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ARTICLE INFO

Article history:
Accepted 7 October 2010

The author would like to amend an error in the above article, where an incorrect value was given for the typical fluoroscope settings in Section 2.3, ‘Testing procedure’. The first paragraph of this section appears correctly here:

2.3. Testing procedure

Immediately following the CT scan, the specimen was rigidly fixed with eight 3 in. drywall screws to a 1.25 in. acrylic plate as part of a custom apparatus through the pedicles of the spine (Fig. 2). The experimental setup allowed for unconstrained motion of both shoulders while not permitting lateral bending, flexion/extension and twist of the trunk. The shoulder tested was placed with the glenohumeral joint centered in the imaging volume created by the dual fluoroscopes. Details of the imaging system (Li et al., 2004) have been previously described. Briefly however, the system consists of two digital fluoroscopes (12 in. BVPulsera, Phillips Medical, USA) arranged with the image intensifiers skewed from the orthogonal at approximately 120° to permit unconstrained motion of the shoulder joint. The typical fluoroscope settings were 55 kV and 5.0 mA. Images were acquired with a pulse width of 8 ms and 30 frames per second. These image settings deliver an equivalent ionizing radiation dose of 0.072 μSv per image or equivalently 0.26 mSv per minute for both fluoroscopes.
Non-invasive determination of coupled motion of the scapula and humerus—An in-vitro validation

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Article info

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Accepted 7 October 2010

Keywords:
Shoulder
Kinematics
Fluoroscopy
Radiostereometric
Validation

Abstract

Measuring the motion of the scapula and humerus with sub-millimeter levels of accuracy in six-degrees-of-freedom (6-DOF) is a challenging problem. The current methods to measure shoulder joint motion via the skin do not produce clinically significant levels of accuracy. Thus, the purpose of this study was to validate a non-invasive markerless dual fluoroscopic imaging system (DFIS) model-based tracking technique for measuring dynamic in-vivo shoulder kinematics. Our DFIS tracks the positions of bones based on their projected silhouettes to contours on recorded pairs of fluoroscopic images. For this study, we compared markerless tracking the bones of the scapula and humerus to track them with implanted titanium spheres using a radiostereometric analysis (RSA) while manually manipulating a cadaver specimen’s arms. Additionally, we report the repeatability of the DFIS to track the scapula and humerus during dynamic shoulder motion. The difference between the markerless model-based tracking technique and the RSA was \( \pm 0.3 \) mm in translation and \( \pm 0.5 \) in rotation. Furthermore, the repeatability of the markerless DFIS model-based tracking technique for the scapula and humerus was \( \pm 0.2 \) mm and \( \pm 0.4 \), respectively. The model-based tracking technique achieves an accuracy that is similar to an invasive RSA tracking technique and is highly suited for non-invasively studying the in-vivo motion of the shoulder. This technique could be used to investigate the scapular and humeral biomechanics in both healthy individuals and in patients with various pathologies under a variety of dynamic shoulder motions encountered during the activities of daily living.

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1. Introduction

The shoulder joint, often referred to as the glenohumeral joint in most biomechanical studies, has the greatest range-of-motion of any joint in the human body. An in-depth understanding of shoulder joint biomechanics is instrumental for helping prevent shoulder injury and improving surgical treatment modalities for shoulder pathologies. However, due to its complicated anatomy and large range-of-motion, measuring the dynamic in-vivo kinematics of the shoulder joint is a challenging problem in the field of biomechanics.

Numerous techniques have been developed to study the in-vivo biomechanics of the human shoulder. A comprehensive review of techniques has been compiled by Hill et al. (2007). In a brief summary, in-vivo dynamic shoulder biomechanics have been investigated using the following modalities: electromagnetic tracking (McClure et al., 2001; Borstad and Ludewig, 2002; Crosbie et al., 2008; Ebaugh et al., 2005; Fayad et al., 2008), single plane fluoroscopy (Nishinaka et al., 2008; Kon et al., 2008), magnetic resonance imaging (Graichen et al., 2000a, 2000b; Rhoad et al., 1998; von Eisenhart-Rothe et al., 2002; Hodge et al., 2001), radiostereometric analysis (RSA) (Hallstrom and Karrholm, 2006, 2009; de Bruin et al., 2008), biplane radiography (Bey et al., 2008, 2007, 2010), and optical motion tracking (Inui et al., 2009; Dun et al., 2008; Murray et al., 2001; Fleisig et al., 2006; Barrentine et al., 1998). Additionally, a dual plane fluoroscopic imaging system (DFIS) (Li et al., 2004) has been used to report glenohumeral contact kinematics in healthy volunteers (Boyer et al., 2008) and in patients with total shoulder arthroplasty (Massimini et al., 2010) during quasi-static shoulder motion. However, the use of a DFIS for tracking the scapula and humerus during dynamic shoulder motion has not been assessed.

Therefore, the purpose of this study was to validate a non-invasive markerless model-based tracking technique using a DFIS to quantify the kinematics of the scapula and humerus during dynamic shoulder motion. A radiostereometric analysis (RSA) (de Bruin et al., 2008; Kedgley et al., 2009; Vrooman et al., 1998; Valstar et al., 2000) marker-based tracking technique was used as a reference for measuring shoulder kinematics during simulated shoulder motion of a cadaver specimen. Previously our laboratory...
has validated this technique in the knee (Li et al., 2008), spine (Wang et al., 2008) and ankle (Wan et al., 2006); and based upon these results, we hypothesized that the technique would track the scapula and humerus similarly to the RSA. In addition, the repeatability of the DFIS model-based tracking was assessed for the scapula and humerus in 6-DOF.

2. Material and methods

2.1. Specimen preparation

One male fresh-frozen cadaver torso (age, 30) with upper extremities intact was acquired. The specimen was stored at −20 °C until thawed at room temperature for testing. Titanium spheres 1/8 in. diameter were implanted into the scapula and humerus of both shoulders by an orthopaedic surgeon. For the scapula, a superior approach was utilized along the scapular spine. One sphere was implanted into the acromion, three spheres along the scapular spine and one sphere near the spinoglenoid notch. For the humerus, a deltopectoral approach was utilized to directly visualize the lateral aspect of the humeral head. Five spheres were implanted broadly distributed into the lateral cortical bone of the humeral head and away from the articular cartilage. The procedure used to implant the titanium spheres was as follows: (1) directly visualize the location to implant the sphere; (2) mark the location with the tip of a Steinman pin; (3) drill a 3/32 in. diameter hole through the marked location; and (4) gently hammer the sphere into the undersized hole until flush with the bone surface. The compression of the cortical bone securely held the spheres from dislodging. A running locking stitch was used to close the deltopectoral and superior approaches.

2.2. Bone model reconstruction

The specimen was CT scanned in a LightSpeed Pro 16 (GE Healthcare). The scanner captured the torso in 281 axial slices with an image spacing of 0.625 mm, capturing from the acromion to approximating motion of the shoulder joint. The typical fluoroscope field of view was approximately 280 by 420 mm with an image resolution of 512 by 512 pixels. DICOM files of the scan were transferred to a personal computer and automatically segmented by an in-house custom MATLAB (The Mathworks Inc., Natick, MA) script based on the intensity gradient of each pixel. The segmented contours were imported into Rhinoceros 3D (Robert McNeel & Associates, Seattle, WA) and arranged into layers based on the intensity gradient of each pixel. The segmented contours were imported into Rhinoceros 3D (Robert McNeel & Associates, Seattle, WA) and arranged into layers corresponding to the CT slice spacing of 0.625 mm. B-splines were connected between the segmented contours to create 3D surface meshes of the scapula and humerus (Fig. 1). The average mesh size was 36,000 polygons and 15,000 vertices. Two sets of bone models were reconstructed, one with titanium spheres for RSA tracking and one with the spheres removed for model-based tracking.

On the right shoulder complex, a coordinate system was created on the scapula by constructing a line between the superior and inferior rim of the glenoid. The midpoint of this line was taken as the origin. The positive Y-axis was defined along this line in the direction of the origin to the superior rim. The positive X-axis was defined perpendicular to the Y-axis in the direction of the origin to the anterior glenoid rim. The positive Z-axis was constructed as the cross product of the X-axis and the Y-axis (Fig. 1). Similarly, a humeral coordinate system was created by fitting a sphere to the humeral head. The center of the sphere was taken as the origin. The Y-axis was defined along the line from an area centroid of the bony contour of the humeral head to the vertical and simulated a cycle from maximum internal to external rotation. The positive sense of the Z-axis was from the origin in the direction of distal to proximal. The positive Z-axis was defined perpendicular to the Y-axis from the origin in the direction of the greater tuberosity. Lastly, the positive X-axis was defined as the cross product of the Y-axis and the Z-axis (Fig. 1). A coordinate system for the left shoulder complex was created similar to the right shoulder complex, but the direction of the Z-axis was flipped to maintain a right hand coordinate system.

2.3. Testing procedure

Immediately following the CT scan, the specimen was rigidly fixed with eight 3 in. drywall screws to a 1.25 in. acrylic plate as part of a custom apparatus through the pedicles of the spine (Fig. 2). The experimental setup allowed for unconstrained motion of both shoulders while not permitting lateral bending, flexion/extension and twist of the trunk. The shoulder tested was placed with the glenohumeral joint centered in the imaging volume created by the dual fluoroscopes. Details of the imaging system (Li et al., 2004) have been previously described. Briefly however, the system consists of two digital fluoroscopes (12 in. BV Pulsera, Philips Medical, USA) arranged with the image intensifiers skewed from the orthogonal at approximately 120° to permit unconstrained motion of the shoulder joint. The typical fluoroscope settings were 0.5 kV and 0.5 mA. Images were acquired with a pulse width of 8 ms and 30 frames per second. These image settings deliver an equivalent ionizing radiation dose of 0.072 μSv per image pair or equivalently 0.26 mSv per minute for both fluoroscopes.

Two motion patterns were simulated by manually manipulating the specimen’s arms: abduction/adduction and internal/external rotation. The right shoulder was tested in abduction/adduction at approximately 79° and 180° and in internal/external rotation at 130°. The left shoulder was tested in abduction/adduction at approximately 62° and 128° and in internal/external rotation at 65°. Abduction/adduction motion was in the coronal plane and simulated approximately 0° to 130° cycle (abduction beyond 130° was not tested as superior migration of the humeral head was noted causing impingement). Internal/external rotation of the humerus about its long axis was tested in the scapular plane at 90° abduction of the humerus to the vertical and simulated a cycle from maximum internal to external to internal rotation (approximately 360° total rotation). In total, six motion patterns...
were simulated. The rotation rates were controlled with a stopwatch. The objective was a fast and slow abduction/adduction cycle for each shoulder. For the right shoulder, 79 °/s ± 3 ° cycle and 180 °/s ± 1.5 ° cycle. For the left shoulder, 62 °/s ± 4 ° cycle and 128 °/s ± 2 ° cycle. For internal/external rotation, we arbitrarily chose which shoulder received the fast or slow rotation rate of 118 °/s ± 3 ° cycle and 65 °/s ± 6 ° cycle.

2.4. Dual fluoroscopic imaging system (DFIS)

The recorded fluoroscopic image pairs were transferred to a personal computer workstation (2.4 GHz Xeon Quad Core, Dell Inc., USA) for image processing and analysis. Each image was corrected for geometric distortion caused by environmental perturbations of the X-ray beam and from the slightly curved surface of the image intensifier. An adapted (Gronenschild (1997, 1999) global surface mapping technique was utilized. A virtual representation of the physical DFIS was created in solid modeling software (Rhinoceros 3D, Robert McNeel & Associates, Seattle, WA) to identify the geometry of the physical fluoroscopes used for testing, termed a virtual DFIS. The corrected pairs of fluoroscopic images were imported into the virtual DFIS and placed on their respective virtual intensifier. Similarly, the reconstructed 3D bone models of the scapula and humerus were imported into the virtual DFIS for kinematics reconstruction.

2.5. Model-based tracking technique

The technique of model-based tracking has its roots in stereophotogrammetry (Selvik, 1989). To briefly summarize this technique, a ray trace is constructed from a point on an image plane to the source location from two or more independent views. The intersection of these rays determines the 3D position of the point in space. By simultaneously tracking multiple points on an object, the 3D position of the object in space can be determined. Model-based tracking employs a variation of this technique to determine the 3D object position based on its projected silhouette, to segmented contour in place of individual points. The scapula and humerus bone contours were manually segmented from the fluoroscopic images within the virtual DFIS. Bone models of the scapula and humerus with titanium spheres removed were manually translated and rotated within the virtual DFIS until their projected silhouettes aligned with the segmented contours on both image planes simultaneously; thereby recreating the positions of the scapula and humerus (Fig. 3). One researcher (D.F.M) performed all data analysis. This model-based tracking procedure was used to calculate a standard deviation, variance, and standard error of the mean in translation (X, Y, and Z) and rotation (Euler angles). The standard deviations calculated were taken as the repeatability of the model-based tracking technique. One researcher (D.F.M) extremely familiar with the matching technique performed the repeatability assessment.

3. Results

3.1. Comparison of the model-based with RSA

The data obtained from the dynamic non-invasive model-based tracking technique compared to the RSA marker-based technique are shown in Table 1. The average difference between the two techniques was 0.27 ± 0.19 mm and 0.49 ± 0.36° for all simulated motions of the scapula and humerus, respectively. The rotation rate (62 °/s, 79 °/s, 128 °/s, and 180 °/s) of the long axis of the humerus in abduction/adduction did not influence the magnitude of the difference between the two tracking techniques. However, internal/external rotation about the long axis of the humerus from 65 °/s to 118 °/s showed an increase in magnitude of rotation about the long axis of the humerus from 0.78 ± 0.31° to 0.91 ± 0.35° between the two tracking techniques.

3.2. Model-based repeatability

The average repeatability of the model-based tracking technique was ±0.13 mm and ±0.44° for the humerus and ±0.23 mm and ±0.42° for the scapula in ten independent matches for the left and right shoulder combined. The translational repeatability of the humerus was about half the magnitude of the scapula, whereas the rotational repeatability was about the same (Table 2).

4. Discussion

This study presents the translation and rotation differences between a non-invasive markerless DFIS model-based tracking technique for measuring shoulder biomechanics with respect to a widely accepted RSA (de Bruin et al., 2008; Kedgley et al., 2009; Vrooman et al., 1998; Valstar et al., 2000) marker-based technique during simulated dynamic shoulder motion. The results show that this dynamic model-based tracking technique was close to the RSA within approximately ±0.3 mm in translation and ±0.5° in rotation. The simulated shoulder motion or rotation rate did not detrimentally influence the performance of the model-based
Dynamic markerless biplane radiography applied to the extreme motions of the shoulder by preventing skin motion over bone and an electromagnetic tracking system have been used for tracking techniques have the ability to capture extremely fast movements (Bey et al., 2006) and puts the healthy volunteer through an experiment, flexion/extension was not examined as the fluoroscopy setup and cadaver fixturing apparatus interfered in such a manner to restrict this motion pattern. However, for capturing the activities of daily living in healthy volunteers this will not impose a limitation, as a fixturing apparatus will not be used. In addition, fluoroscopic image acquisition using a 3 ms pulse width does limit the maximum rotation (Varadarajan et al., 2008) rate of the shoulder joint. Although in the present study, we did not determine the maximum rotation rate, but found that rotation rates up to 180°/s are within the DFIS capabilities and this was sufficient for quantifying the kinematics of the activities of daily living. Furthermore, the scapular and humeral coordinate systems were not based on the recommendations of the ISB (Wu et al., 2005), as these require a more complete model of the humerus and scapula for anatomic landmarks. The imaging protocol employed, which images to approximately the mid-shaft of the humerus and based on a previous protocol (Boyer et al., 2008) for generating 3D bone models is based on reducing living subjects’ exposure to radiation and scan time. Coordinate systems based upon these 3D models does not influence the ability to investigate glenohumeral contact as has been previous studied (Boyer et al., 2008; Massimini et al., 2010).

In conclusion, we present a non-invasive model-based DFIS tracking technique for quantitatively measuring the dynamic biomechanics of the human shoulder joint. This dynamic model-based tracking technique achieves an accuracy that is similar to an invasive RSA marker-based tracking technique. This technique could be a useful tool to investigate the scapular and humeral biomechanics in both healthy individuals and in patients with various pathologies under a variety of dynamic shoulder motions encountered during the activities of daily living.

Conflicts of interest statement

The authors of this manuscript have nothing to disclose that would bias our work.

Table 1

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Table 2

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Funding

This funding project was from unrestricted internal hospital research funds. No external funding sources were used for any part of this study.

References


