motion of internal body components relative to the external landmarks of the body. The system is a right-handed system if x, y, and z are identified respectively with i, j, and k directions used in Figures 1 through 7. Furthermore, the illustrated direction of heart rotation, $\dot{R}_x$, $\dot{R}_y$, $\dot{R}_z$ would also be identical to the directions of the angular acceleration components described in Figure 4. However, for usage in impact acceleration experiments the reactive coordinate system has the drawback of describing motion of one body component in terms of another. This has the effect of interposing an extra body-coordinate system which is not needed to describe the motion in terms of a laboratory-reference frame. Also, as a matter of usage, the +X and +Z directions are opposite from the directions commonly assigned.

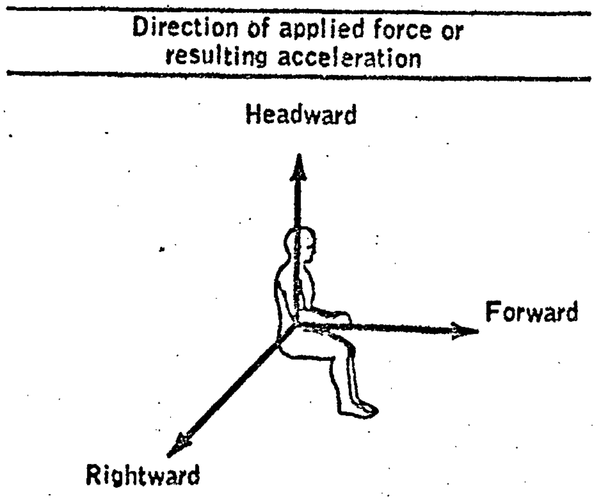

Figure 8. Reproduced from Table I, reference 7.

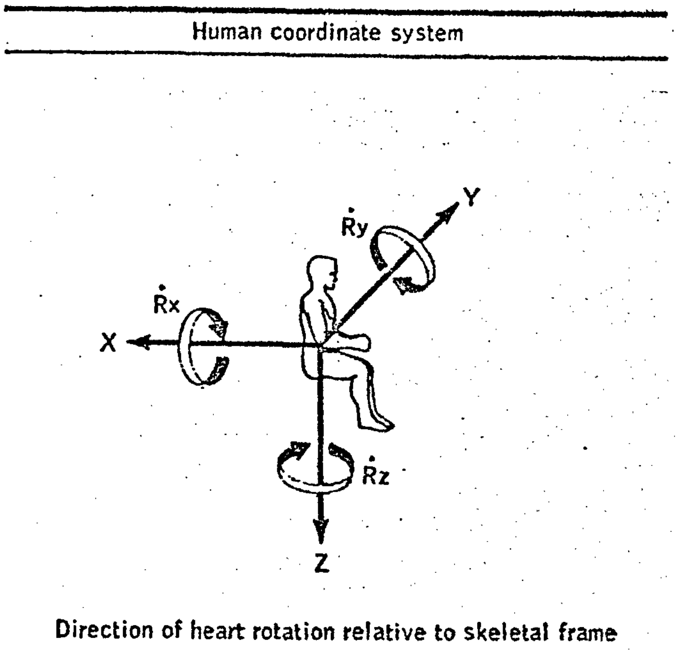

Figure 9. Reproduced from Table II, reference 7.

An extensive analysis of the problem of coordinate systems and associated nomenclature for vestibular research application has been presented in a monograph (10). The basic coordinate system adopted for vestibular nomenclature is presented in Figure 10, which is reproduced from the monograph (10). All the linear and angular variables listed in Table I and including the Euler angles of roll, pitch, and yaw, are discussed in this monograph. The result is an extensive description of a coordinate system for the head for vestibular research that appears to meet all of the kinematic requirements for impact acceleration experiments as they relate to the head, with minor changes and extension. For impact acceleration the precise anatomical definition of the i, j, k remain to be selected, although the definitions given for x, y, z directions in Figure 10 may suffice for i, j, and k, respectively. Also, the quaternion representation should be amended to the description (reference 10). As a result, there is a single approach to coordinate-system definition that is conceptually identical for impact acceleration experiments and prolonged or vestibular acceleration experiments as the experiments relate to the head. However, for impact acceleration there is the additional requirement to continually identify coordinate systems within the anatomy for each body component of interest as experimentally needed. This is readily accomplished in accordance with the procedures described in the theoretical analysis, once the anatomy of interest has been identified.

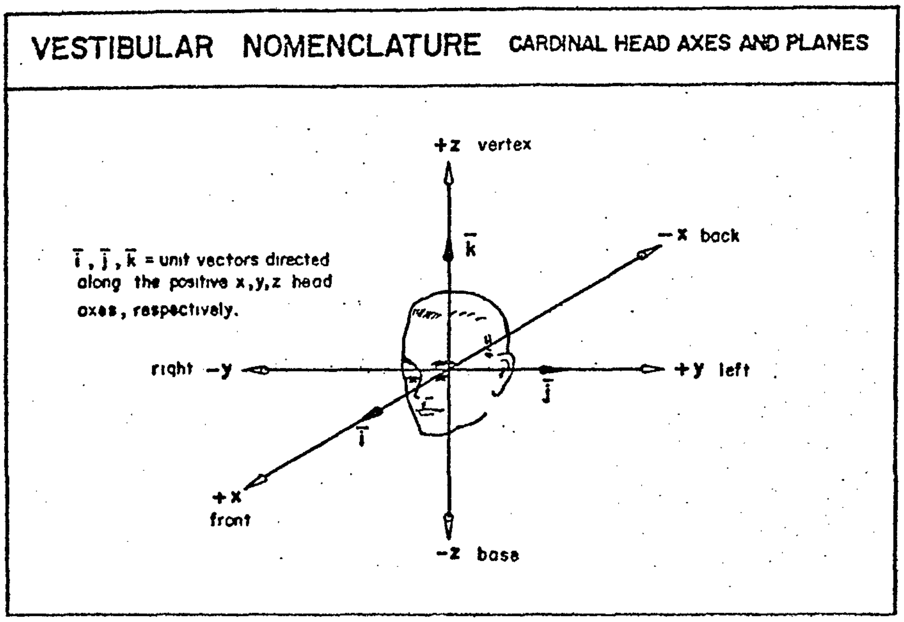

Figure 10. Reproduced from Figure 1, reference 10.

CONCLUSION

Review of the geometrical and kinematic requirements for the description of impact acceleration experiments that induce unconstrained three-dimensional motion has led to a simple set of rules for defining coordinate systems (Figure 1). The human coordinate system description published by AGARD (7) for prolonged acceleration is not readily adaptable to the several rules developed in this paper for impact acceleration. However, there does exist a description of a coordinate system for the human head used for vestibular research (10) that is conceptually identical. As a result, it is feasible to develop a single unified approach to coordinate system derivation and kinematic variable definitions that will serve for human impact and prolonged acceleration experimentation.

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