Human Body Segments

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Contributor: Antonio Cicchella

The knowledge of human body proportions and segmental properties of limbs, head and trunk is of fundamental importance in biomechanical research. Given that many methods are employed, it is important to know which ones are currently available, which data on human body masses, lengths, center of mass (COM) location, weights and moment of inertia (MOI) are available and which methods are most suitable for specific research purposes. Graphical, optical, x-ray and derived techniques, MRI, laser, thermography, has been employed for in-vivo measurement, while direct measurements involve cadaveric studies with dissection and various methods of acquiring shape and size of body segments.

human body segments inertial parameters morphometrics anthropometrics measurement methods

1. Introduction

Human body dimensions have been studied in-depth for a number of reasons: the building of houses and objects, work optimization and workspace design, clinical assessment of walking, in arts, military tasks, aerospace and weapons construction, sports, garment design, ergonomic, and studies on growth. Being aware of body segment lengths and circumference, weight, density, inertial parameters and their own mass displacements is thus important, and the scientific literature reflects this interest. Of special interest is the study of head and trunk and the determination of the body center of mass (COM). COM is a conceptual construct, dating back to the beginning of science. Whole-body COM is paramount for several reasons. The laws of motion are impossible to apply to several objects moving in space, and this is true especially for sports techniques or complex movements because of the constraints imposed by the sport setting. During Olympic or international competitions, it is difficult to directly measure body segment motions with high precision (it is not possible to put markers on the subjects, and joints are covered by garments or sports devices). The COM concept simplifies the calculus and provides a synthetic view of the movement, and the calculation of whole-body kinematics and kinetics. The subject has developed quickly since the availability of fast computation methods. For the biomechanist, it is important to choose the right method considering its reliability, feasibility, ethics and administrative aspects of each method. Additionally, it important to know the origins of the methods; a historical perspective helps in the understanding of how the concept of the measurement of the human body has developed. The measurement and computational methods of choice are important to achieve reliable results. Today, several methods and technological tools are available to the researcher, with their advantages, disadvantages, and proper application.

2. Modern and Contemporary Times

Only with the availability of computerized gamma-ray scanning methods was it possible to calculate, on living humans, body segment dimension (lengths, volumes, and MOI) precisely, without dissection. In the present, there are some concerns about the gamma irradiation of young human subjects, but at the time, these methods seemed ethical and effective. Zatsiorsky and Seyulianov [1] employed gamma-ray scanning to determine body segments inertial parameters, volumes and densities in young, healthy men. These data, like the previous, refer to Caucasian men. Only relatively recently inertial parameters have been published, in relation to different genders and races [2][3], and norms for Asian men were also provided [4][5][6]. There have been attempts to profile a single state population or special small populations, for example, a study on Bulgarian [7] or Indonesian population which showed very different distributions in dimensions, COM location and inertial parameters of these populations in comparison to Caucasian [8]. In particular, feet and hands showed to be longer in Indonesian men relative to Caucasian men. This latter study also provided measurements for the elderly and children.

The affordability of X-ray, MRI, CT scan, double beam low dose X-ray absorptiometry (DEXA) [8][9], and 3D infrared scanning [10][11], allows for the screening of large cohorts, and for the personalized screening of body sizes, making population studies feasible. The data structures provided by these methods are quite different. X-ray is used for images of joint center locations as MRI and CT scans, while these two last methods allow also for tissue discrimination, and thus for density calculation, using complex calculations methods. To employ these techniques, a multidisciplinary team is needed. 3D infrared scanning has the advantage of not being irradiating. A problem of possible irradiation remains, even with low doses, for DEXA methods, and the measurements are difficult to replicate due to the subject positioning. 2D biplanar X-ray, resulting in 3D images, is a cheaper method in comparison to MRI, albeit more time consuming and irradiating [12]. Recently, 3D body scanners with optical double triangulation have been proposed as a suitable method for acquiring volumes with a small measurement error of ±1 mm [13]. The subjects are scanned with a surface laser beam, volumes are calculated by light refraction, and COM identified. Irradiating methods have an ethical justification for clinical purposes. All these methods have significant differences, making comparability between different studies difficult [14] and they require an understanding of image processing algorithms. We will consider the issue of variability when examining the literature on single body segments. In addition to the variability between the different methods, there are sources of errors coming from the subject of measurement itself: the human body is not stable over time, and even over a short period of time, due to fluid losses, nutrition and changes in muscular stiffness. This concept of variability is emerging in the scientific literature. For example, during the impact after a jump, localization of segments COM changes up to 17% due to the soft tissue displacement [15].

The study of body segments also attracts new interest today due to the development of additive manufacturing in the industry (e.g., 3D printing) [16] for example, allowing for high customizable limb prostheses. According to Rao et al. [17], the choice of the model for body segment parameter estimation has a strong influence on error results ranging from 9.73% up to 60% for joint kinetics calculation, using the inverse dynamics approach. After reviewing and statistically testing the most used models of the human body for joint kinetics calculations, by using the inverse dynamics approach, they concluded that the Seyulianov–Zatsiorky model obtained with gamma radiation was the most accurate [17]. The need for data on women has fostered by the evidence that body segments inertial parameters are significantly different between men and women in large samples, for example in the study of Challis et al. on 1756 males and 2208 females of different ages [18].

Some body segments deserve special consideration due to their relevance, and because the methods used for their calculation are more complex and informative on the developments of technologies. Studies about the head biomechanical parameters are particularly relevant for understanding trauma, while the trunk segment, being the largest in the body, contributes heavily to whole-body kinematics and kinetics. Displacements of internal organs of the trunk also affect the inertial parameters of the whole body.

2.1. Head Segment

The mass and inertial characteristics of the head are of special relevance for injury prevention, mechanics of the impact, the search for brain lesions and evaluation of pre-peri and post-surgery interventions on the brain. Before the availability of accurate CT scan techniques (and mixed CT/MRI techniques) and of fast and accurate software for FEM (finite analysis modeling), these studies were performed on human specimens of head employing destructive trials. The values for head mass found by Yoganandan [19] on nine specimens were similar to the values found by Rousch on four specimens [20], of 4.07 ± 0.0077 kg.

Computational models of the head underwent tremendous advances with the increasing computing possibilities [21]. The propagation of shock waves in the skull can be modeled with a certain accuracy knowing the head biomechanical characteristics, using FEM mathematical models. Finite Element Models of the head, fed with CT scan data, allows for the detailed modelization of bones and soft tissue, and enable the very precise estimations of many biomechanical parameters, such as densities, and even joints and muscle actions. The density of the human head was computed giving a density of 1900 kg/m^3 for the skull, and an almost double 3300 kg/m^3 for the jawbone [21]. University of Michigan Visible Human Project [22] provides data for volume estimation of a human male body, head and limbs, publicly available. These data can be also useful for the construction of FEM computational models of human limbs. Age and sex of the subjects also affect these calculations, and special population models have also been proposed. Pregnant women underwent a rapid change in body mass distribution [23] with important consequences on back pain. Children, with a more pronounced head mass, have a different distribution, and undergo rapid and uneven changes in segmental development and thus deserve dedicated studies, considering the growth [24].

2.2. Trunk Segment

The human trunk, being the largest mass in the body (41.6% of total body mass according to Pearsal et al. [25]), contributes largely to the whole body CG, and deserved special attention in the scientific literature. Many biomechanical models of the human trunk have been proposed, and show a considerable range of error ranging from up to 50% whereas the best ones are in the range of 6% [26]. They found a whole trunk mass ranging from 27 ± 2.52 to 30.86 ± 2.10 kg for females and from 35.90 ± 6.07 to 40.41 ± 5.61 kg for male replicating several different formulas on a cohort of 25 adult males and 25 adult females. The trunk was normally modelized as one or two segments [27], and there have been recent attempts to a more detailed modelization using a four-compartment model: shoulder girdle, thorax, abdomen, and pelvis [28]. The trunk is composed more than other parts of the body, like moving organs. We know that the inertial properties of the lower limb change during an impact, with 17% of leg mass shifts toward the upper part of the limb [15]. We can hypothesize a larger change in the trunk due to internal organ displacements during impact, although no experimental data exists on this point. A model accounting for trunk impact should consider the stiffness and damping ratio for each internal organ. The trunk biomechanical modelization is useful for sports such as rhythmic gymnastics, high jump, gymnastic, and all the movements where a back arch is required or when contact injuries are frequent, such as in American Football. The same study [28] shows that in young people, the lower limb accounts for 37% of total body mass, compared to the 32% found by Zatsiorsky and Seyulianov [17]. This difference can be due to the fact that Zatsiorsky and Seyulianov did not use standard endpoints for segments, and in fact, their data were later adjusted for corrections [29]. CT scan of the trunk shows that trunk CM is 2 forward to L1/L2 while transversal vertebral CM was up to 5 cm forward of vertebral centroids in the lower thoracic region. Trunk modelization is also of interest for not widely practiced sports [30]: the human trunk has been modeled as a two-segment mass in the study of the high jump Fosbury flop technique, which requires to pass the bar performing a back arch [30]. Such a model allowed for the exact determination of the clearance, e.g., the distance between the back and bar at the maximum high of the center of gravity [30].

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