Title:
Morphological evaluation of shoulder instability: a customized module

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Introduction:
The shoulder is the most mobile joint and one of the most complex articulations in the musculoskeletal system, which is why it is susceptible to pathology [1]. Concavity compression is the predominant mechanism by which the humeral head is centered in the glenoid cavity that is inherently small in comparison to the humerus [2].

Instability is a condition in which the shoulder moves beyond its normal range of motion, often due to traumatic events. An unstable shoulder can easily lead to a dislocation, which occurs when the humeral head become permanently out of its physiological position, causing pain. If it protrudes anteriorly, an anterior dislocation happens; if it protrudes posteriorly, a posterior dislocation occurs. Anterior dislocation is much more common (95% of the total shoulder dislocation) and often occurs in young patients, and more often in males than in females [3] [4] [5]. The event tends to recur because the structures responsible for glenohumeral stability, the capsule and ligaments, are injured after a dislocation, further reducing the stability of the joint.

Previous studies have shown that there are several factors that contribute to risk of shoulder instability including age, sex, presence of hyperlaxity, soft tissues and bony anatomical features, such as glenoid morphology [3], [6]. Glenoid plays an important role in maintaining glenohumeral joint stability. The bone structure includes glenoid width, height, depth, glenoid angle, glenoid area and shape [3].

The quantification of shoulder morphology and in particular of the glenoid bone could be useful for identifying the potential risk factors for anterior shoulder instability. It permits to develop specialized care programs, in which patients with an increased risk may receive advice for their sports and professional careers to reduce the incidence of the disease. Furthermore, the treatment after a primary dislocation can be tailored according to the patient's risk of recurrence [7].

Advances in image processing techniques permit to obtain realistic three-dimensional models starting from bidimensional images. Guan et al. claim the need to integrate 2D images obtained through computed tomography (CT) or Magnetic Resonance (MR) techniques with three-dimensional models of the shoulder [8]. 3D modelling method permits the reconstruction of a virtual three-dimensional model of the region of interest and allows to perform measurements in three planes. 3D model, which displays data as a combined volume rather than as slices, overcome the problem of slice selection and reduces the risk of error due to inaccuracy in setting the plane of measurement [9]. Glenoid and humeral head can be freely rotated to identify and apply the desired measurement point. In this way, the risk of error due to a misplacement of the projection of the initial measurement, as in the two-dimensional method, is reduced [10]. Stefaniak et al. found that 3D reconstruction is more reliable than 2D-CT for assessing humeral head parameters and bone defects. They also showed that 3D-CT assessment appears resistant to bias due to the investigator's level of experience [11]. Bois et al. investigated both the reliability and accuracy of several indicators and quantification methods with 2-D and 3-D CT for the evaluation of glenoid bone loss in anterior glenohumeral instability [9].

Main aim:
The first aim of the present research is the identification of the glenoid anatomical risk factors at the basis of the shoulder instability, through a literature research. Then, a package for morphological evaluation for shoulder instability is developed. It consists in a guided procedure to assess the chosen parameters both in 2D images or three-dimensional models. Data about the morphology of the shoulder obtained through the proposed method can be very informative to distinguish between healthy and pathological conditions and can drive treatments.

Identification of risk factors:
Many researchers have studied the relationship between shoulder instability and the glenoid bony morphology to understand why this condition occurs. The most significant parameters for shoulder instability are selected from the literature as the most indicative for shoulder instability (Table 1).

Hong et al. assessed shoulder structure of patients with anterior dislocation by MR images. They revealed significant risk factors for shoulder instability in the Chinese Han population. In particular, they found the glenoid height to width ratio [12]. Cohn et al. suggested that bony and soft tissue factors may have different effects on stability in male and female patients. Compared to controls, men with instability had a smaller glenoid width, a smaller glenoid surface area, and a glenoid width that was proportionally smaller than the humeral width. For females, there was no significant risk factor for instability [6]. Peltz et al. showed that there are significant differences in glenohumeral joint morphology between healthy controls and patients with traumatic glenohumeral instability. Specifically, patients with instability have flatter glenoid than controls in the anterior/posterior and superior/inferior directions [13]. Jacxsens hypothesized that a taller, narrower, and flatter glenoid may be linked to recurrence instability [5]. Zhao et al. suggested that glenoid shape, depth, height to width ratio and maximum fitting circle area are risk factors for recurrent shoulder dislocation [3]. Other researchers reported that increased glenoid anteversion is an important risk factor for recurrent anterior shoulder dislocation [14] [15] [16] [17].

Study	Techniques	Risk factors
Hong et al. (2019) [12]	MR	- Glenoid height to width ratio
Cohn et al. (2022) [6]	MR	- Glenoid width - Glenoid area
Peltz et al. (2015) [13]	CT, 3D models	- Flatter glenoid
Jacxsens et al. (2019) [5]	3D models	- Glenoid shape
Zhao et al. (2022) [3]	CT, 3D models	- Glenoid shape (oval-shaped) - Glenoid depth - Glenoid height to width ratio - Maximum fitting circle area
Saygi et al. (2018) [16]	MR	- Glenoid version - Glenoid height - Glenoid width
Aygün et al. (2018) [14]	CT	- Glenoid version
Hohmann et al. (2015) [15]	MR	- Glenoid version
Paopongthong et al. (2022) [17]	MR	- Glenoid version

Tab. 1: Risk factors for shoulder instability.

Module development:
A module for the morphological evaluation of shoulder instability is developed in 3D Slicer. The main phases of the procedure are shown in Fig. 1. It requires the upload of DICOM data of the shoulder, such

as CT or MR images. The user is asked to reconstruct the main bones of the shoulder by means of segmentation. Glenoid bone is isolated to permit the user to measure its anatomical features. He/she is guided in the process of measuring the parameters, identified as risk factors for the development of the glenohumeral joint instability. Based on the measurements, a morphological assessment can be drawn, to support the physician diagnosis.

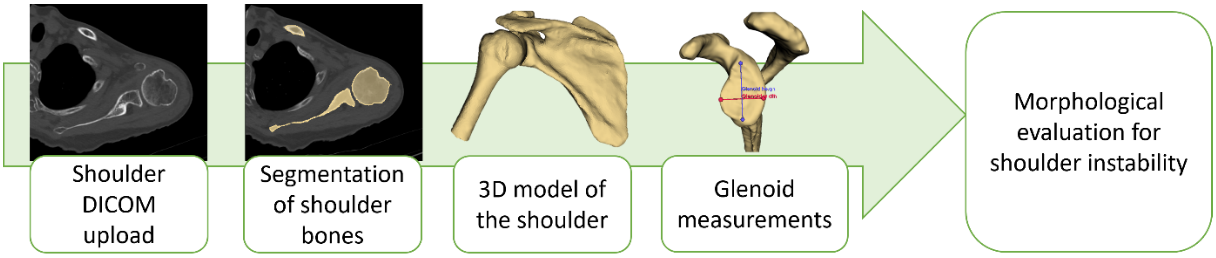

Fig. 1: Phases of the morphological evaluation tool for shoulder instability.

In the module it is possible to measure glenoid features: height, width, shape and version. Height is defined as the maximum distance from the superior apex of the glenoid at the level of the coracoid base (12 o'clock position) to the inferior pole (6 o'clock position). The width is measured orthogonally to the previously measured height as the maximum length between the anterior and posterior glenoid rims. Thus, height to width ratio is calculated by dividing these two values [4]. The shape of the glenoid can be classified into: inverted comma, in which the glenoid cavity has a distinct notch, pear shape, in which the glenoid cavity has an indistinct notch or oval shape, in which the glenoid cavity has no notch [3] [4]. The above-mentioned parameters are measured in the three-dimensional space. Fig. 2 shows 3D view of the glenoid of shoulder after subtraction of the humeral head used for measurement of the glenoid height and width and the recognition of its shape.

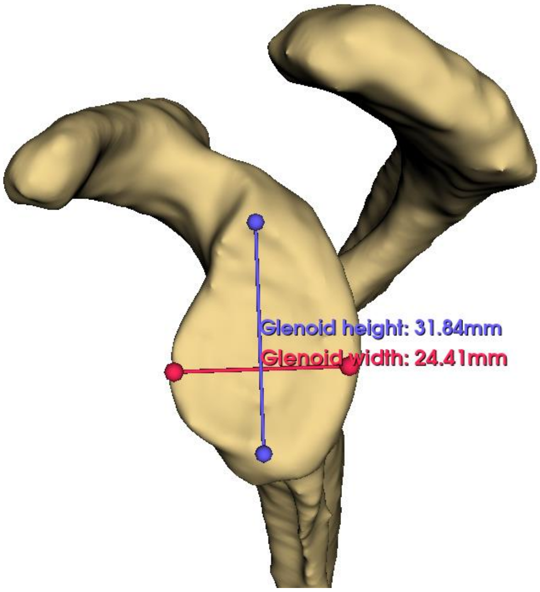

Fig. 2: 3D view of a glenoid with height of 31.84 mm and width of 24.41 mm with a pear shape.

The glenoid shape can be concave, flat, or convex. The diameter of the glenoid concavity is measured by drawing a straight line from one apex to the other. Glenoid depth is the distance from the deepest point of the glenoid concavity to the glenoid diameter line [18]. It is measured on CT images, as shown in Fig. 3(a).

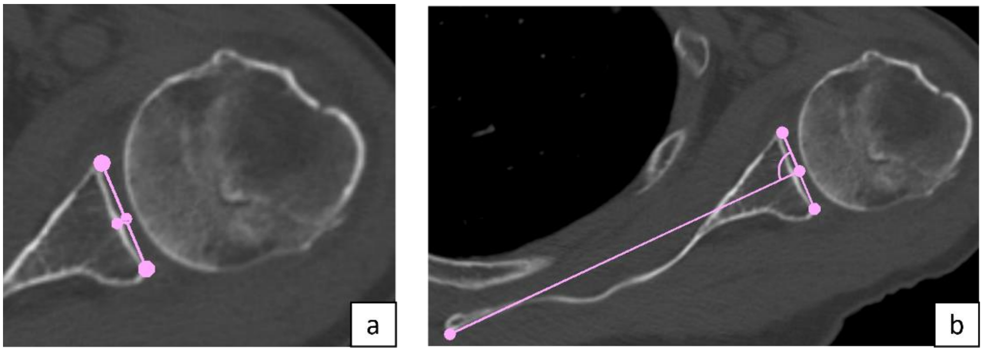

Fig. 3: (a) Diameter glenoid concavity. (b) Glenoid version.

Furthermore, glenoid version can be evaluated in 2D images (Fig. 3(b)). It is measured by placing a tangential line on the glenoid concavity and a second line from the medial border of the scapula through the centre of the glenoid concavity. The anteromedial angle is the measure of glenoid retroversion. It is known that in healthy shoulders, glenoid version angles range from 2° anteversion to 9° retroversion [14]. All the described parameters are measured both on 2D images and on 3D models of the glenoid. Then, they are compared to the normal ranges and used to compute the risk of developing shoulder instability or dislocation.

Conclusions:

The present research proposes a medical support tool for evaluating shoulder instability. The developed method makes it possible to obtain an indication of the condition of the shoulder in a semi-automatic way. The quantification of morphology, exploiting 3D modeling techniques, can give useful information about the predisposition of developing injuries. Knowledge of the risk in advance is useful for preventive action: patients and athletes could be screened and receive personalized preventive care to reduce the incidence of shoulder disease. The effectiveness of the proposed approach will be tested in clinics with a larger sample of patients. Feedback from the physicians will help in improving and simplifying the interface. Furthermore, the procedure will be employed for other shoulder diseases.

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