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The relationship between the morphological axis and the kinematic axis of the proximal radius

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Abstract

Purpose Surgical procedures for impaired forearm rotation such as for chronic radial head dislocation remain controversial. We hypothesized that the morphological axis of the proximal radius is important for stable forearm rotation, and we aimed to clarify the relationship between the morphological axis and the kinematic axis of the proximal radius using four-dimensional computed tomography (4DCT).

Methods Ten healthy volunteers were enrolled. Four-dimensional CT of the dominant forearm during supination and pronation was obtained. The rotation axis of forearm rotation was calculated from all frames during supination and pronation. The principle axis of inertia, which represents the most stable rotation axis of a rigid body, was calculated for the proximal radius by extending its surface data incrementally by 1% from the proximal end. The angle between the kinematic rotation axis and the morphological rotation axis of each length was calculated.

Results The rotation axis of the forearm was positioned on the radial head 0.0 mm radial and 0.4 mm posterior to the center of the radial head proximally and 2.0 mm radial and 1.2 mm volar to the fovea of the ulnar head distally. The principle axis at 15.9% of the length of the proximal radius coincided with the forearm rotation axis (kinematic axis). Individual differences were very small (SD 1.4%).

Conclusion Forearm rotation was based on the axis at 16% of the length of the proximal radius. This portion should be aligned in cases of severe morphological deformity of the radial head that cause "rattling motion" of the radial head after reduction procedures.

Keywords Computed tomography · Radius · Rotation axis · 4DCT

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Introduction

Cases of chronic radial head dislocation are mostly the result of missed fractures in childhood or congenital disorders [1]. The most common cause of radial head dislocation is Monteggia fracture, which is a combination of ulnar fracture and radial head dislocation. Although Monteggia fractures account for 2–13% of all forearm fractures [16, 17], the radial head dislocation is easily neglected by initial care providers [5]. Once radial head dislocation is overlooked, the severity of radial head dislocation usually progresses over time and leads to limitation of the range of motion or pain due to osteoarthritic change [6, 10]. Several surgical procedures have been advocated for chronic radial head dislocations. Among these procedures, ulnar osteotomy, which aims to reduce the radial head through the interosseous membrane, has demonstrated

good results, suggesting that ulnar osteotomy is a promising treatment for chronic radial head dislocation [2, 18]. However, a recent study also reported that the results of ulnar osteotomy are not as good as originally thought [19]. Some patients showed unstable radial head rotation after correction of the ulnar alignment or re-dislocation several months after the operation. We hypothesized that the morphology of the radius is also an important factor for stable rotation of the forearm. Risk factors for poor operative results include the age of the patient, time from injury, and morphological changes of the radial head and capitellum [13, 15]. With morphological changes in the radial head, most studies concluded that joint incongruity contributes to re-dislocation. Almost no study has described the alignment of the proximal radius. We hypothesized that the relationship between the morphological axis of the proximal radius and the forearm rotation axis is the important factor for radial head stability during forearm rotation. In this study, the aim was to calculate the rotation axis of the forearm during active supination and pronation using four-dimensional computed tomography (4DCT) and to clarify the relationship between the morphology of the proximal radius and the forearm rotation axis.

Methods

Subjects and data acquisition

Ten healthy volunteers (5 men, 5 women; mean age 22.3 years, SD 0.5 years) were enrolled. None had a history of injuries or limited ranges of motion in the upper extremities. The dominant forearm (all were right) was examined using 4DCT, using an Aquilion ONE VISION Edition (Toshiba Medical Systems Corporation, Otawara, Tochigi, Japan). It consisted of 320 0.5-mm detectors delivering 16 cm of coverage in a single rotation of the gantry (rotation time, 0.275 s) and achieved five volumetric data per second in dynamic 4DCT examination. The subject sat and positioned the dominant forearm in the CT gantry with the elbow flexed at 90° and the shoulder abducted at 90°. Before the examination, the subject fully pronated the forearm. After the examination started, the subjects rotated the forearm to full supination and back to full pronation in 10.275 s, obtaining 51 volumetric CT data sets during supination and pronation. Additional static 3DCT images of the whole radius and ulna were also obtained. Volume data were stored as Digital Imaging and Communications in Medicine (DICOM) format in 0.5-mm-thick slices for surface reconstruction. This study was approved by the Institutional Review Board of our institution (approval number: 20,150,128).

Image data analysis

Surface data of the whole radius and ulna were each reconstructed by semi-automatic segmentation from the static 3DCT using software (AVIZO 9.3.0, MAXNET Japan, Tokyo, Japan). Whole surfaces of the forearm in all 4DCT frames were also reconstructed by automatic segmentation. The surfaces of the whole radius and the whole ulna were matched with the surface data of the forearm in each 4DCT frame by surface registration (Fig. 1). Surface registration was performed using an iterative closest point (ICP) algorithm that matches the point cloud of one surface data with other surface points to minimize the sum of the distance between two surface points (VTK 6.3.0 Kitware Inc., Clifton Park, NY, USA). From the rotation matrices that represent the rotation and translation of the radius and ulna to match with the surface data of each frame, relative motions of the radius around the fixed ulna and relative motions of the ulna around the radius were reconstructed (Fig. 1).

Rotation axis of the forearm

The rotation axis during supination and pronation was calculated using least squares solutions from all frames during supination and pronation [4]. In the proximal forearm, the rotation axis of the ulna around the radial head was described in the radial coordinate system, which was determined by the center of the radial head, radial styloid, and the ulnar border of the lunate fossa (Fig. 2). In the distal forearm, the rotation axis of the radius around the ulnar styloid was described in the ulnar coordinate system, which was determined by the ulnar styloid, the center of the ulnar head, and the tip of the olecranon (Fig. 2).

Morphological axis of the proximal radius (principle axis of inertia) (Fig. 3)

The principle axis of inertia of the proximal radius was defined as the morphological axis. The principle axis of inertia represents the most stable rotation axis of a rigid body. The total length of the radius was defined as the length from the center of the radial head and the tip of the styloid. When the length of the proximal radius was extended from proximal to distal incrementally by 1% along the long axis, the principle axis of inertia of each length's surface data was calculated. The angles between each principle axis and the rotation axis of the ulna were calculated for each length, and the length that yielded the minimum angle was identified. The percentage of the proximal radius of which the principle axis of inertia was the closest to the kinematic rotation axis
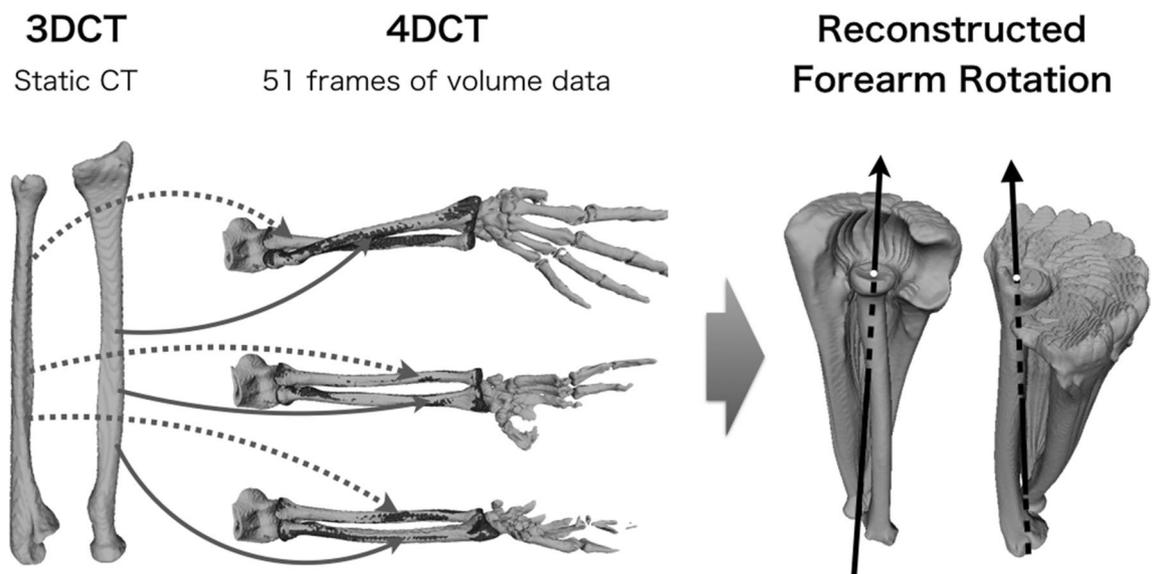
Fig. 1 The whole surfaces of the radius and the ulna are matched with the surface data in each 4DCT frame. From these rotation matrices, rotation of the ulna relative to the radius and rotation of the radius relative to the ulna are reconstructed. The rotation axis is calculated by the least squares solution from all frames during pronation and supination

was identified. Forearm rotation was attributed to the most stable rotation of this proximal portion.

Results

The rotation axis of the forearm was positioned on the radial head 0.0 mm (SD 1.1 mm) radial and 0.4 mm (SD 0.6 mm) posterior to the center on the radial head proximally. Distally, the rotation axis was positioned 2.0 mm (SD 1.2 mm) radial and 1.2 mm (SD 0.9 mm) volar to the fovea on the ulnar head (Fig. 4).

The principle axis of inertia at 15.9% (SD 1.4%) of the length of the proximal radius was the closest to the average forearm rotation axis (Fig. 5). The average of the minimum angle between the principle axis of inertia of that proximal portion and the rotation axis was 4.7° (SD 1.9°). These differences increased and then again decreased as the length of the radial surface extended to 100%. The difference was the largest, 11.6° (SD 0.7°), at 49.2% (SD 4.8%) of the proximal radius. The angle between the principle axis of inertia of the whole radius and the rotation axis was 7.6° (SD 0.9°).

Discussion

The forearm rotation axis was the closest to the principle axis of inertia at 16% of the length of the proximal radius, which is identical to the distal end of the biceps attachment anatomically. This suggests that normal forearm rotation is based on the most efficient rotation of this proximal portion. The morphological axis of the whole radius does not coincide with the forearm kinematic axis, because the rotation axis passes through almost the center of the radial head and ulnar fovea. From this, it is important to clarify which proximal portion of the proximal radius contributes to stable forearm rotation. Various kinds of morphological changes in chronic radial dislocation have been reported, such as radial head deformities, arthritic changes of the radio-humeral joint, and deformities of the ulnar notch [9]. Rodgers reported that chronic dislocation leads to early closure of the physis of the proximal radius, which resulted in these morphological changes [17]. This could change the axis alignment of the proximal radius. The principle axis of inertia was used, because it represents the most stable axis of a rigid body and has also been related to the kinematic axis in human motions [7, 8].

Several surgical procedures have been advocated for chronic radial dislocations. Some studies have reported excellent results of ulnar osteotomy, which applies traction onto the interosseous membrane to pull the radial head back into its original position. However, re-dislocation after ulnar osteotomy is also common [19]. The morphological change in the proximal ulnar notch has been thought to be the cause of instability of the radial head during forearm rotation, and radial head osteoplasty or ulnar notch osteoplasty has been performed [9]. However, off-axis rotation of the proximal radius often results in a "rattling" movement of the radial head. Miyake et al. analyzed the rotation axes in patients with chronic Monteggia fractures, and they reported that
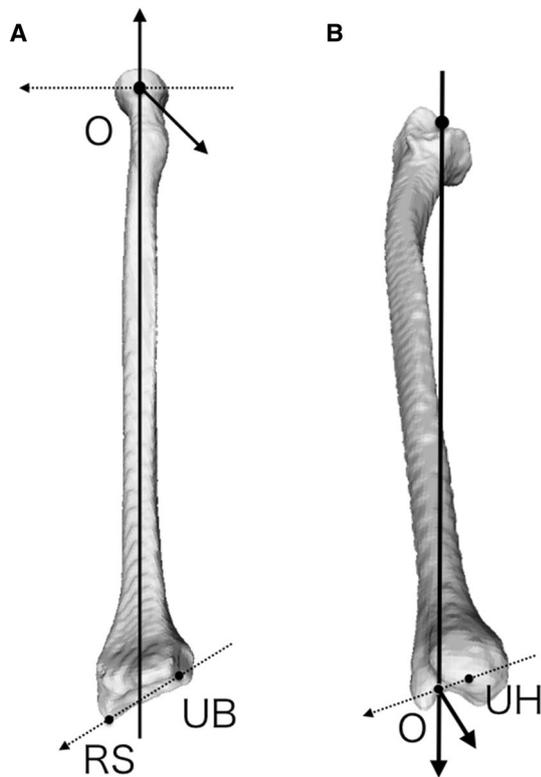
Fig. 2 a The coordinate system of the radius: The long axis is the line connecting the center of the radial head (O) and the midpoint between the radial styloid (RS) and the center of the ulnar border of the lunate fossa (UB). The anteroposterior axis is defined as the line perpendicular to both the long axis and the line between the RS and UB. The radial-ulnar axis is defined as the line perpendicular to the long axis and AP axis. **b** The coordinate system of the ulna. The long axis is the line between the tip of the olecranon and the ulnar fovea. The anteroposterior (AP) axis is the line perpendicular to the long axis and the line between the center of the ulnar head (UH) and the ulnar fovea (O). The radial-ulnar line is perpendicular to both the long axis and the AP axis

type 4 Monteggia fractures showed changes of the rotation axis around the proximal radius, and they suggested that alignment change of the radial shaft could affect the rotation axis of the proximal radioulnar joint [11]. Radial osteotomies have also been attempted for chronic radial head dislocation [3, 18, 20]. However, most of them tried to reduce only the center of the radial head to face the center of the capitellum. This might not align the radial proximal shaft axis on the forearm rotation axis.

Recently, 3D templating technology has been used for forearm deformities using flipped surface data of the intact radius and ulna. Murase et al. reported excellent results when treating a patient with forearm fracture malunion using surface registration with the flipped surface data of the intact side [12]. This method has been established on the hypothesis that the affected side is almost the same as the intact side except for the injured portion. However,

in chronic radial head dislocation, various morphological changes occur with the primary deformity. Given this situation, it is important to clarify the relationship between the anatomical shape and the kinematics of the intact bone and reproduce the kinematic alignment that yields normal forearm rotation. The present study could contribute to 3D simulation of stable forearm rotation, namely the alignment of the proximal radius can be matched with the forearm rotation axis, which is the line between the head of the radial center and the ulnar fovea. This alignment could provide the most stable rotation of the proximal radius. From these rotation kinematics and the morphology of the radial head, we could judge whether the radial notch of the proximal ulna is spacious enough for radial head rotation. After the appropriate shape of the radius is achieved, ulnar osteotomy should be performed to reduce the radial head through traction from the interosseous membrane.

There are some limitations in the present study. Chronic radial head dislocation is caused not only by morphological abnormalities, but also by soft tissue imbalance, such as interosseous membrane or scar tissue around the radial notch [15]. However, it is critical to reproduce the bony alignment of the radius. After this process is finished, we can devote ourselves to adjusting the stable soft tissue balance. Second, the kinematics were analyzed in healthy volunteers. Thus, it is difficult to directly conclude that this difference between the morphological and kinematic axes promises stable forearm rotation in patients with chronic radial head dislocations after ulnar osteotomy. Therefore, further studies enrolling more patients will be needed to determine how much difference between the principle axis of the proximal axis and the forearm rotation axis is acceptable. In addition, it was assumed that bone density is uniform, and only surface data of the radius were used to calculate the principle axis of inertia. However, surface data including the biceps tuberosity mainly reflect the morphological axis, and the influence of the bone marrow area is thought to be negligible. Finally, 4DCT was used to calculate the rotation axis of the forearm, in which the arm position is limited due to the field of view. However, forearm rotation was active motion, and multiple frames were used to calculate the axis. The error is thought to be acceptable considering that previous studies used two static positions [14, 21].

The present study demonstrated the relationship between the forearm rotation axis and the morphology of the proximal radius. The forearm rotation axis can be estimated from the position of the center of the radial head and the ulnar styloid. Using this axis, we can predict the shape of the radius that is stable in forearm rotation and prevents "rattling" movement of the proximal radius during forearm rotation.

Fig. 3 The principle axis of inertia represents the axis that provides the most stable rotation of a rigid body. The surface data of the radius are extended incrementally by 1% from the proximal end to the distal and the angle of the principle axis of inertia and the rotation axis, which is calculated from 4DCT, is measured. Thick line: principle axis of inertia (morphological axis) of the proximal radius. Thin line: rotation axis of the forearm (kinematic axis). θ The angle between the morphological axis of the proximal radius and the forearm kinematic axis. **a, b** Examples of the axis differences of 25% and 50% of the radial length, respectively
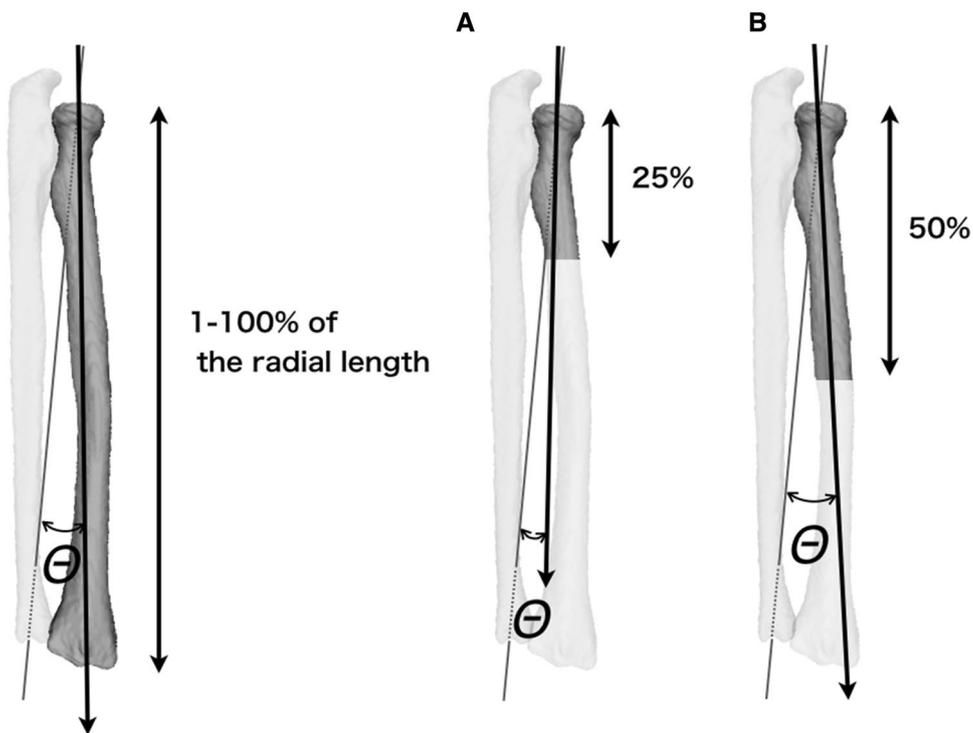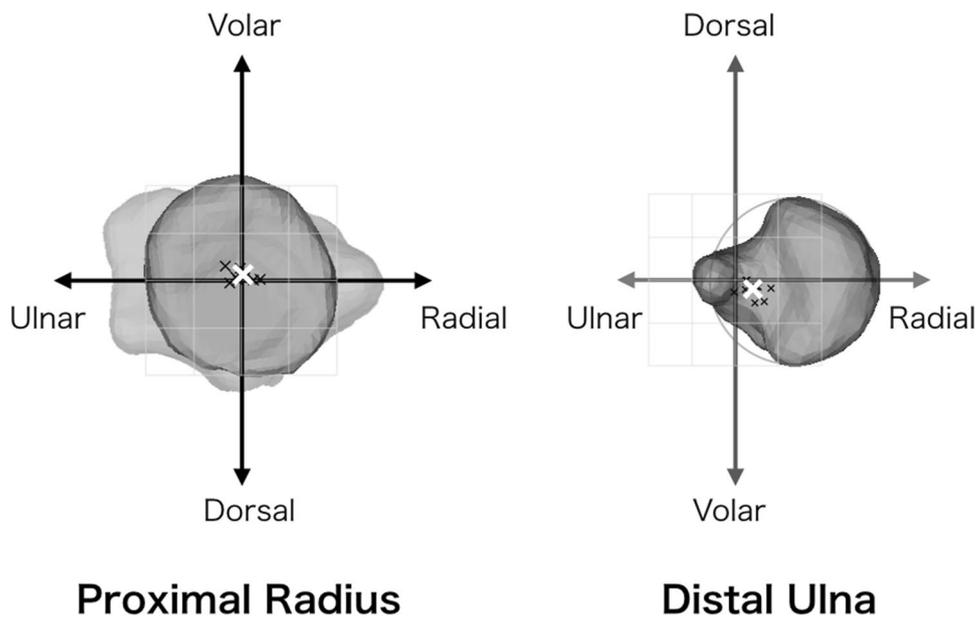
Fig. 4 The rotation axis on the proximal radius and the distal ulna. Black crosses: individual data White crosses: The average of all subjects

Significance

The relationship between the morphology of the proximal radius and the forearm rotation axis was clarified. The axis at 16% of the proximal radius should match the forearm rotation axis to restore normal rotation kinematics in cases of chronic radial head dislocation.

Fig. 5 The angle between the principle axis of the proximal radius and the rotation axis. The forearm rotation axis corresponds to the most stable axis at 16% of the proximal radius
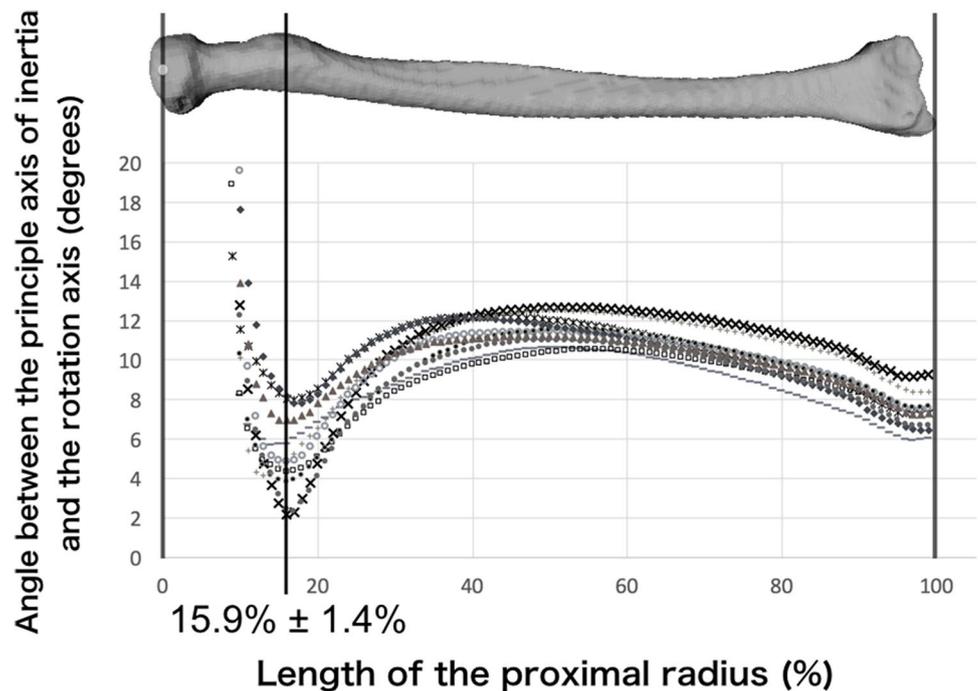
Author contributions SO: Data analysis, manuscript writing and management. NI, NM, TI and TN: Protocol development. MJ and YY: Protocol of 4DCT data acquisition.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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