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Asymmetry of hands on modern human: a geometric morphometric analysis of metacarpal bones

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Muséum national d'Histoire naturelle



Universitat Rovira i Virgili



**Master Erasmus Mundus en
Quaternaire et Préhistoire**

Mémoire de Master:

***Asymmetry of hands on modern human; a geometric
morphometric analysis of metacarpal bones***

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Tuteur : Carlos Lorenzo

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ABSTRACT

The subject of this master thesis concerns the asymmetry of modern human hands. The aim of this dissertation was to know which measures taken with a geometric morphometric analysis allowed us to recognize the asymmetry in metacarpal bones and to develop a method that can be reproduced in future researches.

To do so, we selected individuals from the San Pablo cemetery (13th to 15th centuries) and scanned their metacarpals with the *Breuckmann* surface scanner, in order to obtain a three-dimensional image of each bone. Then, we applied twenty-two preselected landmarks on every bone. Once the coordinates of the landmarks were exported in a database, we used a mathematical formula to obtain eleven measures.

To study and interpret these measures, four statistical tests were made. The Two-sample paired test (T-test) allowed us to see which measures had a statistically significant difference. Our results showed that for all the metacarpals, the maximal length (ML) and the articular length (AL) exhibit the most the asymmetry between the right and the left sides, while the distal maximal breadth (DMB) follows. However, some measures don't or almost don't exhibit the asymmetry. Also, this test expresses that some metacarpals, like the MC1, have more measures that can exhibit the asymmetry than others, like the MC2. Finally, we did a Principal Component analysis. This test confirmed the importance of the ML and AL measures by making them the principal components in the ordination of the data. We also noticed that no individual is really different or asymmetrical, compared to the rest of the group, for all the metacarpal bones.

All these tests have allowed us to state that it is possible to discern the asymmetry in human modern hands, more specifically in metacarpal bones, using geometric morphometric analysis and this by the ML and AL measures. And that, by the results we obtained with the repeatability test and the statistical tests, we can also state that this method is effective, reliable and can be reproduce.

RÉSUMÉ

Le sujet de ce mémoire de master concerne l'asymétrie des mains chez l'humain moderne. Le but de cette dissertation est d'identifier quelles mesures, prises grâce à une analyse géométrique morphométrique, permettent de reconnaître l'asymétrie des métacarpes et de développer une méthode pouvant être reproduite dans de futures recherches.

Pour ce faire, des individus du cimetière de San Pablo (13^e au 15^e siècles) ont été sélectionnés et leurs métacarpes ont été numérisés par l'entremise du scanner de surface *Breuckmann*, ce, dans le but d'obtenir une image en trois dimensions de chaque os. Ensuite, vingt-deux points d'intérêts (landmarks) ont été apposés sur chacun des os. Une fois les coordonnées des points exportées dans une base de données, une formule mathématique fut utilisée afin d'obtenir onze mesures.

Afin d'étudier et d'interpréter ces mesures, quatre tests statistiques ont été réalisés. Le test apparié à deux échantillons (T-test) a permis d'observer quelles mesures ont une différence significative statistiquement. Nos résultats démontrent que, pour tous les métacarpes, la longueur maximale (ML) et la longueur articulaire (AL) expriment le plus l'asymétrie entre les côtés droit et gauche, suivi par la largeur maximale distale (DMB). Cependant, certaines mesures n'expriment pas ou presque pas l'asymétrie. Également, ce test démontre que certains métacarpes, comme MC1, ont plus de mesures pouvant exprimer l'asymétrie, que d'autres, tel MC2. Finalement, une analyse des Composants Principaux a été faite. Ce test a confirmé l'importance des mesures ML et AL en faisant d'elles les composantes principales dans l'ordination des données. Il a aussi été noté qu'aucun individu est réellement différent ou asymétrique, comparé au reste du groupe, et ce pour tous les métacarpes.

Tous ces tests permettent de déclarer qu'il est possible de discerner l'asymétrie des mains chez l'humain moderne, grâce à une analyse géométrique morphométrique et ce par les mesures ML et AL. Et que, par les résultats obtenus avec le test de répétabilité et les tests statistiques, il est aussi possible de déclarer que cette méthode est efficace, valide et peut être reproduite.

RESUMEN

La presente memoria estudia la variación de la asimetría de las manos en los humanos modernos. El objetivo principal del trabajo es identificar cuáles medidas, de acuerdo al análisis geométrico morfométrico, permiten reconocer la asimetría de los metacarpos. Así, se busca desarrollar un método que pueda ser reproducido en futuras investigaciones.

Para esto, se han utilizado los metacarpos de los individuos del cementerio de San Pablo (siglos XIII al XV), los cuales han sido digitalizados a través del escáner de superficie *Breuckmann*. De esta manera, se obtuvo un modelo en tres dimensiones de cada uno de los huesos. Posteriormente, se situaron veintidós landmarks tridimensionales sobre la superficie, cuyas coordenadas se utilizaron para obtener once variables de cada uno de los metacarpos.

Para poder estudiarlos e interpretarlos, se aplicaron cuatro pruebas. El test para dos muestras pareadas (T-test) permitió la identificación de cuatro medidas con una diferencia estadística significativa. Nuestros resultados demuestran que, para los metacarpos, son la longitud máxima (ML) y la longitud articular (AL) que presentan el mayor grado de asimetría entre los lados derecho e izquierdo, seguido por la máxima anchura distal (DMB). En cambio, otras medidas apenas presentan asimetría. Así también, este test da cuenta de que, ciertos metacarpos, como el MC1, presentan más medidas que puedan explicar la asimetría que otras, como ocurre con MC2. Finalmente, se efectuó un análisis de componentes principales que confirmó la importancia de las medidas ML y AL, haciendo de ellas elementos centrales en la ordenación de los datos. Por otra parte, se observó que ningún individuo es realmente diferente o asimétrico comparado con el resto del grupo.

Todas estas pruebas nos permiten afirmar que es posible distinguir la asimetría de las manos en los humanos modernos gracias al análisis geométrico morfométrico, específicamente mediante las medidas ML y AL. Sumado a esto, los resultados obtenidos del test de repetitividad y las pruebas estadísticas, sugieren que este método es eficaz, válido y reproducible en otros casos.

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1. INTRODUCTION

The human hand is particular. It allows us, among other things, to be precise and to grab things easily. We use our hands as tools. But, because we use one side more than the other, even if they look alike, our two hands are not exactly the same. They are asymmetrical and it is created by handedness or laterality, which is mostly unique for each individual.

This present dissertation is the reflection of the work of a master thesis studying the asymmetry of hands, more specifically of the metacarpal bones of modern *Homo sapiens* by a geometric morphometric analysis. The general objective of the master thesis is the work and study of a new methodology. Over this dissertation, we will explain how this methodology is important and the processes that brought our results.

The current chapter will serve to put in context the present research; we will detail the general aspect of our subject. The aim of the master thesis, the objectives and the hypotheses will also be revealed in this part.

In the following chapters of this dissertation we will describe and explain our processes of how we were able to answer our questions.

The next chapter (chapter two) concern the material and methods used. We will describe our assemblage, where it came from and why it was appropriate for our research. We will also explain why the choice of the metacarpals was made and which parts of it were studied. Finally, we will describe the tools used and how we used them to collect the data we needed for the statistical analysis.

The third chapter concern the results. We will demonstrate the different outcomes of the many statistical tests we applied, more specifically for the Two-sample paired test (T-test) and how the results are important in order to answer our questions.

In the fourth chapter, we will explain our interpretations of the data according to the results of the different statistical tests and what it can mean. This chapter is dedicated to the discussion.

The fifth chapter is devoted to the conclusions. In this part, we will summarize our results and interpretations and, mostly we will answer our questions.

The chapters six is constituted of the references, and a list of the figures used in this dissertation is at the end.

Hand laterality and asymmetry

As we get older, our bones evolve and change. Bones carry the markers of our life. Markers are created by the activities that we do. The traces left by the muscles and ligaments are called stressed markers (White et al. 2012). The markers can be studied and can give us answers about many questions we have concerning humans; locomotion, ontogenesis, cognition and evolution (Cartmill et al. 2012, Heyes 2012, Hopkins et al. 1993, Liu et al. 2009, Steele & Mays 1995, Ward et al. 2014). To analyse the markers of the bones, different methods are used; like X-rays, manual measurements by calliper, cortical analysis and geometric morphometric analysis. One of the markers we can observe concern the differences between the bones, it is the asymmetry as an expression of the hand laterality.

Hand laterality is linked with cognition, language, the ability to make tools and much more (Corballis 1989). It is important to study hands in order to understand better how the brain works, and by that to understand better the human evolution and *Homo sapiens* itself.

For many years now, we know that the hand laterality is important for *Homo sapiens* and all the hominines (Corballis 1989). Hand laterality is the fact that most of people have a “preference” for using their left or right side, in most activities they are doing. It is in fact that we use preferably one hemisphere of our brain. We can see on the bones the marks of the laterality, it is the asymmetry, the differences in size and shape between the left and the right sides. The asymmetry is developed by the use of one side of the body more than the other during the life of an individual. Both sides, left and right, developed markers that are slightly different, resulting in an asymmetry.

Two main types of asymmetry exist; fluctuating and directional. Fluctuating asymmetry is the variation between the left and right sides created by a stress. In fluctuating asymmetry, there is usually an external factor that influences the development and makes it not equal for both sides (Bonzom 1999). It refers to non-symmetry due to genetic or environmental pressures experienced through the development of an individual.

The directional asymmetry is not a variation across the population. It is the fact that one side, the same for every individual, is bigger than the other. There is no influence from an external factor, by a stress (Van Valen 1962).

Over the years, researches have observed the asymmetry in the human body and in other living beings (Albert & Greene 1999, Blackburn & Knüsel 2006, Corballis 1983, Corballis 1989, Hopkins et al. 1993, Hopkins et al. 2007, Kivell et al. 2011, Liu et al. 2009, Mays et al. 1999, Reuter-Lorenz & Miller 1998, Schaafsma et al. 2009, Service 1999, Steele & Mays 1995, Volpato 2012). We can clearly state that there is asymmetry in different skeletal parts. Researches also have been made to observe more specifically the asymmetry of hand related to laterality in *Homo sapiens* (Livshits et al. 1998, Plato et al. 1980). These studies attest that there are differences between the left and the right hand bones of the same individual; we can see the asymmetry of the hands. By knowing how to recognize and how to measure the asymmetry of hands, we have the ability to determine the laterality of individuals and to go on with more studies about brain development, cognition, evolution, language, tools making and more.

The aim of the present thesis: Objectives and Hypotheses

The purpose of this master thesis is within the physical anthropology framework. It was intentionally chosen that all the individuals studied were *Homo sapiens* because, it is by knowing the marks of laterality left on modern human bones that we will be able, eventually, to apply this method of analysis on fossils of hominines or other hominoids.

The aim of the present thesis is to understand which measurements, taken by geometric morphometric analysis, allow us to recognize the asymmetry in metacarpal bones related to the laterality of an individual, and the relevance of using this type of analysis. We also want to develop a method that can be reproduced in future researches.

Our general objectives are:

- 1) To analyse the metacarpal bones of *Homo sapiens* individuals in order to see signs of asymmetry that are associate with handedness lateralisation,
- 2) To do a morphometric analysis in 3D of the diaphysis, the epiphysis and of the articular surfaces of the metacarpal bones.

Our specifics objectives are:

- 1) To scan the metacarpal bones in order to obtain three-dimensional models,
- 2) To apply the preselected landmarks on the three-dimensional models of each metacarpals, and to export the coordinates of the landmarks in a database,
- 3) To calculate the measures, with the three-dimensional coordinates and the mathematical formula,
- 4) To do a statistical analysis of the data in order to understand better the data and to answer the questions,
- 5) To interpret the results of the statistical analysis in order to determine which measures exhibit better the asymmetry.

Our hypotheses are:

- 1) That it is possible to discern the asymmetry by measurements of the metacarpal bones using geometric morphometric analysis (3D),
- 2) That the measures that will exhibit better where the asymmetry is more manifested are the ones from the articular surfaces (proximal and distal).

State of the question

Over the years, hand laterality and asymmetry were studied by many anthropologists. Papers have been published in the past about this subject. However, no 3D morphometric analysis has been done on this matter. However, a good review of literature was important. Some authors developed methods, measurements and statistical analyses that were relevant for the realisation of this dissertation.

Mays et al. (1999) talk about the lateral asymmetry by studying, morphologically, clavicles from a medieval assemblage, in pair. They are using statistical tests, like the Two-sample paired test, that are relevant for our research.

The statistics used by Plato et al. (1980) are also useful in our case. The latter are studying the bilateral differences in hand and cortical bones. Their research gave us also useful information about measurements of metacarpals.

In their 1998 publication, Livshits et al. explain the measurements they took relatively to study hand asymmetry. In their publication, they used radiographs to study fluctuating asymmetry and coefficient of variation in hand bones.

Vandermeersch & Trinkaus (1995) give measurements they took on a Neanderthal hominine. They did measurements on clavicles, humeri, radii and ulnae for both the left and the right sides in order to describe and compare them with other specimens.

Albert & Greene (1999), Blackburn & Knüsel (2006) and Steele & Mays (1995) did different studies on bilateral asymmetry in postcranial bones. They compared asymmetry of the right and the left sides but also included different variables like sex and age.

General knowledge of human laterality and the concept of asymmetry are primordial for the well understanding of the subject of this thesis, Corballis' publications (1983, 1989) were of a great help. He explained the origin of the laterality in human in comparison with other primates, and the link of laterality with cognition, tool making, language and more.

Slice (2007) and Zelditch et al. (2012) along with Weber & Bookstein (2011) and Zollikofer & Ponce de Leon (2005) published articles and books about geometric morphology and about the work with virtual images. To work with three-dimensional

models requires different instruments and methods than to work with the physical bones. Their publications are useful as guides about this way of research.

Buikstra & Ubelaker (1994) developed methods to analyse data collection of human bones. They explained the growth patterns and how to identify the sex and age of an individual. These methods were used to have information about the individuals used for this research.

A revue of literature gives information about what was made in the past and what can be applied in this study. It is a new methodology but the general concept of the determination of the asymmetry regarding the handedness or laterality is not new and gave results that cannot be ignored.

2. MATERIAL AND METHODS

The individuals

This research was done with the help of a collection of fifty (50) individuals that are coming from individual graves from the medieval cemetery of San Pablo (Burgos) in Spain. The individuals are dated between the 13th and 15th centuries.

All our individuals are *Homo sapiens*. These individuals, twenty-five (25) males and twenty-five (25) females, have been chosen because of the good conservation of the bones, as well as for the complete information obtained from them (sex, biological age and pathologies). All the individuals are adults to prevent any bias that a still growing and changing individual, such as a child or teenager, can represent (Buikstra & Ubelaker 1994, White et al. 2012). Our individuals have a biological age between 18 and over 50 years old.

The sexes and biological ages were previously identified by a team, using mostly Buikstra & Ubelaker (1994) methods.

Well-preserved individuals in anatomical connexion, along with their information are essential for the good proceedings of this research. That ensures the reliability of the results by reducing extrapolation of the data.

The bones and the areas selected

The human hand is composed of nineteen bones (Figure 1). The five metacarpals are the most proximal bones. The five proximal phalanges are the first bones of the fingers. There are only four intermediate phalanges; the thumb is lacking this bone. Finally, the five distal phalanges are the bones at the end of the fingers. The hand bones are long bones aligned in rays (fingers). The rays of the hand are numbered from one (the thumb) to five (the little finger) (White & Folkens 2005).

The bones have articular surface at their proximal and distal ends for the articulation with the other bones. Metacarpals articulate with the carpal bones (bones of the wrist) at the proximal end and the proximal phalanges at the distal end. Proximal phalanges articulate with the metacarpals at the proximal end and intermediate phalanges at the distal end (except for the thumb which has his proximal phalange articulated with the distal phalange). The intermediate phalanges articulate with the proximal phalanges at the proximal end and the distal phalanges at the distal end. And, the distal phalanges articulate with the intermediate phalanges at the proximal end (except for the thumb which has his distal phalanges articulated with his proximal phalange).

The human hand is considerably mobile and has adroitness. To have this ability, the hand possesses, in addition to the bones, a great number of muscles and ligaments (Patzner 2007). These muscles and ligaments leave traces that we can see on the surface of all bones of the hand (markers) and can shape the bones differently not only for each bone but for each individual.

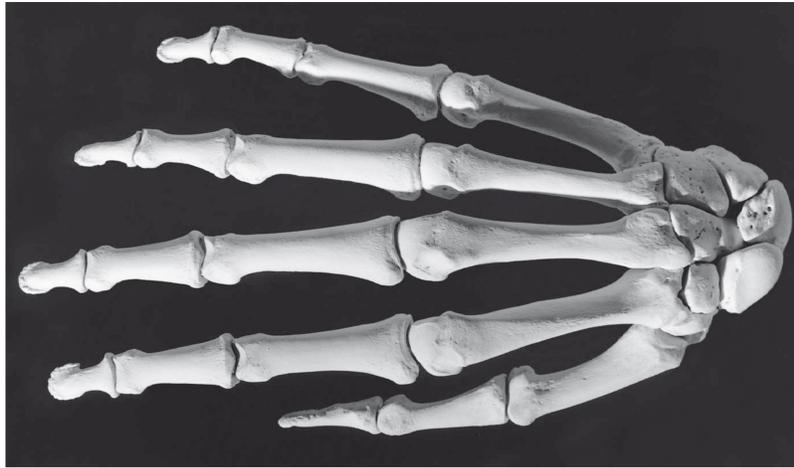


Figure 1. Right hand, dorsal.

Image from White & Folkens 2005

The metacarpal bones (MC) are bigger than the phalanges. Their head (distal end) is rounded and covered by the articular surface; it is quite similar for all of the metacarpals, while the base (proximal end) is mostly rectangular. The general shape of the diaphysis is tubular with a palmar face slightly concave and the dorsal face slightly convex. They are going from bigger to smaller starting from the second metacarpal to the fifth metacarpal. All the metacarpals have different shapes (Figures 2 and 3). The first metacarpal (MC1) has a general shape larger and shorter with a robust diaphysis; it also has a saddle-shaped proximal articular surface. The second metacarpal (MC2) has a long diaphysis. Its articular surface of the base has a notch, for the articulation with three carpal bones (trapezoid, capitate and trapezium), while it has also an articular surface on its medial side for the articulation with the third metacarpal. The third metacarpal is characteristic for its styloid process at its proximal end, which is latero-dorsal. It has a proximal articular surface for the articulation with one carpal bone (capitate), a lateral articular surface for the articulation with the second metacarpal and two medial articular surfaces for the articulation with the fourth metacarpal. The general shape of the proximal base of the fourth metacarpal bone (MC4) is squared with a half-moon form on its middle. It articulates on its proximal end with carpal bones (capitate and hamate); on its lateral side of the proximal end with the fourth metacarpal (two articular surfaces) and on its medial side of the proximal end with the fifth metacarpal. The last but not least is the fifth

metacarpal (MC5). It is the smallest of the metacarpal bones. It possesses one articular surface on its medial side of the proximal end with the fourth metacarpal and no articular surface on its lateral side considering that it is the last bone. Although, it has another articular surface on its proximal end that correspond to the articulation with one carpal bone (hamate) (Platzer 2007, White & Folkens 2005, White et al. 2012).

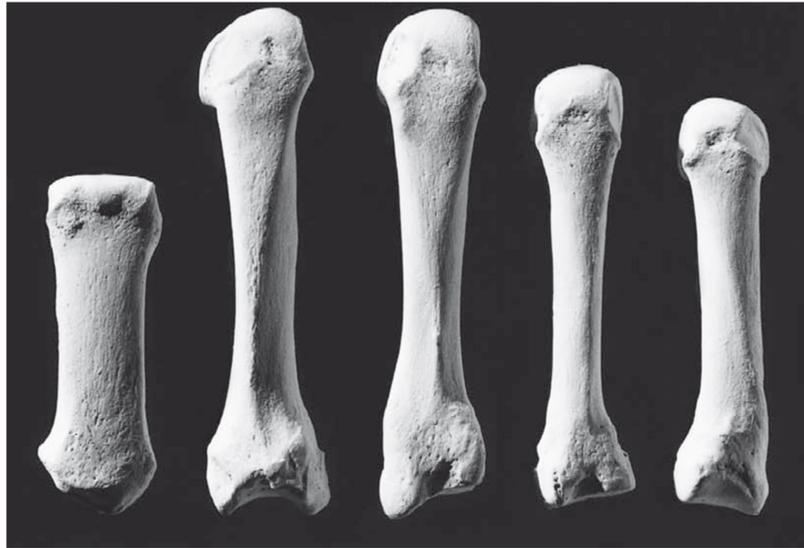


Figure 2. Metacarpals from the right hand, dorsal. From MC1 (left) to MC5 (right).

Image from White & Folkens 2005



Figure 3. Metacarpals from the right hand, palmar. From MC5 (left) to MC1 (right).

Image from White & Folkens 2005

For this master thesis, we decided to analyse only the metacarpal bones. In the hand, the metacarpals are the bones that received most of the pressure. So, they are the bones that can exhibit the most the asymmetry due to handedness. All five metacarpals of the hand were analysed. This choice over others, like the study of specific fingers or the inclusion of the phalanges and of the surface areas, was made due to time limitation for the realization of this master thesis and due to the fact that not all individuals preserved all of their hand bones by pair (right and left). Our priority was the analysis of the metacarpal bones in the purpose of developing a good methodology. Also, few researches focus on only metacarpals, most of them focus on specific rays (fingers) or different bones. Consequently, we decided to take measures from different places on the diaphysis, the epiphysis and on the articular surfaces; therefore most of the bone is included in the analysis.

From our collection of fifty (50) individuals, forty (40) individuals were selected, twenty-one (21) males and nineteen (19) females. These individuals were chosen mainly because they have all of their metacarpal bones represented by the pair (right and left), which is essential for the comparison intra individual. This number of individuals allows us to remove some of the bones or measurements if they are not appropriate (broken bone, pathology, etc.), and still have enough individuals remain to have a sample of an appropriate size (around thirty (30) individuals) for the quality of the statistical analysis.

Although we know the sex of the individuals, we did not use this information to segregate more the data. In our case, the sex is not requisite. In different studies, Albert & Greene (1999), Blackburn & Knüsel (2006) and Steele & Mays (1995) showed that there is no particular difference, statistically, in the asymmetry of bones, between males and females.

The scanning process

The first step was to scan the bones with the 3D scanner *Breuckmann*. The scanning process consists of obtaining three-dimensional models of the metacarpal bones. The resulting images were then used for the analysis.

The majority of the right hands were scanned by Fotios Alexandros Karakostis for his master thesis in 2015 (Karakostis 2015). It was necessary to scan the metacarpals of the left hands as well as a part of the right hands that had not been made previously. At the same moment, the 3D images of the bones were treated by the software *Geomagic (mesh doctor)*.

The scanner that we used was a *Breuckmann SmartScan* (Figure 4) with the software *OPTOCAT 2012* and an automatic turntable platform. This scanner is a surface scanner. It works with three digital cameras and sends a light that reflects on the scanned object. By capturing the reflection, the scanner is able to record the spatial depth, the distance between the object and the cameras. It will then create an image with the different points captured and by combining them together (Figure 5). Photographs can be taken at the same time to record the texture and the color. That will result in a three-dimensional model of the object (Zollikofer & Ponce de Leon, 2005).



Figure 4. Scanner *Breuckmann Smartscan*
Image from <http://www.smartsan3d.co.uk/>
(July 26, 2017)



Figure 5. 3D model of the left MC4 of SP26

In order to have a high-resolution image, lens of M-250 were used. We scanned over five hundred (500) bones; including the phalanges that were not included in the final work for this master; with texture, color and geometry. All of the adjustments were the same for each of these bones. The scan was set to *Automatic*, the parameters were set to full-resolution, with a number of captures of four, with seven scans per rotation. The *Teach* option allowed us to set the lights and cameras of the scanner at the appropriate distance from the bone. We placed the bones in a vertical position on the turntable platform. The *Scan* option obtained for us the images of the scanned bone. After alignment of the images and their merging, the 3D data result was exported in a *.ply* format. These *.ply* files were then imported in the *Geomagic Studio 2013* software and were treated with the *Mesh Doctor* option.

The scanning process took place in the laboratory of Paleoanthropology at the Catalan Institute of Human Paleoeology and Social Evolution (IPHES).

The landmarks

Once all the bones were scanned, it was time to decide which landmarks will be use. The landmarks are points, dots that are applied on the three-dimensional image of the bone. The landmarks can then be exported in raw data that will give coordinates (x, y, z) (Zelditch et al. 2012). These coordinates will be saved in a general database.

The main benefits of the new technology are the precision in the taking of the measures as well as the possibility to have more of these measures. In the prior researches, measures were taken manually, with callipers on X-rays or directly on the bones. These methods are valid but a three-dimensional image gave us more precision in the application of the points because we can manipulate the image more easily and increase the image to be closer to the bone (zoom) as for a better visibility of the entire bone. Also, using a 3D model, instead of the physical bone, guaranties less manipulation of the bones, so a better preservation of it, which can be precious in fossils cases or damaged bones.

Because it is the first time a geometric morphometric analysis study is made about this subject, we had to make a decision and choose the appropriate landmarks that will

help answer our questions. The landmarks were chosen in regard of the literature and researches, and about the measures that they published.

For the sake of this dissertation, we used mainly landmarks that were coming from classical measurements, from a semi-standardized system. Most of the time these measures are taken following the works inspired by Martin (1928) and Martin & Saller (1957) who developed a great methodology for anthropologists. Case et al. (2015), Franks & Cabo (2014), Livshits et al. (1998), Plato et al. (1980), Vandermeersch & Trinkaus (1995) are some authors that used different measurements, on hand bones or other long bones from the upper limb. We selected our measurements according to what they published. The landmarks were then created from the measures we wanted to obtain. More landmarks could be added to have more measures, however due to time restriction we decided to use only the measurements that were used in previous analyses. Also, this allows us to compare the different methods and to see if the geometric morphometric analysis is useful in this kind of research.

After a period of experimentation, a conclusion of landmarks and the exact places where to place them was reached (Table 1 and Figure 6). We applied twenty-two (22) landmarks on each metacarpal of our forty (40) individuals with an objective of having all the points at the same place for all the bones. The landmarks that go together (rightmost/leftmost, palmar/dorsal) are in a straight line that is perpendicular to their opposite measure (rightmost-leftmost/palmar-dorsal). Each landmark was export in raw numerical data; in three-dimensional coordinates (x, y and z), and put in a database.

Landmark	Definition
1	Most proximal point of the base
2	Most distal point of the head
3	Centre of the proximal articulation
4	Centre of the distal articulation
5	Rightmost point of the proximal epiphysis
6	Leftmost point of the proximal epiphysis
7	Most dorsal point of the proximal epiphysis
8	Most palmar point of the proximal epiphysis
9	Rightmost point of the proximal articulation
10	Leftmost point of the proximal articulation
11	Most dorsal point of the proximal articulation
12	Most palmar point of the proximal articulation
13	Rightmost point of the midshaft of the diaphysis
14	Leftmost point of the midshaft of the diaphysis
15	Most dorsal point of the midshaft of the diaphysis
16	Most palmar point of the midshaft of the diaphysis
17	Rightmost point of the distal epiphysis
18	Leftmost point of the distal epiphysis
19	Rightmost point of the distal articulation
20	Leftmost point of the distal articulation
21	Most palmar point of the distal articulation
22	Most dorsal point of the distal articulation

Table 1. Description of the landmarks applied on each metacarpal.

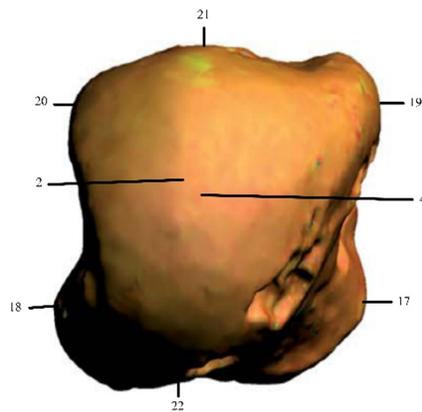
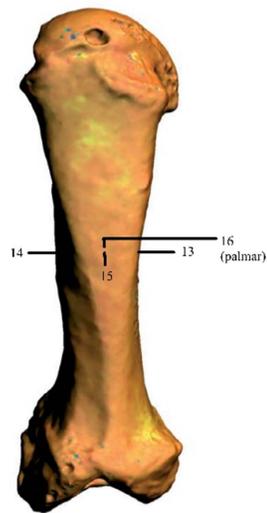
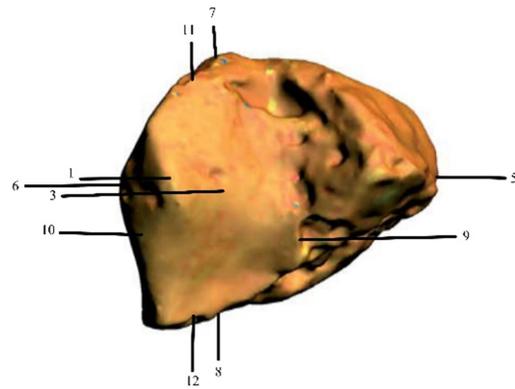


Figure 6. Landmarks applied on left MC2 of SP133, from proximal view, dorsal view and distal view. The numbers correspond to the numbers in Table 1.

In order to apply the landmarks the software *Landmark* version 3.0, from the Institute for Data Analysis and Visualization (IDAV) was used. The software allows us to create a new project and to import a *.ply* file that give access to the three-dimensional image of the bone. Once we have the image of one of the metacarpals, it is possible to move it in every positions needed. By selecting the *add single point* option, we were able to place the landmarks at the preselected positions. Once all the landmarks were correctly positioned, we exported the data in *Raw Landmark Points (.pts)*. We were then able to import the three-dimensional coordinates x, y, z of each landmark via the *.pts* files in an Excel database.

The measures

The landmarks are going in pairs that allow us to have eleven measures (Table 2). These measures are the important data of this work. We used them to do the statistical analysis and the comparison between right and left metacarpals. Once all the landmarks were exported in the database from their *.pts* files, we used a mathematical formula to obtain the measurements, in millimeters. To confirm the accuracy of the formula, we also did manual measurements with a digital calliper on an individual (SP26). All the measurements were conclusive.

The mathematical formula is the following:

$$=\sqrt{((x1-x2)*2+(y1-y2)*2+(z1-z2)*2)/10000000}$$

Landmarks	Definition of the measure	Abbreviation
1-2	Maximum length	ML
3-4	Articular length	AL
5-6	Proximal maximal breadth	PMB
7-8	Proximal maximal height	PMH
9-10	Proximal articular breadth	PAB
11-12	Proximal articular height	PAH
13-14	Midshaft breadth	MB
15-16	Midshaft height	MH
17-18	Distal maximal breadth	DMB
19-20	Distal articular breadth	DAB
21-22	Distal articular height	DAH

Table 2. Description of the measures obtained with the coordinates of the landmarks and the formula, and their abbreviations.

The database

The database we created for the compilation of all our data was made from an Excel sheet. In the first column we have our individuals in order of number (SP5, SP8, SP10, etc.); each individual is there ten times, once for each of the five metacarpals of the two hands. In the second column, we have the sex (F for female, M for male) of each individual. The third column is for the bones, from MC1 to MC5, twice for each individual to correspond with the two hands. The fourth column was used to indicate the side (R for right and L for left) of each bone. From the fifth column to the seventieth column, the data is separate following the twenty-two (22) landmarks and their three coordinates (x, y, z) (Table 3). The final eleven columns are for the results of the measures obtained with the formula from the landmark's coordinates. Finally, some blue color was used to segregate the data, the color was applied when the coordinates were false or incomplete – like for a broken bone. We applied the color to the coordinates and to the corresponding measure. This was to avoid errors and to avoid collecting non representative data.

From that database, others were created; one for each metacarpal without the landmark's coordinates, and one for each metacarpal without the landmark's coordinates and with the side as a separation of the measures instead of separation of the individual (Table 4). The advantage of having many databases containing the same data differently is that it is easier to use it, depending on the statistical tests or other analyses we wanted to do.

Landmark 1			Landmark 2		
L1-X	L1-Y	L1-Z	L2-X	L2-Y	L2-Z
-3,12E+07	1,43E+08	9,41E+07	-5,82E+07	1,23E+08	5,15E+08
4,27E+07	-2,45E+06	6,46E+08	3,29E+07	-6,48E+07	8,68E+05

Table 3. Example of the database. Expression of the data from the fifth to the seventieth columns, corresponding to the coordinates of the landmarks.

Mesures			
ML - R	ML - L	AL - R	AL - L
64,80	65,37	62,64	62,20

Table 4. Example of a database. Expression of the data using the side as a separation of the measures, per metacarpal.

Limitations

The positioning of the points comported certain limitations. Some were the consequences of the lack of experience from the student, others were resulting from the software itself, and finally a few are coming from the bones themselves. The most important limits noticed were the exactness in the position of the points, especially when the bone was twisting or for the midshafts measurements, the non-possibility to do *undo* and the poor visibility of the bone in certain position. The transfer of the data was also a possible place for error by the fact that it needed a lot of manipulation of the data. Plus, we also noticed that with a higher resolution image, it was not more easy or precise to position the points, but it would slow down the process considerably.

After a period of tests and experimentations, despite the limitations; errors and inaccuracies were resolved and avoided, and we can assert that the data was collected with reliability.

Repeatability

In order to be efficient, we repeated the application of our landmarks. We selected three individuals – SP175, SP207 and SP210 – because, during the first application, we were able to apply all of the twenty-two (22) landmarks on each of their metacarpals, producing the eleven measures. For these individuals, we reapplied all of the landmarks to obtain the measures again. We then compared these new measures with the one we obtained on the first application. This allowed us to know if our method of application of the landmarks was effective and if we can reproduce it with certitude and reliability; this allowed us to compare the measures in order to know the intra-observer error.

To do so, we calculated the standard deviation between all of the first and second measurements, for all of the individuals and metacarpals. Our results showed a low intra-observer error, with low deviation between the measurements. The standard deviation is less than one millimeter for every result except two. Both are for the left MC5 and for the PMH. The first one is from the SP175, the standard deviation is *1.04*. This result is still low, around one millimeter. The second is from the SP210, the standard deviation is *2.33*. This result is slightly higher but not different enough to cause major change in the results. These two different results correspond to *1.21%* of all of our results; we can consequently conclude that the intra-observer error is low. This means that our application of the landmarks is reliable and can be reproduced.

Main statistical analysis

With the intention to understand better our data, it was imperative to do a statistical analysis. The data we obtained with the measurements were absolute frequencies. We wanted to know if there were statistically significant differences between the right and the left measures, for each metacarpal, in order to know the coefficient of asymmetry. We wanted to know which measure was the most different between the right and the left metacarpals of one individual; which measures demonstrated the most the

asymmetry between right and left metacarpals and consequently the handedness of an individual.

All our tests have been done with the help of the software *PAST version 3.15* (© Hammer & Harper¹) designed for statistical paleontological data analysis (Hammer & Harper 2006). The four tests made were of descriptive statistics, normality test, Two-sample paired test (T-test) and Principal Component analysis. All tests were made in the purpose of understanding better the data and to answer our questions.

Our data is composed of quantitative values, absolute frequencies; we had parametric variables. This is important because depending of the kind of variable, the tests are different. The data we had were the eleven measures obtained with the landmarks and the mathematical formula. We had eleven measures for each of the five metacarpals of the two hands, for our forty (40) individuals; our data is constituted of four thousand four hundred (4400) numbers. We regrouped the numbers in groups, by metacarpal, by side and by measure, which gave one hundred and ten (110) groups. Doing a descriptive statistical test gave us a general idea of what this data looks like. We obtained, among other things; the mean, the median, the standard error, the kurtosis and the skewness for each group of data. This test was an overview of our data.

To interpret better all these numbers and their relationship it is important to choose the right test. To make the proper decision, the test had to be appropriate for two things; our data and our questions. Our main question was about founding if there was or not a statistical difference between the right and the left metacarpals for each measure, we needed a test that would allow us to compare two groups at once, a univariate test. Our data is constituted of parametric variables, of absolute frequencies. The Two-sample paired test (T-test) seemed the most appropriate because it is a test that let us calculate the difference between the mean of each pair (right and left) for each measure and per metacarpal (Albert & Greene 1999, Blackburn & Knüsel 2006, Harashawardhana 1999, Mays et al. 1999, Zelditch et al. 2012). With each *p(same mean)*, we can know if there is a statistically significant

¹ Hammer, Ø., Harper, D.A.T., Ryan, P.D. 2001. PAST: Paleontological statistics software package for education and data analysis. *Palaeontologia Electronica* 4(1): 9pp. http://palaeo-electronica.org/2001_1/past/issue1_01.htm

difference or not between the right and the left. We could evaluate the significance of asymmetry. Then, we were able to compare these results across the metacarpals, related to the measures.

But, before performing the Two-sample paired test (T-test), it was better to confirm that our data was normal. In our case, it was expected that our data was normal because, except in some extreme cases, human beings grow similarly. The test we used was the Shapiro-Wilk. To determine if the data was normal or not we looked at the $p(\text{value})$. It had to be $p(<0.05)$ to be considered like probably not normal.

The Two-sample paired test (T-test) could help us to answer our questions and hypothesis by determining whether the difference is statistically significant between two independent groups of samples that have a quantitative variable. It does that by comparing the mean of the two groups in order to create a relation between these groups, and so, to reject or not the null hypothesis (Madrigal 2012, Zelditch et al. 2012).

The null hypothesis is a hypothesis that postulates that there is no significant difference between the means of the two studied groups. The difference, so the rejection of the null hypothesis, allows to deduce that there is a link between the two studied groups. The null hypothesis is considerable because the rejection or not of it, permits to take a statistical decision.

Our null hypothesis was the following:

There is no statistically significant difference between the measures of the left and the right sides for each metacarpal.

For each of the fifty-five (55) results, we asked if $p(<0.05)$. If the answer was *yes*, we refuted the null hypothesis, it meant that there was a difference between that measure of the left and of the right for that metacarpal, that there was an asymmetry between the means, ergo between the right and left bones. By comparing and cumulating the *yes* results, we could give an interpretation of our data.

A Principal Component analysis (PCA) was also done. It was used for the ordination of the data. This multivariate test did not give us specific detail about our data, it is more general, to have an overview of the data. It permitted to link the individuals according to their right and left hands. By that, it was possible to see which individuals are more different than the others, which ones are more asymmetrical.

It also allowed us to confirm which measures are more important in the asymmetry by understanding which variables are associated and to have a degree of similarity between the variables that is showed on x and y axes (Slice 2007, Zelditch et al. 2012).

Starting with our variables – the measures and the individuals (left and right hands), for each metacarpal – the PCA gave us an *eigenvalue* for each measures (the components); more this value is high, more the measure is significant. The important components are the ones that give an *eigenvalue* higher than 80%, when summed. That gave the principal components of our analysis. Once the components are selected, we were able to see our data on axes; the x axis represented the component 1 and the y axis represented the component 2.

3. RESULTS

Descriptive statistics

The first step to understand what kind of data we had was to describe it. With the use of the software *PAST*, we were able to obtain different kinds of results that allowed us to summarize our data. We applied the descriptive statistics to the measures of each right and left metacarpals – so one hundred and ten (110) groups – because they are the data that we wanted to compare and understand in this dissertation. Mean, median, standard deviation, kurtosis and skewness are part of the information that we obtained. The summary of the descriptive statistics (means and standard deviation) is showed in Tables 5 to 15.

Metacaps	Measures	n=	Mean	SD
MC1	ML - R	31	42,614	2,425
	ML - L	31	42,291	2,309
MC2	ML - R	29	63,346	2,953
	ML - L	29	62,901	3,158
MC3	ML - R	31	62,394	3,162
	ML - L	31	61,709	3,267
MC4	ML - R	31	53,503	3,070
	ML - L	31	52,989	3,222
MC5	ML - R	32	50,278	2,725
	ML - L	32	49,715	2,603

Table 5. Results of the means and standard deviation (SD) of the ML measure for all MC.
The highest SD is 3,267 and the lowest is 2,309.

Metacaps	Measures	n=	Mean	SD
MC1	AL - R	29	40,751	2,371
	AL - L	29	40,474	2,201
MC2	AL - R	28	60,891	2,895
	AL - L	28	60,182	3,154
MC3	AL - R	31	58,478	2,774
	AL - L	31	58,046	2,720
MC4	AL - R	31	52,819	2,890
	AL - L	31	52,440	3,149
MC5	AL - R	30	49,654	2,486
	AL - L	30	49,192	2,636

Table 6. Results of the means and standard deviation (SD) of the AL measure for all MC.
The highest SD is 3,154 and the lowest is 2,201.

Metacaps	Measures	n=	Mean	SD
MC1	PMB - R	30	15,276	1,036
	PMB - L	30	14,782	0,978
MC2	PMB - R	33	17,303	1,450
	PMB - L	33	17,328	1,587
MC3	PMB - R	36	14,242	1,644
	PMB - L	36	13,823	1,287
MC4	PMB - R	38	11,810	1,181
	PMB - L	38	11,846	1,132
MC5	PMB - R	37	13,424	1,389
	PMB - L	37	13,358	1,494

Table 7. Results of the means and standard deviation (SD) of the PMB measure for all MC.
The highest SD is 1,644 and the lowest is 0,978.

Metacaps	Measures	n=	Mean	SD
MC1	PMH - R	27	15,075	1,447
	PMH - L	27	14,544	1,133
MC2	PMH - R	31	15,790	1,210
	PMH - L	31	15,904	1,268
MC3	PMH - R	35	15,529	1,412
	PMH - L	35	15,663	1,270
MC4	PMH - R	35	12,154	0,922
	PMH - L	35	11,706	1,048
MC5	PMH - R	35	11,451	1,250
	PMH - L	35	11,196	1,082

Table 8. Results of the means and standard deviation (SD) of the PMH measure for all MC.

The highest SD is 1,447 and the lowest is 0,922.

Metacaps	Measures	n=	Mean	SD
MC1	PAB - R	31	13,334	1,156
	PAB - L	31	12,797	0,996
MC2	PAB - R	33	10,432	1,593
	PAB - L	33	10,708	1,260
MC3	PAB - R	34	10,289	1,111
	PAB - L	34	9,958	0,822
MC4	PAB - R	34	6,804	0,979
	PAB - L	34	6,610	1,108
MC5	PAB - R	36	9,247	1,244
	PAB - L	36	8,704	1,124

Table 9. Results of the means and standard deviation (SD) of the PAB measure for all MC.

The highest SD is 1,593 and the lowest is 0,822.

Metacaps	Measures	n=	Mean	SD
MC1	PAH - R	28	10,711	1,132
	PAH - L	28	10,576	0,892
MC2	PAH - R	31	13,695	1,298
	PAH - L	31	13,738	1,216
MC3	PAH - R	33	13,520	1,529
	PAH - L	33	13,211	1,313
MC4	PAH - R	31	9,320	0,949
	PAH - L	31	8,629	1,269
MC5	PAH - R	36	9,930	1,049
	PAH - L	36	9,923	0,772

Table 10. Results of the means and standard deviation (SD) of the PAH measure for all MC.

The highest SD is 1,529 and the lowest is 0,772.

Metacaps	Measures	n=	Mean	SD
MC1	MB - R	37	11,873	1,158
	MB - L	37	11,560	1,131
MC2	MB - R	38	8,292	0,851
	MB - L	38	8,043	1,122
MC3	MB - R	38	8,173	0,674
	MB - L	38	8,388	0,799
MC4	MB - R	39	6,627	0,606
	MB - L	39	6,554	0,634
MC5	MB - R	37	7,530	0,761
	MB - L	37	7,312	0,779

Table 11. Results of the means and standard deviation (SD) of the MB measure for all MC.

The highest SD is 1,158 and the lowest is 0,606.

Metacaps	Measures	n=	Mean	SD
MC1	MH - R	37	8,238	0,811
	MH - L	37	8,222	0,808
MC2	MH - R	38	8,875	0,741
	MH - L	38	8,978	1,168
MC3	MH - R	38	9,126	0,825
	MH - L	38	9,016	1,448
MC4	MH - R	39	7,576	0,723
	MH - L	39	7,538	0,925
MC5	MH - R	37	6,819	0,703
	MH - L	37	6,776	0,711

Table 12. Results of the means and standard deviation (SD) of the MH measure for all MC.

The highest SD is 0,703 and the lowest is 1,448.

Metacaps	Measures	n=	Mean	SD
MC1	DMB - R	33	15,461	1,395
	DMB - L	33	15,269	1,399
MC2	DMB - R	32	14,576	1,061
	DMB - L	32	14,386	1,046
MC3	DMB - R	28	14,546	1,056
	DMB - L	28	14,225	1,016
MC4	DMB - R	33	12,732	1,187
	DMB - L	33	12,409	1,141
MC5	DMB - R	33	11,865	1,143
	DMB - L	33	11,569	0,977

Table 13. Results of the means and standard deviation (SD) of the DMB measure for all MC.

The highest SD is 1,399 and the lowest is 0,977.

Metacapals	Measures	n=	Mean	SD
MC1	DAB - R	31	13,393	1,337
	DAB - L	31	13,263	1,293
MC2	DAB - R	31	13,264	1,044
	DAB - L	31	13,248	0,986
MC3	DAB - R	28	13,293	1,183
	DAB - L	28	13,155	0,972
MC4	DAB - R	32	11,368	0,987
	DAB - L	32	10,974	0,893
MC5	DAB - R	29	10,674	0,886
	DAB - L	29	10,547	0,765

Table 14. Results of the means and standard deviation (SD) of the DAB measure for all MC.

The highest SD is 1,337 and the lowest is 0,765.

Metacapals	Measures	n=	Mean	SD
MC1	DAH - R	31	12,782	1,382
	DAH - L	31	12,445	1,261
MC2	DAH - R	29	13,357	1,009
	DAH - L	29	13,017	0,825
MC3	DAH - R	30	13,542	1,066
	DAH - L	30	13,172	0,919
MC4	DAH - R	31	12,167	0,887
	DAH - L	31	12,057	1,030
MC5	DAH - R	31	11,069	1,049
	DAH - L	31	10,965	0,932

Table 15. Results of the means and standard deviation (SD) of the DAH measure for all MC.

The highest SD is 1,382 and the lowest is 0,825.

The mean is important for our following test, the Two-sample paired test (T-test). The standard deviation (SD) can give us already some useful information about our data and our measures. The results are low for most of the measures. It means that the asymmetry is there but is not necessarily strong. For the majority of the measures; PMB, PMH, PAB, PAH, MB, MH, DMB, DAB and DAH; the SD is lower than 2, while for the ML and AL measures, the results are lower than 3 and higher than 2. We can already assess that there might have more asymmetry between the left and right sides in the ML and AL measures than the other measures.

Normality test

The next step was to do a normality test. It was important that our data was normal, it is better for the Two-sample paired test. The test we used was the Shapiro-Wilk. We applied the normality test to the measures of each right and left metacarpals, as for the descriptive statistics (Tables 16 to 20). That gave us one hundred and ten (110) $p(\text{value})$; of these, six were considered possibly not normal because their $p(\text{value})$ was $p(<0.05)$. But we still considered them normal because the difference was not big (not lower than $p(<0.01)$). This result is not different enough to cause some anomaly in the results of the Two-sample paired test. However, five results had a $p(<0.01)$, this may indicate that we have an individual with “strange” bones, and that it is reflected in our measurements. Because these bones exist and because we don’t want to force our data to be normal, we kept all the data. Moreover, these five results represent less than 0.05% of our data, which is minor. We considered that, because most of our values were parametric and normal, our data was parametric and normal.

MC1	ML - R	ML - L
N	31	31
Shapiro-Wilk	0,9773	0,9565
p(normal)	0,7329	0,2344
MC1	AL - R	AL - L
N	29	29
Shapiro-Wilk	0,9826	0,9673
p(normal)	0,8987	0,4896
MC1	PMB - R	PMB - L
N	30	30
Shapiro-Wilk	0,9772	0,9525
p(normal)	0,7461	0,1967
MC1	PMH - R	PMH - L
N	27	27
Shapiro-Wilk	0,9239	0,9674
p(normal)	0,0492	0,5341
MC1	PAB - R	PAB - L
N	31	31
Shapiro-Wilk	0,9706	0,9626
p(normal)	0,5369	0,3403
MC1	PAH - R	PAH - L
N	28	28
Shapiro-Wilk	0,9816	0,9513
p(normal)	0,8863	0,2134
MC1	MB - R	MB - L
N	37	37
Shapiro-Wilk	0,971	0,9776
p(normal)	0,4350	0,6492
MC1	MH - R	MH - L
N	37	37
Shapiro-Wilk	0,9768	0,9682
p(normal)	0,6193	0,3607
MC1	DMB - R	DMB - L
N	33	33
Shapiro-Wilk	0,9768	0,9299
p(normal)	0,6851	0,0348
MC1	DAB - R	DAB - L
N	31	31
Shapiro-Wilk	0,9803	0,9787
p(normal)	0,8201	0,7751
MC1	DAH - R	DAH - L
N	31	31
Shapiro-Wilk	0,9557	0,9824
p(normal)	0,2236	0,8764

Table 16. Normality test of Shapiro -Wilk for all the right (R) and left (L) of MC1, by measures.

All results are considered normal.

MC2	ML - R	ML - L
N	29	29
Shapiro-Wilk	0,9757	0,9636
p(normal)	0,7202	0,4015
MC2	AL - R	AL - L
N	28	28
Shapiro-Wilk	0,9504	0,9364
p(normal)	0,2029	0,08942
MC2	PMB - R	PMB - L
N	33	33
Shapiro-Wilk	0,9775	0,9644
p(normal)	0,7084	0,3431
MC2	PMH - R	PMH - L
N	31	31
Shapiro-Wilk	0,9802	0,9715
p(normal)	0,8182	0,5607
MC2	PAB - R	PAB - L
N	33	33
Shapiro-Wilk	0,8863	0,88
p(normal)	0,002399	0,001675
MC2	PAH - R	PAH - L
N	31	31
Shapiro-Wilk	0,9746	0,9521
p(normal)	0,6522	0,178
MC2	MB - R	MB - L
N	38	38
Shapiro-Wilk	0,9723	0,8093
p(normal)	0,4563	1,62E-05
MC2	MH - R	MH - L
N	38	38
Shapiro-Wilk	0,9215	0,8108
p(normal)	0,01092	1,75E-05
MC2	DMB - R	DMB - L
N	32	32
Shapiro-Wilk	0,9636	0,9873
p(normal)	0,3428	0,963
MC2	DAB - R	DAB - L
N	31	31
Shapiro-Wilk	0,9767	0,9742
p(normal)	0,7154	0,6403
MC2	DAH - R	DAH - L
N	29	29
Shapiro-Wilk	0,9719	0,9645
p(normal)	0,6124	0,4229

Table 17. Normality test of Shapiro -Wilk for all the right (R) and left (L) of MC2, by measures.

PAB-L and R, MB-L, MH-L have a p(<0.01).

MC3	ML - R	ML - L
N	31	31
Shapiro-Wilk	0,9847	0,9665
p(normal)	0,9256	0,4278
MC3	AL - R	AL - L
N	31	31
Shapiro-Wilk	0,9616	0,9604
p(normal)	0,3222	0,2998
MC3	PMB - R	PMB - L
N	36	36
Shapiro-Wilk	0,9839	0,9816
p(normal)	0,8668	0,7991
MC3	PMH - R	PMH - L
N	35	35
Shapiro-Wilk	0,9235	0,9723
p(normal)	0,01801	0,5098
MC3	PAB - R	PAB - L
N	34	34
Shapiro-Wilk	0,9554	0,9735
p(normal)	0,1777	0,5647
MC3	PAH - R	PAH - L
N	33	33
Shapiro-Wilk	0,9864	0,9765
p(normal)	0,9444	0,6776
MC3	MB - R	MB - L
N	38	38
Shapiro-Wilk	0,9695	0,8693
p(normal)	0,3792	0,0003862
MC3	MH - R	MH - L
N	38	38
Shapiro-Wilk	0,9781	0,6302
p(normal)	0,6499	1,47E-08
MC3	DMB - R	DMB - L
N	28	28
Shapiro-Wilk	0,9846	0,9556
p(normal)	0,9429	0,2722
MC3	DAB - R	DAB - L
N	28	28
Shapiro-Wilk	0,9624	0,956
p(normal)	0,3971	0,2789
MC3	DAH - R	DAH - L
N	30	30
Shapiro-Wilk	0,9645	0,9728
p(normal)	0,4013	0,6173

Table 18. Normality test of Shapiro -Wilk for all the right (R) and left (L) of MC3, by measures.

MB-L and MH-L have a $p(<0.01)$.

MC4	ML - R	ML - L
N	31	31
Shapiro-Wilk	0,9656	0,9692
p(normal)	0,4079	0,4979
MC4	AL - R	AL - L
N	31	31
Shapiro-Wilk	0,9504	0,9572
p(normal)	0,1599	0,2454
MC4	PMB - R	PMB - L
N	38	38
Shapiro-Wilk	0,9713	0,9626
p(normal)	0,4292	0,2312
MC4	PMH - R	PMH - L
N	35	35
Shapiro-Wilk	0,9496	0,9857
p(normal)	0,1105	0,9189
MC4	PAB - R	PAB - L
N	34	34
Shapiro-Wilk	0,9587	0,982
p(normal)	0,2233	0,8346
MC4	PAH - R	PAH - L
N	31	31
Shapiro-Wilk	0,9722	0,9579
p(normal)	0,5821	0,257
MC4	MB - R	MB - L
N	39	39
Shapiro-Wilk	0,9666	0,9626
p(normal)	0,2936	0,2177
MC4	MH - R	MH - L
N	39	39
Shapiro-Wilk	0,9798	0,9551
p(normal)	0,6954	0,1216
MC4	DMB - R	DMB - L
N	33	33
Shapiro-Wilk	0,9668	0,96
p(normal)	0,3984	0,2577
MC4	DAB - R	DAB - L
N	32	32
Shapiro-Wilk	0,9713	0,9315
p(normal)	0,5372	0,04324
MC4	DAH - R	DAH - L
N	31	31
Shapiro-Wilk	0,9875	0,9542
p(normal)	0,9691	0,2037

Table 19. Normality test of Shapiro -Wilk for all the right (R) and left (L) of MC4, by measures.

All results are considered normal.

MC5	ML - R	ML - L
N	32	32
Shapiro-Will	0,9343	0,9671
p(normal)	0,05168	0,4239
MC5	AL - R	AL - L
N	30	30
Shapiro-Will	0,9738	0,9611
p(normal)	0,6472	0,3298
MC5	PMB - R	PMB - L
N	37	37
Shapiro-Will	0,9833	0,98
p(normal)	0,8397	0,7314
MC5	PMH - R	PMH - L
N	35	35
Shapiro-Will	0,983	0,9823
p(normal)	0,8526	0,8305
MC5	PAB - R	PAB - L
N	36	36
Shapiro-Will	0,9764	0,981
p(normal)	0,6226	0,7798
MC5	PAH - R	PAH - L
N	36	36
Shapiro-Will	0,9618	0,9591
p(normal)	0,2433	0,2018
MC5	MB - R	MB - L
N	37	37
Shapiro-Will	0,9678	0,9579
p(normal)	0,3517	0,1727
MC5	MH - R	MH - L
N	37	37
Shapiro-Will	0,9763	0,9877
p(normal)	0,6024	0,9486
MC5	DMB - R	DMB - L
N	33	33
Shapiro-Will	0,9719	0,983
p(normal)	0,5358	0,8707
MC5	DAB - R	DAB - L
N	29	29
Shapiro-Will	0,9792	0,9774
p(normal)	0,8176	0,7689
MC5	DAH - R	DAH - L
N	31	31
Shapiro-Will	0,9165	0,9748
p(normal)	0,01905	0,6592

Table 20. Normality test of Shapiro -Wilk for all the right (R) and left (L) MC5, by measures.

All results are considered normal.

Two-sample paired test

The Two-sample paired test (T-test) was our most important test. It is with the results of this one that we could mostly interpret our data and then answer most of our questions and hypotheses.

As mentioned previously, we had one hundred and ten (110) groups, one for each metacarpal's side and measure. We compared the means of the groups, two by two according to the side. For example, the mean of all ML-R of the MC1 was compared with the mean of all ML-L of the MC1. So, we obtained fifty-five (55) results. These results are composed of a *T-test* and a *p(same mean)* (or *p(value)*). It is the latter that is more meaningful in the interpretation of the data. Like for the normality test, the $p(<0.05)$ is an indicator, it allows us to reject or not the null hypothesis.

As said previously, our null hypothesis was:

There is no statistically significant difference between the measures of the left and the right sides for each metacarpal.

For each of the fifty-five (55) results, we asked if $p(<0.05)$. If the answer was *yes*, we refuted the null hypothesis. The results we obtained can be differently explained according of the way we compared the data; between the measures (Tables 21 to 31) or between the metacarpals (Table 32).

Metacapals	Measures	n=	Mean	T-test	p (same mean)	<0,05=
MC1	ML - R	31	42,614	2,4086	0,022365	Yes
	ML - L	31	42,291			
MC2	ML - R	29	63,346	2,5329	0,017199	Yes
	ML - L	29	62,901			
MC3	ML - R	31	62,394	2,8575	0,0076872	Yes
	ML - L	31	61,709			
MC4	ML - R	31	53,503	3,6904	0,00088733	Yes
	ML - L	31	52,989			
MC5	ML - R	32	50,278	2,7774	0,0092153	Yes
	ML - L	32	49,715			

Table 21. Results of the Two-sample paired test (T-test) of the ML measure for all MC.

All results are $p(<0.05)$.

Metacapals	Measures	n=	Mean	T-test	p (same mean)	<0,05=
MC1	AL - R	29	40,751	2,0718	0,047611	Yes
	AL - L	29	40,474			
MC2	AL - R	28	60,891	5,1617	0,000019725	Yes
	AL - L	28	60,182			
MC3	AL - R	31	58,478	3,1526	0,0036585	Yes
	AL - L	31	58,046			
MC4	AL - R	31	52,819	2,8157	0,0085193	Yes
	AL - L	31	52,44			
MC5	AL - R	30	49,654	3,3728	0,0021257	Yes
	AL - L	30	49,192			

Table 22. Results of the Two-sample paired test (T-test) of the AL measure for all MC.

All results are $p(<0.05)$.

Metacapals	Measures	n=	Mean	T-test	p (same mean)	<0,05=
MC1	PMB - R	30	15,276	4,4183	0,00012722	Yes
	PMB - L	30	14,782			
MC2	PMB - R	33	17,303	-0,15971	0,87411	No
	PMB - L	33	17,328			
MC3	PMB - R	36	14,242	1,8513	0,072575	No
	PMB - L	36	13,823			
MC4	PMB - R	38	11,81	-0,296	0,76889	No
	PMB - L	38	11,846			
MC5	PMB - R	37	13,424	0,42108	0,42108	No
	PMB - L	37	13,358			

Table 23. Results of the Two-sample paired test (T-test) of the PMB measure for all MC.

Results showed that MC1 have $p(<0.05)$.

Metacapals	Measures	n=	Mean	T-test	p (same mean)	<0,05=
MC1	PMH - R	27	15,075	3,024	0,0055522	Yes
	PMH - L	27	14,544			
MC2	PMH - R	31	15,79	-0,8815	0,38506	No
	PMH - L	31	15,904			
MC3	PMH - R	35	15,529	-0,58836	0,56018	No
	PMH - L	35	15,663			
MC4	PMH - R	35	12,154	3,8165	0,00054615	Yes
	PMH - L	35	11,706			
MC5	PMH - R	35	11,451	1,5344	0,1342	No
	PMH - L	35	11,196			

Table 24. Results of the Two-sample paired test (T-test) of the PMH measure for all MC.

Results showed that MC1 and MC4 have a $p(<0.05)$.

Metacapals	Measures	n=	Mean	T-test	p (same mean)	<0,05=
MC1	PAB - R	31	13,334	2,6265	0,013455	Yes
	PAB - L	31	12,797			
MC2	PAB - R	33	10,432	-0,93053	0,35907	No
	PAB - L	33	10,708			
MC3	PAB - R	34	10,289	2,0651	0,046844	Yes
	PAB - L	34	9,9576			
MC4	PAB - R	34	6,8041	1,1734	0,24903	No
	PAB - L	34	6,61			
MC5	PAB - R	36	9,2467	3,7385	0,00066046	Yes
	PAB - L	36	8,7039			

Table 25. Results of the Two-sample paired test (T-test) of the PAB measure for all MC.

Results showed that MC1, MC3 and MC5 have a $p(<0.05)$.

Metacapals	Measures	n=	Mean	T-test	p (same mean)	<0,05=
MC1	PAH - R	28	10,711	0,68934	0,49649	No
	PAH - L	28	10,576			
MC2	PAH - R	31	13,695	-0,22894	0,82047	No
	PAH - L	31	13,738			
MC3	PAH - R	33	13,52	1,3304	0,19278	No
	PAH - L	33	13,211			
MC4	PAH - R	31	9,3197	3,1375	0,0038029	Yes
	PAH - L	31	8,6287			
MC5	PAH - R	36	9,93	0,04296	0,96598	No
	PAH - L	36	9,9233			

Table 26. Results of the Two-sample paired test (T-test) of the PAH measure for all MC.

Results showed that MC4 have a $p(<0.05)$.

Metacaps	Measures	n=	Mean	T-test	p (same mean)	<0,05=
MC1	MB - R	37	11,873	3,6319	0,00086906	Yes
	MB - L	37	11,56			
MC2	MB - R	38	8,2918	1,661	0,10516	No
	MB - L	38	8,0429			
MC3	MB - R	38	8,1729	-2,29	0,02782	Yes
	MB - L	38	8,3879			
MC4	MB - R	39	6,6267	1,309	0,1984	No
	MB - L	39	6,5538			
MC5	MB - R	37	7,53	2,7897	0,0083824	Yes
	MB - L	37	7,3116			

Table 27. Results of the Two-sample paired test (T-test) of the MB measure for all MC.

Results showed that MC1, MC3 and MC5 have a $p(<0.05)$.

Metacaps	Measures	n=	Mean	T-test	p (same mean)	<0,05=
MC1	MH - R	37	8,2376	0,23554	0,81512	No
	MH - L	37	8,222			
MC2	MH - R	38	8,8745	-0,74137	0,46315	No
	MH - L	38	8,9784			
MC3	MH - R	38	9,1258	0,51256	0,61131	No
	MH - L	38	9,0161			
MC4	MH - R	39	7,5762	0,41423	0,68103	No
	MH - L	39	7,5379			
MC5	MH - R	37	6,8186	0,65692	0,51541	No
	MH - L	37	6,7759			

Table 28. Results of the Two-sample paired test (T-test) of the MH measure for all MC.

Results showed that no MC have a $p(<0.05)$.

Metacaps	Measures	n=	Mean	T-test	p (same mean)	<0,05=
MC1	DMB - R	33	15,461	1,3606	0,18315	No
	DMB - L	33	15,269			
MC2	DMB - R	32	14,576	2,4965	0,018069	Yes
	DMB - L	32	14,386			
MC3	DMB - R	28	14,546	2,7199	0,01128	Yes
	DMB - L	28	14,225			
MC4	DMB - R	33	12,732	3,4555	0,0015705	Yes
	DMB - L	33	12,409			
MC5	DMB - R	33	11,865	4,0238	0,00032758	Yes
	DMB - L	33	11,569			

Table 29. Results of the Two-sample paired test (T-test) of the DMB measure for all MC.

Results showed that MC2, MC3, MC4 and MC5 have a $p(<0.05)$.

Metacapals	Measures	n=	Mean	T-test	p (same mean)	<0,05=
MC1	DAB - R	31	13,393	1,1199	0,27165	No
	DAB - L	31	13,263			
MC2	DAB - R	31	13,264	0,14798	0,88335	No
	DAB - L	31	13,248			
MC3	DAB - R	28	13,293	0,9464	0,35234	No
	DAB - L	28	13,155			
MC4	DAB - R	32	11,368	2,9304	0,0063043	Yes
	DAB - L	32	10,974			
MC5	DAB - R	29	10,674	1,1434	0,26254	No
	DAB - L	29	10,547			

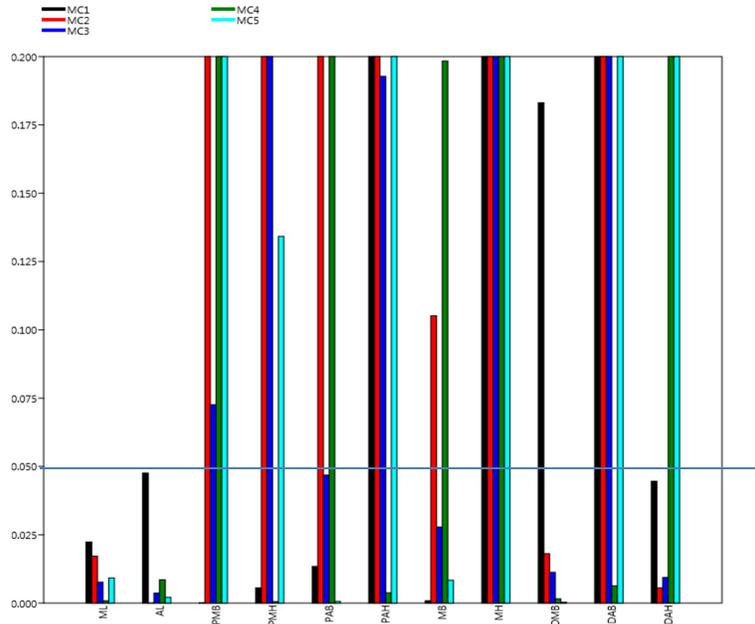
Table 30. Results of the Two-sample paired test (T-test) of the DAB measure for all MC.

Results showed that MC4 have a $p(<0.05)$.

Metacapals	Measures	n=	Mean	T-test	p (same mean)	<0,05=
MC1	DAH - R	31	12,782	2,096	0,04462	Yes
	DAH - L	31	12,445			
MC2	DAH - R	29	13,357	3,0041	0,0055602	Yes
	DAH - L	29	13,017			
MC3	DAH - R	30	13,542	2,7829	0,0093794	Yes
	DAH - L	30	13,172			
MC4	DAH - R	31	12,167	0,75051	0,45879	No
	DAH - L	31	12,057			
MC5	DAH - R	31	11,069	1,0824	0,28772	No
	DAH - L	31	10,965			

Table 31. Results of the Two-sample paired test (T-test) of the DAH measure for all MC.

Results showed that MC1, MC2 and MC3 have a $p(<0.05)$.



Graph 1. Bar graph of the results from the Two-sample paired test (T-test) for each metacarpal.

X = Measure. Y = *p* (same mean).

The results under the line are $p(<0,05)$ and express significant difference.

By measures, between the five metacarpals, our outcome showed that the ML and the AL measures clearly demonstrate that there is a statistically significant difference between the right and the left metacarpals, for each of the metacarpal bones because all of their $p(\text{same mean})$ correspond to $p(<0.05)$. We can also consider that the DMB measure showed that there is a strong possibility that there is a statistically significant difference between the right and the left metacarpals, although $p(\text{same mean})$ of the MC1 does not correspond to $p(<0.05)$. Concerning the PAB, MB and DAH measures, the results showed that there is statistically significant difference for three of the five metacarpals, however because not all the results have this difference, we cannot assert that difference, as for the PMB, PMH, PAH, MH and DAB measurements. These measures have between two and zero metacarpals that have a $p(\text{same mean})$ corresponding to $p(<0.05)$, consequently we consider that the analysis showed that there is not a statistically significant difference between the right and the left metacarpals (Graph 1).

We can assert that there is a statistically significant difference between the right and the left metacarpals when we take these measures: ML and AL. These are the

measures that can help identify asymmetry of the hand of an individual, therefore his laterality.

	MC1	MC2	MC3	MC4	MC5
ML	Yes	Yes	Yes	Yes	Yes
AL	Yes	Yes	Yes	Yes	Yes
PMB	Yes	No	No	No	No
PMH	Yes	No	No	Yes	No
PAB	Yes	No	Yes	No	Yes
PAH	No	No	No	Yes	No
MB	Yes	No	Yes	No	Yes
MH	No	No	No	No	No
DMB	No	Yes	Yes	Yes	Yes
DAB	No	No	No	Yes	No
DAH	Yes	Yes	Yes	No	No

Table 32. Results of the Two-sample paired test (T-test), of the $p(\text{same mean})$ corresponding or not to $p(<0.05)$, by metacarpals and measures.

By metacarpals, between the eleven measures, we can say that the MC1 is the one with the more significant difference because it had seven of the eleven measures with a $p(\text{same mean})$ corresponding to $p(<0.05)$. Then the MC3 is next with six measures that had a $p(\text{same mean})$ corresponding to $p(<0.05)$. Following are the MC4 and the MC5 with five measures. The MC2 is the one with the less difference with four measures that showed significant difference.

So, we can declare that the most asymmetrical bone is the MC1 and the less asymmetrical bone is the MC2.

Principal Component analysis

We performed a Principal Component analysis (PCA) to each five metacarpals including the eleven variables and all individuals. In every cases, the two firsts components had *eigenvalues* around 80% when summed (Table 33). When using the *Loadings plot* option of PAST, we were able to clearly see that the two principal

components are the ML and AL measures (Graphs 2, 4, 6, 8, 10). In a way, it means that these components are more important in the ordination of the data.

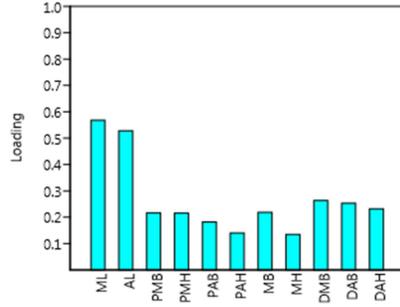
The Principal Component analysis was also used to determine which individuals are more asymmetrical than others. To do so, we used the *Scatter plot* option of *PAST* to have a graph with x and y axes that allowed us to have a graphic representation of the data (Graphs 3, 5, 7, 9, 11). Because of the *Loadings plot*, we know that the ML and AL measures are the principal components that were used to establish the position of each individual's left and right metacarpals. From these graphs we discerned which individuals are more or less asymmetrical by the distance between their right and left metacarpals, and that for every metacarpal bone.

For each of the metacarpal bones, we looked for the five hands, for the five individuals, with the most asymmetry and for the five individuals with the least asymmetry (Tables 34 to 37).

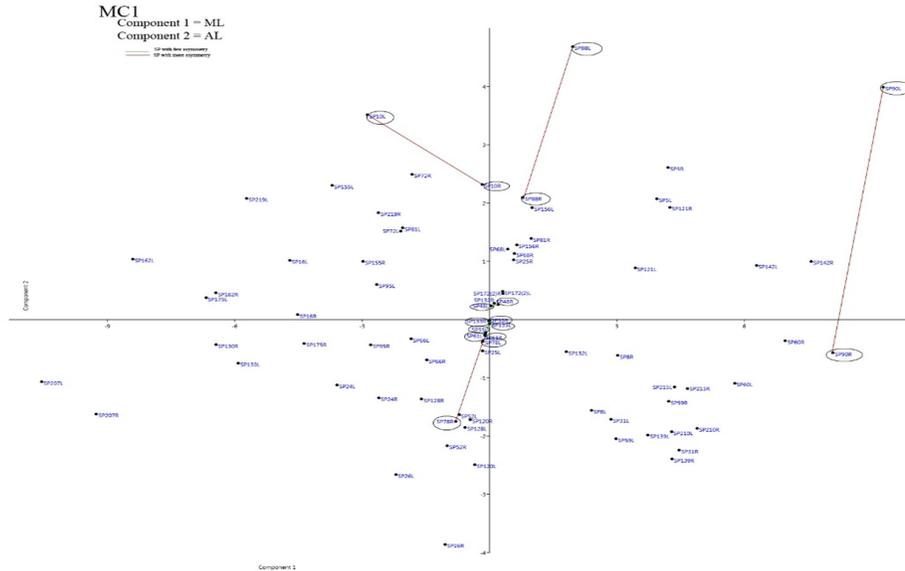
PC - MC1	Eigenvalue	% variance
1	12,81	66,92
2	2,24	11,72
3	1,01	5,29
PC - MC2	Eigenvalue	% variance
1	15,77	66,64
2	2,75	11,61
3	1,34	5,66
PC - MC3	Eigenvalue	% variance
1	16,54	69,29
2	2,06	8,62
3	1,37	5,73
PC - MC4	Eigenvalue	% variance
1	15,91	71,46
2	2,58	11,60
3	1,21	5,43
PC - MC5	Eigenvalue	% variance
1	12,13	64,45
2	2,40	12,74
3	0,97	5,16

Table 33. PCA. Results of the *eigenvalue* for each metacarpal.

Results showed that for all the MC, the addition of the two first components equal 80% or more.



Graph 2. PCA. Results of the *Loadings plot* for MC1, with the ML and AL measures as the two principal components and the DMB as the third one.

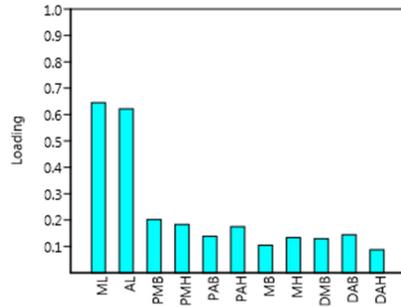


Graph 3. PCA. *Scatter plot* for MC1. The red lines link the hands with the most asymmetry, for the same individual. The green lines link the hands with the least asymmetry, for the same individual. The hands of the selected individuals are in black circle.

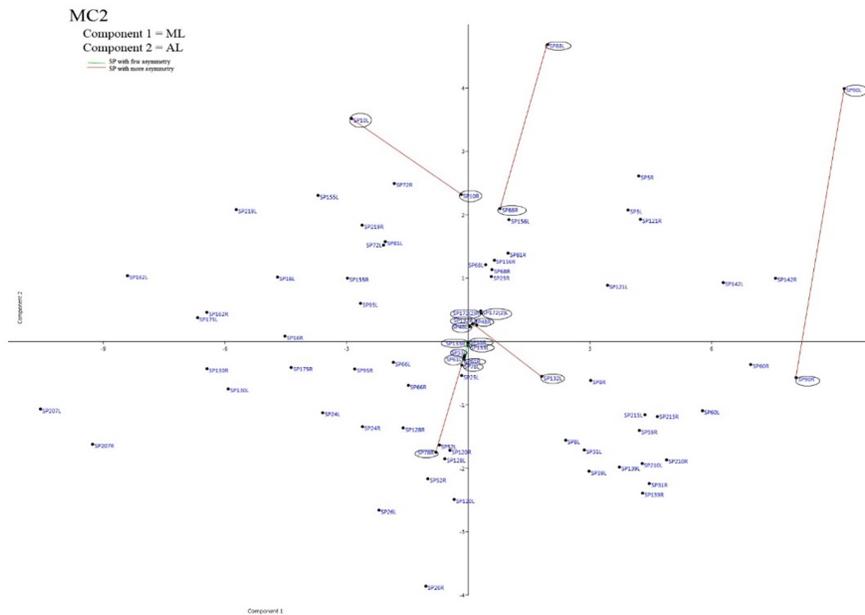
MC1/MC2					
Individuals with the least asymmetry	SP48*	SP55*	SP61*	SP133	SP172(2)
Individuals with the most asymmetry	SP10*'	SP78'	SP88'	SP90*	SP132

Table 34. Representation of the individuals with the least and the most asymmetry, for MC1 and MC2.

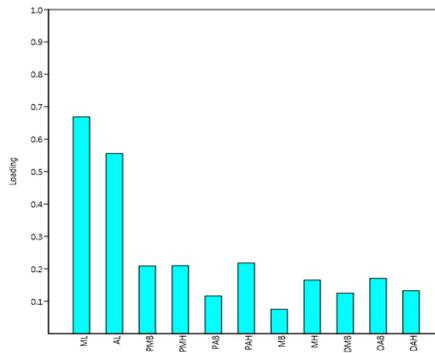
*correspond to the individuals that are represented three times, 'correspond to the individuals that are represented in the least and the most asymmetrical categories.



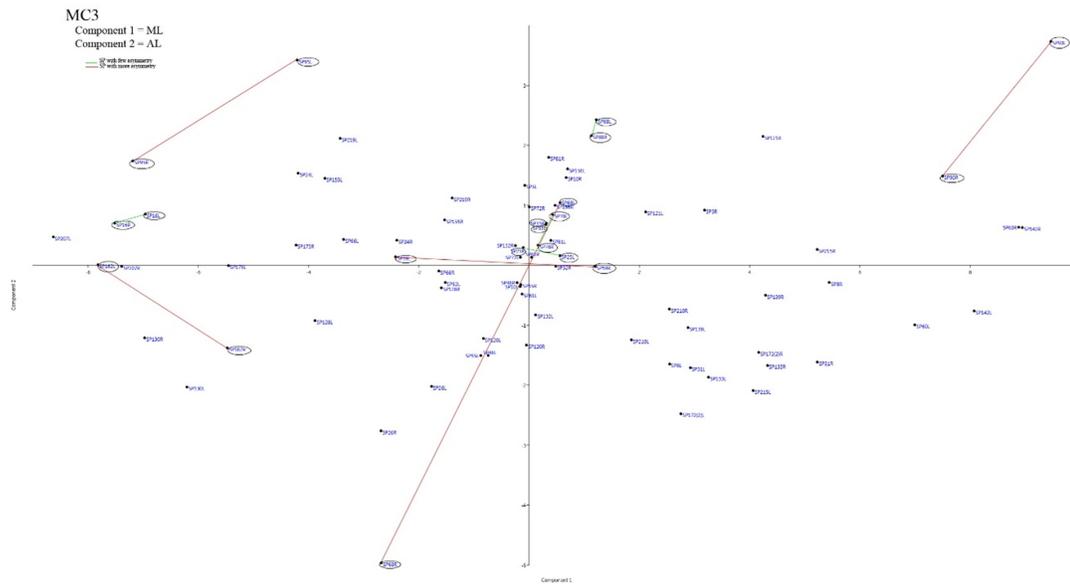
Graph 4. PCA. Results of the *Loadings plot* for MC2 with the ML and AL measures as the two principal components and the PMB as the third one.



Graph 5. PCA. *Scatter plot* for MC2. The red lines link the hands with the most asymmetry, for the same individual. The green lines link the hands with the least asymmetry, for the same individual. The hands of the selected individuals are in black circle.



Graph 6. PCA. Results of the *Loadings plot* for MC3 with the ML and AL measures as the two principal components and the PAH as the third one.

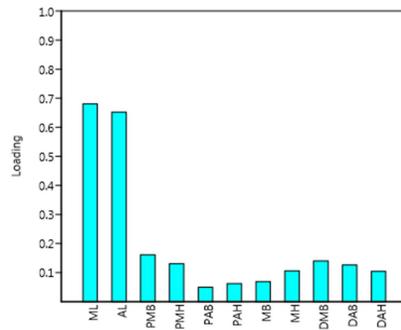


Graph 7. PCA. *Scatter plot* for MC3. The red lines link the hands with the most asymmetry, for the same individual. The green lines link the hands with the least asymmetry, for the same individual. The hands of the selected individuals are in black circle.

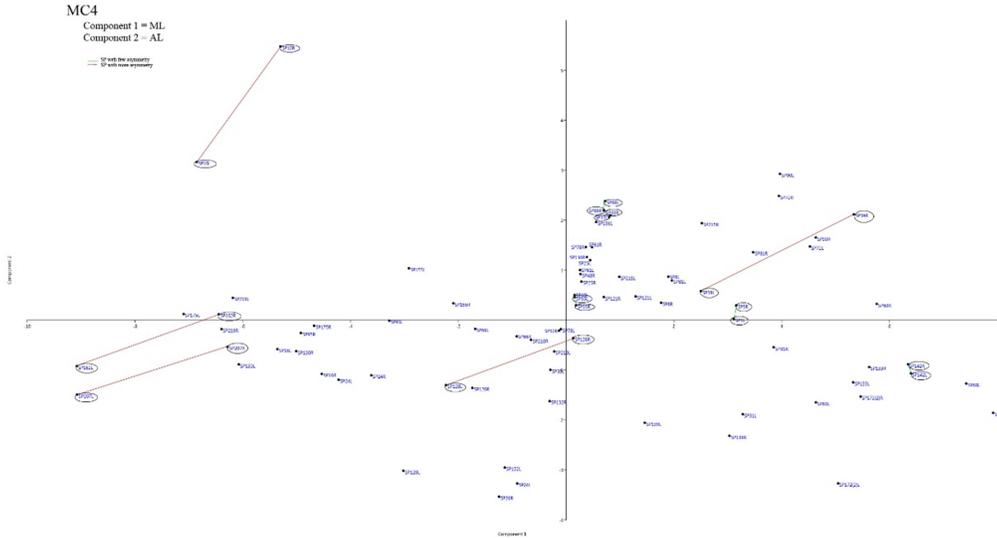
MC3					
Individuals with the least asymmetry	SP16	SP25	SP33*	SP78'	SP88'
Individuals with the most asymmetry	SP59	SP68	SP90*	SP95	SP162

Table 35. Representation of the individuals with the least and the most asymmetry, for MC3.

*correspond to the individuals that are represented three times, 'correspond to the individuals that are represented in the least and the most asymmetrical categories.



Graph 8. PCA. Results of the *Loadings plot* for MC4 with the ML and AL measures as the two principal components and the PMB as the third one.

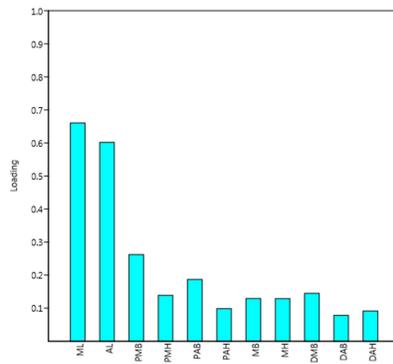


Graph 9. PCA. *Scatter plot* for MC4. The red lines link the hands with the most asymmetry, for the same individual. The green lines link the hands with the least asymmetry, for the same individual. The hands of the selected individuals are in black circle.

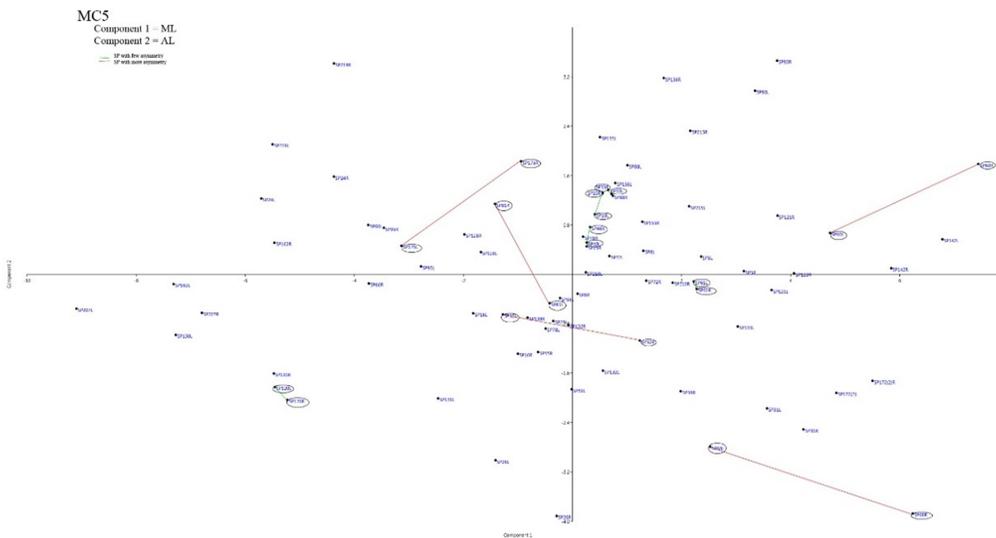
MC4					
Individuals with the least asymmetry	SP5	SP33*	SP55*	SP88'	SP142
Individuals with the most asymmetry	SP10* ²	SP59	SP128	SP162	SP207

Table 36. Representation of the individuals with the least and the most asymmetry for MC4.

*correspond to the individuals that are represented three times, ' correspond to the individuals that are represented in the least and the most asymmetrical categories.



Graph 10. PCA. Results of the *Loadings plot* for MC5 with the ML and AL measures as the two principal components and the PMB as the third one.



Graph 11. PCA. *Scatter plot* for MC5. The red lines link the hands with the most asymmetry, for the same individual. The green lines link the hands with the least asymmetry, for the same individual. The hands of the selected individuals are in black circle.

MC5					
Individuals with the least asymmetry	SP10'	SP33*	SP48*	SP61*	SP120
Individuals with the most asymmetry	SP52	SP60	SP68	SP81	SP175

Table 37. Representation of the individuals with the least and the most asymmetry for MC5.

*correspond to the individuals that are represented three times, ' correspond to the individuals that are represented in the least and the most asymmetrical categories.

As said previously, the ML and AL measures are the principal components for all of the metacarpals. For the rest of the measures, the results are changing for each metacarpal, having different position of importance. Although, the PMB measure arrived in third positions for three of the five metacarpals (MC2, MC4 and MC5), the DMB measure is the one in third position for the MC1, while the PAH measure is the third one for MC3.

Concerning the individuals, we noticed that for the MC1 and the MC2, the exact same ten individuals are represented in the with the most asymmetry and with the least asymmetry categories. They also have similar *eigenvalues*. From these ten individuals, five are represented also in a third metacarpal. In total, for all the individuals selected, six are represented three times, and three are represented in the most and the least categories. Two individuals (SP10 and SP88) are represented more than the others, four times in total and in both categories.

4. DISCUSSION

From our results, we can make some statements, some interpretations of our data. It is not just about the numbers but about the individuals and what their bones are saying. The metacarpals are influenced by external factors, by stresses. It is reflected on the bones themselves. In the case of our metacarpals, the fluctuating asymmetry is what was studied.

With the different tests we applied on our data, we were able to state that some measurements stand out more than others.

The fact that the ML and AL are the measures that have a significant difference statistically and that are principal in the ordination of the data, expresses the importance of these measures in the determination of the asymmetry of an individual. They also have a standard deviation higher than the other measures.

It means that in all the measures taken; breadth and height of articular surfaces, breadth and height of the epiphyses, breadth and height of the midshaft of the diaphysis and length of the bone; the length of the bone is the one changing the most between the two sides. The actual size of the metacarpal is actually influenced by

external factors, like physical work or handedness, but it is mainly influenced on its length whether it is articular or maximal; and that for all of the metacarpals.

To complete the ML and AL measures, the DMB can also be useful in the determination of asymmetry. It means that the size of the breadth of the distal epiphysis is also influenced by external factors for all of the metacarpals except for the MC1.

The distal epiphysis is close to the proximal phalange, so a relationship between the two bones over the external stress factors might be possible. It is a joint with a lot of movement, therefore possibly more subjected to handedness and to its asymmetry.

However, some measures don't have so much importance. For instance, the MH measure shows no significant difference for all of the metacarpal, while the PMB, PAH and DAB have only one metacarpal with significant difference (MC4 for PAH and DAB, MC1 for PMB). These four measures are less influenced by the external factors that create the asymmetry, and by that they are not as relevant in the detection of asymmetry and handedness. Still, the PMB, PAH and DAB could be used to obtain more information, especially in case of broken bones, for the metacarpals they are significant for. As for the last four measures; PMH, PAB, MB and DAH, they have two or three metacarpals where there is a significant difference, where the bone is affected by external factors and shows asymmetry. These measures could be complementary to the ML, AL and DMB in order to have more data or to enrich the data of an incomplete bone.

The results of our tests also show that not all of the metacarpals are equally asymmetrical. The MC1, the thumb, is the one that has more measures that express an asymmetry. It means that in order to study the asymmetry of an individual, the MC1 will be more fit to give more meaningful data because it has seven measures that can show differences between left and right sides. It also means that the MC1 is the metacarpal that is the most influenced by the external factors that create the fluctuating asymmetry. The MC1 is also the metacarpal that is the most mobile. A correlation between the fluctuating asymmetry and the mobility of the bone might be present.

This master thesis was not about to determine if our individuals were left-handed or right-handed, but to examine the measures that can express the asymmetry in the human metacarpals. Consequently, we did not define the handedness of our individuals. However, we are able to state that there are measures that can express the asymmetry by giving different measurement's results between the right and the left metacarpal of an individual and that this difference is big enough to be significant. Other studies (Blackburn & Knüsel 2006, Plato et al. 1980, Purves et al. 1994) assert that the biggest of the bones – between right and left of the same individual, in fluctuating asymmetry – is the one that is more used, therefore, in the case of the hand bones and the metacarpal bones, the biggest bone could express the handedness of an individual. For this research, the handedness was not determined for our individuals for two reasons; because of the time limitation, and because we did not have the information of the handedness of our individuals to compare them with the results we obtained.

5. CONCLUSIONS

The purpose of this master thesis was to study the metacarpal bones of modern humans in order to establish if some measures can determine the asymmetry between the left and the right hands. We wanted to know if there was a statistically significant difference between the means (by pair) of eleven measures coming from the five metacarpals of both hands.

To answer our questions and to test our hypotheses, we collected the data from a collection coming from the San Pablo cemetery (Burgos, Spain). After scanning the left and some of the right metacarpals with the *Breuckmann* scanner, we used the *Landmark* software to apply twenty-two (22) landmarks on our four hundred (400) bones selected. Once our data was exported in our database, we used the mathematical formula to calculate the measures with the three-dimensional coordinates of each landmark, by pair. These measurements were our main data. To understand it better, we did a descriptive statistics test. Then we needed to know if our data was normal, so we did a Shapiro-Wilk test. Next, we applied a Two-sample paired test (T-test) to our data in order to have the possibility of comparing and interpreting our data. Finally, we did a Principal Component analysis for each

metacarpal in order to know which individuals are more asymmetrical and which measures are more important in the ordination of the data.

Results

After doing the descriptive statistics that gave us, among other things, the means and the standard deviations; we tested these groups in order to know if they were normal or not. Our previous assessment that our data was normal was mainly correct. The five results that had a $p(<0.01)$ could be seen like a weakness in the research. It is true that in a general population, all the individuals have a growth that is similar one to another. However, there are often individuals that have a different development that result in having out-of-the-norm dimensions, whether it is smaller or bigger. So, these “strange” bones we have probably correspond to that. It is not because they are probably not normal statistically that they are abnormal. It is part of the life and it was actually appropriate that we kept these out-of-the-norm results and not forced our data to be normal.

The results of the Two-sample paired test (T-test) along with the results from the Principal Component analysis are fairly clear and help elucidate our hypotheses. In both cases, some measures stand out.

- 1) We notice that it is possible to discern the asymmetry by measurements of the metacarpal bones using geometric morphometric analysis. This method is effective, we can state that by the clear and positive results we obtained. It is also reliable and can be reproduced, like showed in the repeatability part.
- 2) The measures that exhibit better where the asymmetry is more manifested are the ML and AL ones. That is express in the Two-sample paired test because all of the metacarpals have a $p(<0,05)$ result and in the Principal Component analysis because these two measures correspond to the two components having more importance in the ordination of the data.

Although, in the Two-sample paired test, the DMB can also show the asymmetry in some of the bones. We also noticed that the asymmetry was

more present, or more easily detected in some metacarpal, like the MC1, than others, like the MC2.

With the Principal Component analysis, we noticed that the PMB might have some sort of influence on the data, and that some individuals are more asymmetrical than others. However, no individual is really different from the rest of the group, for all the metacarpal bones. Each metacarpal have different individuals that are the least or the most asymmetrical.

That means that our previous hypothesis was not correct. The articular surfaces are not the ones with the measures that express the most where the asymmetry is more manifested on the metacarpal bones. The length of the bone is where the asymmetry is more manifested on the metacarpal bones.

Future perspectives

Markers are created by the activities that we do. These activities reflect differently on our bones. Usually, someone who is right-handed will use more of his right hand to do these activities, and someone who is more active will have more distinction between both sides. But some works demand the use of both hands, both arms; in these cases, the activities can create symmetry instead of the expected asymmetry (Blackburn & Knüsel 2006). In our case, the small level of asymmetry that is exhibit in our collection could also be a result of a use of both arms relatively equally. It would have been interesting to know the type of tasks, works and activities done by the individuals of our collection.

It is also important not to forget that a small percentage of the population is ambidextrous. These people may exhibit less or no asymmetry in their metacarpals.

Another way to test the asymmetry between the two hands of an individual would be to measure the area of the articulation surfaces of the metacarpals. That will give a different kind of data that could be interesting to test and to compare with the results we obtain in this master thesis.

Also, studying the proximal phalanges; with the same landmarks and measures; but more specifically by studying the proximal epiphysis can expose the relationship with the DMB measure of the metacarpals. The study of the proximal phalanges could give more information by obtaining more data for each individual and for each measure

and therefore contribute to the acknowledgement of our hypotheses answers. By adding the proximal phalanges, it could also be possible to add measures that could allow having more information on the rays, on the hands.

To know more about the determination of the handedness, related to the asymmetry of the metacarpals, it could be interesting to test the measures on individuals with their handedness known.

A coming step would be to test the methodology in fossils of other hominines or early *Homo sapiens*.

The ML and AL measures that we used in this master thesis along with the confirmation that a bigger bone is related to the most used hand can allow researchers to establish the handedness of an individual, and therefore go on with other studies concerning human evolution. Our results reveal that our methodology is reliable and can be reproduce in future study of metacarpal bones, especially in archaeological context because even if the hand is not complete, it is possible to use the measures along with a geometric morphometric analysis, and that will reflect the handedness of the individual on each metacarpal of the human hand.

All these tests have allowed us to state that it is possible to discern the asymmetry in human modern hands, more specifically in metacarpal bones, using geometric morphometric analysis and that these measures are the maximal length (ML) and the articular length (AL) ones. And that, by the results we obtained with the repeatability test and the statistical tests, we can also state that this method is effective, reliable and can be reproduce.

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