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Feasibility of reconstructing the glenohumeral center of rotation with a single camera setup

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Abstract

Background: An accurate estimation of the glenohumeral joint center of rotation (CoR) is important during alignment of braces and exoskeletons, as a misalignment will introduce undesired forces on the human body. The aim of this research was to develop a new method to estimate the glenohumeral CoR and register the location to the body using a single camera and two printed markers.
Methods: During shoulder anteflexion, the arm roughly describes an arc in the sagittal plane, with the glenohumeral joint in the center. Two binary square-fiducial ArUco markers were secured to the upper arm and the scapula, their position and orientation were obtained, and a sphere was fitted to the coordinates of the arm marker. The sphere center position was then registered on the skin. The accuracy was assessed with a test bench with a known rotational center. The repeatability was assessed in vivo with five healthy participants.
Results: The mean absolute offset between the true CoR of the test bench and the fitted sphere centers across multiple trials was 2.7 mm at a velocity of 30 degrees/s, and 2.5 mm at 60 degrees/s. The root mean squared distance from the estimated sphere centers after each trial to the mean sphere center across all trials per participant was 5.1 mm on average for the novice examiner and 5.2 mm for the expert examiner.
Conclusions: The proposed method is able to accurately and precisely estimate the glenohumeral CoR.

Keywords
center of rotation, shoulder, brace, exoskeleton, alignment, glenohumeral joint, functional method, fiducial markers

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Background

The center of rotation (CoR) is the point around which an object rotates. Locating the CoR of a limb inside a joint is important when aligning braces and exoskeletons. A misalignment between the CoR of a brace or exoskeleton and the anatomical CoR creates undesired forces on the human body and will negatively interfere with the working principle of the brace or exoskeleton.[1]

Recently, we developed a shoulder brace that provides support to patients with shoulder pain because of glenohumeral subluxation.[2] Springs apply a restoring force between the humerus and glenoid joint surface of the scapula, such that the joint is repositioned while residual motion is not impeded. Correct positioning of the springs that create this upward force depends on a correct estimation of the glenohumeral joint CoR (GH-CoR) in the sagittal plane. Incorrect assumptions about the location of its rotational center will create external forces that impede arm movement.

Typically, brace alignment involves positioning a mechanical (2D) hinge relative to a plane of motion. So, instead of representing the CoR as a three-dimensional coordinate, we only have to deal with the CoR as a two-dimensional coordinate. Brace alignment requires a reliable method to accurately locate the GH-CoR using low-cost equipment. Also, the estimated location should be easily registered on the patient's body to allow alignment of the brace to the estimated CoR. Besides, the method should be quickly performed to be accepted in the clinical practice.

CoR estimation

During brace alignment, often bony landmarks are palpated to estimate the location of the rotation axis of a joint. Unfortunately, palpation of the GH-CoR is not possible as it is an internal anatomical landmark.[3]

Functional identification methods estimate the CoR from the relative motion of adjacent body segments. Motion of one segment is recorded with respect to another segment.[4] A spherical or circle fit on the cluster of the measured marker positions will reveal the rotational center of the joint in 3D or 2D, respectively. These methods are valid for the glenohumeral joint because it can be considered a spherical (or ball-and-socket) joint with a fixed rotational center.[5]

Different techniques have been proposed to obtain the relative motion of moving body segments, including (miniaturized) magneto-inertial measurement units,[6-9] optical motion tracking with two or more synchronized cameras[4,10-12] (e.g. stereophotogrammetry[13]), electromagnetic tracking,[3,14] or ultrasound.[12] Many of these methods involve the use of expensive equipment, or are time-consuming, which limits their availability and usability.

Square-based fiducial markers

Square-based fiducial markers are passive markers that are placed in the field of view of a camera. Knowing the markers are square, their pose with respect to the camera can be estimated.[15] If the markers are attached to body segments such as the upper arm or scapula, the 3D position and orientation of these segments can be

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obtained. The setup may consist of only one cheap fixed-focus webcam. The markers itself are printed on paper.

Several types of square-based fiducial markers are reported in literature, such as ArUco[16,17] and AprilTag.[18] These markers consist of a black border and a unique inner (black and white) binary code for identification. Based on fiducial marker performance criteria such as false-negative rate (probability that a marker is present while not reported) and intermarker confusion rate (probability that a wrong marker id is reported),[19] ArUco markers were selected.[20] Previously, fiducial markers have been used for motion capture purposes.[21,22] To our best knowledge, these markers have never been used before to estimate the rotational center of the glenohumeral joint for brace alignment.

Registration

Registration of the estimated CoR position on the skin allows us to visually align the rotational centers of the brace and the glenohumeral joint.

Aim

The objective of this study is 1) to develop a procedure to estimate the GH-CoR using a single-camera setup and two square-based fiducial ArUco markers and to register the estimated location on the skin, and 2) to evaluate the proposed procedure by determining the repeatability and accuracy of the estimated values. Accuracy was assessed with a test bench with a known rotational center. Repeatability was assessed in vivo with healthy participants.

Methods

CoR estimation

Because the GH joint is a ball-and-socket joint, a marker attached to the arm describes an arc that approximates a sphere with respect to the GH-CoR. The projected center of this sphere on the sagittal plane is defined as the GH-CoR in the sagittal plane. The CoR estimation procedure described below provides an estimate of the GH-CoR.

Setup

The setup for the CoR estimation consisted of a generic, fixed-focus webcam with a resolution of 1920 × 1080 pixels (C-400, Hama), a computer for data processing, a chair with backrest, and two ArUco markers (Figure 1). The webcam was mounted on a tripod, with its principal axis aligned perpendicular to the sagittal plane of the glenohumeral joint. One ArUco marker (M_a) was secured to the upper arm with a strap, and the other marker (M_s) was secured to the scapula with a custom L-shaped holder and double-sided adhesive. Both markers were printed on plain paper and their size was 32.5 × 32.5 mm.

It is important to tightly fasten both markers to their respective body segments because relative motion between the marker and the body segment may introduce errors when estimating the CoR. The webcam was calibrated by obtaining several views of a calibration pattern with a known geometry to quantify distortions that were introduced by the lens. The calibration procedure only has to be performed once for each camera.

Aruco markers

The pose of the two ArUco markers was detected with the open-source ArUco library.[16,17,23] To increase the accuracy of the marker pose estimation, the marker pose tracker algorithm with discriminative correlation filters was implemented.[23] This algorithm detects the initial position of each marker and tracks the marker's position in subsequent frames.

Procedure

The CoR estimation procedure consists of four main steps:

1. *Obtain arm marker coordinates from video.* Video recordings (frame rate = 25 frames per second) of arm flexion movements in the sagittal plane were processed with the ArUco marker pose tracking algorithm[23] to obtain the transformation matrices that express the translation and rotation from the local coordinate systems Ψ_S (scapula) and Ψ_A (arm) to the (global) camera coordinate system Ψ_C (Figure 2). H_S^C is the 4x4 homogeneous transformation matrix from Ψ_S to Ψ_C, and H_A^C from Ψ_A to Ψ_C.

2. *Transform arm marker coordinates from camera coordinate system to scapula marker coordinate system.* To account for possible trunk movements of the subject with respect to the camera during a measurement, the arm marker coordinates (H_A^C) were expressed in the scapula marker coordinate system Ψ_S. This transformation is provided by the 4 × 4 homogeneous matrix (H_A^S), which transforms data from Ψ_A to Ψ_S:

$$H_A^S = \left(H_S^C\right)^{-1} H_A^C \quad (1)$$

3. *Fit sphere to arm marker data.* The equation of a sphere is given by

$$(p_x - s_x)^2 + \left(p_y - s_y\right)^2 + (p_z - s_z)^2 = R^2 \quad (2)$$

With (p_x, p_y, p_z) points on the sphere, (s_x, s_y, s_z) the center of the sphere and R its radius.

A sphere was fitted to the 3D arm marker coordinates (expressed in Ψ_S) using a least-squares method. Finding the least-squares fit corresponds to minimizing the squared Euclidean (geometric) distances (d_i) between the arm marker coordinates ($p_{x,i}$, $p_{y,i}$, $p_{z,i}$) and the estimated sphere center (s_x, s_y, s_z):

$$\mathrm{minF} = \sum_{i=1}^{n} d_i^2, \quad (3)$$

with

$$d_i = \sqrt{\left(p_{x,i} - s_x\right)^2 + \left(p_{y,i} - s_y\right)^2 + \left(p_{z,i} - s_z\right)^2} - R \quad (4)$$

4. *Project sphere center coordinates on to image plane.* Finally, the (3D) sphere center coordinates (s_x, s_y, s_z), which are expressed in reference frame Ψ_S, were projected onto the camera plane using OpenCV's *projectPoints* function.[24] The resulting sphere center location in the camera plane ($\bar{c}_x, \bar{c}_y$) allows for registration of the estimated sphere center to the body.

Registration

The estimated sphere center location should be registered on the upper arm to be able to align the brace to the shoulder CoR in the sagittal plane.

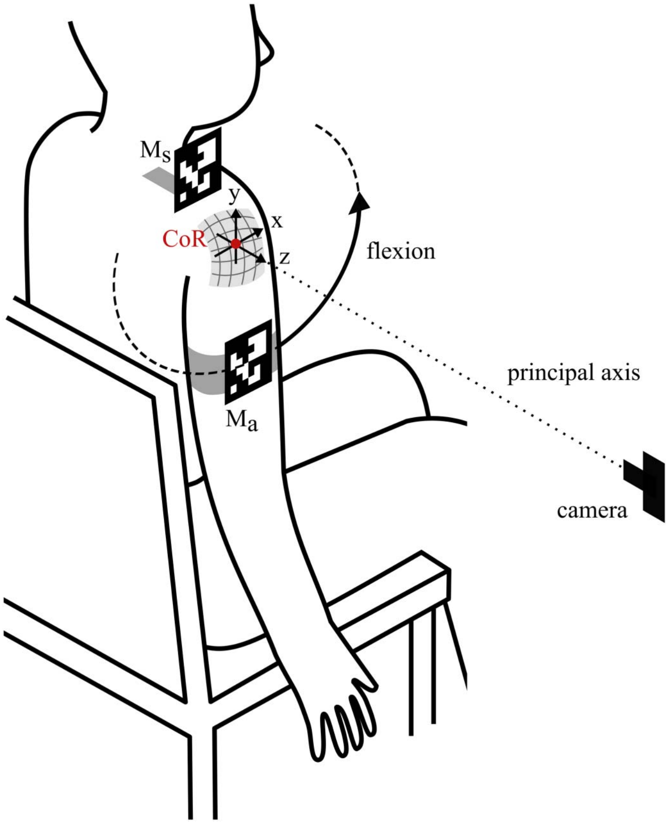

Figure 1. Schematic overview of the measurement setup showing a subject sitting on a chair with the two ArUco markers (M_a and M_s) and camera with its principal axis placed perpendicular to the sagittal plane, approximately in line with the *z*-axis of the CoR. When the subject is performing an anteflexion movement of the arm (movement in the sagittal plane), marker M_a that is attached to the upper arm describes an arc. Marker M_s is attached to the lateral portion of the scapula. From the relative movement of the marker M_a with respect to the marker M_s, the CoR can be estimated through sphere fitting. An adhesive with grid pattern is placed on the humeral head region, and is used for registering the estimated CoR position to the skin. CoR, center of rotation.

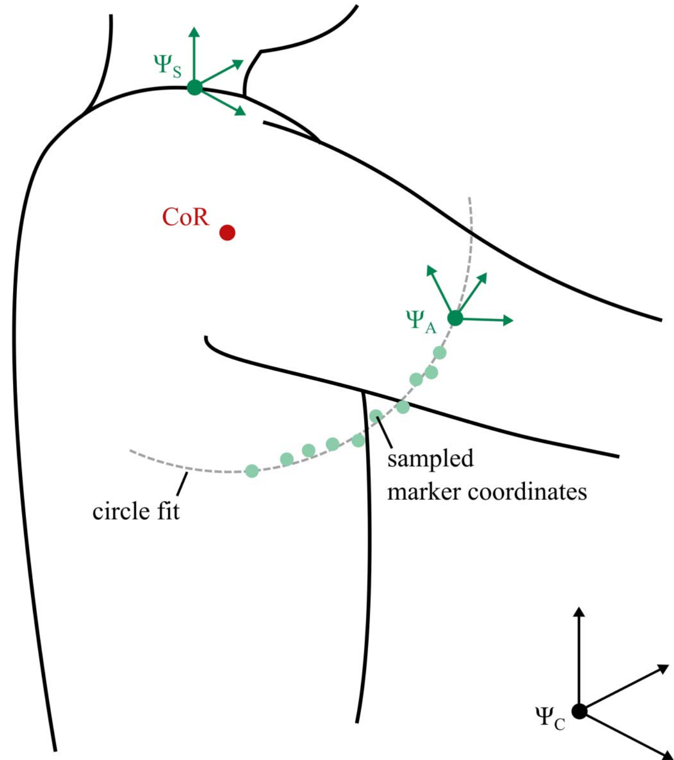

Figure 2. Schematic overview of the local marker coordinate systems (Ψ_S and Ψ_A) and global camera coordinate system (Ψ_C). In each video frame the arm marker coordinates are estimated. The center of rotation in the sagittal plane is defined as the projected center of a sphere that is fitted to the processed marker coordinates.

Setup

Before the measurement, an adhesive with a grid pattern (5 × 5 mm grid size) was placed on the lateral region of the shoulder (Figure 3(A)) to guide the registration of the estimated rotational center on to the body.

Procedure

The registration procedure consisted of three steps: 1) Plot the projected sphere center (in pixels) on the captured image using Matlab 2019a (MathWorks). 2) Measure the center position in the grid coordinate system (where (0,0) is the lower left corner of the grid). 3) Mark the location on the body. In Figure 3(B), a close-up image of the adhesive with grid pattern is shown, together with the estimated projected sphere centers across individual trials and its mean value.

Experimental procedure

With two experiments, both the accuracy and repeatability of the CoR estimation procedure were determined.

Accuracy

Accuracy is defined as the mean difference between the estimated rotational center and the true rotational center across multiple trials. A test bench with a known rotational center was used to determine the accuracy of the CoR estimation procedure (Figure 4). The test bench consisted of a fixed and moving segment to which two ArUco markers (size = 32.5 mm) are attached. The camera was placed 50 cm from the test bench and was horizontally aligned with the rotational center of the test bench. The distance from the moving marker to the rotational center was 10 cm. The rotation of the moving segment was controlled with a servo motor and custom software. Measurements were performed at two velocities: 30 and 60 degrees/s. For each trial, the segment was moved 5 times between 0 degrees and 60 degrees anteflexion.

In total, 10 trials were recorded and the data were processed with Matlab 2019a (Mathworks). The estimated CoR ($\bar{c}_x, \bar{c}_y$) was obtained for every trial by performing the steps described in the CoR estimation procedure. The true CoR (c_x, c_y) was obtained by manually registering the actual location on the image. The mean absolute offset (d_{off}) between the estimated and true rotational center across *n* trials was calculated according to

$$d_{off} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\left(\bar{c}_{x,i} - c_x\right)^2 + \left(\bar{c}_{y,i} - c_y\right)^2} \tag{10}$$

The mean offset was reported, and a two-sample *t*-test was performed to determine whether the offset distance between the true and estimated rotational center significantly changed ($P < 0.05$) for different velocities (30 degrees/s and 60 degrees/s).

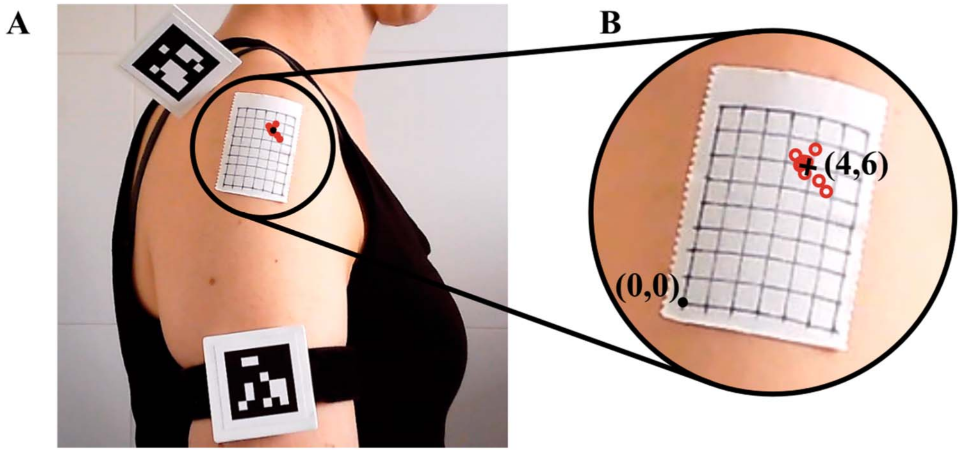

Figure 3. A, The projected sphere centers can be plotted on the captured video frame. The adhesive that was attached to the subject's skin serves as a reference during registration of the found center to the skin. B, Close-up image of the grid pattern showing the estimated sphere centers across individual trials (o) and the mean sphere center (+) and its position in the grid coordinate system.

Repeatability

Repeatability is defined as the degree to which repeated measurements would lead to similar results under similar circumstances and was evaluated with five nonimpaired subjects with a median age of 35 years (range: 32–63). The subjects had no history of shoulder-related complaints and were able to follow simple instructions. Ethical approval for this study was obtained from the Ethics Committee of the University of Twente (ref. number 2021.74). All participants provided their written informed consent before the start of the study. The subjects were seated on a chair with backrest, and faced such that their sagittal body plane was perpendicular to the camera. The subjects were instructed to lift their right arm, with fully extended elbow, in the sagittal plane without excessively moving their trunk. One movement consisted of moving from a neutral position to 60 degrees anteflexion and back. One trial consisted of five consecutive movements, with a constant velocity of approximately 30 degrees/s that was guided by a metronome. Before each measurement session, an adhesive with a grid pattern (5 mm spacing) was attached to the subject's skin at the humeral head region for registration purposes. The distance from the shoulder to the camera was 60 cm. The camera was positioned at an approximate equal height with the shoulder joint.

Subjects were instructed to move their arm between 0 degrees and 60 degrees anteflexion. Although participants were able to lift their arm higher, a maximum angle of 60 degrees anteflexion was chosen to restrict the motion from occurring in other joints of the shoulder complex than the glenohumeral joint as much as possible. During the first 60 degrees, the movement primarily occurs at the glenohumeral joint, with only a small contribution from the scapulothoracic joint.

A strap with marker M_a was attached to the upper arm, approximately 15 cm from the glenohumeral axis of rotation. Marker M_s was attached to the flat portion of the acromion (lateral portion of the scapula, above the spinal process) using a 3D-printed part and double-sided adhesive tape. This reduced skin movement artifacts as much as possible, as the acromion is said to have the least amount of skin movement artifact compared with other locations on the scapula.[25]

Each trial was repeated 20 times. This includes putting on both markers, and positioning the subject in front of the camera. During the first 10 trials, the subjects placed the markers on their body

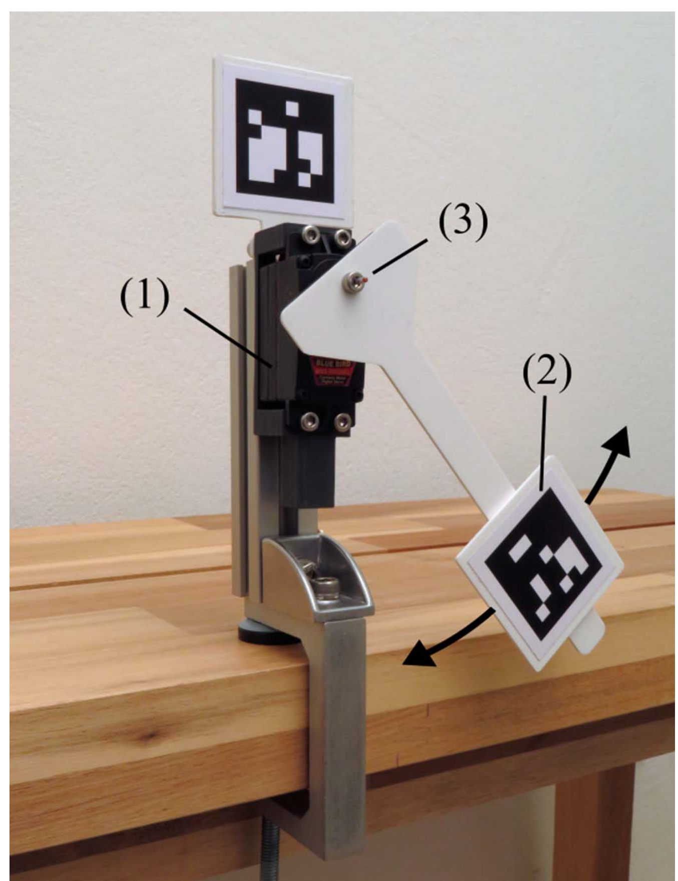

Figure 4. Setup that was used to determine the accuracy of the center of rotation estimation method. A servo (1) rotates the moving ArUco marker (2) at a fixed speed. Because the true rotational center (3) is known, the offset of the estimated sphere center with respect to the actual center can be determined.

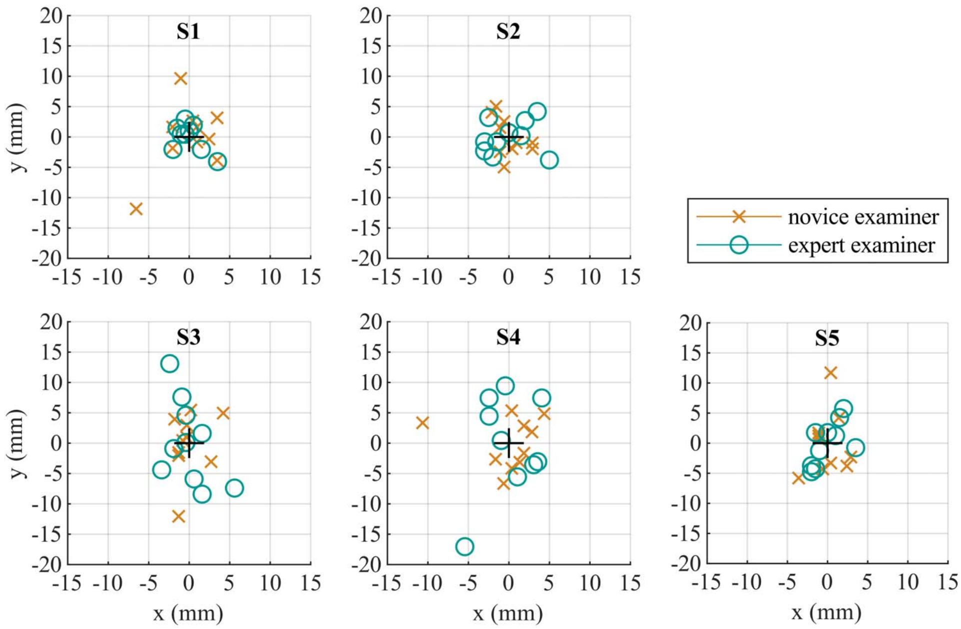

Figure 5. Mean-centered projected sphere center estimates for each of the five subjects (S1-S5) displayed on a 5-mm spaced grid. Trials where the novice examiner performed the measurements are marked with (x) and where the expert examiner performed the measurements are marked with (o).

themselves. This condition resembled a novice examiner. During the last 10 trials, the researcher placed the markers on the subject. This condition resembled an experienced examiner.

Video recordings were made during all measurements, and the data were processed according to the CoR estimation and registration procedure described above. The repeatability of the method was assessed by calculating the root mean squared distance (RMS) from the estimated projected sphere centers ($\bar{c}_{x,i}, \bar{c}_{y,i}$) after each trial to the mean sphere center across all n trials $(\bar{x}, \bar{y})$ per subject:

$$RMS = \sqrt{\frac{1}{n}\sum_{i}\left(\left(\bar{c}_{x,i} - \bar{x}\right)^2 + \left(\bar{c}_{y,i} - \bar{y}\right)^2\right)}.$$

A paired t-test was performed to detect significant differences in RMS ($P < 0.05$) between the two examiners.

Results

Accuracy

The mean absolute offset (d_{off}) between the true CoR of the test bench and the fitted sphere centers across multiple trials was 2.7 mm (SD 0.72) when moving at a velocity of 30 degrees/s. The mean absolute offset was 2.5 mm (SD 1.0) at 60 degrees/s. A two-sample t-test revealed no significant difference between the two velocities.

Repeatability

The repeatability was assessed by evaluating how close individual measurements are to each other. For two participants, only 19 trials were available for analysis, instead of 20: one because the video was not properly recorded, and one because the arm marker was rotated such that it was not detected by the marker pose tracker algorithm. For the other three subjects, 20 trials were available: 10 conducted by the novice examiner, and 10 by the expert examiner. A pairwise comparison per subject revealed a mean distance of 6.6 mm (range: 2.4–10.8 mm) between the novice and expert examiner estimations.

In Figure 5, the estimated projected sphere center positions for each individual trial are shown per subject. To allow for a visual comparison of the data between the two conditions ("novice" and "expert"), the sphere center positions were mean-centered on the grid.

The mean RMS value across all subjects was 5.1 mm (range: 3.4–6.0 mm) for the novice examiner and 5.2 mm (range: 2.7–8.5 mm) for the expert examiner. A paired-sample t-test was performed. The difference between examiners was not statistically significant ($P = 0.96$). The 95% confidence interval of the difference was (−3.2, 3.0 mm).

Discussion

In this study, we have shown that our proposed method can accurately estimate the rotational center of the glenohumeral joint. Accurate knowledge may improve the quality of the brace alignment. Not only because proper fitting will increase the performance of the brace, but also because undesired external forces may cause the brace to loosen over time. The accuracy and repeatability of our method is comparable with state-of-the-art methods, such as those presented by Crabolu et al[8] (accuracy mechanical test bench <3 mm) and Lempereur et al[5] (in-vivo repeatability <4.11–8.25 mm). Compared with other methods, our setup only comprises a cheap webcam (around €40) that can be used for many measurement sessions and the total assessment (including preparation time) takes less than three minutes to complete, which will further improve uptake in the clinical practice. In addition, we have created a simple technique to register the found sphere center location to the body.

Relative movements between the marker and the bony segment to which it was attached may have potentially negatively affected the quality of the sphere fitting process. All trials have therefore been visually inspected for any large deviations from the marker coordinates to the fitted sphere. In general, the data seemed to match the fitted sphere outline well. Incidental skin marker artifacts may have occurred, but their influence on the CoR estimation was considered be minor, as the sphere fits were always based on the averaged data of one full trial (five movements). Still, skin marker artifacts could have contributed to the variation among subjects, especially if they have a high body fat percentage. Difficulties in maintaining a constant arm speed throughout the measurement may have caused an uneven spreading of sampled marker coordinates within the movement range for several trials. This may affect the performance of the marker tracking algorithm. Also, excessive rotation of the upper arm during flexion-extension movements may have decreased the algorithm performance.

Conclusion

In this study, we proposed a method to estimate the GH-CoR and register this location on the body for brace alignment. The accuracy of the method ranged from 2.5 to 2.7 mm under the assumption of no skin artifacts. The repeatability ranged from 5.1 to 5.2 mm for the novice and expert examiners. From these results, we can conclude that our method is able to accurately estimate the GH-CoR with a high degree of repeatability. We observed no significant differences between the measurements that were conducted by novice or expert examiners, which means that the proposed method is robust for inter-rater differences.

In the current study, healthy participants performed anteflexion movements from a neutral position to 60 degrees anteflexion and back. Patients may not be able to perform these complete movements because of pain or other limitations. For these patients, we will explore the influence of a smaller movement arc (e.g. 30 degrees anteflexion) on the quality of the estimation in a future research. However, it should be noted that patients with a very limited range of motion may not benefit from a dynamic orthosis that requires alignment with the shoulder joint.

In the current work, we only applied the method to the glenohumeral joint. In future research, we will explore the possibilities of transferring the method to other joints such as the hip, knee, or elbow.

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Declaration of conflicting interest

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Supplemental material

No supplemental digital content is available in this article.

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