**User defined tasks: 2.1 Literature review**

**Palaeoanthropology and the advent of digital tools**

There has been a move from traditional measurements to digital tools in all disciplines with the development of efficient and advanced algorithms to solve theoretical problems (Van Sint Jan, 2005). Geometric morphometrics has been increasingly used in palaeoanthropology in the last two decades (Rein and Harvati, 2014). Geometric morphometrics can be described as a method of analysis which retains specimen shape through the use of landmark coordinate data. By analysing the same landmarks on each specimen, new aspects of skeletal shape variation can be explored (Rein and Harvati, 2014).The advent of the wide use of CT and surface scans combined with geometric morphometrics has given rise to a new approach which has been called ‘Virtual Anthropology’ (VA) (Weber, 2015). VA is characterized as “a multi-disciplinary approach to studying morphology, particularly that of humans, their ancestors, and their closest relatives, in three or four dimensions (space or space- time)” (Weber, 2015).

Although, virtual anthropology (VA) has most frequently been linked with geometric morphometrics, paleoanthropologists should also consider other digital tools. The 3D approach in general can allow more relevant spatial information gathering from 3D objects that is not possible with 2D images or projections (Weber, 2015). The digitisation of objects also gives an accessibility throughout the whole object (including hidden features not possible with normal measurements (Weber, 2015), (i.e. digitisation can give both the external and internal shape). The creation of a digital object is also a back up should the object become lost or damaged (Chapman et al., 2014; Mathys and Brecko, 2014). 3D digitised objects can also be shared with other researchers around the world (Chapman et al., 2014; Mathys and Brecko, 2014). The digitisation of objects also offers the possibility to create a virtual museum or to display small objects with extensive detail on a large screen (Mathys and Brecko, 2014). Finally, digital tools are necessary for anthropology as many fossils are unique fragile objects which can become easily damaged (Mathys and Brecko, 2014; Weber, 2015).

**Traditional measurements in palaeoanthropology**

Anthropology and palaeoanthropology have focused on measurements on specimens for many years. One of the reasons that metric data methods are so prevalent is they are seen as more objective than visual assessments of the skeleton (Langley and Meadows, 2016). Metric data is also not only used in palaeoanthropology but in a very wide variety of disciplines such as morphometric studies, anatomical and evolution studies and forensic sciences (Langley and Meadows, 2016). Measurements are largely used to differentiate between species and populations and large databases in all disciplines and many different fields exist where measurements have all been taken in the same way. Measurement standards are important as they enable comparisons with different research studies. There are many osteology and measurement guide books, although the following are those that are most commonly used by student and professional paleoanthropologists: (Martin, 1928; Martin and Saller, 1957; Buikstra and Ubelaker, 1994; Moore-Jansen et al., 1994; Bass, 1995; White et al., 2012).

Standardised Protocols for taking specific types of measurements related to palaeoanthropology are clearly described in each of these books (Martin, 1928; Martin and Saller, 1957; Buikstra and Ubelaker, 1994; Moore-Jansen et al., 1994; Bass, 1995; White et al., 2012). Osteological measurements are generally taken with sliding callipers or an osteometric board (with the exception of circumference measurements which are done with tape). Sliding callipers are measuring instruments which consist of an L-shaped frame with a linear scale along its longer arm and an L-shaped sliding attachment with a Vernier, which is used to directly read the dimension of an object represented by the separation between the inner or outer edges of the two shorter arms. An osteometric board is used to measure bone lengths which are too long or too difficult for measurement with sliding callipers (Hepburn, 1899). An osteometric board is an anthropometric instrument that consists of a flat board with two ends, one of which is movable and travels along a routed track. The object to be measured is placed between the two end pieces and the movable end is then brought up to the object, where the [measurement](http://human-biology.key-spot.ru/search.php?key=measurement) scale can then be read.

Martin (1928) and Martin and Saller (1957) are the original authors of many of the measurements detailed in the later osteology and measurement guide books (although it is often not explicitly stated) and they are frequently cited in paleoanthropological and anthropological journal articles. Martin (1928) as well as later works by the same author also details in full all the measurements to be taken with an osteometric board on each individual bone.

**Traditional measurements in the virtual world**

***Simulation of physical callipers in lhpFusionBox and other systems***

As detailed in the section above on traditional measurements, Anthropology and palaeoanthropology have focused on taking the same metric measurements on specimens for many years. The majority of measurements are taken with a calliper or with an osteometric board and follow a guideline produced by Martin (1928) (Original in German). It is therefore clear that it would be a very useful tool if measurements can be taken in the same way in the virtual world as in the physical world, to allow comparisons between existing datasets. Numerous software programmes exist which enable you to measure distances by directly placing anatomical landmarks (ALs) on an object which then automatically create distance measurements (AMIRA, MESHLAB, IMAGEJ, Polyworks, GomInspect, Netfabb) (See Table 1 for a full list of software reviewd websites). This is a very fast way to measure distances easily and quickly and the results are displayed on the screen. It also means that lots of measurements can be done on the same object in a short amount of time The main downside to this type of measurement is that landmarks are not given names and thus you cannot usefully use them afterwards (i.e. for specific functions such as gait analysis in lhpFusionBox). In the majority of programmes it is also not possible to repeat these measurements in an automated way. Polyworks are one such software that has developed automated measurements. With a few simple clicks on the 3D object, it is possible to have the same measurements on all other similar objects. They also have a useful function which is a gauge toolbar which creates a standard calliper which can measure things such as distance and thickness etc. It is equally possible to constrain the calliper along the X, Y, Z axis which is a useful tool and there are both 2D or 3D callipers. There are also numerous apps which give you virtual callipers on your mobile (Screen Callipers – ‘Softonic’, Calliper App – ‘Pongosoft’, Digital Calliper, Calliper etc. – ‘CASA’). The fact that so many software companies are offering programs virtual calliper apps demonstrates the requirement to have a virtual digital calliper.

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| Software analysed | Open source | website |
| Geomagic | No | http://www.geomagic.com/en/ |
| ImageJ | Yes | <http://rsb.info.nih.gov/ij>/) |
| GomInspect | Yes | http://www.gom.com/3d-software/gom-inspect.html |
| MIMICS | No | http://www.materialise.com/en/medical/software/mimics |
| Meshlab | Yes | http://www.meshlab.net/ |
| AMIRA | No | https://www.fei.com/software/amira-avizo/ |
| Netfabb | Yes | https://www.autodesk.eu/products/netfabb/overview |
| Polyworks | No | https://www.innovmetric.com/ |

Table 1. List of commercial software examined

An early study by some of the authors analysed the feasibility of conducting sex determination using the method of Probabilistic Sex Diagnosis (DSP: Diagnose Sexuelle Probabiliste) (Chapman et al., 2014) on virtual specimens using a distance meter tool (which is a kind of virtual calliper) in lhpFusionBox. The Probabilistic Sex Diagnosis (DSP: Diagnose Sexuelle Probabiliste) method developed by Murail et al. (2005) is based on a worldwide hip bone metrical database (2040 adult specimens of known sex from 12 different reference populations). Sex on the dry bone is determined by comparing specific measurements taken from each specimen using sliding callipers and computing the probability of specimens being female or male using an online spread sheet (<http://www.pacea.ubordeaux1>. fr/publication/logiciel/?id=2) (Murail et al., 2005). The study found that it was possible to recreate calliper measurements in a virtual environment (The software used to analyse virtual calliper measurements was lhpFusionBox, which was developed at ULB).

Metric measurements on the 3D models were found to be comparable to calliper measurements on the dry bone and the DSP method was found to be particularly suitable virtual analysis with the lhpFusionBox proving to be a useful tool to take digital calliper measurements. There was a difference in terms of mm (average 0–2 mm) from the virtual and manual DSP method (Table 3) although this was not statistically significant. There are many advantages to using lhpFusionBox to analyse DSP in that it is user friendly as opposed to other modelling systems and is very simple to use. The software is also open source.

Three-dimensional models from CT scans of most bones can be created in under 10 min using AMIRA. Once models are created, the researcher simply has to palpate anatomical landmarks (ALs) and measure distances between landmarks to recreate a virtual calliper. The programme allows the researcher to move individual ALs and view the maximum or minimum distance between two ALs on the bone. A significant advantage of the software lhpFusionBox is that this function is similar to a sliding calliper and can also perform measurements that are not possible with callipers. Previously palpated ALs can also be moved and the researcher is able to easily find the maximum or minimum distance. However, the main downside for the lhpFusionBox software is that is that it is currently very time consuming in comparison to the manual DSP method and other visual sex determination methods.

One other consideration is that Chapman et al. (2015) found that, for inexperienced users, the virtual application of the sex estimation method by DSP can initially be more difficult than measuring with callipers on the dry bone. This is due to the fact that by using simulation of callipers onscreen it is difficult to understand scale in a model as you frequently change the scale on the screen by zooming in and out, (although this does not affect measurements and the simulation of the sliding calliper does help the researcher see measurements in real time, similar to a digital calliper). There is also the problem of not knowing where on the object to palpate the points of a 3D model. This difficulty of palpating accurate landmarks in 3D space has been cited by several authors (Murail et al., 2005; Klales et al., 2012; Wee and Ning., 2014, Lee et al., 2017). Wee and Ning (2014) created a Vernier calliper using Easy Java Simulation and stated that they recommended a simple 2D view to be more appropriate for measurements. Chapman et al. (2015) however found that the problem could be ameliorated with a series of visual pictures (Fig. 1) and text which gives guidelines on how each landmark should be palpated which is available to any researcher using this method. However, this problem could further be ameliorated by using a digital osteometric board and using planes in 3D space to take measurements, which do not rely on single manually palpated landmarks.

***Digital osteometric board***

Lee et al., (2017) similarly notes the difficulty to compare measurements taken in 3D, as detailed above, due to difficulties in manual landmark placement and cites this as a reason to create a virtual osteometric board. Lee et al., (2017) further states that the distance between two vertical planes (i.e. in a physical osteometric board) is not the same as maximum femur length (as depicted in (Martin, 1928)) measured using Computed Tomography (CT) (Lee et al, 2017) and thus it would not be possible to compare new virtual studies with the large number of other studies who have used traditional osteometric boards. Reynolds et al. (2017) further highlight the benefit of a plane application in that planes are able to be automatically aligned to the most extreme points of the bone quickly and with ease which reduces observer bias, present in manual selections. These two papers detail in full how they devised a virtual osteometric table (Lee et al., 2017; Reynolds et al., 2017).

In short, Reynolds et al. (2017) created a protocol for conducting linear measurements of postcranial skeletal elements using three-dimensional (3D) models from CT scans in ‘Geomagic Design X’. A posterior base plane was generated using three manually placed points on the posterior part of the bone (3 landmarks: medial and lateral condyle and posterior part of greater trochanter). An external contour of the distal bone and tangent vector were obtained from these landmarks and then a rotational plane was generated (perpendicular to the base plane). The proximal boundary of the femoral head was used to define other plane. There is an automated placement of extreme position planes in Geomagic Design X.

Lee et al. (2017) analysed femora by placing them on an object on a horizontal coronal plane in MIMICS (they confirmed the object was on the plane by checking the three lowest points of the femur were on that plane). They then created a centre line in the same software and this was projected on the horizontal plane. Two additional planes (vertical axial planes) were added that were perpendicular to the projected centre line and to the horizontal coronal plane. The vertical planes were added by locating the most proximal and distal points of the femur using ‘Create datum plane’ and ‘create extreme analysis’ functions in MIMICS. Maximum length of femur was then analysed by looking at distance between vertical axial planes.

Reynolds (2017) stated that alternative software to Geomagic could do some of the steps to create a virtual osteometric board and (Reynolds (2017) quotes lhpFusionBox as one of these software programmes).

It is also possible to have a surface outline and a cross section in Geomagic and MIMICS which is useful to diaphyseal measurements and surface area.

**New measurements in the virtual world**

***Centre line of an object or centroidal path***

The centre line was used to define a virtual osteometric box in Sookyoung (2017) and seems to be extremely intuitive in MIMICS. Similar to a function previously developed at ULB in MATLAB (Chapman et al., 2017a), you can specify the distance between control points and take measurements along the centre line in MIMICS. You can also create best fit diameter, ellipses and sectional area which are useful tools in bone analysis and comparison. The creation of the centre line of an object is also an option in SOLIDWORKS and AutoCad 2017.

ULB has previously developed a method to analyse ribs using best fitting ellipses of external contours of the cross section areas, created from the centre line of the rib in the software MATLAB (Chapman et al., 2017a). This method is of interest to paleoanthropologists as they allow the quantification and analysis of ribs (but this can also be applied to other long bones) in 3D space which are not possible through physical measurements (i.e. the method seeks to analyse the curvatures of the bone which is difficult to do in physical measurements).

The protocol at ULB was developed and implemented in Matlab® and the method was organised following Kindig and Kent, (2013) and Sandoz et al., (2013). In order to compare rib geometry from all subjects, each rib vertex cloud (presented in the original CT scan coordinate system) was analysed using a rigid transformation into the local coordinate system (LCS), which was defined by the rib principal axes (Fig. 1). Each rib cloud was then processed using rib slices (Kindig & Kent, 2013) obtained from “a rescanning” process within MATLAB in order to get cross-section shape, size and area using best fitting ellipses of the external contour of the cross-section area (Fig. 1), similar to the tools available in MIMICS. The centroid of each ellipse was used to measure the centroidal pathway between each slice (the rib midline) and it was possible to get several geometrical parameters were obtained from the centre line of the rib: arc length, chord length, rib width, rib curvature in the XZ plane which was measured in an axial plane (rib curvature), rib curvature in the YZ plane (rib torsion), rib curvature in the XY plane, and anterior-posterior bending (difference in mm between the sternal and head ends of the rib). The option of the fitted ellipses also enabled rib torsion to be calculated (angles were computed as the sum of angles between adjacent lines connecting two centroids). Rib torsion is of particular interest as it is difficult to measure on the physical bone.

The developed suite of tools in Matlab® from ULB are of particular interest to paleoanthropologists and those workig in anatomy as they allow a quantitative analysis of rib geometrical parameters such as rib curvature and torsion that was not previously possible in physical measurments. Bone curvature has previously been difficult to analyse. Previous studies have tended to use methods such as the radius or curvature or maximum curvature of the bone. This only gives an overall sum of curvature and not curvature along the length of the bone. The development of the centre line of the object (the centroidal path) is therefore also a useful application for other long bones as the analysis of the centre line shows the distribution of curvature throughout the bone. Su et al., (2015) further used MIMICS to create the centre line of a femur with which to examine the femoral canal. Modern humans are known to have femoral curvature, although currently there is no consencus on why femoral curvature occurs in the sagittal plane of the femur (Chapman et al., 2017b). Curvature in the femur is also known to differ between populations, particularly in the place of maximum curvature (Stewart, 1962; Walensky, 1965; Gilbert, 1976; Trudell, 1999; Egol et al., 2004; Harma et al., 2005; Tang WM et al., 2005; Yehyawi et al., 2007; Karakas and Harma, 2012; Zhang S et al., 2013; Chapman et al., 2015a; Su et al., 2015; Chapman et al., 2017b). Other long bones such as the radius are also known to show differing curvature between populations (De Groote, 2011b). Both the radius and the femur are known to be particularly marked in Neandertals for example (Trinkaus and Shipman, 1992; Shackelford and Trinkaus, 2002; De Groote, 2011a; De Groote, 2011b; Chapman et al., 2017b). The development of the tool of the analysis of the centre line in the lhpFusionBox software would therefore be of significant interest to those working in anatomy, palaeoanthropology and human evolution.

***Quadric surfaces***

QS-fitting has previously been widely used in biomechanics (Charlton and Johnson, 2001; Gatti and Hughes, 2009; Gu et al., 2008; Heistand et al., 2006; Lee and Guo, 2010; Vasavada et al., 2008), astronomy and metrology. QS fitting has most recently been used for palaeoanthropology for anatomical comparisons between both modern humans and Neandertals (Chapman et al., 2015a, 2017a). Prior to the development of the centre line in Matlab®, ULB developed a method of analysing curvature and other variables in long bones using quadric surfaces (Sholukha et al., 2009, 2011).

Bone shape is of interest for a variety of biomechanical applications. Soft tissue wrapping and joint contact problems based on bone shape analysis help predict muscle moment arms and forces such as joint reaction forces (Charlton and Johnson, 2001; Vasavada et al., 2008; Gatti and Hughes, 2009; Stavness et al., 2012; Scholz et al., 2016). Quadric surface (QS) fitting methods for human (Matsuura et al., 2010; Sholukha et al., 2011)(Matsuura et al., 2010; Sholukha et al., 2011; Xi et al., 2003) and animal (Ogihara et al., 2010) studies allowed parameterization of joint surface morphologies. Quadric surface fitting of joint surface areas is also often performed to allow further processing of joint component size, location and orientation (pose), or even to determine soft tissue wrapping by collision detection and muscle moment arm evaluation (Sholukha et al., 2011) which is used in fossil biomechanical analysis. Accurate vertex fitting by QS (Levy, 1995) not only solves the surface collision problem in virtual space, but also enables the derivation of bone morphological characteristics such as joint centre and shape approximation (e.g. diaphysis bending and twisting for longitudinal bones).

The QS fitting study was also developed in Matlab® and further aimed to determine if the position of the morphological JCs and the shape morphology of the bone could be approximated with satisfactory accuracy from a limited amount of palpable ALs found on the bone-of-interest itself (this was found to be possible with three landmarks on the femora). Morphological multiple regression methods have also previously used spatial AL locations to determine JCs using regression analysis (Barbaix et al., 2000; Bell et al., 1990, 1989; Meskers et al., 1997; Sholukha et al., 2011, 2009).Most ALs can be located either by manual palpation through the skin (if human volunteers) or virtual palpation on 3D models, or a combination of both (Van Sint Jan, 2007). Spatial location of ALs are also required to build and obtain regression equations. ALs are also required to define anatomical frames to represent movement data according to the frame definition convention (Cappozzo et al., 2005).

The validated regression method enabled the location of various characteristics (joint center location, joint dimensions, joint orientation) of all joint surfaces of the bones involved in the thigh and shoulder joint complex (Sholukha et al., 2011, 2009). The research aimed to extend the paradigm from Sholukha et al., (2011, 2009) to the long bones, augmented by QS-fitting for shape and orientation prediction of various bone components such as condyles, shaft twisting and bending, etc.

The previous studies using quadric surfaces developed in Matlab@ were found to accurately analyse femoral curvature, demonstrating a difference in femoral curvature between populations (Chapman et al., 2015a, 2017a). The previous method was that the diaphyseal shaft was divided into five QS shapes and curvature was measured by degrees of difference between QS shapes. Each bone was placed in a local coordinate system enabling each bone to be analyzed in the same way. This is a function which is very useful for comparative analysis of bones (also to be able to produce 3D data for analysis in geometric morphometrics). The use of 3D quadric surface fitting allowed the distribution of curvature with similarly curved femora to be analyzed and the different patterns of curvature between groups to be determined (Chapman et al., 2015a, 2017a). Quadric surfaces (QS) were created from the triangulated surface vertices in all areas of interest (neck, head, diaphyseal shaft, condyles) extracted from previously placed anatomical landmarks. These QS also allowed different femoral measurements and angles to be analysed such as widths of condyles, lengths, cervicodiaphyseal angle etc. The advantage of virtual measurements done in the same local coordinate system is that all measurements can be done in the same way and data can then by processed by geometric morphometric tools (such as principal components analysis and Procrustes fitting (Dryden and Mardia, 1998)). The placement of these tools, which are essential for many different disciplines, in lhpFusionBox would be of interest to palaeoanthropologists and biomechanics alike. Quadric surfaces are also essential components for muscle wrapping (in that they create objects which you can wrap a muscle around – the bone surface is too complex to put a muscle on directly)

***Muscle wrapping and fossil biomechanical analysis***

In the last few decades there has been an interest in palaeoanthropology in fossil hominid biomechanical analysis and muscle simulation (Miller and Gross, 1998; Polk, 2004; Sellers et al., 2004; Steudel-Numbers and Tilkens, 2004; Nicolas et al., 2007; Nicolas et al., 2009; Chapman et al., 2010). However, a major problem of fossil hominid biomechanical analysis is a lack of complete specimens in the fossil record with many individual fossil specimens damaged by the impact of diagenesis and excavation (Chapman et al., 2010). LhpFusionBox has demonstrated that it is a useful tool in fossil hominid reconstruction. It was previously used to virtually reconstruct an entire Neandertal skeleton (Chapman et al., 2015b). This skeleton was then used for biomechanical analysis, also using the lhpFusionBox software (Chapman et al., 2010). A recent study (Chapman, 2017) used the reconstructed skeleton to analyse the moment arms of the major muscles of the hip and knee joint. This final study showed that the Neandertal model largely had relatively greater moment arms than the AMH model in the muscles of the hip and knee joint (Chapman, 2017). The study demonstrated that it was possible to analyse fossil hominids, however there were some constraints with the current lhpFusionBox. The main constraint is that the direct method was used to analyse muscle moment arms and the muscles were therefore not representative of the true muscle path (Chapman et al., 2017).

This review therefore examined current methods in soft tissue wrapping and details the Natural Geodesic Variation (NGV) method for the fast and accurate computation of a musculotendon's shortest path across an arbitrary number of general smooth wrapping surfaces (Scholz et al., 2016).

Musculoskeletal simulations provide a quantitative means to predict internal body loads given a set of experimentally measured body kinematics and ground reaction forces. Therefore, musculoskeletal models are widely used to study pathological gait patterns (Arnold et al., 2001; Kerr Graham and Selber, 2003; Arnold et al., 2005; Hicks et al., 2008; Steele et al., 2010), to predict the contribution of individual muscles to motion such as walking (Neptune et al., 2001; Zajac et al., 2002, 2003; Liu et al., 2006; van der Krogt et al., 2012), running (Hamner et al., 2010) and shoulder motion (Van der Helm, 1991; Yu et al., 2011), to quantify bone-on-bone contact forces and joint loads (Winby et al., 2009; Lin et al., 2010; Sasaki and Neptune, 2010; Moissenet et al., 2014), and for surgical planning (Giat et al., 1994). Internal body loads depend on muscle forces and the paths of muscles inside the body. It is now well-established that a muscle’s ability to generate force depends on the path’s current length and its rate of length change, yet the in-vivo measurement of muscle paths and forces is still extremely challenging. While it is possible to accurately measure the coordinates of muscle origin and insertion points from cadavers (Brand et al., 1982; Ackland and Pandy, 2009), experimental data of muscle forces and paths has only been obtained in few cases using MRI (Blemker et al., 2007; Webb et al., 2014) and force transducers attached to tendons (An et al., 1990; Schuind et al., 1992).

Musculoskeletal models require algorithms that compute muscle paths, their lengths and their rates of length change to determine muscle forces and the contribution of individual muscles to motion. Muscles commonly wrap around multiple complex anatomical obstacles such as bones and neighboring tissue, thus most muscle paths cannot be represented adequately by straight lines. Therefore, a broad variety of muscle wrapping approaches has been reported in the literature (van der Helm F.C.T., 1991; Arnold et al., 2010; Audenaert and Audenaert, 2008; Blemker and Delp, 2006; Carman and Milburn, 2005; Charlton and Johnson, 2001; Esat and Ozada, 2010; Favre et al., 2010; Gao et al., 2002; Garner and Pandy, 2000; Gatti and Hughes, 2009; S. Marsden et al., 2008; Röhrle et al., 2008; Scholz et al., 2014; Spyrou and Aravas, 2012; Stavness et al., 2012; Vasavada et al., 2008).

In the majority of musculoskeletal models, muscle paths are approximated by length-minimizing curves (geodesics) that transmit forces to the skeleton while wrapping around geometric obstacle surfaces representing bone and tissue ( van der Helm F.C.T., 1991; Arnold et al., 2010; Audenaert and Audenaert, 2008; Carman and Milburn, 2005; Charlton and Johnson, 2001; Esat and Ozada, 2010; Gao et al., 2002; Garner and Pandy, 2000; Gatti and Hughes, 2009; Marai et al., 2004; S. Marsden et al., 2008; Scholz et al., 2014; Stavness et al., 2012; Vasavada et al., 2008). Such curved-line approaches have been widely used to simulate the upper limb (Audenaert and Audenaert, 2008; Garner and Pandy, 2000; Gatti and Hughes, 2009), the lower limb (Arnold et al., 2010; Carman and Milburn, 2005; Gao et al., 2002), and the shoulder (van der Helm F.C.T., 1991; Yu et al., 2011).

Curved-line muscle wrapping approaches can roughly be subdivided into two groups: approaches using path or surface discretization (Audenaert and Audenaert, 2008; Carman and Milburn, 2005; Esat and Ozada, 2010; Gao et al., 2002; Gatti and Hughes, 2009; S. Marsden et al., 2008) and approaches using smooth curves on smooth wrapping surfaces (Audenaert and Audenaert, 2008; Charlton and Johnson, 2001; Garner and Pandy, 2000; S. P. Marsden et al., 2008; Stavness et al., 2012; Vasavada et al., 2008). Discretized surfaces such as bone meshes obtained from CT or MRI scans (Desailly et al., 2010; Gao et al., 2002; Marai et al., 2004) provide generality and low computational costs, but cause a non-smooth rate of length change during path evolution and wrapping over surface edges. This can slow down variable step size integrators during simulation and introduces discontinuities in muscle force. Researchers have also applied nonlinear optimization to compute discretized shortest muscle paths (Audenaert and Audenaert, 2008; S. Marsden et al., 2008). They minimized the energy of a series of lumped springs, given implicit surface equations as unilateral constraints.

Smooth curves and surfaces are necessary for muscle wrapping to avoid the non-smooth behavior of discretization. An early smooth wrapping approach was presented by van der Helm (van der Helm F.C.T., 1991). He used spheres, cylinders, and ellipsoids for single-object wrapping around the shoulder, approximating surface geodesics by planar curves. Garner and Pandy (Garner and Pandy, 2000) introduced the Obstacle-Set method which computes the exact shortest (geodesic) path across a maximum of two spheres, cylinders, or a combination of both. Their method requires a series of case distinctions and does not generalize for more than two elementary surfaces. Stavness et al. (2012) regarded the total path as a concatenation of straight-line segments between two geodesic segments on each surface, where each geodesic segment is assumed to emanate in the direction of its adjacent straight-line segment. They computed the shortest path across multiple implicit surfaces by iterating the origin-point positions of the geodesic segments such that the two geodesic segments on each surface connect collinearly at their closest points, and the adjacent straight-line segments are tangent to the surface. This approach is general and accurate but computationally slow as it relies on finite-differences Jacobians and requires nested loops for finding the closest points on each pair of local geodesic segments. Scholz et al. (2014) used a single geodesic segment per surface and formulated the constraints for the shortest path solely at the transitions between the geodesic segments and their adjacent straight-line segments. In that work, each geodesic segment was parameterized by the coordinates of its boundary points on general parametric surfaces, and a system of local path-error constraints was introduced which enforces that the transitions between all geodesic segments and adjacent straight-line segments are collinear. That method allowed for the computation of shortest muscle paths across multiple surfaces by solving a system of nonlinear path-error constraints with an explicit Jacobian. Hence, that method is more efficient than, yet it still requires nested loops for computing geodesics between two points on a surface.

There is no muscle wrapping algorithm in the literature that computes a muscle’s shortest path over multiple biologically realistic surfaces in real time, as well as the path’s exact rate of length change. As a result, biomechanists face a trade-off between the computational speed and the accuracy of their models. In a recent paper (Scholz et al., 2016), introduced the Natural Geodesic Variation (NGV) method which allows for both accurate and fast computation of a muscle’s shortest path as it wraps across an arbitrary number of general smooth wrapping surfaces. Analogously to (Scholz et al., 2014), the path is regarded as a concatenation of straight-line segments which have to connect collinearly to local geodesic segments on the surfaces. The collinearity conditions are used to state a nonlinear path-error constraint equation, whose root is computed iteratively to find the shortest muscle path.

Muscles have previously often been virtually simulated at ULB by finding the muscle origin and insertion sites and creating a distance line to simulate the muscle’s line of action. However, as detailed above, the muscle path is often not straight and additional points are needed to define the muscle paths as current musculoskeletal models are not far enough advanced to recognize complex bone shape. A more effective wrapping methodology that is coherent with real musculoskeletal behaviour would be of high value and give more accurate insight into musculoskeletal physiology, compared to current tools and would allow an accurate modelling of muscular movement of fossil individuals. Quadric and parametric surfaces can be used in fossil and modern human biomechanical analysis to define muscles in lhpFusionBox although only in the direct line method. One option may be to implement the NGV method within lhpFusionBox.

**Formats in lhpFusionBox.**

High accuracy 3D digital images can be an extremely useful tool for cultural heritage as this aids in conservation, study and restoration of work (Pieraccini et al., 2001). There are many different formats and techniques of scanning The geometries that lhpFusionBox are currently able to read and display are VRML, STL, INP, MTR. The RBINs museum and many other museums scan objects with a surface scanner. These objects are then in the textured format of PLY and OBJ. One of the limitations of the actual version of lhpFusionBox is that the software is not able to display 3D models with a colour texture in the same way as other software viewers such as MESHLAB or BLENDER. However, textured objects are important for museum studies as the digital files can act as a permanent record. It is therefore a high priority that you can import and visualise textured objects into lhpFusionBox to make the software more accessible for paleoanthropologists and other people working in similar cultural institutions.

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