A novel computational method for evaluating osteochondral autografts in distal radius reconstruction

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Published online: 4 June 2014
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Abstract

Background We describe a novel computational method for assessing the fit of an osteochondral graft. We applied our software to five normal wrist computed tomography (CT) scans to determine the fit of the scaphoid to the lunate fossa of the distal radius.

Methods CT scans of five wrists were digitally rendered. The capitate facet of the scaphoid was fit to the lunate fossa of the distal radius using custom software based on the iterative closest point (ICP) algorithm. This approach iteratively determines the optimal position of a model surface to minimize the sum of squares of distances from all points on a target surface. The fit of the two surfaces was reported by calculating the mean residual distance (MRD) between each point on one surface and its nearest neighbor on the other.

Results The MRD for the five subjects was found to be 0.25 mm, with 82.8–98.3 % of the articular surfaces within 0.5 mm of each other.

Conclusions We have developed a software algorithm for comparing two articular surfaces to test fit for a proposed joint reconstruction. The software is versatile and may be applied to any bony surface to identify new graft donor sites. The fit assessment renders a richer, three-dimensional understanding of the fit of the graft as compared to traditional two-dimensional assessments.

Level of Evidence: Decision analysis, Level V

Keywords Autograft · Fracture · Wrist arthritis · Computation · Osteochondral graft · Distal radius

Introduction

Complex distal radius fractures in high-energy injuries and elderly osteopenic patients often have extensive articular comminution that is not amenable to primary fixation. In open fractures, there may be substantial bone loss with missing osteochondral fragments. Moreover, concomitant carpal fractures and dislocations are often present, presenting further treatment challenges. Primary total wrist arthrodesis has been suggested in the treatment of these difficult injuries [1]. Alternatively, motion preserving salvage procedures can be performed, including limited wrist fusion, proximal row carpectomy, and total wrist arthroplasty. Limited wrist fusion and proximal row carpectomy (PRC) require an intact lunate fossa of the distal radius and may not be options in cases with substantial articular surface loss. Total wrist arthroplasty is contraindicated in younger, more active patients due to concerns of high complication rates in high demand patients [2].

Autogenous osteochondral graft reconstruction of the articular surface of the distal radius has been described in small clinical case series [3–7]. Prior studies of osteochondral graft reconstruction of the distal radius have not included quantitative analysis of fit. We have developed a computational technique to assess the fit of an osteochondral graft using the iterative closest point (ICP) algorithm. This approach iteratively determines the optimal position of a model surface to minimize the sum of squares of distances from all points on a target surface.

The scaphoid is an ideal potential osteochondral donor graft for reconstruction of the distal radius since it requires neither a separate graft harvest procedure nor additional donor site morbidity. Proximal row carpectomy is a salvage procedure used in the treatment of carpal collapse and advanced radiocarpal arthrosis. Proximal row carpectomy involves resection of the scaphoid, lunate, and triquetrum, allowing the capitate to articulate with the lunate facet of the distal radius.

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We hypothesize that the capitate facet of the scaphoid is a potential osteochondral donor graft for the lunate facet of the distal radius. The method proposed in this paper would be suitable as a quantitative approach to preoperative planning for osteochondral reconstruction using autologous donor grafts.

Materials and Methods

Computational Model

Approval of this retrospective research protocol was obtained from the University of Washington IRB in accordance with the Declaration of Helsinki prior to any data collection.

The ICP algorithm is a computational method which takes as inputs of two point clouds which represent surfaces. The algorithm begins with the “best guess” initial alignment which may be selected by the operator of the program or may be calculated automatically. Then, for each point on one surface, the program identifies the nearest neighboring point on the other surface and calculates the sum of squares of the distance between all nearest neighbor pairs. Small adjustments in positioning are automatically made, and the sum of squares is recalculated such that a global minimum is attained. A simplified example is shown in Fig. 1, wherein segments of a sphere and an ellipsoid are fitted together. In this example, the “best fit” of these two shapes is to stack the smaller shape inside of the larger like two nested bowls with their axes of symmetry aligned (Fig. 1c).

To evaluate the fit of the capitate facet of the scaphoid to the lunate facet of the distal radius, computed tomography (CT) scans of the wrists were reviewed. Inclusion criteria included freedom from fracture to the carpal bones or distal radius. Five normal wrist CT scans were selected. DICOM stacks of each wrist with slice thickness of 0.32 mm and slice spacing of 0.625 mm were segmented in ScanIP (Simpleware, Exeter, UK) to isolate the entire scaphoid and the distal radius. The segmented bones were then represented as point clouds (Fig. 2b). Regions of interest on the articular surfaces were then identified by drawing an ellipse over the appropriate area. The largest possible elliptical area was selected from the articular region of each bone. The ICP algorithm was then

Fig. 1 Segments of a sphere (a) and ellipsoid (b) rendered as point clouds. c The output of the iterative closest point program shown as a three-dimensional representation of the best relative alignment of the two surfaces. In this case, the ellipsoid is stacked inside the sphere, and the axes of symmetry of the two shapes are aligned

Fig. 2 a Distal radius and scaphoid articular surfaces in a cadaveric specimen. Gray arrowheads indicate the lunate fossa, while black arrowheads indicate the capitate facet of the scaphoid. b Digital point cloud representation of the distal radius and scaphoid. Gray arrowheads indicate the lunate fossa. Black arrowhead indicates the capitate facet of the scaphoid

applied to optimally align the two surfaces. The mean residual distance (MRD) between nearest neighbors and the standard deviation were then calculated and reported. The proportion of points <0.5 mm from their nearest neighbor were also reported, and a color plot of the distances was rendered. Poor fit was prospectively defined as $\text{MRD} > 2$ mm, as remodeling of the bone and cartilage occurs in articular step-offs of 1 mm or less.

Results

Computational Model

Results of the computational model are given in Table 1. The nearest-neighbor distances for the optimally aligned articular

Table 1 Mean residual distance and standard deviation

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Row average
Mean residual distance (mm)	0.26429	0.27837	0.18018	0.24401	0.28887	0.251144
Standard deviation (mm)	0.16513	0.20858	0.11115	0.12753	0.17872	0.158222
Percentage of nearest neighbors <0.5 mm apart	92.5	89.8	98.3	93.7	82.8	91.4

mm millimeters

surfaces of each subject are presented in Fig. 3 as contour plots. The MRD for the scaphoid reconstruction of the distal radius was found to be 0.25 mm, with 82.8–98.3 % of the contours of the articular surfaces within 0.5 mm of each other. The optimal position of the two bony surfaces is depicted in Fig. 4.

Discussion

We have developed a computational method for comparing two joint surfaces that uses CT scan images as an input. This digital comparison is more robust than manual measurement methods because it takes into account the entire articular surface of the bone. Surfaces may be transformed with six degrees of freedom to identify the best-fit orientation. Previous studies assessing graft suitability have focused on radius of curvature and linear dimensions [14, 16]. We identified areas of best and worst fit through a graphical color plot of the distances between the two surfaces. The information obtained with this technique provides a much richer understanding of intra-articular anatomy and suitability of an osteochondral graft, with wide clinical applications. The ability to assess the degree of similarity between two articular

surfaces opens the possibility of identifying multiple, novel osteochondral graft donor sites for articular injuries and may offer joint-preserving, reconstructive options when traditional treatment would require arthrodesis.

Use of autologous osteochondral grafts in the reconstruction of the articular surface of the distal radius in comminuted intra-articular fractures has previously been described [3, 4]. Mehin et al. reported two cases where an osteochondral graft from the proximal tibiofibular joint was used to reconstruct the scaphoid and lunate facets of the distal radius [3]. Roux described the use of the sigmoid notch of the distal radius to reconstruct the lunate fossa as an island transfer in five patients [4]. The radius was cut and rotated so that the sigmoid notch now served as the lunate fossa, and the distal ulna was resected. Mean follow-up was 11 years, with mean wrist flexion of 40° and extension of 25°, with full pronation and supination and grip strength of 65 % of the contralateral side. The authors ultimately abandoned the technique in favor of total wrist arthrodesis, however, due to concerns over donor site morbidity. Neither study performed quantitative analysis of quality of fit. In their analysis of graft suitability, Mehin et al. only assessed the surface area of the proximal tibia and fibular articular surface, as compared with the scaphoid and lunate facets of the distal radius [3]. The grafts were manually

Fig. 3 **a** Contour plots representing the distances between nearest neighbors when the two articular surfaces were optimally aligned for specimens 1–5. The color scale shows distances from 0 to 2 mm. **b** Distribution of nearest-neighbor distances for the plots shown in Fig. 4a

Fig. 4 The optimal position of the two articular surfaces of the scaphoid (*red*) onto the distal radius (*blue*)

curved and molded to approximate the appropriate contours of the distal radius based on visual comparison and estimation.

Use of vascularized fibular autografts as well as non-vascularized fibular head reconstruction have been described as reasonable options for complete osteochondral articular reconstruction of distal radius defects following giant cell tumor [5–7]. In their series of 12 patients with complete autogenous fibular reconstruction of the distal radius, Saini [5] demonstrated reasonable fibulocarpal articulation with mean palmar flexion of 42° and dorsiflexion of 31° . However, there were three cases of wrist subluxation due to the incongruence of the new radiocarpal articulation [5]. Similarly, Minami et al. reported carpal subluxation and degenerative changes after wrist arthroplasty with a vascularized articular fibular head. Patients who underwent a vascularized partial wrist arthrodesis with fibular shaft graft had better functional scores [6]. In addition, there is a risk of donor site morbidity with harvesting of the proximal fibula as well as dissection around the common peroneal nerve.

Numerous other osteochondral autografts have been described in the hand including the rib in carpal and finger reconstructions [8–12], medial femoral condyle to the metacarpophalangeal joint [13], the base of the small finger metacarpal to the distal proximal phalanx [14], and the metatarsal to the metacarpal [15]. Fit assessment has remained to be limited primarily to visual comparison, and in many cases, cartilage is shaped by hand with a scalpel.

Previous assessments of joint congruency, if they were performed, have relied primarily on two-dimensional representations of joint surfaces, such as X-rays, and digital or manual measurements of dimensions and radius of curvature [3, 12, 14, 16, 17]. No standard has yet been established for how closely the radii of curvature must resemble one another for an appropriate graft. More sophisticated measurement techniques relying on three-dimensional CT scan imaging are available, however. One study of the talus contour used CT scan images to reconstruct a three-dimensional image of the talus and measured depth and radius of curvature at several locations [18]. These authors demonstrated that in the coronal plane, the medial edge radius of curvature and the lateral edge

radius of curvature are significantly different [18]. This finding calls into question the adequacy of manual, two-dimensional measurement techniques such as application of circular templates to a radiograph to estimate radius of curvature since osteochondral grafts are by nature three-dimensional.

We found that the capitate facet of the scaphoid demonstrated a high degree of similarity to a native lunate facet of the distal radius. We envision application of this program in both research and clinical settings as a means to identify new potential osteochondral graft donor sites with a high degree of similarity to recipient sites. We selected this particular donor-recipient pair because the scaphoid is an often-available by-product of wrist motion-salvage procedures, including PRC and four-corner fusion, and may also be available as a donor in traumatic injuries.

There are, however, several limitations inherent in the current procedure. The 3-D point clouds of the bone surfaces are produced from CT scans, and since cartilage is radiolucent, the resulting surfaces are approximations rather than true representations of the surfaces being investigated. MRI scans are suitable for use with the software. However, CT scans are more commonly obtained for fractures and osteochondral injuries; therefore, we utilized CT scans in this study. The results may also be subject to error in selection of the joint surface area. Just as the earth appears flat to an observer on its surface, a curved surface approaches to be flat as the relative area of the sample decreases. Thus, a very good fit may be obtained when very small samples of each surface are selected. Every effort was made in this study to select the largest area possible on each surface to get the most accurate calculation of goodness of fit. The values presented here for the mean residual difference between the two surfaces are specific to the particular slice thickness and slice spacing used in the CT scans. A future study should examine the effects of variation in these parameters on MRD, particularly the identification of convergence towards an asymptotic MSR value with increasing image resolution.

Comparisons are currently limited to proposed surface replacements, because our algorithm allows the two surfaces

to penetrate each other. This is an accurate representation for a proposed replacement surface on which some points may be higher and some may be lower than the native surface. Two articulating surfaces may not penetrate, however, and surfaces are not, therefore, candidates for analysis using this current algorithm. Future donor-recipient pairs to be investigated using this software technique include the hemi-hamate for proximal interphalangeal (PIP) fracture dislocations, toe PIP as a possible donor to hand PIP, and medial femoral condyle as a donor source for carpal bone grafts.

In conclusion, we have developed a technique for assessing the fit of a proposed osteochondral autograft compared to a joint's native surface. When applied to the distal radius, this technique demonstrates that the scaphoid may be an excellent donor site for reconstruction of the lunate fossa of the distal radius. Applications for this new methodology are numerous, opening the possibility for discovery of multiple novel osteochondral grafts for joint preservation.

Conflict of Interest Kathleen M. Kollitz declares no other conflict of interest.

Jennifer W. Hsu declares no other conflict of interest.

Jerry I. Huang declares the following: consultant for Arthrex, Inc., for education and product development; grants from Arthrex, Inc., for fellowship education; honoraria from AO North America as course faculty; payment for service on speakers' bureau for Auxilium; travel and accommodation expense from Arthrex and Auxilium.

Peter R. Cavanagh declares no conflict of interest.

Statement of Human and Animal Rights No human or animals subjects were used in the above study.

Statement of Informed Consent No identifiable patient data were used in this study. All data were collected with approval of the institutional review board.

Grant Support No grants or support was received for this study.

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