Evaluating Humeral Bilateral Asymmetry by Means of a Virtual 3D Approach

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Abstract

We describe a new methodology for the evaluation of bilateral asymmetry in the humerus. It consists of the virtual comparison of three-dimensional (3D) digital models of the right and left humeri of one individual from the Middle Ages. The 3D geometric models, obtained using a NextEngine laser scanner, were oriented in PolyWorks® 10.1. In the same software, a mirror image of the left humerus was produced. Proximal and distal epiphyses of the oriented humeri were cut at the 15% and 85% points of the humerus' physiological length in order to individually compare the three obtained parts (proximal epiphysis, distal epiphysis and diaphysis). The epiphyses were directly superimposed and the deviation quantified by inspection analysis. For the diaphysis, the best fit cylinder of the mirrored left humerus was created and used as a reference shape for the inspection analysis. The inspection analysis allows us to identify the areas where the two humeri differ morphometrically and to quantify the differences with high precision.

Keywords

Asymmetry, Humerus, Reverse Engineering, Inspection analysis

1. Introduction

Bilateral bone asymmetry is an interesting research field due to the strong relationship between behavioural and morphological asymmetry (Steele 2000; Cuk *et al.* 2001; Lazenby 2002). Even if genetic factors are involved to a lesser extent, it is well know that bone asymmetry is essentially a product of disproportionate mechanical loading regimes and resultant compensatory bone remodelling (i.e. hypertrophy and/or hypotrophy/atrophy) (Churchill 1993; Trinkaus *et al.* 1994; Churchill and Formicola 1997). Particularly for the upper limb, behavioural use of the limbs can strongly affect diaphyseal structure, as supported by observations of asymmetry between playing and non-playing arms of tennis athletes (Krahl *et al.* 1994; Bass *et al.* 2002; Kontulainen *et al.* 2002). Generally, without a particular pathological condition, differential loading is most often a reflection of limb dominance (handedness) (Roy *et al.* 1994).

Therefore the analysis of functional asymmetry involves different research areas, including not only biomechanics and ergonomics, but also palaeoanthropology and archaeo-anthropology in order to better reconstruct human behaviour or pathology in the past (Stirland 1993; Mays 1999; Trinkaus 1999; Mays 2002; Marchi *et al.* 2006; Sladek *et al.* 2007; Wanner *et al.* 2007).

In general, the traditional approach to asymmetry evaluation relies on some measurements, mainly the physiological length of the bone, the perimeter and the diameter in the middle of the diaphysis (Auerbach and Ruff 2006). These measurements, generally carried out as recommended by Martin and Saller (1957), are usually performed by means of the following instruments:

- taper for perimeters;
- sliding caliper for diameters;
- metric board for bone's lengths.

Another method assesses the mechanical performance of the diaphysis, taking into consideration perimeters, areas and the second moment of area of bone sections (Rhodes and Knüsel 2005; Weiss 2005). Based on these considerations, it is evident that cross sections, as compared to the traditional methods, can provide more information on bone morphology. In any case, information collected by both methods is limited to the specific area under investigation. In fact, diameters and circumferences as well as cross sections are usually measured in specific regions of the bone (e.g., at the half of the humerus shaft), so that portions that are not included in the anthropometrical measurements cannot contribute to the analysis. Since muscle insertion covers a wide area of the bone, these approaches are somewhat reductive. Multiple sections of the bone could provide a partial solution, providing that the compared humeri are properly oriented. However in this case, it is difficult to appreciate whole morphometrical differences between humeri and to calculate bone asymmetry in those points which undergo mechanical solicitations and that are notoriously subject to modifications.

A valid alternative could be offered by geometric morphometric methods (GMM), the most reliable approach to shape analysis, particularly for the evaluation of asymmetry. Unfortunately these studies require a number of anatomical landmarks that are not easily identifiable on the diaphyses of long bones. For this reason, GMM could be useful when only the epiphyses have to be analysed, given that the extremities of long bones usually contain the majority of true landmarks.

In the present study a new method for the visualization and the quantification of humeral asymmetry was tested. We used technologies originally conceived for engineering purposes, such as reverse engineering techniques and inspection analysis, for comparing the right and left human humerus of an individual from the Middle Ages. In engineering, the purpose of the inspection analysis is to ascertain the differences between a virtual model obtained by CAD (Computer Aided Design) techniques and the prototyped model, comparing the first one (defined as the reference object) with a second one (target object), in a three-dimensional (3D) virtual space.

Extended to humeri, the inspection phase allows us to compare the reference bone (i.e., the diaphysis of the right humerus), with the target bone (the left diaphysis), providing clear indications of morphometric differences between the two bones.

2. Material and Methods

Humeri deriving from the excavation of a Lombard necropolis (San Faustino a Casalmoro, Mantua, northern Italy) were used for 3D virtual asymmetry evaluation. The subject is an adult male of about 48 years old and around 173cm in height whose remains appear to be intact and in a good state of preservation. Both humeri were complete, with only a small portion of cortical bone lacking on the antero-inferior margin of the right humerus head (*Fig. 1*).

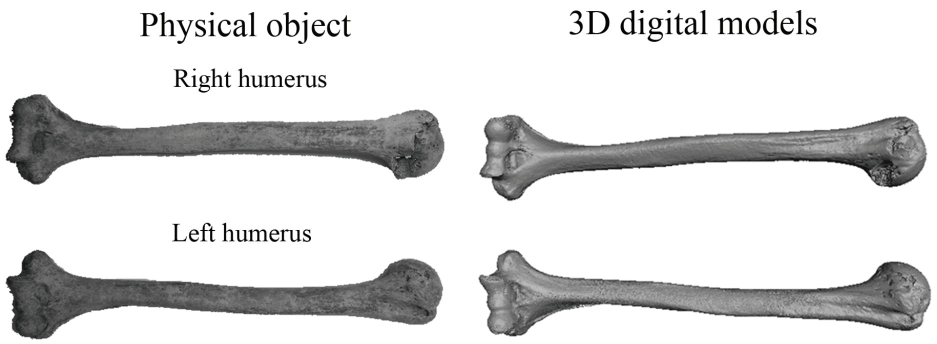


Fig. 1. Left: anterior view of the original humeri; right: anterior view of the 3D digital models of the humeri.

Three-dimensional acquisition of the humeri was performed by a Nextengine™ laser scanner using the Macro scanning mode (resolution=0.127mm). By means of Scanstudio Core software, we carried out the usual post-processing operations in order to obtain the 3D digital models (*Fig. 1*).

Both the models (left humerus=model A; right humerus=model B) were imported in PolyWorks® 10.1 (InnovMetric Software, Inc., Québec, Canada). A mirror copy of model A was produced (model Am). As a first test, model Am was superimposed directly to model B in order to quantify their deviation. However, the superimposition caused problems with regards to the strong and incorrect influence of the epiphyses during the alignment process. This is clearly illustrated by performing a cross-section in the mid-diaphysis (*Fig. 2*). Therefore, humeral superimposition could not be considered a reliable approach for comparing humeral morphology.

With regard to these considerations, epiphyses were separated from the diaphyses. The first step

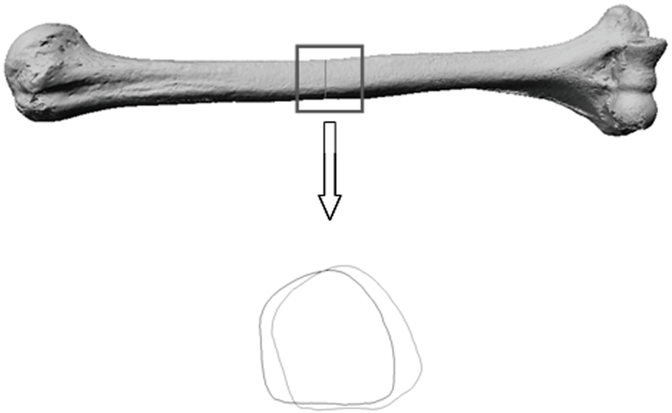


Fig. 2. The sections of the superimposed humeri (model Am and model B) in the middle of the diaphysis show a clear mismatch of the diaphysis, pointing out the unreliability of the superimposition approach.

involved the orientation of the humeri. The plane created by three points, including the upper point of the humerus head (point a) and the two most external epicondylar points (mesial=b, lateral=c) was set parallel to the xy-plane of our Cartesian coordinate system. Finally, the segment that joins point a with the center point of the troclea (d) (following the physiological length of the bones) was rotated parallel to the x-axis (*Fig. 3*).

Subsequently, multiple sections of the oriented 3D models were performed at 5% intervals of the humerus' physiological length. By means of cutting planes built in correspondence to the sections at the 15% and 85% of the physiological length, the proximal and distal epiphyses were separated from the diaphyses (*Fig. 4a*).

With regard to the sub-cylindric shape of the diaphysis, a reference geometry represented by a cylinder was used for diaphyseal analysis. In detail, in PolyWorks® 10.1 the best fit cylinder of model Am was created (*Fig. 4b*). Then, a further cylinder was fitted onto model B, constraining its radius to the same value of model Am's cylinder (r=9.76mm). Distance (or deviation) between the humerus and its own cylinder were displayed directly onto the surface of the 3D models by means of a colour map (*Fig. 5*). It is worthwhile to note that these deviations are quantified in relation to an identical reference shape. In fact, even if the two cylinders have slightly

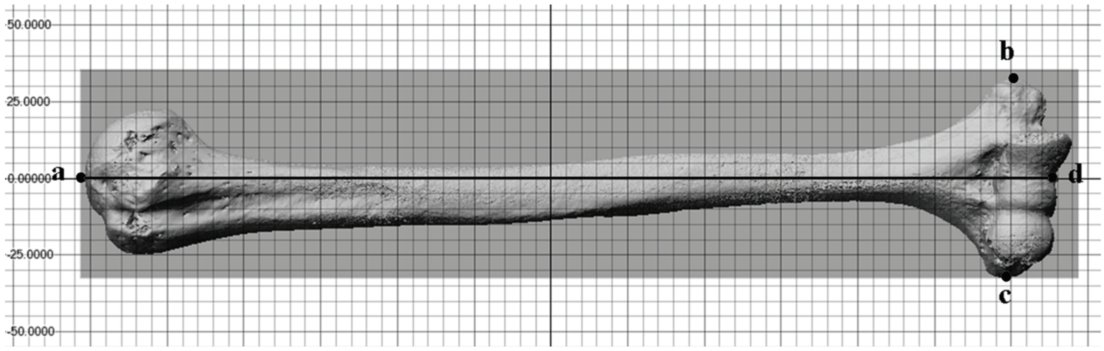
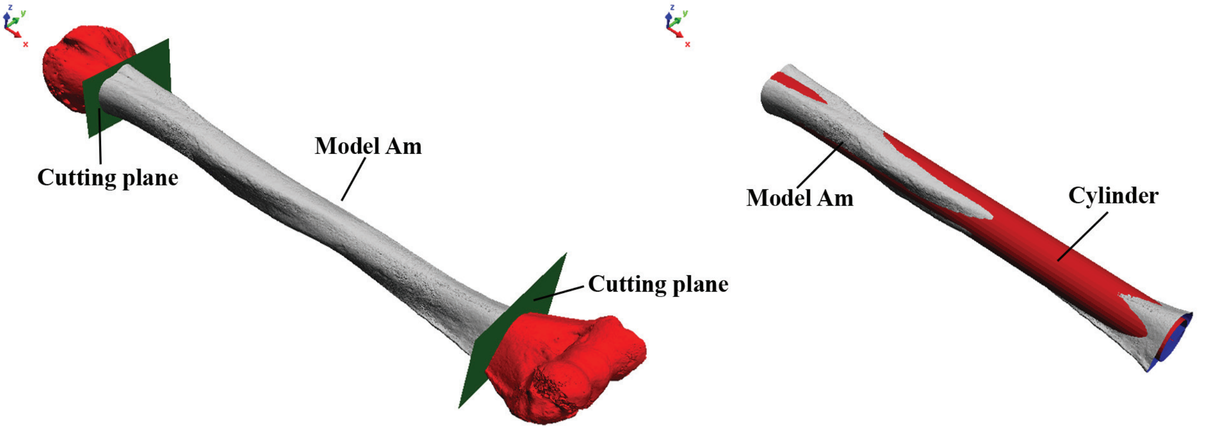


Fig. 3. Orientation of model Am (anterior view): a=upper extremity of the humerus head; b=mesial epicondyle; c=lateral epicondyle; d=middle point of the troclea. In grey the plane passing through point a,b,c; in black the segment ad.



a) **b)**

Fig. 4. Model Am: a) epiphyses separated form the diaphysis by cutting planes at 15% and 85% of the humerus physiological length; b) best fit cylinder of model Am.

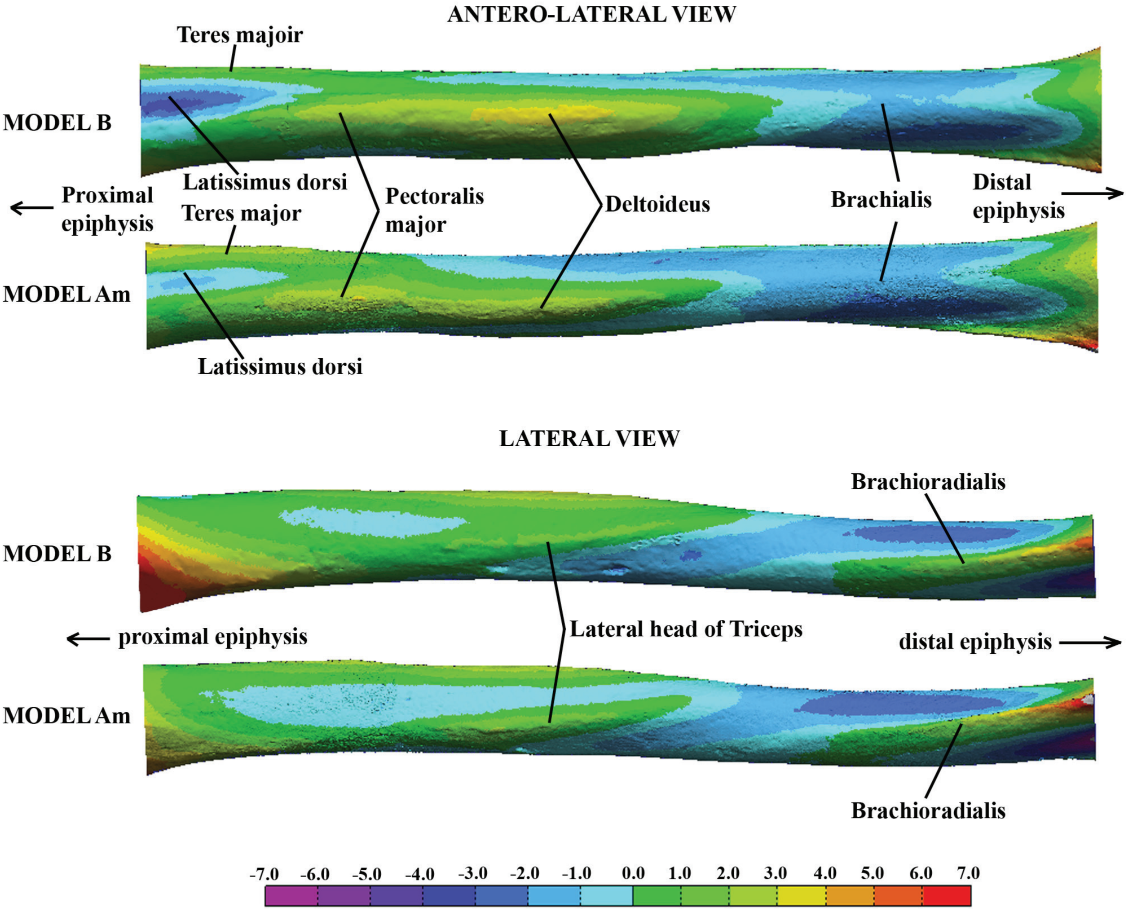


Fig. 5. Inspection analysis between model B/cylinder and model Am/cylinder. Since the inspection was performed relatively to the best fit homologous cylinder, the color map provides a graphic visualization of the difference between model B and model Am.

different lengths (model B is about 1mm longer than model Am), they have identical breadths.

Consequently, we can quantify the relative deviation between model Am and model B in the specific area of the diaphysis by subtracting values obtained from model Am/cylinder and model B/ cylinder respectively (*Fig. 5*). In order to simplify the comprehension of *Figure 5*, the color bar has a step of one millimetre. It is also possible to either reduce the steps or to calculate interactively the real amount of deviation between 3D model and cylinder by simply picking a point directly on the desired area of the model surface. In *Figure 5* the latter option was not visualized even though it was used to collect data for the results. By means of the error annotation function implemented in PolyWorks® 10.1, the deviation value is automatically obtained by moving the cursor onto the model surface. For each muscle insertion area, the maximum deviation between model and cylinder was chosen.

Due to the impossibility of creating an exhaustive reference shape, analyses of the epiphyses were carried out with the superimposition of the epiphysis of model Am with the epiphysis of model B, with the latter considered as the reference shape.

3. Results

The entire diaphysis of model B is slightly larger than the diaphysis of model Am. The insertion area of two antagonist muscles, deltoideus (involved in arm abduction along the frontal plane) and latissimus dorsi (responsible for extension and adduction of the arm), play an interesting role in differentiating model B from model Am. In fact, it is worthwhile to note the major deviation of the right deltoideus from the cylinder (maximum=3.5mm) when comparing to the left one (maximum=2.6mm). This means that the deltoideus insertion area of model B exceeds the insertion of model Am by about one millimetre. Additionally, the insertion area of the latissmus dorsi in the intertubercular groove (*Fig. 5*) is more depressed in model B (-3.4mm) than in model Am (-1.2mm) (relative deviation=-2.2mm).

Nevertheless, other muscle insertions were slightly more pronounced in model Am than in model B. It is interesting to underline that the maximum deviation of the lateral head of triceps insertion was about 2.1mm in model Am and 1.2mm in model B (relative deviation=0.9mm). The pectoralis major of model Am was 3.2mm while 2.6mm in model B (*Fig. 5*).

In general, the epiphyses of model Am are smaller than the epiphyses of model B (*Fig. 6*). In the proximal epiphysis, a major difference was observed in the greater tuberosity (locus for insertion of the supraspinatus, infraspinatus and teres minor), with a deviation up to 1.5mm between the 3D models (*Fig. 6 a,b*). Less difference was observed in the distal epiphysis. Even if the general smaller dimension of model Am is confirmed, the troclea of model Am tends to be slightly bigger that the right one (*Fig. 6c,d*).

4. Conclusions

Results obtained by the aforementioned analysis (general larger dimension of model B than model Am; slightly larger muscle insertions in model B except for the triceps and the pectoralis major), suggest a clear asymmetry of the humeri. Obviously it is difficult and somehow incorrect to provide a general overview of the physical activities of the individual based on the information collected on a the typology of a single bone (humerus). Nevertheless, the combination of these results with other information collected by an accurate anthropological analysis of the skeleton could be useful help in understanding the functional stress pattern generated by physical activities.

However, with regard to the epiphyseal superimposition, it is important to mention some limits of this approach. In fact, the outcome of the alignment depends on the similarity between the two superimposed shapes. The more similar is the shape, the more correct is the alignment and hence the more reliable will be the results. This makes sense in the field of engineering, because the 3D virtual models are very similar, e.g. the model obtained by CAD techniques and the model obtained by the 3D scan of the physical prototyped CAD model. Increasing the morphological difference between the compared models reduces the reliability and the usefulness of the alignment procedure.

For this reason, we would like to stress that the method, either for the diaphysis or for the epiphyses, has to be further tested in a larger sample before being

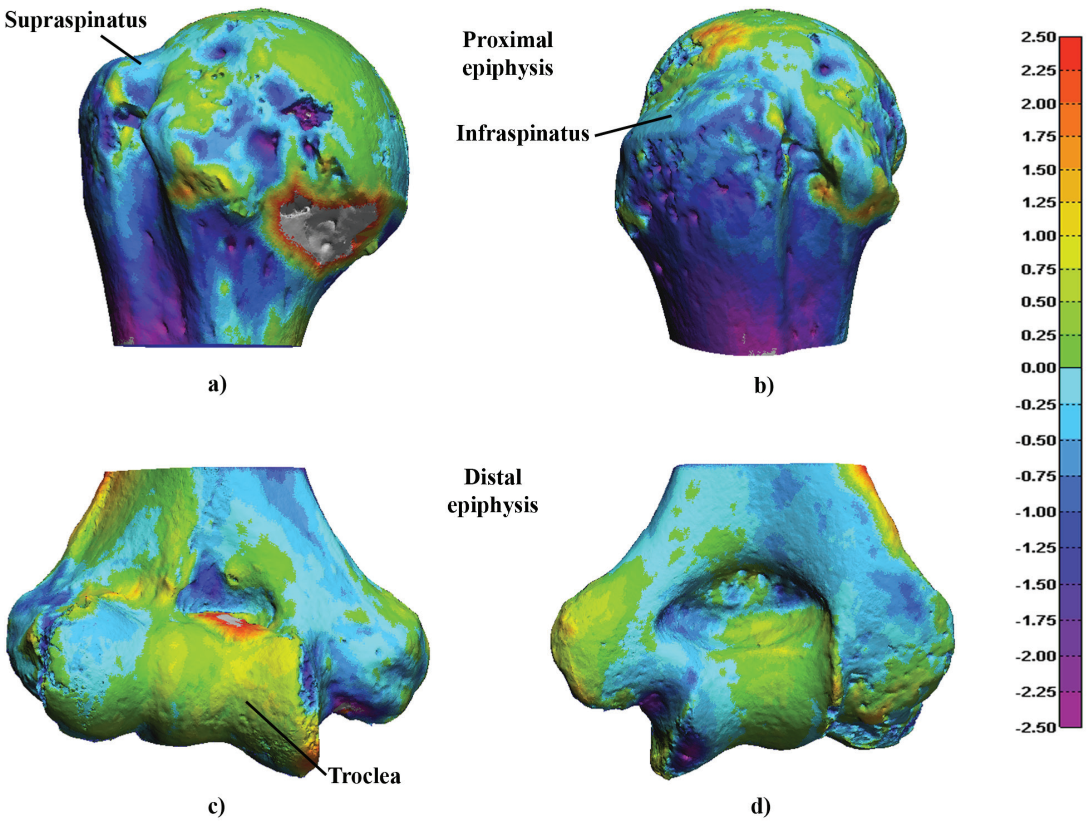


Fig. 6. Inspection analysis of the epiphysis with model B as reference shape. Proximal epiphysis: a) anterior view; b) lateral view. Distal epiphysis: c) anterior view; d) posterior view.

considered a reliable approach for the visualization and quantification of asymmetry in long bones. Therefore, it is our intention to extend this approach to a larger sample of humeri in which the subjects' gender and activities are known.

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