Migration of the instantaneous center of rotation in the shoulder during abduction: implications for scapulohumeral muscle function

P. Blaimont (1), A. Taheri (1), A. Vanderhofstadt (1)

(1) 5, avenue de la Brise, 1420 Braine-l’Alleud, Belgique.
(2) Service de Kinésithérapie, Hôpitaux Iris Sud, site Etterbeck-Ixelles, 63, rue J. Paquot, 1050 Bruxelles, Belgique.
(3) Service de Radiologie, Hôpitaux Iris Sud, site Etterbeck-Ixelles, 63, rue J. Paquot, 1050 Bruxelles, Belgique.

ABSTRACT

Purpose of the study
To date, studies of glenohumeral stress forces have been based on the notion of a unique center of rotation situated at the geometric center of the humeral head. Early work, e.g. Fischer et al in 1977, suggested that the instantaneous center of rotation can migrate during abduction producing muscle vectors with variable moments and consequently variable stress forces. We conducted a kinematic analysis of the shoulder forces during continuous movement.

Material and methods
An imaging device commonly used for angiography enabled acquisition of one image per second during a continuous abduction movement. Images were obtained for twenty healthy shoulders in ten subjects.

Results
The instantaneous center of rotation was not situated at the geometric center of the humeral head. Although there was significant interindividual variability, the preferred positions for the instantaneous center of rotation implied a constant reproducible succession of gliding, rolling, and translation in variable proportions during the abduction movement. When the same movement was performed with a 3500g load held in the hand, the ICR migrated towards the upper part of the humeral head, implying a predominance of rolling motion over gliding and translation motions. Between 40° and 60° glenohumeral abduction, the instantaneous center of rotation exhibited a metaphyseal displacement, producing a longer lever arm for the supraspinatus and an abduction function for the infraspinatus and subscapularis, unrecognized to date. After 60° medialization of the instantaneous center of rotation lengthened the lever arm of the deltoid.

Discussion
A valid analysis of the glenohumeral stress forces must take into consideration the localization of the instantaneous center of rotation. In a clinical setting, our findings demonstrate that the infraspinatus and subscapularis play an important role which must be considered both in surgery and rehabilitation.

Key words: Shoulder, instantaneous center of rotation, kinematic analysis.

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INTRODUCTION

When a movement is made, the strength of a muscle depends on its lever arm, i.e. its distance from the center of rotation (fig. 1). Some congruent joints, such as the coxofemoral joint, have a fixed center of rotation, at least as long as the femoral head and acetabulum remain spherical. However, in other less congruent joints such as the knee and the ankle, the instantaneous centers of rotation may vary. This is particularly the case for the glenohumeral joint, where the comparative radius of curvature for the head and glenoid cavity can be significantly different (fig. 2). The instantaneous center of rotation is by definition the point which remains immobile during a slight movement; in other words it is the point around which basic, gliding, rolling or translation movement occurs.

For a better understanding of these notions, which may at first seem to be quite abstract, we shall consider the example of a car wheel moving over a dry surface (fig. 3). Points $a'$, $b'$, $c'$ on the wheel come into contact with the corresponding points $a$, $b$, then $c$ on the ground. This is a rolling movement where movement occurs around instantaneous centers of rotation (ICRs) on the rolling plane.

In the case of gliding, by analogy to that of a wheel spinning on ice, the ICRs are situated on the axle and points $a'$, $b'$, $c'$ move past $a$.

Translation movement can be compared to the movement of a locked wheel skidding on ice: in this case, there are an infinite number of ICRs.

In the case of complex movements combining gliding, rolling and translation, the ICR is situated on axis $X$ at a point depending on the predominant type of movement (fig. 4).

As early as 1911, Fick (1) established the centers of rotation for the shoulder, which were later defined in more detail by Fischer et al. (2) in 1977. Our study was based on an examination of successive radiograms of the shoulder frozen at different degrees of abduction and flexion. The ICRs are scattered within two circles for abduction (fig. 5) and just one central circle for flexion.

The work of Favard et al. (3) shows that when the arm is elevated in the plane of the scapula, the humeral head moves upwards then downwards, indicating that rolling and translating movements occur together. Previous studies conducted by others show ICRs close to the geometrical center of the humeral head, which implies clear
Predominance of gliding movements. However radiograms of healthy shoulders show that the point of glenohumeral contact can move significantly during abduction. This would indicate associated gliding movements and therefore a variation which is probably greater than supposed from the position of ICRs during abduction movement.

In this paper, we will study the glenohumeral joint during more physiological continuous movement rather than a succession of static positions. We will also try to define the type of movement (gliding, rolling or translation) which each new ICR position involves during free abduction and abduction with counter-force.

**EQUIPMENT AND METHODS**

Twenty shoulders on ten subjects (five men and five women) with an average age of thirty-four years (between twenty-one and forty-eight) were studied with methods used in angiography testing (Siemens Fluorospot Erlangen, acquisition data: one image per second, 80 Kw). The subjects had no problem or antecedents with their shoulders; their degree of articulation and the morphology of their scapula and thorax were normal.

Abduction movement was carried out over approximately ten seconds with one image per second; accurate measurements of the difference in angles between two images were made. Since the speed of movement varied from one individual to another, the basic angle difference was not necessarily identical, displaying a five per cent variation.

During the test, which was repeated three times, we ensured that abduction occurred in the plane of the scapula in neutral rotational position, in order to minimize automatic rotational movement of the humerus. To keep movement in the plane of the scapula, we placed a triangular cushion behind the subject to support the shoulder at an angle of 30° forward from the frontal plane. Initially, the ICRs were identified during free movement, then with a 3.5 kg weight held in the hand in neutral position. All the subjects were able to lift this weight. It should be noted that for certain female subjects a 4 kg weight was too heavy.

The ICRs were identified using the most commonly used graphic method in joint kinematics (fig. 6), which consists of:

- choosing, on the first image (A), any point \( a \), which must be able to be identified throughout the movement; we chose the edge of the joint opposite the greater tubercle;
- situating this reference point on the following image (B), located at an angle defined as the distance between the humeral shaft and the line drawn between the upper and lower rims of the glenoid cavity;
- drawing a straight line between points \( a \) and \( b \) occupied by the reference point and dropping a perpendicular at the centre of this line;
- repeating the same procedure on the following image (C);
- the intersection of the two perpendiculars defines the instantaneous centre of rotation during angular movement separating the first image from the third.
The lines were drawn in fine-point marker pen in order to reduce mistakes in readings. Between ten and twenty degrees before the torso is used in total abduction, the reference point $a$ is less clearly identified and so the position of ICRs is less accurate; these readings were not taken into account.

RESULTS

Location of ICRs during free abduction movement

The ICRs we identified during continuous movement were considerably more scattered than those reported by Fischer et al. (2). The same test repeated three times on the same individual gave comparable results.

For each individual, we took note of the position of ICRs and associated amplitudes. Having calculated both average values for all the subjects and the amplitude of gleno-humeral abduction, we were able to locate three areas within the humeral head in which the ICRs were situated (figs. 7 and 8):

- area I is the average ICR between 0 and 40°;
- area II is the average ICR between 40-60°;
- area III is the average ICR greater than 60°.

With abduction of 40-60° (average of 48°), in seventeen cases out of twenty, the ICRs moved towards the lower part of the humeral head. In fourteen shoulders out of twenty, ICRs were situated outside the humeral head. This outward location occurs on average with glenohumeral

FIG. 6. – Depending on the graphic method used, the progress of reference points during movement enables ICR identification.

FIG. 7. – This study shows that ICRs are found in a third area in the juxta-metaphyseal region (II), though far less frequently than in the other two areas. This alters the moment of action of the deltoid and supraspinatus abductor muscles, providing the infraspinatus muscle, and to a lesser extent, the subscapularis muscle, with additional abduction potential.

FIG. 8. – ICRs in the context of scapulohumeral amplitude.
abduction of 69°, i.e. with an overall abduction greater than 100°.

**Location of ICRs during abduction movement with counter-force**

As with free abduction, ICRs can be found over a wider area than that found by Fischer et al. (2). In addition to this, we found that ICRs were in general higher than in the case of free movement, and that their dispersal was concentrated in a smaller area (fig. 9).

The shifting of ICRs to the metaphysal region found in free movement also occurs in abduction with counter-force but only in twelve out of twenty cases, with an average of 42° glenohumeral abduction. On the other hand, ICRs are found outside the humeral head in fifteen out of twenty shoulders with an average of 63° glenohumeral abduction.

**DISCUSSION**

Despite the inaccuracies due to the method used and individual differences in the location of ICRs at the same points of abduction, it is clear that significant kinematic patterns do exist. The difference between our findings and those of Fischer et al. (2) arise from the methodology used. In irregular movement, the humeral head has the time to return to the center of the socket between two radiograms, which explains the fact that the areas where ICRs are to be found are closer together.

For glenohumeral abduction of 0-40°, the central position of ICRs implies predominantly gliding rather than rolling movement. This suggests that a point Y on the lower pole of the humeral head will move further than point X on the upper pole (fig. 10).

**FIG. 9.** During abduction movement with counter-force, the areas of where ICRs are situated are reduced and closer to the top of the humeral head, as shown by considerably more rolling as compared to gliding movement.

**FIG. 10.** From 0-40° abduction, the ICRs are situated towards the top. Both gliding and rolling movements are found simultaneously. Movement occurs such that point Y covers a greater distance than point X (b > a).

**FIG. 11.** The higher position of the lines of action of the infraspinatus and subscapularis muscles compared to the ICRs (abduction between 40-60°) affords additional abduction value to the action of the supraspinatus and deltoid muscles.
Muscle length variation will therefore be different depending on whether it is closer to X or Y.

From 40-60°, the migration of the average metaphysal ICR affords considerably increased leverage to the supraspinatus muscle. Since the infraspinatus and subscapularis muscles are below the ICR, their function changes considerably. Whilst continuing to depress the shoulder and rotate the humeral head, they gain abduction value (fig. 11).
The electromyographic studies done by Kronberg et al. (4) showed that these muscles are the most active when they are almost horizontal. The activity of the subscapularis muscle remains fairly negligible in experimental conditions, i.e. in the frontal plane.

The increase in the lever arm in usual and occasional (infraspinatus and subscapularis) abductor muscles combined with a peak of electromyographical activity at 60° makes abduction more effective, just before gravity has its greatest effect on the upper limb.

In reparative surgery and rehabilitation, it is important to bear in mind the essential role of the infraspinatus muscle, which combines simultaneous depressing of the humeral head and impaction of the glenohumeral joint, whilst acting as an agonist for the deltoid and supraspinatus muscles during abduction between 40-60°. In cuff pathology, it compensates for the defective supraspinatus muscle by neutralizing the lifting effect of the deltoid on the humeral head. It is however surprising that in the case of rotator cuff tears, the greatest weakness occurs when the infraspinatus muscle is affected.

During abduction beyond 60°, the ICRs are situated near the glenohumeral articulation. As the ICRs are centered, the lever arm of the deltoid is increased. Movement is mostly rolling. Some images indicate a lower glenohumeral diastasis with the risk of the greater tubercle touching the acromion (fig. 12). This is a critical moment for the supraspinatus muscle which is almost compressed between its humeral insertion and the acromion.

During abduction beyond 90°, the ICRs tend towards infinity and are found outside the joint, indicating lower translation movement avoiding conflict between the greater tubercle and the acromion. The subacromial conflict is that of the rolling movement from the phase before which is not compensated by the lower translation brought about by the depressor muscles.

Abduction finishes with a gliding-rolling movement involving distension of the inferior glenohumeral ligament.

A load carried at arm’s length reduces the dispersion of ICRs as though the joint were behaving in a relatively static way.

The migration of ICRs follows an identical path for a given individual whenever the same abduction movement is made. It is different however for the opposite shoulder and all the more so for other individuals.

Studies done, for example by Inman et al. (5) and Poppen and Walker (6), which attempted to calculate stress on the glenohumeral joint based on the existence of only one center of rotation, are bound to be erroneous, as the lever arm measurements taken from the geometrical center of the humeral head do not correspond to the actual situation.

The differences observed in the incidences of ICRs may come from the predominance of certain muscles according to the morphology of the individual and their professional activity and sports practiced.

CONCLUSION

The study carried out during continuous glenohumeral abduction movement shows that between 40° and 60°, of a group of instantaneous centers of rotations (ICRs) exhibiting metaphysial displacement, compared to two others when the arm approaches the horizontal plane. This implies that the infraspinatus and, to a lesser extent, the subscapularis, muscles gain abduction value and that these muscles along with the supraspinatus have increased leverage when gravity has its highest effect. Beyond an abduction of 60°, the ICRs in the glenohumeral joint move towards the center, increasing the lever arm of the deltoid muscle.

The position of ICRs is not only particular to each individual, but is different in either shoulder in the same individual.

The change in ICRs has an effect on kinematic patterns, since there are different phases of different lengths during abduction: I. gliding-rolling; II. mainly gliding; III. rolling; IV. inferior translation, in varying proportions.

Rolling, a movement which is less mechanically destructive movement for cartilage than restrained gliding, occurs when at the point of maximum glenohumeral impaction, i.e. when the arm is horizontal.

When a load is carried, the ICRs are closer together and displaced towards the surface of the glenohumeral joint.

Inferior translation movement observed beyond 90° avoids contact between the acromion and the humeral head.

The neuromuscular conditioning for shoulder movement maintains the humeral head in the best position with respect to the glenoidal cavity according to the effort to be made.

In any attempt to study the forces involved in the glenohumeral articulation, ICR position for the moment under study must be known beforehand.

References