Human body dimensions for biomechanical modelling: a review.

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Abstract.

The knowledge of human body proportion and segmental properties of limbs, head and trunk are of fundamental importance in biomechanical research. As many methods are employed, it is important to know which they are currently available, which data on human body masses, lengths, center of mass (COM) location, weights and moment of inertia are available and which methods are most suitable for a specific research purposes. The present review examines the literature concerning human body segments properties for biomechanical purposes. It emerges that data obtained in studies on cadaveric specimens are still the most accurate, whilst technological tools currently available are manifolds, each one with proper advantages and disadvantages. Classical studies were focused mainly on white men, while in recent year the available data of body segments has been extended to children, woman, and other races. Also, data on special population (obese, pregnant women) are starting to appear in the scientific literature.

Keywords: human body segments, body dimensions, biomechanical modelling, anthropometry.

Introduction.

Human body dimensions has been deeply studies for a number of reasons: building of houses and objects, work optimization and work spaces design, medical issues, arts, and more recently, sports. The measurement and computational methods of choice, is important to achieve reliable results. Today several methods and technological tools are available to the researcher, with their advantages, disadvantages and proper application. Thus the aim of this review, is to made an updated survey of existing methods and their development since recent developments. An historical perspective will be considered, and some methodological issues will be discussed.

Methods.

An online literature search was performed using PubMed, Google, Jstor archive, from inception of the databases to September 2020 with the following keywords used in different combinations: "human body proportions" "computational methods for human segments" "human segments measurement" "human body modelisation" "mathematical methods for human body measurement" "human body proportions and computation", "segmental biomechanics". The search strategies were combined, and duplicates were removed by Endnote X7 (Clarivate Analytics, previously Thomson Reuters, Philadelphia, PA, US) and manually. All titles and abstracts were carefully read, and relevant articles were retrieved for review. In addition, the reference lists from both original and review articles retrieved were also reviewed. A total of 70 relevant papers were found. Eligibility criteria limited the search to studies performed on humans, and to studies which are related to biomechanics. 43 studies met the eligibility criteria and were included in the review. Of the retrieved papers, 5 were reviews, 5 were theoretical, and 33 were experimental. Inclusion criteria were: (i) research conducted with human participants and (ii) related to biomechanics. The exclusion criteria were (i) studies written in languages other than English, French, German and Russian (ii) animal or in vitro studies, (iii) congress abstracts. No limits were used concerning the year of publication. The inclusion or exclusion of articles was determined by applying the above criteria on the title and abstract as a first screening and on full texts as a second screening. Case studies were excluded, although the respective references were consulted and integrated into this revision if responding to the above-mentioned criteria.

Development of body measurement techniques and methods for biomechanical purposes.

The roots of using optimal human body proportion for design are probably in ancient Egypt. The body proportions according to the Neb Aurea (N): $1/N + 1/N^2 = 1$ (0,618 + 0,382 = 1), give a ratio of 1,618. Apart the seminal work of Leonardo Da Vinci, the golden proportion has been studies by the mathematician Fibonacci in his series. Alfonso Borrelli, in the famous book "De Motu Animalium" provide the locations of the centre of gravity of human and animals (horse, bird), and served as a reference for many scholars in the years to come. Volumes, masses, COM location on human body segments, as well as regression equations. and moments of inertia are the common outcome of all the studies dealing with body masses. Distribution of masses in the human body were first calculated directly on 2 cadavers by Hassler in 1860. In the architectural domain, Zeising (1854) studied the human body proportions based on the Aurea section as well as the architect Neufert at the beginning of 1900 (Neufert, 1936) using only graphical methods, for architectural design purposes. The current development of machine learning for body size recognition to be used in building character for movie or in security systems, re-vamped the golden ratio studies, for example, Abu-Thaie et. al (2018) wrote a deep review about the golden ratio and developed a new biometric model based on it.

The search for a standardization never ended from the ancient time and continued over the centuries. Every changes of times is usually accompanied by new a vision, in social life and in science as well. Thus in '800 and '900 new standards were proposed for human body proportions and scientific approaches bloomed. Braune and Fischer in Germany, pioneering the biomechanics of human motion building apparatus to study the motion. They also performed autopsy on 3 specimens. Notably in Russia, linked to ergonomics of the heavy "metallurg" industry, Nicholas Bernstein studied the mechanics of human body for work related purposes (1931) and provided references for body segments mass, CG and moments of inertia.

Application of human body proportions studies continued to arise interest for military or space missions purposes. Examples are the classical studies of Dempster (1955) and Drillis and Contini (1963), based on the measurement of human cadaver's specimens, aiming at describing the space requirements of a seated operator, his segments lengths and so on. Later, experimental methods developed, including the immersion method (Plagenhoef et al. 1983) for determining segmental volumes (from which masses can be obtained), the reaction-change method for estimating segmental masses and locations of centroids, and several techniques (quick-release technique, oscillation method, suspension method, etc.) for determining moments of inertia about segmental joint axes (Dempster 1955). These data were later helpful in the biomechanical studies of Inman (1981) for prostheses research after the world war II.

Computational approaches were also attempted. The Hanavan Model of 1964, is a mathematical model considering split the human body in 15 different solids, each one having a proper center of mass and proper inertial characteristics, and estimated volumes, weights, and lengths.

Chandler and Clauser (1975), later extended (Hinrichs 1985) determined body segments moment of inertia, calculating it using the pendulum methods on 6 degree of freedom axis, using the frozen specimen of 14 male elder cadavers, and obtaining reliable results compared to living subjects. Their studies were very accurate and even accurately measured the local gravitational constant. They provided the regression equation for each body segments on the 3-principal spatial axis. Hatze (1980) provided a model of high computational complexity which need as input the anthropometric measurement of 17 body segments on living subject, and that require about 80 minutes to be performed for each subject.

Only with the availability of computerized scanning methods was possible to obtain these data on humans. Seyulianov and Zatsiorsky using gamma ray scan determined body segments inertial parameters, volumes and densities. These data are referred to Caucasian men, and only relatively recently has been published inertial parameters related to different gender and race (Shan and Bohn 2003, Young et al. 1983) and norms for Asian men (Ho et al. 2013, Park et al. 1999, Shi et al. 1990). There has been attempted to profile a single state population or special small populations (Nikolova et al. 2007, Hartono 2016). Actually, the affordability of x ray, MRI, CT scan and double beam low dose x-ray absorbiometry (DEXA) (Durkin et al. 2002) , 3D infrared scanning (Pearsal et al. 1996, Smith et al. 2018), allows for the screening of large cohorts, and for personalized screening of body sizes.). 2D biplanar X ray, resulting in 3 D images, is a cheaper methods in comparison to MRI, albeit more time consuming and radiating (Dumas et. al. 2004).3D body scanners with optical double triangulation are also a suitable method for acquiring volumes with a measurement error ± 1mm (Lu et al. 2008). Among these methods, there are significant differences, making comparability between different studies difficult (Durkin and Dowling 2003). However, is emerging the concept in scientific literature, that inertial parameters of body segments are not stable, and that there are changes in the localization of segments CG up to 17% due to the soft tissue movement, for example during impact (Furlong et al. 2020). These studies attract today newest interest due to the development of additive manufacturing in the industry (e.g. 3D printing) (Culmone et al. 2020). Segmentation mode of the human body has a strong influence on the mass determination, volume, lengths, and inertial parameters of course. The method choice has a strong influence on the results errors ranging from 9.73% up to 60% for joint kinetics using the inverse dynamics approach according to Rao (Rao et al. 2006). After reviewing and statistically testing the most used models of human body for join kinetics calculations using the inverse dynamics approach, they concluded that the Seiulianov-Zatsiorky model obtained with gamma radiation resulted the most accurate (Rao et al. 2006). Lower limbs inertial parameters, has been proven to be significantly different between man and woman in a large sample study (1756 males and 2208 females, Challis et. al. 2012

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Head.

The mass and inertial characteristics of head is of special relevance for injury prevention, mechanic of the impact, lesions search and evaluation and pre-peri and post-surgery interventions on the brain. The propagation of shock waves in the skull, can be modelized with a certain accuracy knowing the head biomechanical characteristics, using finite element modelling (FEM) mathematical models. Before the availability of accurate CT scan techniques and of fast and accurate software for FEM, these studies were performed on human specimens of head (e.g. Yoganadan et al. 2009) employing destructive trials. The values found by Yogandan (Yoganadan et al. 2009) on 9 specimens were similar to the found by Rousch on 4 specimens (2010), of 4,07 ± 0,0077 Kg reference. Yoganadan (Yogonadan et al., 2009) reported the data from the literature summarized in the Table I (modified from Yoganadan et al. 2009).

Author	Year	Specimens	Head Mass(kg)
Harless	1857	2	4,15±0,57
Braune &nFisc	1889	3	4,40±0,80
Fischer	1906	1	3,88
Mertz	1967	3	3,49±0,90
Clauser et al.	1969	13	4,73±0,32
Hodgson et al.	1970	13	3,98±0,53
Hodgson			
and Thomas	1971	37	4,72±0,78
Walker et al.	1973	19	4,38±0,59
Becker	1972	6	3,88±0,47
Chandler et al.	1975	6	3,99±0,53
Beier et al.	1980	19	4,32±0,40
Albery	2002	1	3,17
Plaga et al.	2005	8	3,66±0,58
Rousch	2010	4	4,07±0,077
Dempster	1955	9	4,60±0,60
(head and neck)			

Table 1. Mean ± standard deviation of male head mass measured on human specimens. Due to the difficulty of the technique, the different dissection methods, the age span (19 to 70) the results are quite scattered. Only 9 females specimens were analysed in literature (7 in Plaga et. al and 2 in Beier et. al study). Modified from Yogonadan et al. 2009.

Computational models of the head has undergone tremendous advances with the increasing computing possibilities (Anderson et al. 2017). Finite Element Models of the head, feeded with CT scan data, allows for detailed modelization of bones and soft tissue, and enable very precise estimations of many biomechanical parameters, such as density, and even joints and muscle actions. Density of human head is computed giving a density of 1900 kg/m^3 for the skull, and an almost double 3300 kg/m^3 for the jaw bone (Anderson et al. 2017). University of Michigan Visible Human Project provide data for volume estimation of a human male body and limbs public 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 has also been proposed. Pregnant women undergone a rapid change in body mass distribution (Sunaga et al. 2016) with important consequences on back pain. Children, with a more pronounced head mass, has a different distribution, and also undergone rapid and uneven changes in segmental development and thus deserve dedicated studies (Schenider et. al. 1992).

Trunk.

The human trunk, being the largest mass in the body (41,6% of total body mass according to Pearsal et al. 1996), contribute largely to whole body CG, and deserved a special attention in scientific literature. Many models of the human trunk exist measured by means of DEXA technique, and someone show a considerable range of error ranging from up to 50% whereas the best ones are in the range of 6% (Wicke et al. 2009). Trunk was normally modelized as one or 2 segments, and there have been recently attempts to a more detailed modelization using a 4 compartments model: shoulder girdle, thorax, abdomen, and pelvis (Erdman et al. 2020). If the inertial properties changes in the lower limb as result of rapid stop (impact) (17%, Furlong and al. 2020) we can hypothesize a larger change in the trunk due to internal organs displacements during impact, but any experimental data exists on this point. A model accounting for trunk impact should consider the stiffness and damping ratio for each internal organs. This model could be useful for sports such as rhythmic gymnastics, high jump, gymnastic, where a back arch is required or when contact injuries are frequent, such as in American Football. This study also shows that in young people lower limb account for a 37% of total body mass, compared to the 32% of older people as found by Seyulianov and Zatsiorsky. 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 lower thoracic region.

Conclusion.

Aims of this short review were to analyse the current available methods for body segments determination in biomechanics in a historical perspective. From a graphical approach, methods has developed toward computational with the parallel development of hardware technologies. The Caucasian centered approach of the early times has developed into a more comprehensive view, encompassing different ethnicity and different human conditions (maternity, growth, obesity). These basic studies are the fundamental for building up more complex biomechanical analysis. Today, the biomechanist can chose among different methods and available tools to assess the anthropometric characteristics of their subjects, allowing for in deep analysis and more accurate results. Application of new techniques such as machine learning to the field of human body modelling is a promising approach to give better solutions to old problems.

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