Abstract

Introduction

Biomechanical modeling has become an important tool for the medical and bioengineering problems. For a 3-D model the inertial data for each bodylinkage includes mass, length, mass centroid, and principal moments of inertial. Some imaging (Huang and Saurez, 1983; Martin, *et al.*, 1989; Rodrigue and Gagnon, 1983; Zatziorsky and Seluyanov, 1983), mechanical techniques (Allum and Young, 1976; Bouisset and Pertuzon, 1967; Drillis and Contini, 1966; Fenn, 1938; Hay, 1973; Peyton, 1986), or mathematical methods (Cornelis, *et al.*, 1978; Hanavan, 1964; Hatze, 1980; Jensen, 1976, 1978; Sady, *et al.*, 1978; Yeadon, 1990; Whitsett, 1963) have been used to estimate these data for living subjects. Unfortunately, in biomechanical studies the inertial data from living subjects are relatively rare especially for oriental nations, and cadaveric data are still the primary sources (Becker, 1972; Braune and Fischer, 1889; Clauser, *et al.*, 1969; Dempster, 1955; Drillis, 1975; Fischer, 1906; Harless, 1860; Miller and Nelson, 1976; Roebuck and Kroemer, 1975).

Among these experimental and mathematical studies, the following reasons limit the use of these data: (1) The existing cadaveric data can not provide three principal moments of inertia for all bodylinkages. Moreover, the size number of these studies is small and the subject population usually differs from the living subject under consideration. (2) Some mechanically experimental methods such as oscillation and quick-release techniques that require elaborate instrumentation are not easily practicable for the measurements of the inertial data of trunk and three principal moments of inertia for the other bodylinkages. (3) The *in vivo* experimentally imaging estimation of inertial data is complex, expensive, time-consuming, and radiation exposing. (4) The drawbacks of the existing mathematical models are that the number of direct anthropometric measurements for a given subject may be large, e.g., 242 (Hatze, 1980) and 95 (Yeadon, 1990), or segmentation of a single bodylinkage may be indefinite. In addition, all the inertial formulae used to calculate the inertial data are not available in the existing literatures.

The purposes of this study are two folds. Firstly, we synthesize and modify the geometric solid simulated by the other modelers for the better anatomical resemblance to the bodylinkage geometry. Secondly, we implicitly provide all the inertial formulae of the bodylinkages and arrange their involved and lengthy form as simple as possible. With these formulae, the researchers can use them with a computer to calculate the personalized inertial data of living subject. This study first describes the geometric simulation of the bodylinkages and derives the inertial formulae for simulated solids. The anthropometric measurements of the individual bodylinkage and the applications of this simulation model are then given.

Materials and Methods

The modeling procedure is to divide a body into bodylinkages that turn into mathematically analytical geometry and obtain the inertial data by a series of integration. The main bodylinkages include hands, forearms, upper arms, thighs, shanks, feet, head, neck, thorax, abdomen, and pelvis. Some bodylinkages can be further segmented, if the better anatomical resemblance is expected. Schematic illustration of this 17–bodylinkage model is shown in Fig. 1. The more detailed representation of the simulated bodylinkages and their local coordinate systems are given in Fig. 2. In this study, if the inertial formulae cannot be solved to close forms, the simpler numerical formulae are given. Because the derivation procedures involve lengthy integration and many times transformation of the coordinate systems, the detailed derivation procedures will not be described in the paper. Only the inertial formulae are provided.

Tapered Elliptic Cylinder (Limb and Neck)

The limbs and the neck are assumed to consist of elliptic rather than circular tapered cylinders. For a tapered elliptic cylinder the lengths of semiaxes are a_T and b_T for the upper bounding ellipse and a_B and b_B for the lower bounding ellipse (Fig. 2-A). The height of the cylinder is denoted by h. The inertial formulae for such a solid are as follows.

Mass

$M=®Dha_Bb_BF_1(\sim,\ )$

Mass Centroid

$x_{MC}=0 \quad y_{MC}=0 \quad z_{MC}=Ah$

Principal Moments of Inertia about the Mass Center

$I_{x\,MC}=M[Bh^2+¼b_B^2C(\sim,\ )-z_{MC}^2] \quad I_{y\,MC}=M[Bh^2+¼a_B^2C(\ ,\sim)-z_{MC}^2] \quad I_{z\,MC}=¼M[b_B^2C(\sim,\ )+a_B^2C(\ ,\sim)]$

Assumed Symbols and Functions

$\sim=(a_T-a_B)/a_B \quad =(b_T-b_B)/b_B \quad F_1(x,y)=1+½(x+y)+xy/3 \quad F_2(x,y)=½+(x+y)/3+xy/4$

$F_3(x,y)=1/3+(x+y)/4+xy/5 \quad F_4(x,y)=1+(3x+y)/2+(3xy+3y^2)/3+(3xy^2+y^3)/4+xy^3/5$

$A=F_2(\sim,\ )/F_1(\sim,\ ) \quad B=F_3(\sim,\ )/F_1(\sim,\ ) \quad C(x,y)=F_4(x,y)/F_1(x,y)$

Where D denotes the bodylinkage density. In contrast to ankle, elbow, and knee, the boundaries of the hip joint are more difficult to be identified. The majority of the muscles motivating the motion of the thigh around the hip joint attach to the iliac crests. Hence, the region surrounded by points D, E, and F moves with the thigh not with the pelvis (Fig. 1). Above all, the femoral head that its loading conditions are the major interests to some biomechanists lies on the line DE rather than EF.

Hence, in this study the upper boundary of the thigh is assumed to be along the line DE rather than along the line EF, as assumed by Yeadon (1990). Thus, the penetrating subsolid of the thigh into the pelvic is assumed as a diagonally truncated elliptic cylinder. The subsolid below the perineum (line EF) consists of n coaxially elliptic tapered subcylinders (Fig. 2-B). With conjunction to the head that is modeled as a partial ellipsoid (Fig. 2-C), the neck, like the thigh, is also assumed to consist of two subsolids.

Height

$h=\sum^{n}_{i=1} h_i$

Mass

$M=M_T+\sum^{n}_{i=1} M_i$

Mass Centroid

$x_{MC}\text{ø}0 \quad y_{MC}=0 \quad z_{MC}=[\sum^{n}_{i=1} M_i(z_{MC(i)}+h_{i-1})+M_T(h+5h_T/16)]/M$

Principal Moments of Inertia about the Mass Center

$I_{x\,MC}=M_T(6b_T^2+h_T^2)/48+M_T[5h_T(h-z_{MC})/8+(h-z_{MC})^2]+\sum^{n}_{i=1}[I_{x\,MC(i)}+M_i(z_{MC}-z_{MC(i)}-\sum^{i-1}_{j=1} h_j)^2]$

$I_{y\,MC}=M_T(6a_T^2+h_T^2)/48+M_T[5h_T(h-z_{MC})/8+(h-z_{MC})^2]+\sum^{n}_{i=1}[I_{y\,MC(i)}+M_i(z_{MC}-z_{MC(i)}-\sum^{i-1}_{j=1} h_j)^2]$

$I_{z\,MC}=M_T(a_T^2+b_T^2)/8+\sum^{n}_{i=1}I_{z\,MC(i)}$

Assumed Symbol

$M_T=\frac{1}{2}\text{®}Dh_T a_T b_T$

Where h_i, M_i, $z_{MC(i)}$ are respectively the height, mass, and z coordinate of the mass center of the i^{th} tapered elliptic subcylinder with respect to the coordinate system passing through the centroid of the bottom bounding ellipse of that subcylinder. $I_{x\,MC(i)}$, $I_{y\,MC(i)}$, and $I_{z\,MC(i)}$ are the principal moments of inertia of the i^{th} tapered elliptic subcylinder about the principal axes passing through its mass center. Their values can be calculated with the aforementioned equations.

Partial Ellipsoid (Head)

Tapered Rectangular Solid (Foot)

Partial Elliptic Plate (Hand)

Stadium Solid (Abdomen)

$(x/a)^2+(y/b)^2=(z/h_T)^{0.25}$ $(0 \leqq z \leqq h_T$

Quasi-Elliptic Paraboloids (Pelvis)

$(x/a)^2+(y/b)^2=(z/h_T)^{0.25}$ $(0 \leqq z \leqq h_T$

$(x/a)^2+(y/b)^2=(z/h_T)^{0.1}$ $(0 \leqq z \leqq h_T$ for

Application

Results

Discussion

van, 1964;

Hatze, 1980; Jensen, 1978; Whitsett, 1963), thorax (Cornelis, *et al.*, 1966), and stadium (Sady, *et al.*, 1978; Yeadon, 1990). A circle is mathematically convenient to be dealt with, but is not exactly the same as the contour of the limbs, which are simulated as an ellipse in this study. As an example of subject C, the eccentricity ($e=a/b$) significantly deviates from 1 ($1.09<e<1.25$ for shank, $0.98<e<1.21$ for thigh, $0.75<e<1.33$ for upper arm, $0.72<e<0.82$ for forearm). The values of r_{Mass} by simulating limb's cross-section as ellipse (circle) are respectively as follows: -4.67% (-11.9%) for forearm and 1.59% (-10.6%) for shank, compared with the predicted values of cadaver study (Dempster, 1955).

Conclusions

Legends