The Application of SSM and Other Methods in Studying the Morphology of Anatomical Shapes

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Introduction

Through this literature review, the bone morphology of various anatomical regions will be explored with a focus on a variety of key points; such as the average shape, the modes of variations between groups, and the assessment of the reliability/validity of various methods. The collection of this knowledge is useful to our lab, as this is a fairly new area of research and it permits us to gather more insight on this topic. Moreover, this information holds great value for those in the fields of orthopedics, prosthetics, or obstetrics/gynecology, while bringing to attention the ethnical differences and sexual dimorphism that are evident in specific anatomical shapes.

Method

The obtained articles in this report were found through the use of various search engines, which included: The U of A Library databases, Google Scholar, PubMed, and Scopus. The keywords that were used were: "average bone shape", "SSM", "bone shape" "talus shape", "craniofacial shape", and "pelvis shape". The information of each article was entered into a spreadsheet for organization purposes; each study was downloaded as a PDF and then stored into the corresponding sub-folder.

Statistical Shape Modeling (SSM)

Average shape

These researchers studied the geometry of the talus[1] and wrist[2] using statistical shape modeling (SSM) to determine their average shapes. Created from correspondence mapping; SSM is used to depict the geometric average of numerous three-dimensional shapes, as well as their variations.

Due to the numerous blood supply and complexity of the articular interconnections, fractures of the talus (ankle bone) region are frequently linked with complications. Customized talus implants have proven to be an effective treatment for talus fractures, yet the patient-specific method is very time consuming and expensive. Thus, finding implant sizes that fit a larger population is most desirable. In the experiment conducted by Tao Liu et al, 98 tali (57 males and 41 females) were registered[1]. To lower inconsistencies and errors, the geometry of the talus bone was explored using the statistical shape model with an automatic GroupWise registration and a 3D deviation analysis was performed between the implants [1]. Random tali were selected as a reference shape. The points were taken and moulded/realigned to compare and find an average. As a result, the study deduced that the female and male tali were scaled to the same volume[1].

Within the wrist, all eight carpal bones and the first metacarpal bone (thumb) were closely analyzed in this study. The participants were between the ages of 21-28 and were all healthy [2]. The method used in this study, registration-based bone morphometry, consists of atlas selection and atlas warping. The atlas used a single subject from the population whose wrist bones were closest in terms of the distance metric to the rest of the population [2]. The results of this study demonstrated a reliable and standardized approach to shape the analysis of bones, especially the human wrist bones [2].

Differences in pop. (Comparison - healthy groups, e.g. sex, ethnic)

These studies entailed investigating the differences and similarities between healthy ethnic groups and sexual dimorphism with the groups, using statistical shape model [3,4, 5].

Sexual dimorphism has shown prevalent within the human femur shape and quadriceps, this study entails an investigation to address the differences within the knee shapes amongst various ethnic groups [3]. The study had 1000 subjects, who were divided into three main ethnic groups: 80 African American, 80 East Asian, and 860 Caucasian. 3D statistical shape models were created for each bone and were used to build the 3D statistical bone atlases [3]. The results of this study indicate that there are significant differences in terms of the shapes of the bones in the knee, between the ethnic groups and the females and males within a group. This study establishes the need for further discussion for ethnic-based and gender-based implants[3].

In this study, 73 high-resolution peripheral CT scans of proximal femurs were used to create a combined SSM, statistical shape model [4]. The results of this study show that there was no correlation in terms of the distribution of the bone shape, bone fabric, or TV/BV (volume fracture) [4].

As of 2020, most artificial bone models (ABMs) are shaped towards the morphology of Europeans. ABMs are used for the research of biomechanics, developing implants, and various other educational purposes. This could be an issue since they might not depict to the Asian anatomy, as each ethnic group differs to a certain extent, in terms of anatomy. In this study, 100 CT images were produced from 50 Asian males and 50 Asian females (of Malay, Chinese, and Indian descent) [5]. 3D Statistical pelvic models were generated, constructed into ABM, and analyzed. Large differences revolving the size and shape were observed in between the Asian ABM and the "European"/pre-existing ABM, moreover, there was also a sex divergence. This indicates that gender-based ABM and Asian-specific ABM are necessary and should be taken into consideration, especially for the development of implants [5].

Differences in pop. (Comparison - healthy vs. specific case)

These researchers evaluated the differences and similarities between an injured/diseased group and a group of healthy patients, using statistical shape model[6, 7].

Examining the right leg of 24 females, this study used statistical shape model and MRI data to compare the tibia and femur of patients that are at risk of developing osteoarthritis (OA) and those that are healthy [6]. The obtained results established that there was not a significant geometrical difference between the femur and tibia of the two groups [6].

Patients that have suffered a spinal cord injury (SCI), have a drastic loss in bone mineral density, which could range from a 1% to 40% decrease during the first year [7]. This experiment looked at 25 SCI patients; their distal femur and proximal tibia were scanned <5 weeks (baseline), 4 months, 8 months, and 12 months post-injury using peripheral Quantitative clanging tuning fork test (CTF). The bone mineral density loss was analyzed by comparing the baseline to the last scan (12 months), using multiple linear regression. A mode of variation from each statistical shape model established that there was a total of approximately 17.6% bone loss on average, at the 12-month mark [7].

Investigation of the technique

These studies evaluated the various approaches used to study the morphology of human bones [8 9, 10, 11, 12, 13, 14] and justified the usage of cadavers[15, 16].

This study focuses on comparing shape variations in the subtalar joint (STJ) between patients with chronic ankle instability (CAI) and those with healthy controls; this is done so through creating 3D statistical shape models of the subtalar joint bones [8]. The study comprised of 26 CAI patients (14 males and 12 females) and 26 (14 females and 12 males) healthy controls and used the statistical shape model and the analysis of the covariance test to come to the conclusion that the shape of the subtalar joint bones of the CAI patients greatly differs from those with normal controls. On average, the CAI patients' talus and calcaneus have a relatively flatter surface, once indicating that individuals who have a flatter talus and calcaneal surface are at a higher risk of developing chronic ankle instability, after sustaining a lateral ankle sprain (LAS) [8].

Hip osteoarthritis (OA) is a joint disease that causes the cartilage in the hip joint to gradually disintegrate; often affects those that are older than 50 years of age and/or that are obese [9]. This study closely analyzed the cartilage and the proximal femur bone shape, in 80 subjects that suffer from OA, through the use of MRI-based statistical shape model and gait analysis. As a result, those affected by OA had a higher neck-shaft angle within the coronal plane, a thicker femoral neck and the femoral head was less spherical than usual. Moreover, the study deduced a well-defined correlation between markers of hip joint degeneration and the shape variation of the femur bone [9].

Thirty CT scans of the male subjects' (between the ages of 17 to 63) left (15) and right (15) tarsal bones were obtained [10]. The models were built through image segmentation, unifying feature position, and the use of various mathematical techniques. The SSMs of the talus, navicular, and cuboid were accurate morphometric and provided insightful information for bone reconstruction/implant design, preoperative planning, and better diagnosis. Published in 2017, the goal of this article was to develop an SSM for the tarsal bones [10].

In this study, an algorithm for automatic segmentation from CT scans was developed that is based on the statistical shape model [11]. This study focused on evaluating the human pelvic bones, thus using the Generalized Hough Transform, the average pelvis shape was automatically placed within the CT data. This method demonstrated to be reliant and effective in automatically placing the initial shape model within the CT data, therefore meeting the requirements of clinical routine[11].

Using tracked ultrasound and 3D statistical shape modelling on three complete female cadavers that were preserved using the W.Thiel method, a technique that consists of preserving the corpse with natural colours (1992); this study focused on the femur and the pelvises [15]. The result implied that the SSMs that were generated can dismiss the need for preoperative CT scans [15].

This mainly cadaver-based study aimed to use a statistical shape model inspired the reconstruction method to create patient-specific models of the pelvis [16]. Using a single standard anterior-posterior X-ray radiograph, 14 patient-specific surface models of the pelvises were reconstructed, directly from the landmark-based initialization [16].

With a cohort of 121 females, this study analyzed the use of a statistical deformation model (SDM) [12]. The model was constructed specifically for the human pelvis and the femur and was found to be effective, cost-efficient and non-invasive; it did not require a preoperative CT scan, thus limiting the need for an additional radiation dose [12].

The method used in this study of the female pelvis included a combination of manual landmarking, spline warping, and surface morphing [13]. The models of the 20 pelvises were built, measured, and evaluated. In conclusion, the method has proven to be efficient, accurate and is deemed suitable for future computer-assisted surgery fields [13].

Clavicle fractures often occur during a vehicle collision, due to the exposure that the shoulder belt creates. To get a better understanding of the geometric differences of the clavicular cortical bone, this study evaluates 20 human clavicles [14]. This is done so, through the use of statistical shape analysis. The bone surfaces were reconstructed from the CT scans that were taken of each subject and various methods that were used were compared against one another. The models derived from the Levenberg-Marquardt ICP (LM-ICP) proved to be the best method for the construction of the human clavicle models[14].

3D geometry analysis

Average shape

These researchers studied the geometry of the talus and pelvis using 3D geometry analysis to find their average shapes[17, 18, 19].

This study consisted of 28 subjects, 24 of which were male and four were female [17]. All of the subjects were in a supine position and the study solely focused on the left foot. The CT scans were imported to a 3D image processing software (Mimics) to be digitalized and then made into an STL (stereolithography file). A uniform scaling approach was used, and the volume of each talus was quantified. The five universal volumes within this study were:

1. 26 961.15 mm^3
2. 33 810.44 mm^3
3. 40 659.73 mm^3
4. 47 509.02 mm^3
5. 54 358.31 mm^3

The most common size being 40 659.73mm^3. Thus, these five sizes would most likely fit a larger population and the talus bones are geometrically similar[17].

50 male tali and 41 female tali were scanned and imported into Mimics to be processed; a mask was generated to cover the talus [18]. A 3D model was then produced from the mask and the tali were scaled to the

corresponding average size, based on the gender. The models were then compared between one another in their designated group (the tali were split into two groups, based on sex). Female and male tali were geometrically similar, thus unisex models are made possible. Ten universal talus implant sizes suited well the 91 subjects within this experiment [18].

In this study, 200 females were grouped based on their height; 100 females were in the under 5'5 ft group, whereas the other 100 females were placed in the over 5'5 ft group [19]. A physical examination, erect lateral examination, and X-ray of the pelvis were performed in order to collect the data. It is concluded that taller women who possess a "large" and "well-curved" pelvis, are less susceptible to any defects that may disturb the general growth of the fetus and are less likely to have obstructed labour [19].

Differences in pop. (Comparison - healthy groups, e.g. sex, ethnic)

These studies entailed investigating the differences and similarities between healthy ethnic groups and sexual dimorphism with the groups, using 3D geometry analysis[20, 21].

Sexual dimorphism is observed when the female and male from the same species present different characteristics; sexual dimorphism in the human pelvis is believed to be caused by an evolutionary response to locomotion (walking, hopping, etc...) and childbirth [20]. This study consisted of 99 females and males; their pelvises were measured by a geometric morphometric analysis of a set of landmarks. The findings concluded that although the sizes of the pelvis in both men and women were similar, their average shapes greatly differed [20].

Unlike other organisms, obstetrical dilemmas explain why most females require assistance during childbirth. This study used geometric morphometric analysis (landmarks) to analyze the correlation between the size/shape of 99 female pelvises and their head size/shape [21]. The results deduced that females with larger heads have birth canals that have the ideal shape for large-headed babies, whereas shorter females possess a rounder inlet and may have more difficulty during childbirth, thus will benefit from assistance during labour [21].

Differences in pop. (Comparison - healthy vs. specific case)

Kota Watanabea et al. evaluated the differences and similarities between patients with Hallux Valgus (a common foot deformity) and healthy patients, using 3D geometry analysis[22]. This study explores the different responses of the tarsal bone to axial loading in patients with hallux valgus and those with normal feet [22]. The patients with hallux valgus were all female and ranged from 51 to 74 years of age, whereas the rest of the subjects had no previous foot pain, injuries, or surgeries. There was a total of 22 participants, five of whom were male. The CT scans were taken with a neutral ankle position and then transferred to a PC, where the 3D bone models were created, using image analysis software [22]. The coordinates of each tarsal were set; the translated distance and rotational displacement were then calculated through computer-aided design software. The data was then compared between the hallux valgus and the controlled group, using the unpaired t-test. In conclusion, there wasn't much of a difference in terms of the displacement between the two groups and the navicular was displaced in the same direction. Yet, there was a significant difference in terms of the translation of the anterior/posterior between the HVA and the controlled group [22].

Principal Component Analysis (PCA)

Differences in pop. (Comparison - healthy groups, e.g. sex, ethnic)

These studies entailed investigating the differences and similarities between healthy ethnic groups and sexual dimorphism with the groups, using principal component analysis[23, 24,25, 25].

This study examined the nasal shapes within three socially distinctive South African groups [23]. They used 310 crania from cadavers (164 males and 145 females) were digitized through 14 standard landmarks, with a 3D coordinate digitizer. Principal component analysis was used to identify the modes of variations between the models; the differences were given from most distinctive and impactful to least important [23]. Various statistical analyses were used to deduce that sex does not affect the nasal bone and that it is most difficult to distinguish coloured/black South Africans apart based on the structure of their nasal bone [23].

Obtaining CT scans of 66 individuals (55 males and 11 females), the study constitutes of investigating whether or not the subtalar joint (STJ) bones vary in shape in the left and right foot and if there is a difference in sex [24]. Principal component analysis was used to identify the modes of variations between the models; the differences were given from most distinctive and impactful to least important. The results proved that the STJ bones in both the left and right foot of each individual are generally, geometrically similar. Whereas, the STJ bones slightly differ when comparing the females' ankles to the males. Differences were found in the lateral/medial condyles of the tibia, the length and height of the calcaneus, and on the surfaces of the posterior/anterior talar of the calcaneus [24].

Principal component analysis (PCA) has been used in the past to analyze craniofacial relationships. Yet, few have established the craniofacial relationship with sexual dimorphism; thus, this study investigates this matter. 140 CT images of 3D heads were produced, landmarks were manually marked, and the statistical shape spaces were constructed using PCA [25]. PCA was used to identify the modes of variations between the models; the differences were given from most distinctive and impactful to least important. The findings suggest that the accuracy of the method increases as the number of face-based PCs increment [25].

Differences in pop. (Comparison - healthy vs. specific case)

Alina Cocos et al. evaluated the differences of the craniofacial bones using 3D geometry analysis[26], between patients that have lost at least one tooth, that were born without wisdom teeth, and those that have never lost a tooth/born with all third molars. The 456 subjects within this study were allocated into three groups: 100 patients have at least one missing tooth (excluding third molars), 52 patients were missing one to four third molars (wisdom teeth), and 304 patients without any missing teeth. [26] Following the 127 landmarks and 15 curves, the main craniofacial structures were traced and digitized. The principal component analysis was used to identify the modes of variations between the models; the differences were given from most distinctive and impactful to least important. Those that were missing one to four third molars showed no differences in terms of skeletal pattern to those without missing teeth, yet those that have at least one missing tooth (tooth agenesis) revealed complex distinctions in comparison to the two other groups [26].

Discussion

Throughout the explored studies, it can be observed that the most common method that was used was statistical shape modeling; proving that this technique has demonstrated to be consistent and effective for the study of the morphology of numerous human anatomical shapes. Numerous studies (e.g. Marc-Daniel Ahrend et al.) highlighted the differences of the shapes of various bones between different ethnic groups and the presence of sexual dimorphism, while other articles focused on the average shapes of the talus to develop a universal implant, or of the pelvis for educational purposes (midwifery/gynecology).

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