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Cup Alignment Error Model for Total Hip Arthroplasty

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Almost all computer-assisted orthopaedic surgery systems that rely on the anterior pelvic plane definition, such as in computed tomography and magnetic resonance image-based, fluoroscopy-based, and nonimage total hip replacement approaches, are derived from identifying two pairs of pelvic bony landmarks: anterior superior iliac spines and the pubic tubercles. Although these systems strive to achieve cup alignment accuracy of approximately 1°, even a minor failure to correctly identify these anatomic landmarks can lead to higher inaccuracies in the final cup alignment. This study shows how to examine the effects of these inaccuracies on the final acetabular cup implant orientation during total hip replacement by generating a kinematic model, which then is simulated. Simulation results indicate that, for example, a total error of 4 mm in measuring the anterior superior iliac spine and the pubic tubercles would result in a final cup orientation of 47° and 27° in abduction and version respectively, resulting in a 2° abduction error and 7° error in version when targeting 45° abduction and 20° version results. These calculations can be repeated for any error values.

Alignment of the acetabular component during total hip arthroplasty (THA) is a crucial step for reducing the chances for joint dislocation,[1,4,6,7,11,15,22] prosthetic component wear, and impingement.[2] Consequently, the determination of the optimal orientation of the acetabular components during THA has been the focus of numerous studies. A wide range of parameters is reported.[19] Harris[9] recommended 30° abduction and 20° anteversion for cup orientation. Harkess[8] recommended an abduction angle of 45° and an anteversion of 15° ± 5°, and Lewinnek et al[12] recommended an abduction angle of 40° ± 10° with an anteversion of 15° ± 5°. However, most methods for acetabular component alignment are designed to provide 45° ± 50° abduction and 15° ± 25° operative anteversion (also known as flexion) with respect to the anterior pelvic plane (APP). Moreover, implant manufacturers usually provide mechanical guides that place the acetabular components at 45° and 20° abduction and operative version. These mechanical guides assume a fixed, predetermined pelvic orientation, when in practice the position of the acetabular component may vary considerably depending on the pelvic orientation of the patient on the operating table.[17,18] McCollum and Gray[13] reported that accurately aligning the pelvis with the patient in the lateral decubitus position is an almost impossible task. They also reported that pelvic malalignment could lead to improper cup alignment, and indicated that pelvic flexion and soft tissue contractures can result in changes in native acetabular orientation from the apparent position of the patient on the operating table and may lead to component malposition. Eddine et al[5] studied the influence of pelvic rotation on computed tomography (CT) measurements of position of the cup after THA. In their study, 22 patients had retroversion of the pelvis by a mean of 7° (2°–18°) and two others had anteversion of 3°. This relatively large variation of the pelvic position between the standing and lying down positions provides an explanation why CT examinations made with the patient lying down do not allow for anteversion of the cup in the standing position, during which displacement may occur. Schneider et al[18] suggested standardization of the patient's position on the operating table by setting the position of the central xray beam and the anterior pelvic plane alignment to a standard value.

To define the APP, the anterior superior iliac spines and the pubic tubercles need to be determined.[12] Yet, when determining these anatomic landmarks, errors that affect the final definition of the APP can be introduced, which results in improper cup alignment. These errors occur mainly when using an image-free computer-assisted navigation technique such as in the nonimage total hip replace-

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ment approach, or freehand technique using mechanical guides. Although these systems strive to achieve cup alignment accuracy, even a minor failure to correctly identify the anatomic landmarks can lead to error in the anterior pelvic plane axis definition, resulting in errors in final cup orientation.

We hypothesized that even small errors introduced during the anatomic landmark localization process would substantially affect the final cup orientation. We reasoned that the abduction and version angles should be modified to compensate for the anatomic landmark localization errors.

MATERIALS AND METHODS

Cup orientation is expressed relative to a specific reference system. There are three definitions of cup orientation commonly used in clinical practice, each resulting from a particular application: radiographic, operative, and anatomic[14] (Fig 1). Regardless how the cup orientation is expressed, an error in definition of the reference system resulting, for example, from inaccurate localization of bony landmarks would affect the cup orientation.

To evaluate the effect of the errors introduced during the anatomic landmark localization process on the final cup orientation, we used a kinematic model that incorporates all rotational errors into an accumulated three-dimensional rotational error in the APP axes definition.[21] Our simulations indicated that this error has a significant effect on the final cup orientation.

All current computer-assisted THA systems rely on the APP as a reference frame for the pelvis, as do the conventional cup alignment guides. To define the APP, the anterior superior iliac spines and the pubic tubercles need to be located.[12] The transverse axis is defined as a line connecting the anterior superior iliac spine points. The anterior pelvic plane then is defined by the transverse axis and the midpoint between the two pubis symphysis tubercles. The second axis of the coordinate system lies in that plane and is perpendicular to the transverse axis, and the third axis is perpendicular to the APP (Fig 2). The three errors in anatomic landmark localization (ie, the anterior superior iliac spine points and the pubis symphysis tubercles) are converted to

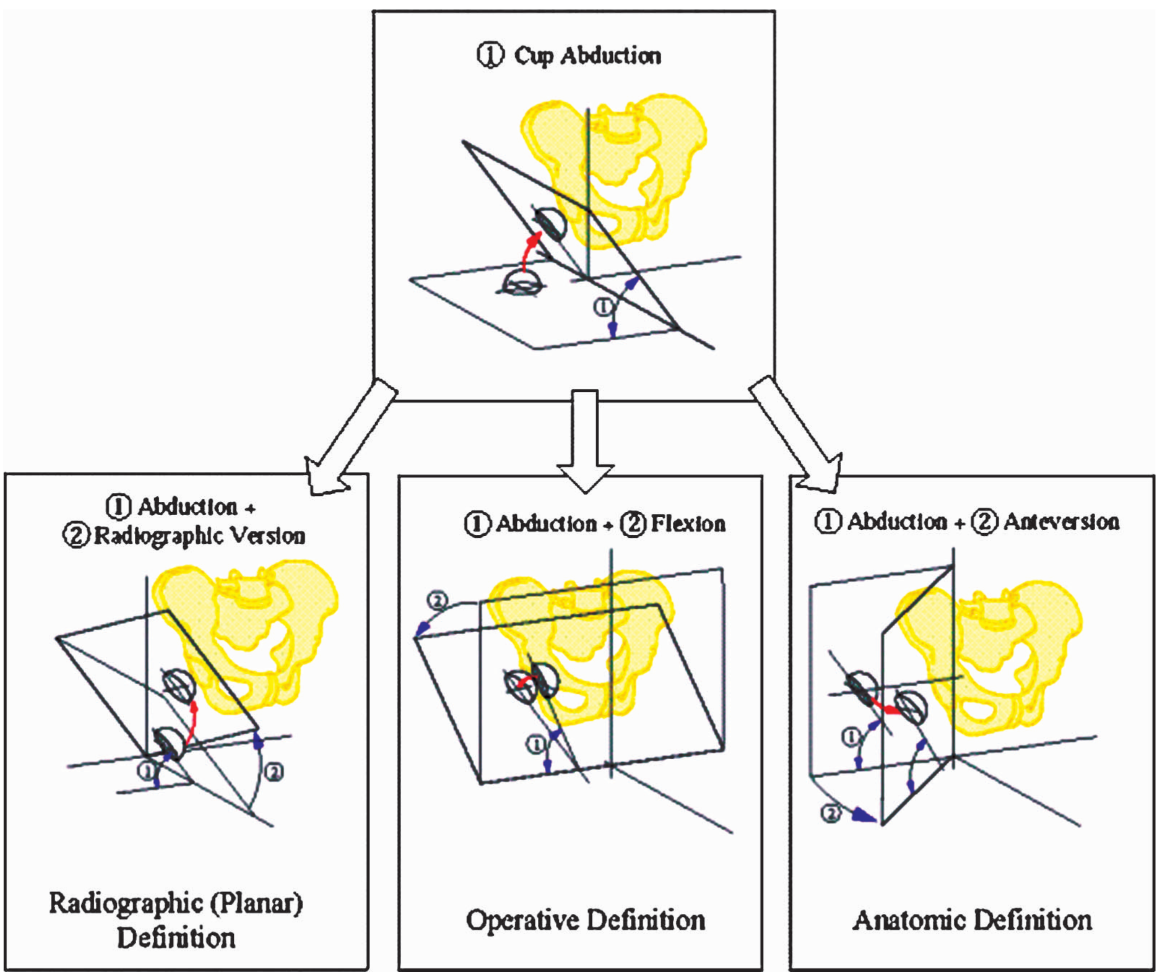

Fig 1. The definition of cup orientation according to Jaramaz et al[10] is shown.

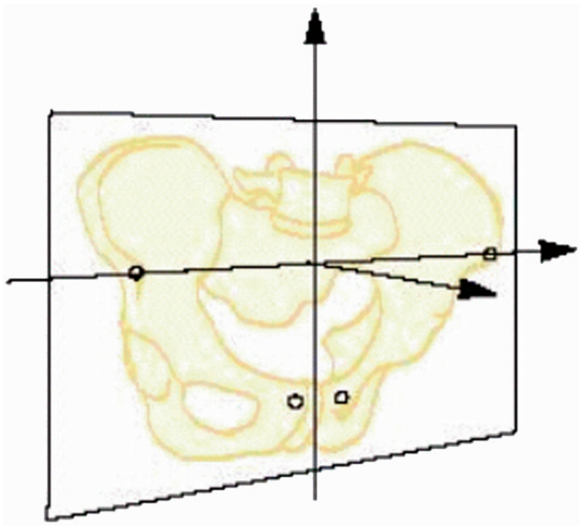

Fig 2. The anterior pelvic plane (APP) axes are illustrated.

three rotational errors of the APP axes, θ_1, θ_2, and θ_3 (Figs 3–5). These three rotational errors then are introduced into the kinematic error model (Fig 6) as the first three concurrent axes of rotation, followed by the version and abduction rotations θ_4 and θ_5, which are defined relative to the previous θ_1, θ_2, and θ_3. By using this model, we vary the values of landmark localization error (θ_1, θ_2, and θ_3) then the conventional abduction and version angles and obtain the resulting cup orientation (Fig 6). The cup location therefore is given by: ${}^0T_5 = {}^0T_1{}^1T_2{}^2T_3{}^3T_4{}^4T_5$, where ${}^iT_j$ is the transformation matrix from reference system j to reference system i; reference system 0 is the global reference system (eg, operating table) and reference system 5 is the cup system (Fig 6).[21] Using the model, we generated a computer simulation, shown in graphs, that correlate the errors θ_1, θ_2, and θ_3 in APP axis definition to final cup orientation.

A different approach (the inverse approach) assumes a predetermined final cup orientation (eg, 45° and 20° abduction and version, respectively) and solves for alignment errors θ_4 and θ_5, which are a priori unknown (Fig 6), that would result in the given

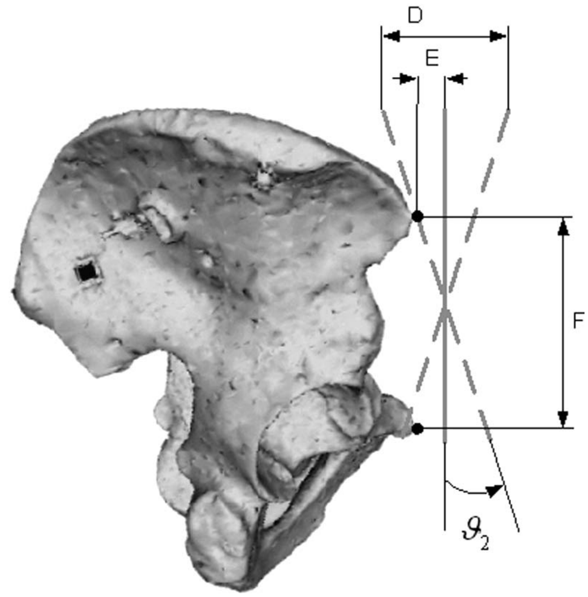

Fig 4. The error in determining the pubic tubercles and the anterior superior iliac spines is illustrated by an error of E with a range of error D, resulting in flexion error angle θ_2.

cup orientation, while taking into account the three rotational errors resulting from the measurement errors. To use the inverse kinematics approach in the operating room, the measurement errors need to be defined, which is not always feasible. Yet, if we were able to determine the presence of a systematic error, then the following method would be very powerful, as the resulting actual cup orientation would be the same as planned. DiGioia et al[3] reported that the measurements of a traditional cup alignment using the mechanical guide showed a systematic bias because of the pelvis' rotation on the operating room table. In this example, using the inverse approach with the known bias, and applying the corrected values of abduction and version using a conventional procedure would result in the cup alignment values of similar dispersion, but with means equal to the intended target values of 45° abduction and 20° operative version.

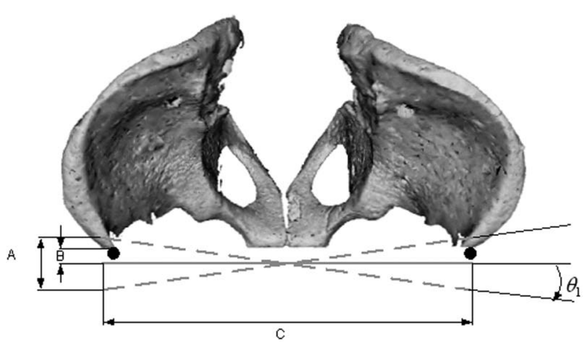

Fig 3. Errors in determining the anterior superior iliac spines are shown by error of B with a range of error A, resulting in an anteroposterior error version angle ± θ_1.

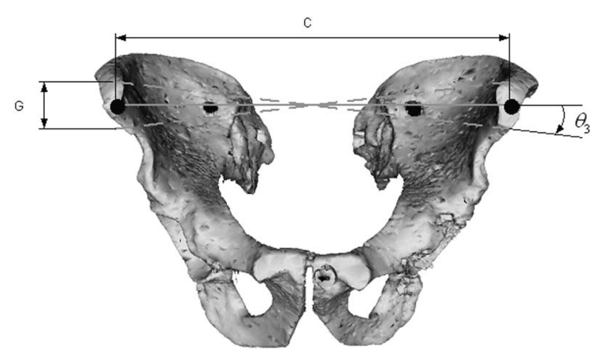

Fig 5. The error in determining anterior superior iliac spines results in the superior inferior error angle θ_3.

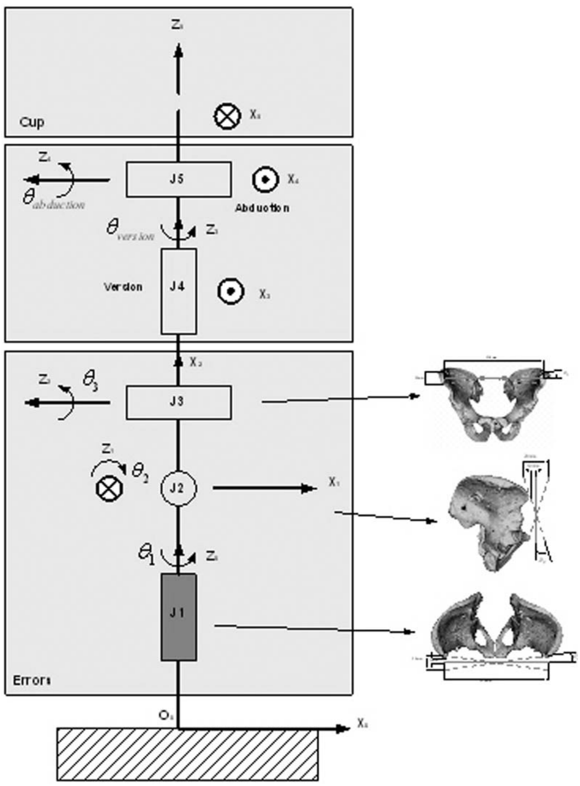

Fig 6. A kinematic skeleton is shown that incorporates measurement errors and the resulting cup orientation.

Knowing the errors is not always enough to correct them or to correct cup orientation parameters, as the error usually results from two independent rotations. In some patients, a systematic error is committed (patient positioning on the operating room table) or can be estimated (landmark collection in obese patients), yet its direct correction may not be clear. Finally, the three rotational errors of J1-J3 (Fig 6) affect cup orientation by a set of nonlinear equations composed of sine and cosine functions. Having even two unknown parameters would complicate the inverse solution.[21]

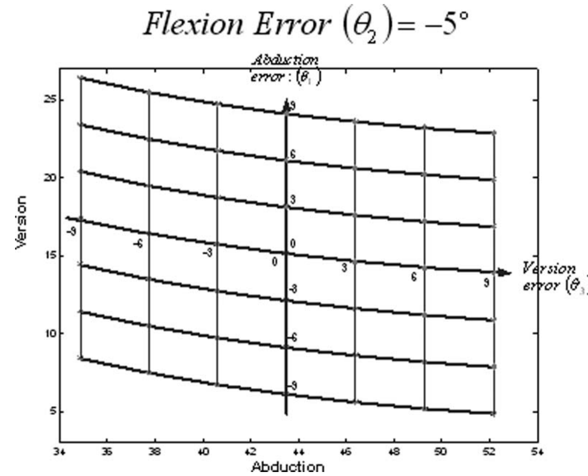

Fig 8. Abduction and version error as functions of measurement error (flexion error, –5°) are shown in this graph.

Without loss of generality, we assume for the parametric study the range of parameters A, D, and G (Figs 3–5) to be 30 mm. Parameters B and E (bias) were estimated to be 10 mm. Also, C, the distance between the anterior superior iliac spines was 240 mm. Finally, F, the distance between the anterior superior iliac spines and the pelvic tubercles was 100 mm.

The results of our simulations are given as graphs (Figs 7–10) and also are summarized in Table 1. Each graph represents a constant value for θ_2, and this value is indicated at the top of each graph. The X and Y axes represent the version and abduction angles resulting from the θ_1 and θ_3 error combination. These errors are given on a grid and θ_1 and θ_3 are given in brackets. Each horizontal line represents a constant θ_3 value, and each vertical line represents a constant θ_1 value.

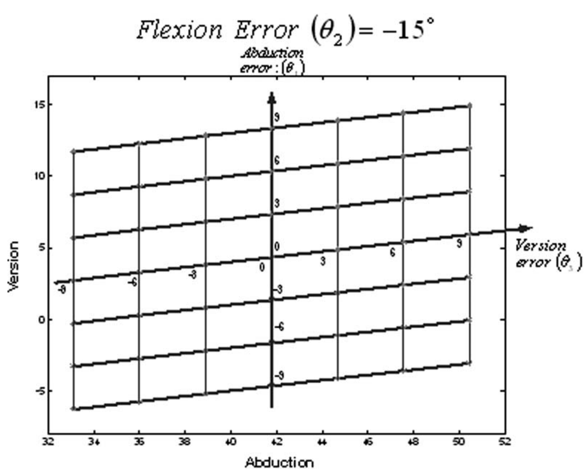

Fig 7. The graph shows abduction and version error as a function of measurement error (flexion error, –15°).

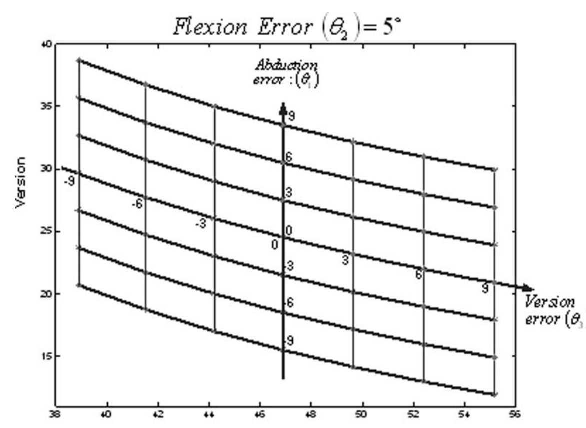

Fig 9. With a flexion error of 5°, abduction and version error as functions of measurement error are shown.

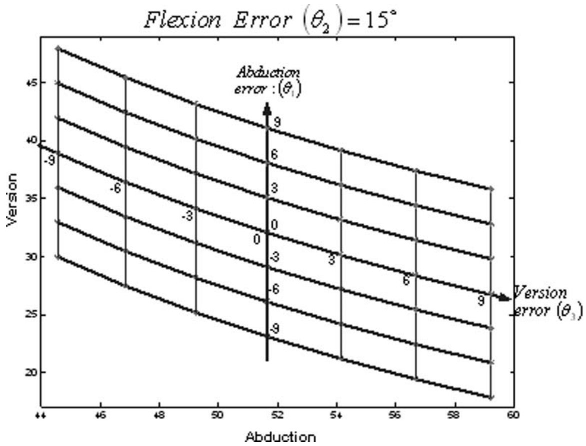

Fig 10. Abduction and version error as functions of measurement error (flexion error, 15°) are illustrated in this graph.

RESULTS

The computer simulations indicate that even small errors (eg, 1–4 mm) in anatomic landmark localization can result in a relatively large error (as much as 11° in abduction and version) in cup orientation as seen in the computer simulations of the APP axis error (Figs 7–10, Table 1). For example, for a total error of 4 mm in measuring the anterior superior iliac spine and the pubic tubercles (Fig 4), the resulting flexion error θ_2 is 4.5°. A flexion error θ_2 of 4.5°, even when neglecting other errors, (ie, $\theta_1 = 0°$ and $\theta_3 = 0°$) results in a final cup abduction angle of approximately 47° and a version angle of close to 25° (Fig 9), when the expected angles are 45° and 20°, respectively. Yet, the 4-mm measurement error of the anterior superior iliac spine and the pubic tubercles also results in a 2° error in θ_1 and θ_3. It can be seen how these errors result in a final cup alignment of 47° and 27° in abduction and version, respectively, meaning a 2° abduction error and 7° version error (Fig 9). This calculation can be repeated for any error values (Table 1).

Our simulations of the inverse approach indicate that the errors while palpating the anatomic landmarks are not negligible and that the version and abduction orientation angles (as much as 10° version and 6° abduction) need to be compensated to achieve the planned cup orientation. Our simulations provide four occurrences of extreme errors and the resulting abduction and version that would result in cup orientation of 45° and 20° (Table 2).

TABLE 1. Simulation Data for Final Cup Version and Abduction Angles

Error			Resulting Cup Orientation	
θ_1	θ_2	θ_3	θ_4 *Version*	θ_5 *Abduction*
−9	−15	−9	−3.1	50.4
9	−15	9	11.7	33.1
−9	−10	−9	0.99	51.1
9	−10	9	19.0	33.7
−9	−5	−9	4.9	52.1
9	−5	9	26.4	34.9
−9	0	−9	8.5	53.5
0	0	0	20*	45*
9	0	9	32.9	36.6
−9	5	−9	11.9	55.2
9	5	9	38.7	38.9
−9	10	−9	14	57.1
9	10	9	43.7	41.6
−9	15	−9	17.8	59.2
9	15	9	47.9	44.6

*No errors, all dimensions are given ind degrees.

DISCUSSION

We explored the effects of errors introduced during the anatomic landmark localization process on the final cup orientation. It should be possible to determine what the abduction and version angles should be to compensate for the anatomic landmark localization errors and accomplish the desired cup orientation. We presumed the errors introduced during anatomic landmark palpation have a substantial affect on the final cup orientation. This assumption is also the main limitation of our approach as it is not always possible because of operating room settings to evaluate these errors unless they are studied systematically. However, even if sampling errors are not always available, our results should increase the awareness of the sensitivity of the final cup orientation to landmark localization errors.

We applied a closed-form mathematical solution for the analysis of the effect of inaccuracies related to determining the location of the APP landmarks and their affect on the final cup alignment during THA. This method also can be applied to validate accuracy of nonimage THA systems. Next, we applied these methods on estimated error sampling models (Figs 7–10). The diagrams show the resulting

TABLE 2. Inverse Kinematic Solution Data Resulting in 45° Abduction and 20° Version

Errors			Corrected Angles	
θ_1	θ_2	θ_3	θ_4 *Version*	θ_5 *Abduction*
−7	−15	7	41.8	42.3
0	10	3	9.3	44.7
3	10	0	6.8	47.1
−7	0	−7	30.8	51.2

All dimensions are given in degrees.

cup orientation when orienting the cup in 20° version and 45° abduction using erroneous landmark data. These results indicate the magnitude of errors potentially introduced during a THA. The errors can result from anatomy sampling errors or by variation in pelvis orientation on the operating table.

We also presented a method to calculate corrected version and abduction angles that would result in desired cup orientation. These angles are determined by solving the inverse kinematic problem with the version and abduction angles as unknowns. This is a powerful technique when each of the three rotational or measurement errors is known or able to be defined.

Our simulation results indicate that version and abduction errors can be as large as ± 10° and ± 6°, respectively, assuming a 4 mm error in anatomic landmark localization. Olivecrona et al[16] reported a mean version error of 2.3° (range, 0°–6.6°) and a mean abduction error of 1.1° (range, 0°–4.6°). Wentzensen et al[20] reported a mean abduction error of 2° (range, 37°–49°) and a mean version error of 1° (range, 10°–28°) in cup orientation. These results are within the range of our simulations results.

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