Title:
A Morphological Evaluation Tool in 3D Slicer

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Introduction:
It is well known that the human body exhibits a range of morphological patterns and dispositions, defined "anatomical variations." Such variations are quite common and often do not have an impact on patient health. However, some of them can cause or contribute to serious medical conditions. An understanding of normal anatomical variation is crucial for performing a wide range of surgical treatment options and medical procedures [1].

Recent advances in imaging techniques and in 3D modeling have facilitated the identification of many variants. Tyler et al. have identified anatomical variations in the knee by means of Magnetic Resonance (MR). Recognizing both normal anatomy and anatomical variants within the knee is important to avoid mis-diagnosis, over investigation and unnecessary intervention [2].

3D modeling of human districts is becoming more and more popular, since 3D models provide an accurate and realistic virtual representation, whereas traditional 2D imaging methods do not always allow to fully understand the morphology. Indeed, it could happen that the anatomical district of interest is not entirely visible in a single image, due to the principles of imaging acquisition. 3D computer models could provide consistent references for direct evaluation which are not affected by the location of cross section or flexion angle [3].

The morphological variations can be quantified by employing measurement tools. Nowadays, indicators are defined on a plane obtained using diagnostic imaging techniques, such as plain radiographs, Computed Tomography (CT) or Magnetic Resonance Imaging (MRI). However, 3D imaging could enrich the study of disease processes, where they involve structural changes and spatial relationships are important. Volumetric visualization and mesh reconstruction techniques are particularly attractive for studying pathologies [4]. Modern technologies allow reconstructing images to create 3D models from DICOM data, leading to easier recognition of the real structural features. The widespread software applications allow to take linear and angular measurements and to create curves on model surface.

New indicators can be introduced in the 3D space to have a better understanding of the district. Toritsuka et al. studied a new way of predisposing factors according to the new indicators in the 3D space for the treatment of patellar instability (PI). The new evaluation does not deny the conventional method, but the authors highlight the necessity to introduce new indicators for 3D imaging to improve the understanding of PI [3]. Morphological analysis of 3D models could be a good practice, especially in the orthopedic field, where the physician can obtain several data about the specific patient. Understanding the anatomical variability of a target population is a critical success factor for designing medical devices, evaluating implant fit and understanding treatment options [5]. Furthermore, the anatomical variations can be studied on 3D models and can be correlated to an injury, by the identification of risk factors. New indicators for studying the three-dimensional shape can involve a linear measurement as well as of a surface or volume.

Polamalu et al. have employed three-dimensional statistical shape modeling to study the tibiofemoral bony morphology features associated with Anterior Cruciate Ligament (ACL) injury. In their research work, they have used three different CAD software applications: Mimics to create 3D surface models of femur and tibia, 3D Slicer for their alignment and Seg3D to create uniform bounding boxes [6]. Changing software and interfaces can be uncomfortable and increase the number of human errors: it could be more efficient to have all the necessary tools in the same environment.

Main Aim:

This research work aims at providing the surgeons with a guided process and a set of tools that allow them to properly investigate each clinical case. A dedicated package will be created, with different functions, to assist in the entire workflow. Starting from DICOM images, it will allow reconstructing the 3D model and performing measurements both in images and on the 3D models. In this way, besides the conventional 2D measures, it will be possible to identify new indicators, measurable on the 3D model because of progress in imaging technology. Furthermore, the solution will make available an algorithm to perform a morphological evaluation. A report will be generated to support the physician's decision. All these steps will be embedded in the same environment. In particular, 3D Slicer will be used for the development of the specific tool. The interaction with the platform will be as simple as possible, to be easily used by the medical staff.

Method and Tools:

A specific SW environment has been developed. It embeds all the main steps of the entire workflow, starting from the medical images load to the creation of a report with an automatic morphological evaluation. It has been built as a scripted extension for 3D Slicer. The 3D modeling capabilities of the Visualization Toolking (VTK) open-source framework have been leveraged, using Python as the programming language. For computationally demanding features, bindings to optimized C++ code have been used. This choice has enabled rapid development without sacrificing the performance of the tool. The user interface has been developed with the QT framework, allowing the layout of the developed module to be consistent with the 3D Slicer application.

The dedicated tool foresees five main phases (Fig. 1). The first one regards the load of DICOM data, such as MR or CT images. The second involves segmentation techniques to reconstruct the three-dimensional models. Segmentation procedures can be classified, based on the user's involvement. An image portion is assigned to a specific label drawn by hand in the manual segmentation, whereas an algorithm automatically divides the image into regions with similar characteristics in the automatic procedure. The semiautomatic method is a compromise between the previous two presented techniques.

In the third step, the operator is guided through the drawing of a small number of landmarks on the surface of the bones. This process is performed by taking advantage of the "Markups" module built into 3D Slicer. Among other features, the module allows defining positions, absolute distances, angles, open and closed curves, and volumes of regions of interest in both 2D and 3D. Landmark points can be used to highlight reference points on the 3D models or in the images, where they can be useful for the registration of medical images obtained with different modalities. Absolute distances can be employed to measure the length and the width of anatomical districts, in order to design medical devices that best fit the patient. Anterior-posterior and medial-lateral length of the femur can be measured to choose the correct size of prosthesis, for example. Angle markups can be employed for the measurement of specific angles, indicators of specific pathologies, such as the sulcus angle for the trochlear dysplasia. Curves can be used to define a region of interest, computing its area, useful for studying a lesion, such as a meniscus tear.

Thereafter, a specific algorithm exploits the user-defined key points to perform an automatic morphological assessment. Finally, the operator can export the results of the assessment in both CSV and PDF formats.

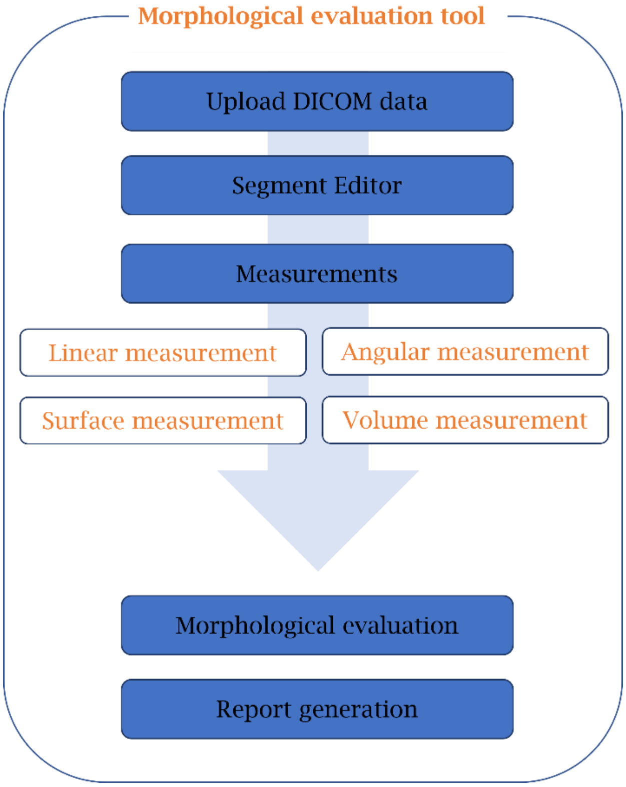

Fig. 1: Structure of the morphological evaluation tool in 3D Slicer.

Application:
The morphological evaluation can be targeted to analyze the risk of injury and calculate the risk factors. Hence, the described morphological evaluation tool has been customized for the evaluation of the risk of developing an ACL injury.

A Package for Assessing the Risk of Developing an ACL Injury
The developed module has been tested by considering as medical purpose the evaluation of the risk of developing an ACL injury. Concerning the scientific literature, ACL injuries are one of the most common and traumatic ligamentous injuries among the active population. Several studies have shown that some individuals are more at risk than others. Identifying risk factors for ACL injury would be crucial for taking preventative actions [5]. Hence, a dedicated package to assess the risk of sustaining an ACL injury has been developed in 3D Slicer. There are many anatomical factors involved in the risk of developing this lesion. Even if there is no absolute agreement, there are three factors that seem to be most involved: the intercondylar notch (ratio of epicondylar width to notch width), β angle (formed by the Blumensaat line and the long axis of the femur) and the tibial plateau slope [7]. Nowadays, the conventional approach suggests taking these measurements on images, as shown in Fig. 2. Intercondylar notches can be classified according to their shapes, as A-shaped (narrow apex), U-shaped (wide apex), or W-shaped (double-peaked notch) [8]. Patients with A-shaped notches had a 2.3 times greater risk of ACL injury compared with patients with U-shaped or W-shaped notches [9]. Intercondylar notch shape typing is usually recognized on axial images. Even, the 3D models can help in understanding the morphology and

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assessing the typology. Furthermore, new indicators can be defined, exploiting the three-dimensional technologies to assess the condylar morphology and study the tibial plateau characteristics (Fig. 3).

Starting from high quality MR images volume of a knee, femur and tibia have been segmented, using the semiautomatic tools of the "Segment editor", such as "Level tracing". This algorithm consists in adding uniform intensity region to a segment, selected by the user. Then, the segmented mesh has been generated and used to take the measurements by means of the customized module. The measured values can be compared to the normal ranges and used by an ad-hoc developed 3D Slicer module to compute the risk of sustaining an ACL injury. A report can be generated either to help the physician in quantifying the risk and to generate data for statistical analysis.

Fig. 2: β angle, intercondylar notch and the tibial plateau slope measurements.

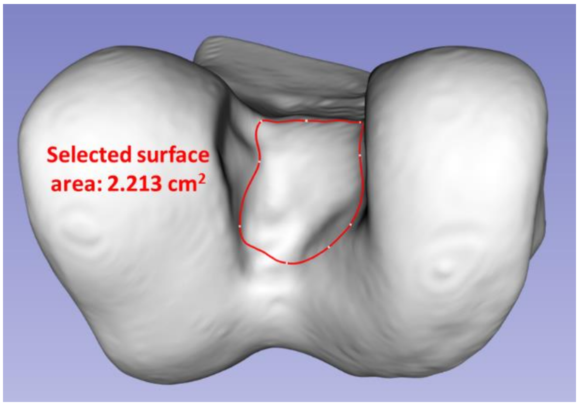

Fig. 3. Selection of a part of the 3D model: the area of the polygonal mesh inside the red contour is computed and shown.

Conclusion:

The present research work claims the importance of 3D modeling in the identification of anatomical variations. The conventional approach for the morphological analysis of human districts should be updated, exploiting a three-dimensional approach. A specific package has been developed in 3D Slicer for the morphological evaluation of anatomical regions. It follows the entire process, starting from DICOM data to the generation of a report with the measures of interest. It has been applied to a specific case: the risk of sustaining an ACL injury. However, it is a method, that can be customized according to the clinical case. Another application could be the computation of the correct size of a knee prosthesis to be implanted, given the anterior-posterior and medial-later length of the femur and tibia.

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