Kinematic Accuracy in Tracking Total Wrist Arthroplasty With Biplane Videoradiography Using a Computed Tomography-Generated Model

Bardiya Akhbari

Department of Biomedical Engineering,
Brown University,
Providence, RI 02912
e-mail: bardiya_akhbari@brown.edu

Amy M. Morton

Department of Orthopedics,
Alpert Medical School of Brown University
and Rhode Island Hospital,
Providence, RI 02912
e-mail: amy_morton1@brown.edu

Douglas C. Moore

Department of Orthopedics,
Alpert Medical School of Brown University
and Rhode Island Hospital,
Providence, RI 02912
e-mail: douglas_moore@brown.edu

Arnold-Peter C. Weiss

Department of Orthopedics,
Alpert Medical School of Brown University
and Rhode Island Hospital,
Providence, RI 02912
e-mail: arnold-peter_weiss@brown.edu

Scott W. Wolfe

Hand and Upper Extremity Center,
Hospital for Special Surgery,
New York, NY 10021
e-mail: wolfes@hss.edu

Joseph J. Crisco

Department of Biomedical Engineering,
Brown University,
Providence, RI 02912;
Department of Orthopedics,
Alpert Medical School of Brown University
and Rhode Island Hospital,
Providence, RI 02912
e-mail: joseph_crisco@brown.edu

Total wrist arthroplasty (TWA) for improving the functionality of severe wrist joint pathology has not had the same success, in parameters such as motion restoration and implant survival, as hip, knee, and shoulder arthroplasty. These other arthroplasties have been studied extensively, including the use of biplane videoradiography (BVR) that has allowed investigators to study the in vivo motion of the total joint replacement during dynamic activities. The wrist has not been a previous focus, and utilization of

BVR for wrist arthroplasty presents unique challenges due to the design characteristics of TWAs. Accordingly, the aims of this study were (1) to develop a methodology for generating TWA component models for use in BVR and (2) to evaluate the accuracy of model-image registration in a single cadaveric model. A model of the carpal component was constructed from a computed tomography (CT) scan, and a model of the radial component was generated from a surface scanner. BVR was acquired for three anatomical tasks from a cadaver specimen. Optical motion capture (OMC) was used as the gold standard. BVR's bias in flexion/extension, radial/ulnar deviation, and pronosupination was less than 0.3 deg, 0.5 deg, and 0.6 deg. Translation bias was less than 0.2 mm with a standard deviation of less than 0.4 mm. This BVR technique achieved a kinematic accuracy comparable to the previous studies on other total joint replacements. BVR's application to the study of TWA function in patients could advance the understanding of TWA, and thus, the implant's success.

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1 Introduction

Total wrist arthroplasty (TWA) is a therapeutic solution for severe wrist joint pathology that is designed to improve function and reduce pain [1,2]. The survival of current metal-on-polyethylene TWA designs is lower (~82% prior to 10 years follow-up [3]), when compared to arthroplasty of larger joints such as the hip (~93% up to 10 years [4]) and knee (~96% up to 10 years [5]). Hip and knee implants have been optimized for biomechanical survivorship through decades of evaluation using large kinematic datasets on normal and post-arthroplasty subjects [6–9]. In contrast, TWA designs have had to develop empirically in the absence of comparable datasets on wrist or wrist arthroplasty biomechanics. It has been suggested that suboptimal kinematics of TWA components may contribute to instability and loosening [10,11]. Nonetheless, the articulation of the carpal component on the radial component has not been studied in vivo.

Biplane videoradiography (BVR) is a technology that has been used to study the dynamic three-dimensional (3D) motion of the knee, hip, and shoulder joints [12–15]. In these applications, it is essential to have accurate 3D models (usually CAD models) of the implant components. Silhouettes of the components are generated by applying ray-casting algorithms to the implant models [13,16], and the components are “tracked” by optimizing the fit of the silhouettes to images in the paired videoradiographs. For TWA, tracking the radial component is relatively straightforward due to its shape and crisp edges, which are comparable to those in femoral or humeral components of knee and hip arthroplasty. However, tracking the carpal component, which consists of a carpal plate and two screws, is challenging. The carpal plate is small, thin, and symmetrical, and it is pierced by fixation screws to the distal row of carpal bones. The screws overlap the carpal plate at various points in each video frame creating a different outline from the outline of the silhouette generated from the model of the carpal plate. Hence, a model of the carpal component with only the carpal plate will likely result in decreased tracking accuracy. In contrast, a model that contains both the carpal plate and the screws provides a large, pronounced, feature-rich model for reliable tracking. However, generating accurate CAD models of the assembled carpal components a priori is difficult because the orientation of each screw is defined at the time of surgery.

Computed tomography (CT) scanning has been commonly used to generate marker position arrays (e.g., tantalum beads implanted into the bones) and digitally reconstructed radiographs for marker-based and markerless BVR analysis of skeletal motion, respectively [17–19]. CT scanning is generally not used to generate implant models because scanning dense metal implants result in streak artifacts [20]. However, the artifacts associated with imaging smaller titanium implants (e.g., pedicle screws) can be modest [21,22]. With that in mind, we sought to implement BVR for TWA by generating a registerable model of the carpal

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component using CT scans, with intentions of getting its unique, feature-rich shape. Accordingly, the aims of this study were to develop a method for generating TWA carpal component models for use in BVR from CT images and then to evaluate the accuracy of model-image registration.

2 Methods

Methodology development and kinematic analysis were performed using BVR data generated from a single cadaver specimen. Simultaneously acquired optical motion capture (OMC) data (Qualisys, Gothenburg, Sweden) was used as the gold standard (<0.25 mm resolution in our experimental setup) for evaluating the kinematic accuracy of BVR.

2.1 Specimen Preparation and Imaging. The radius and ulna of a cadaveric right arm (female, 49 years) were fixed in neutral pronosupination with a Kirschner wire and transected 14 cm proximal to the radiocarpal joint. The proximal bone ends were potted in fast-setting urethane resin (Smooth-Cast[®] 300, Smooth-On, Inc., Macungie, PA). Small size radial and carpal components of a total wrist implant system (Universal2[™], Integra LifeSciences, Plainsboro, NJ) were then inserted by a board-certified hand surgeon. To do so, the distal radius was broached, and the radial component was press-fit without cement. The carpal component was fixed to the distal carpus by press-fitting the central peg into the capitate and inserting screws into the second metacarpal and hamate. After implantation and closing of the soft tissues, retro-reflective markers were attached to the bones for the optical motion capture. A cluster of five marker spheres was attached to the third metacarpal with nylon screws, and five individual markers were fixed to the radius through nylon standoffs (Fig. 1). Finally, a single CT scan was acquired of the wrist at the neutral position (Lightspeed[®] 16, GE Medical, Milwaukee, WI) at tube settings of 80 kVp and 80 mA and reconstructed with a 20-cm field of view, yielding transversely isometric voxels with dimensions of 0.39 mm $\times$ 0.39 mm in the transverse plane of the forearm, and 0.625 mm along its long axis (z-direction).

2.2 Instrumentation. Both BVR and OMC were performed in the W. M. Keck Foundation biplane videoradiography (XROMM) facility at Brown University.¹ The XROMM system consists of two Varian Medical Systems Model G-1086 X-ray tubes (Palo Alto, CA), two EMD Technologies model EPS 45–80 pulsed X-ray generators (Saint-Eustache, Quebec, QC, Canada), two 40 cm Dunlee (Aurora, IL) image intensifiers, and two Phantom v10 high-speed video cameras (Vision Research, Wayne, NJ). The interbeam angle was ~ 120 deg, with the source-image distances of ~ 140 cm for both X-ray sources. OMC data were acquired using eight (8) Oqus 5+ cameras (Qualisys, Gothenburg, Sweden), and the conversion between OMC and BVR coordinate systems was performed using transforms calculated from a simultaneous OMC and BVR acquisition of a cross-calibration cube [23].

2.3 Biplane Videoradiography and Optical Motion Capture Data Acquisitions. The implanted specimen was rigidly mounted to a fixed baseplate through the proximal potting. To facilitate remote manipulation of the hand, a wooden dowel was fixed to the third and fourth fingers. Motion tracking was compared for three tasks: flexion–extension (FE), radial–ulnar deviation (RU), and circumduction (CIRC). Each task was continued for three cycles, with the range limited by the operator's subjective perception of increasing wrist stiffness. The implant range-of-motion that was achieved during these tasks was approximately 68 deg flexion, 41 deg extension, 11 deg radial deviation, 10 deg ulnar deviation, 16 deg pronation, and 17 deg supination. The

Fig. 1 Marker positioning visualized from a rendered CT scan. Five retro-reflective markers were fixed directly to the radius, and five retro-reflective markers were clustered on a thermoplastic plate, rigidly fixed to the third metacarpal via nylon screws.

exposure settings for both X-ray tubes were 68 kVp and 100 mA, continuous, with a camera shutter speed of 500μ s. These settings result in a radiation exposure of ~ 0.03 mSv/s, which is within the guidelines that our institutional review board has approved for in vivo studies of the upper extremity. BVR and OMC were acquired at a rate of 120 Hz, with the start of data acquisition synchronized by an external trigger (Transistor-Transistor Logic signal and active low). The BVR radiographic images were stored in 8-bit format (resolution of $\sim 0.22 \times 0.22$ mm per pixel), and then undistorted and calibrated using XMA Lab software [17,24].

2.4 Implant Model Generation and Data Reduction. A 3D model of the implanted carpal component was constructed from the CT images via threshold-based automatic segmentation using MIMICS[®] (Materialise, Leuven, BE), followed by modest manual

Fig. 2 Photo of a Universal2[™] carpal component (left), and a 3D digital model generated via thresholding and manual editing of CT images (right)

¹<http://www.xromm.org/>

Fig. 3 (a) Neutral posture of the components along with their respective coordinate system; red, green, and blue vectors depict the x-axis (pronation/supination), y-axis (flexion/extension), and z-axis (radial/ulnar deviation). (b) and (c) The edges of the carpal and radial components of the implanted Universal2™ TWA super-imposed on the neutral frame radiographs as captured in the BVR cameras. (d) and (e) The silhouettes of the carpal and radial components of the implant on the neutral frame radiographs.

editing. The manual editing involved the slice-by-slice closing of edge defects and removal of artefactual connections to the radial component. Finally, a digital model of the edited carpal component was exported in STL format (Fig. 2). An STL model of the explanted radial component was generated with the use of an industrial 3D surface scanner (Artec Space Spider™, Artec 3D, LU) with a resolution of 0.1 mm. Generation of radial component models from CT images was unsatisfactory due to streak artifacts that obscured the implant surfaces. The carpal component model contained 7,098 triangles, and the radial component model contained 20,012 triangles.

The BVR and OMC kinematic data were reported in a radius-based coordinate system defined by features of the TWA radial component. The origin of the radius-based coordinate system was located at the geometric center of the radial tray, with the y- and z-axes directed radially and volarly, respectively, parallel to the implant's proximal cut-plane surface (Fig. 3(a)). The x-axis was generated by the cross-product of the y- into the z-axis. A similar coordinate system was generated for the TWA carpal component, with the origin located at the geometric center of the proximal face of the carpal plate, and the y- and z-axes directed radially and volarly, respectively, parallel to the plate's surface. The x-axis was generated by the cross-product of the y- into the z-axis (Fig. 3(a)).

The positions and orientations of the radial and carpal components were calculated for each frame of the OMC and BVR datasets. The gold-standard OMC-derived kinematic data were generated using a custom-written MATLAB code (R2017b, The Mathworks, Inc., Natick, MA). Briefly, the retro-reflective marker signals were smoothed with a fourth-order low pass Butterworth filter with a normalized cutoff frequency of 0.033 Hz [25], and the rigid body transformations for the hand and radius marker clusters were calculated using the Söderkvist singular value decomposition method [26]. The transformations from the marker clusters to the implants coordinate system were calculated based on their relative position in the neutral frame and then applied to the carpal and radial components with the assumption that the marker clusters were rigidly affixed to the implant components.

Fig. 4 Definition of rotation angles and planar ICR for the motion of the carpal components relative to the radial component (this figure depicts only a sagittal plane intersection). In HAM parameters, $\vec{n}$ is the vector defining the orientation of the screw axis (n_x , n_y , and n_z), and ϕ_{tot} is the rotation about the screw axis. This angle can be decomposed into rotational components ($\phi_{tot} \cdot n_x$, $\phi_{tot} \cdot n_y$, and $\phi_{tot} \cdot n_z$). The screw axis intersects each plane of the radial component coordinate system, providing a plane-specific ICR.

Fig. 5 Bland-Altman plots of carpal component rotations throughout each task (flexion–extension, RU deviation, and CIRC) calculated from the BVR and OMC data. Columns report the rotation angles in the radial component's coordinate system for each task (Rows). Across all tasks and directions, there was a bias of less than 1 deg, and the limits of agreement were less than 2 deg for all tasks.

The BVR kinematic data for TWA components were generated using JointTrack Biplane open-source image registration software,² which utilizes two cost functions: contour-matching and intensity-matching (Figs. 3(b)–3(e)) [14]. Within JointTrack, the intensity thresholding parameters (low and high) and edge detection parameters (aperture and thresholding) were selected manually, based on an assessment of implant 2D fit to the BVR images. Both intensity and contour metrics were minimized for the radial component; however, only the intensity metric was used for the carpal component since the Canny edge detection method was suboptimal on the thread features of the screws [14].

To facilitate interpretation, implant kinematics are reported relative to the “neutral” wrist position based on the congruency and alignment of carpal and radial component. The kinematics are described by helical axis of motion (HAM) parameters. HAM parameters describe rigid body kinematics between two positions in terms of rotation (ϕ) about, and a translation along a unique axis in space (i.e., screw axis). Rotational components of the carpal component were decomposed using ϕ angle and the vector components of the screw axis (Fig. 4). Translations were defined as the displacement of the origin of the coordinate system. The planar instantaneous center of rotation (ICR) was defined as the intersection of the screw axis with each plane of the radial component coordinate system (Fig. 4). Since the HAM description of ICR and screw axis is unstable when the axis is parallel to an anatomical plane, a cut-off angle of 5 deg was chosen before comparing the ICR locations between the methods.

2.5 Statistical Analyses. BVR accuracy was determined by direct comparison of the BVR-calculated rotational parameters (flexion–extension, radial–ulnar deviation, and pronation–supination) and translational parameters (radial–ulnar, volar–dorsal, and proximal–distal displacements) to those determined via OMC using Bland-Altman analysis. The root-mean-squared-error (RMSE) of the differences between the two techniques was used as an estimate of the overall accuracy. The planar ICR was evaluated by determining the bias and precision for each task and intersection plane.

3 Results

Overall, the BVR-calculated kinematic parameters were consistent with the gold standard OMC-calculated parameters (Figs. 5 and 6). The bias in calculated flexion/extension, radial/ulnar deviation, and pronosupination angles between the two methods was less than 0.3 deg, 0.5 deg, and 0.6 deg for all tasks (Fig. 5). Among all tasks, Bland-Altman plots of the rotation angle data demonstrated limits of agreement (95% CI) between -1.2 deg and 0.9 deg for flexion/extension angle, -1.6 deg to 1.4 deg for radial/ulnar deviation, and -1.8 deg to 0.8 deg for pronation/supination measurements. The maximum RMSEs of the rotations were 0.4 deg, 0.7 deg, and 0.7 deg, respectively, for the flexion/extension, radial/ulnar deviation, and pronation/supination motions among all FE, RU, and CIRC tasks (Table 1). The differences in calculated translations between BVR and OMC had a bias of less than 0.2 mm with standard deviations less than 0.4 mm (Fig. 6), and submillimeter limits of agreement among all tasks. The limit of agreement was between -0.8 mm to 0.7 mm, and the overall

²<https://sourceforge.net/projects/jointtrack/>

Fig. 6 Bland-Altman analysis of carpal component translations throughout each task (flexion–extension, RU deviation, and CIRC) calculated from the BVR and OMC data. Columns report the translations in the radial component’s coordinate system for each task (rows). The Bland–Altman analysis demonstrates a trivial bias of less than 0.2 mm, and the limit of agreement of less than 1 mm for all tasks.

RMSE was less than 0.30 mm for all translational components (Table 1). The differences in rotation and translation between BVR and OMC did not follow a consistent pattern in any of the tasks.

Planar ICR location calculated by BVR showed an overall bias of less than 1 mm in most of the planes. ICR location’s bias was higher than 1 mm only for the YZ-plane in CIRC and FE tasks, and for the XY-plane in RU task (Table 2). Higher standard deviation in ICR accuracy was seen for the YZ-plane since the screw axis is expected to be parallel to that plane in most of the poses. The overall precision of ICR calculation was less than 3 mm among all planes.

4 Discussion

The aims of this study were to generate a carpal component model from CT image volumes for tracking TWA kinematics

Table 1 Overall RMSE of the differences between OMC and BVR for rotations (deg) and translations (mm) for all tasks. For each task, RMSE rotations are reported for the components of FE, RU deviation, and pronosupination (PS). RMSE translations are reported for the components of radioulnar (RU), volar/dorsal (VD), and proximal/distal (PD).

Task	RMSE rotation (deg)			RMSE translation (mm)		
	FE	RU	PS	RU	VD	PD
Flexion–extension	0.3	0.5	0.5	0.2	0.2	0.2
RU deviation	0.4	0.5	0.5	0.2	0.1	0.1
CIRC	0.4	0.7	0.7	0.3	0.2	0.2

using BVR, and then to evaluate the accuracy of tracking using model-image registration. Three range-of-motion tasks were evaluated and compared to OMC as the gold-standard. Compared to OMC, we found a submillimeter and subdegree bias for BVR-generated rotations and translations across all tasks. The rotation angles and translations had limits of agreement of less than 1.8 deg and 0.8 mm, respectively. These variations are of the same order of magnitude as differences seen in other studies for other implants [12–14,27].

The technique reported here can detect changes in TWA kinematics of ~0.8 mm translation and 1.8 deg rotation. Evaluating the TWA motion is important for understanding its biomechanics and its differences with normal wrist motion. The previous in vivo

Table 2 Differences (mean ± std.) in ICR location (millimeter) between BVR and OMC for the motion of the carpal component relative to the radial component. Tasks are FE, RU deviation, and CIRC. The axis directions are distal (–)/proximal (+), ulnar (–)/radial (+), and dorsal (–)/volar (+). (NA—measurement not applicable).

Task	Component	XY-plane	XZ-plane	YZ-plane
Flexion–extension	x (DP)	0.1±1.2	0.2±1.1	NA
	y (UR)	–0.3±2.3	NA	–3.4±6.5
	z (DV)	NA	–0.2±3.2	–0.4±2.8
RU deviation	x (DP)	0.7±3.2	–1.0±2.8	NA
	y (UR)	–1.3±4.7	NA	–1.6±6.4
	z (DV)	NA	–0.3±2.8	–1.6±4.8
CIRC	x (DP)	0.1±1.0	0.3±1.6	NA
	y (UR)	0.0±2.4	NA	2.0±4.6
	z (DV)	NA	–0.2±1.8	–0.9±2.9

studies on TWA have used electrogoniometers and OMC systems to evaluate the overall wrist range-of-motion after TWA [28,29]; however, these techniques have a high cross-talk error (up to 5 deg) or soft-tissue artifact [23,30]. Here, we demonstrated the BVR's high accuracy in calculating the kinematics of the TWA; hence, investigators may be able to achieve much higher accuracy in studying TWA kinematics in vivo using BVR. Moreover, an accurate measurement of the center of rotation is required for comparing the implant kinematics to the normal joint kinematics [31]. Specifically for the wrist joint, large control databases exist [32] that can be used for comparing the implant ICR location in different planes of motion. Without having an accurate measuring system, the sample size needed to evaluate statistically significant differences among TWA designs, or between TWA and control subjects, could be prohibitive to study.

Total Wrist Arthroplasty has not been previously studied using markerless registration in BVR; however, total knee and hip arthroplasty have been studied in various settings. Tsai et al. evaluated the accuracy of dual fluoroscopic systems for total hip arthroplasties by marker-based radiostereometric analysis (RSA), and they found an accuracy of within 0.33 ± 0.81 mm in translations and 0.45 ± 0.65 deg in the rotation in dynamic motions [12]. Mahfouz et al. compared the kinematics of total knee arthroplasty studied by fluoroscopy to its actual movement measured by the optical sensor. They found an RMS deviation of ~ 0.4 deg in rotation and 0.1 mm of translations in the transverse plane, but up to 1.4 mm difference in translations in superior/inferior directions [14]. Here, we found a bias of ~ 0.2 mm for translations and a bias of less than 0.5 deg for rotations, which is in the same order of magnitude to the bias that the previous studies have found.

In this study, OMC was used as the "gold standard" because of its submillimeter accuracy. Due to the rigid fixation of the implants to the bones, we assumed rigid body motion, which was confirmed with RMSE of less than 0.2 mm in Söderkvist method for our marker clusters (each using 5 markers) [26,33]. Evaluating any inherent movement between metacarpals, screws, or the radial stem and the bones was not assessed here, although the inspection of the in situ implant components after the experiment did not display any loosening.

There are some general limitations in studying the implant kinematics with BVR. The obtained radiographic images and the thresholding parameters affect the outcome of the optimized kinematic pose. Hence, we propose that future investigators optimize the thresholding hyperparameters based on the image quality by inspecting the output of the optimization cost function. Until a robust technique is achieved to make the process less susceptible to image parameters, this limitation cannot be fully eliminated. Moreover, the implant posture in the radiographic images can highly affect the accuracy of the outcome. In this study, we found higher inaccuracies in the images where implant location was occluded by thenar muscles, and/or two screws were overlapping each other. In contrast, radiographs with two high-quality images that clearly demonstrated the implant's unique features had results that were consistent and subdegree accurate. Reconstructing a 3D model from CT images was unsuitable for the radial component studied here due to the large streak artifacts caused by the highly attenuative solid cobalt-chromium stems. In such cases, the radial component models will need to be generated from original CAD files, or via surface scanning of size- and manufacturer-matched implants. This is not an insurmountable challenge, as the number of different radial implants presently in clinical use is relatively modest.

In addition to the inherent limitations of BVR, there are additional limitations in our study. One specimen was studied in our experiment, but we believe that the findings would be similar if the generated model and the quality of scans remain comparable. We used one implant design and results might vary with others but given the similar geometry and material of the implants, we do not expect a large difference across the current designs. The Canny edge detection method (which filters the intensity gradients

of the image using double threshold parameters to determine potential edges) failed to detect continuous edges for the screws of the carpal component because of the relatively high image noise in the region of screw threads. Hence, edge-matching was not used for tracking the carpal component. Finally, a key assumption of our tracking method is that the carpal component and its screws are rigidly fixed relative to each other and to the bones of the hand. Loose screws or carpal component would most likely decrease the accuracy of our tracking approach. Future modifications to our approach may enable measurements of loosening, which could be used to examine mechanisms behind the failures of TWA in a longitudinal study of patients.

To summarize, we demonstrated that the CT-generated model of a TWA system could be used in BVR for accurately measuring dynamic wrist motion. Our methodology's bias was on the order of a degree and submillimeter, achieving an accuracy comparable to the previous studies on other total joint replacements that have used the high-fidelity CAD model of the implants for BVR tracking. Future studies employing this technique will enable the kinematic study of TWA during various functional tasks (e.g., pitcher pouring, hammering, or twisting a doorknob) with the aim of improving the understanding of TWA function in patients.

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