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Selecting best-fit models for estimating the body mass from 3D data of the human calcaneus

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ABSTRACT

Body mass (BM) estimation could facilitate the interpretation of skeletal materials in terms of the individual's body size and physique in forensic anthropology. However, few metric studies have tried to estimate BM by focusing on prominent biomechanical properties of the calcaneus. The purpose of this study was to prepare best-fit models for estimating BM from the 3D human calcaneus by two major linear regression analysis (the heuristic statistical and all-possible-regressions techniques) and validate the models through predicted residual sum of squares (PRESS) statistics. A metric analysis was conducted based on 70 human calcaneus samples (29 males and 41 females) taken from 3D models in the Digital Korean Database and 10 variables were measured for each sample. Three best-fit models were postulated by *F*-statistics, Mallows' C_p, and Akaike information criterion (AIC) and Bayes information criterion (BIC) for each available candidate models. Finally, the most accurate regression model yields lowest %SEE and 0.843 of R^2. Through the application of leave-one-out cross validation, the predictive power was indicated a high level of validation accuracy. This study also confirms that the equations for estimating BM using 3D models of human calcaneus will be helpful to establish identification in forensic cases with consistent reliability.

1. Introduction

Estimating the body mass (BM) or body weight is an indispensable process when evaluating skeletal remains and for the individual identification of skeletal components in forensic cases [1]. One of the most commonly overlooked aspects is that the concept of the BM needs to be distinguished from the body weight [2]. Mass is the amount of matter contained in an object as an inherent property, while the body weight is the product of the BM and acceleration, which can vary according to the place of measurement [3]. Hence, in any given place, the BM can be indicated as a constant value, but then body weight varies from place to place on the Earth depending on the surface gravity [4]. In attempts to derive a definitive estimation equation, constructing a robust relationship between the skeletal elements should be based on the BM rather than on the body weight [1,5].

Skeletal remains can facilitate the identification of individuals for solving forensic cases, including biological profiles such as the sex, age, and stature, and thereby provide a more complete description of the individual that includes the body size and physique [1,6–8]. Certain pathological conditions such as osteoarthritis can also be analyzed based on BM data [9]. The BM can also suggest vital concepts to physical anthropologists, such as human adaptation for diverse environmental conditions (e.g., climate and geometry [10,11]); allometry, which focuses on the relationship between the size and shape of body parts [12,13]; individual lifestyles, which influence diet and metabolic requirements [14]; and paleontology and paleodemography, which trace the scientific evidence of ancient human life [15–17].

The mechanical loads associated with the BM greatly influence weight-bearing forces, which affect the articular surface area of the epiphysis and the cross-sectional dimension of the diaphysis

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[18]. However, it has become increasingly evident that the articular surface area reflects the mechanical load more accurately than does the diaphyseal shaft, due to the smaller effects of confounding factors [19]. In detail, the articular surface area is less influenced by muscular attachments and the level of physical activity during the lifetime than are diaphyseal dimensions [19–21]. In particular, it has been documented that the size of the femoral head is almost linearly proportional to the BM [17,21–24]. These findings are consistent with studies showing that the femoral head diameter (FHD) is more strongly correlated with the BM than with non-weight-bearing skeletal structures such as craniodental elements [5,25–28].

The ankle joint transfers almost 98% of the mechanical load of the body when standing still by connecting leg bones to foot bones as a medium of the weight-bearing axis [29], and 80% of the body weight is directly over the calcaneus upon heel strike during a gait cycle, producing a vertical force that against to the ground [30]. The subtalar joint on the calcaneus is especially important since it not only sustains the weight-bearing load but also makes the leg axis turn around inwards or outwards on the foot bone [31]. The movements of the subtalar joint on the calcaneus are responsible for the rotatory conversion and transmission of the force induced by the weight-bearing load during the gait [32]. It is theoretically possible that most of the mechanical load is conveyed to the ankle joint through the calcaneus itself by the subtalar joint [30–33]. However, despite the importance of the transmission of the weight-bearing loads, few studies of BM estimation have focused on anthropometric investigations of the calcaneus.

The purpose of this study was to develop best-fit models for predicting the BM from three-dimensional (3D) measurements of human calcaneus. This was achieved by extracting 3D calcaneus samples from computed tomography (CT) images, and measuring 10 variables using a 3D image analysis program. To determine the best-fit model in each set of regression candidates, the optimal trade-off between the accuracy and simplicity of subset models was considered in two major linear regression analyses (the heuristic statistical and all-possible-regressions techniques) [34–37]. The best-fit models were then internally validated to maximize robustness using predicted residual sum of squares (PRESS) statistics [38,39].

2. Materials and methods

2.1. Samples and measurements

A metric analysis was conducted based on 70 human calcaneus samples (29 males and 41 females) taken from 3D models in the Digital Korean Database (Korea Institute of Science and Technology Information, Daejeon, Korea). This CT scanning database of 1.0 mm slice thickness was constructed from whole cadavers. The mean age and stature of the samples for males were 52.0 years (range = 21–60 years) and 165.9 cm (range = 159–176 cm), respectively, and for females they were 53.5 years (range = 27–60 years) and 156.4 cm (range = 146–165 cm). The 3D calcaneus models representing a pathology-free condition were obtained from CT images after reconstructing 3D skeletal models using a biomedical image engineering program (Mimics, version 14.1, Materialize, Belgium).

The reference BM were obtained using three formulae based on the FHD for each individual [15,22,40] before performing a regression analysis on the calcaneus, because the FHD is widely used in reconstructing the BM of skeletal remains due to the reported strong correlation between the BM and FHD [1,23,41]. For this, the maximum FHD was measured by applying two parallel planes in 3D coordinates using the Mimics software. The calculated relationship between the BM and FHD was utilized in statistical regression analysis to develop equations for predicting the BM from calcaneal measurements.

The 10 variables measured for 3D calcaneal samples (Fig. 1) comprised three length, four breadth, and three height measurements (Table 1). Each measurement was performed in accordance with the methods described by Bidmos and Asala [42]. At the beginning of each measurement, the calcaneus was aligned in three spatial planes: its base plane, and its coronal and sagittal planes, which play key roles in guiding the anatomical position of the calcaneus. After the base plane was obtained using the outermost three points on the inferior surface of the calcaneus, being perpendicular to the base plane, the coronal plane running parallel with the short axis and the sagittal plane with the long axis of the calcaneus were prepared. With these planes in 3D coordinates, the chord length could be measured between two points at any level on the calcaneus.

2.2. Statistics

A statistical analysis was conducted using SAS (version 9.2, SAS Institute, Cary, NC, USA) and SPSS (version 21.0, SPSS, Chicago, IL, USA). All measurements were taken twice by one of the authors, and the intraclass correlation coefficient is analyzed to assess agreement of quantitative measurement inconsistency dealing with intraobserver reproducibility. After the normality of all 10 variables was confirmed using parametric statistics, an ANCOVA was conducted to verify differences in BM-adjusted calcaneal measurements between sexes. Three different types of criteria with two different techniques were applied as strategies for selecting the best-fit models, including the traditional approach to statistical inference. To select the first model (for Model 1), heuristic statistical techniques were used with *F*-statistics. The all-possible-regressions technique was then applied with Mallows' C_p for Model 2, and AIC and BIC for Model 3. Using these criteria, conditions of autocorrelation, multicollineariy, and homoscedasticity were examined back and forth during the regression analysis

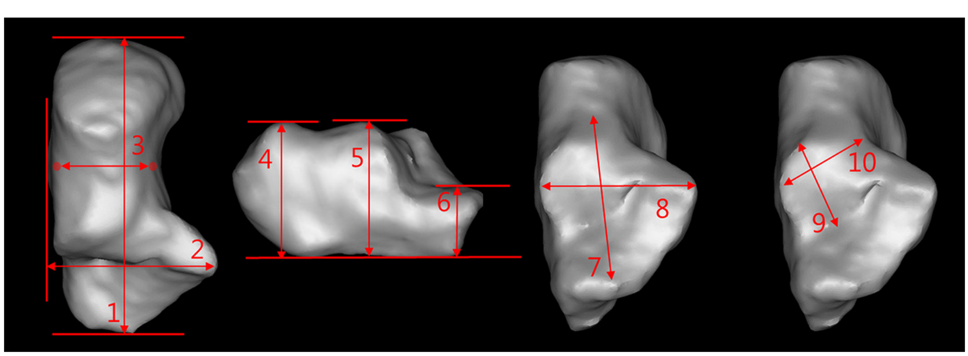

Fig. 1. 3D measurements of the calcaneus, which comprised three length (1, 7, and 9), four breadth (2, 3, 8, and 10), and three height (4, 5, and 6) variables. These numbers are defined in Table 1.