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Registration accuracy in computer-assisted pelvic surgery

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Abstract

Introduction: An *in vitro* study was performed to assess the global registration accuracy of a computer-assisted system in pelvic orthopaedic surgery. The system was applied to a putative tumor resection in a pelvic sawbone.

Methods: Twenty landmarks were created on the surface of the pelvis, and a virtual model of the sawbone was constructed based on surface extraction from computed tomography. The coordinates of the landmarks were defined in the CT-scan coordinate system, and registration of the sawbone with the virtual model was achieved using a surface-based matching algorithm. The landmarks were considered as control points, and deviations between their physical locations and their locations in the virtual model were calculated, thereby quantifying the global accuracy error.

Results: The location of the initialization points was unimportant. The dynamic reference base gave the best results when placed far from the working area. Accuracy was improved when the sampling area was increased, but was decreased by its excessive expansion.

Conclusions: It is recommended that the DRB be located on the contralateral side of the pelvis. Extending the approach posteriorly and including the entire working area in the sampling surface area, if possible, will also help increase accuracy in computer-assisted pelvic surgery.

Keywords: *Registration, surface-based matching, pelvic surgery*

Introduction

The primary advantage of using a navigation system for surgery is improved intraoperative accuracy. This has already been achieved for the placement of pedicle screws in spinal surgery [1, 2], and software has also been developed to enable navigated periacetabular osteotomies [3] and tumor resections in the pelvis [4]. Although many groups have reported that surgical safety and accuracy are improved when navigation systems are used in pelvic procedures [3, 5], the topic remains controversial since other studies found no benefit to using computer assistance in pelvic osteotomies, and indicated that such an application can actually lead to greater preoperative blood loss and increased surgical duration [6].

Only a few studies have attempted to determine the accuracy of computer-assisted pelvic surgery [7, 8]. Obtaining any accuracy <1 mm is difficult, since the pelvis encompasses such a large volume. One study found a mean accuracy of 3.81 mm in such surgeries [7], while another using a postero-lateral approach found registration accuracies of 1.2 mm in the pelvis and 1.4 mm in the femur [8]. In the *in vitro* study described here, we determined the accuracy of a pelvic computer-assisted navigation system using a putative ilio-inguinal approach. In particular, we investigated the influences of the position of the dynamic reference base (DRB), the initialization point locations, and the extent of the sampling surface area.

Materials and methods

Twenty landmarks [7] were created on the surface of a pelvis sawbone (solid foam, full female pelvis,

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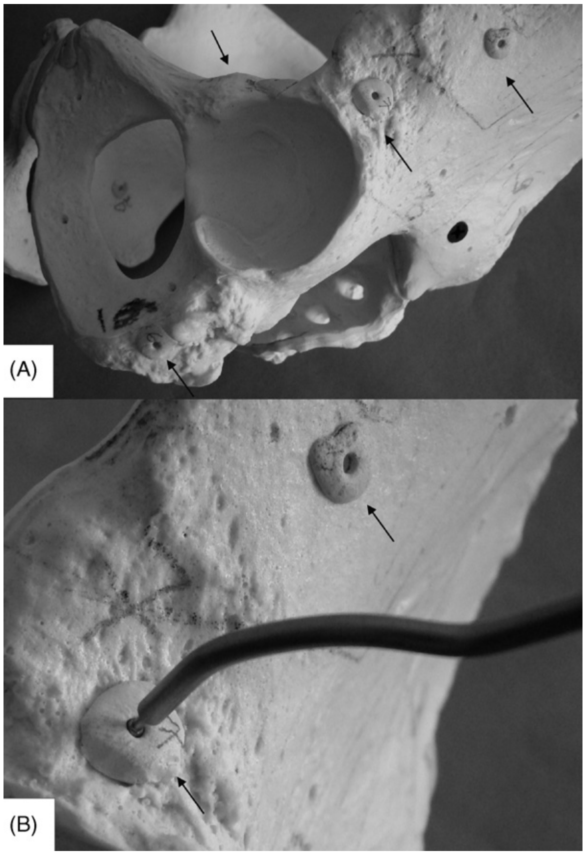

Figure 1. Creation of landmarks on the surface of the sawbone. (A) Epoxy paste was stuck on the surface of the sawbone and a hole (2 mm in diameter) was formed in the paste. (B) The hole fitted perfectly the ball on the tip of the navigation pointer.

48-mm acetabulum; product reference 1302, Sawbones Europe, Malmö, Sweden) (Figure 1A), with ten landmarks on each hemi-pelvis. To create each landmark, a bead of scanner-high-density epoxy paste (PC-7 Heavy Duty Epoxy Paste, PC-Products, Allentown, PA) was stuck to the surface of the sawbone, then a hole 2 mm in diameter, which fitted perfectly the ball on the tip of the navigation pointer, was created in the paste (Figure 1B). A preoperative model of the pelvis was obtained by CT scan, using a spiral Elscint Twin CT scanner with a slice thickness of 1.3 mm and 1 mm of spacing between slices. Image data were downloaded from the PACS system (Kodak Carestream PACS, Carestream Health, Rochester, MY) in DICOM format. The CT data were introduced into the navigation system (Surgetics Station, Praxim, LaTronche, France; Spine application 4.1), and the coordinates of the landmarks, X_{iCTScan}, Y_{iCTScan} and Z_{iCTScan}, were defined in the CT-scan coordinate system and considered to be the control points, CP_{i} (for i = 1 to 20).

The pelvis was placed in a supine position, simulating an ilio-inguinal approach, and was fixed in a loose support that allowed movement. A DRB with three infrared light–reflecting markers was fixed in the iliac wing with an anchoring screw (rotational stabilizer) to improve stability [9]. A navigation system developed for spinal surgery was adapted for use with the pelvis. This system used an optical tracking system or localizer (Passive Polaris, Northern Digital, Inc., Waterloo, Ontario, Canada) which detects the navigation pointer and the DRB and tracks their movements relative to one another. The system computes the position of points acquired by the navigation pointer in the DRB coordinate system. These acquired points are used by a matching algorithm that links the physical sawbone (DRB coordinate system) to its virtual model (CT-scan coordinate system). The matching algorithm was first roughly initialized with three anatomical initialization points that were defined on the CT images. Eight sampling surface areas at the bone surface were then acquired with the navigation pointer. The navigation pointer was moved over the pelvis surface and 65 points were tracked from each sampling surface area. For the first two sampling surface areas, the sampling was based on time, with the 65 points being obtained at regular time intervals. For the next 6 sampling surface areas, the sampling was based on distance, with 65 points being tracked at regular distance intervals. These scatter points were matched against the model surface using an iterative closest-point algorithm that resulted in a spatial transform (T) that mapped the DRB coordinate system to the CT-scan coordinate system. The optical localizer was left in the same position throughout the matching procedure to maintain the distance between the DRB and the optical camera.

The landmarks (CP_{i}s) were palpated with the navigation pointer and the coordinates X_{iDRB}, Y_{iDRB} and Z_{iDRB} were obtained in the DRB coordinate system. These coordinates were transformed using the spatial transformation T to obtain the coordinates of palpated CP_{i}s in the CT-scan coordinate system.

$$CP_{i\ trans\ DRB} = T(CP_{i\ DRB}) \tag{1}$$

The global accuracy error was calculated as follows:

$$Global\ accuracy\ error_i\ (in\ mm) = \sqrt{\left\{\begin{matrix} (X_{i\ trans\ DRB} - X_{iCTScan})^2 + (Y_{i\ trans\ DRB} - Y_{iCTScan})^2 \\ + (Z_{i\ trans\ DRB} - Z_{iCTScan})^2 \end{matrix}\right\}} \tag{2}$$

where global accuracy error is the sum of the optical localizer error, the localization error and the alignment error. The error from the optical tracking localizer is due to its resolution; localization error is defined as inaccuracy in acquisition of the CP_i coordinates in the CT-scan coordinate system [10]; and the alignment error is due to the registration geometrically distorting the pelvis in the DRB and CT-scan coordinate systems.

The root mean square error (RMS) specified by the camera manufacturer for the localizer is 0.35 mm (www.ndigital.com). Using the same registration protocol, the entire set of CP_is was acquired. The distance between the acquisitions of each CP_i was quantified using the following equation for RMS:

$$RMS = \sqrt{\frac{1}{20}\sum_{i=1}^{20} d_i^2} \quad \text{with}$$
$$d_i = \sqrt{(X_{i1} - X_{i2})^2 + (Y_{i1} - Y_{i2})^2 + (Z_{i1} - Z_{i2})^2} \tag{3}$$

where d_i is the distance in mm between two acquisitions of CP_i, X_{i1} is the coordinate X of CP_i acquired from the first palpation, and X_{i2} is the coordinate X of CP_i from the second palpation.

We next tested the influence of initialization point location on global accuracy error. Three sets of initialization points were defined, with the antero-superior iliac spine (ASIS), antero-inferior iliac spine (AIIS) and pubic tubercle (PT) chosen on the left (set 1) or right (set 2) hemi-pelvis. In set 3, we acquired the same three initialization points as in set 1, but with a systematic error (1 cm randomly behind, ahead, medially or laterally for the three points). For each set of initialization points, 6 registrations were obtained, with the same 8 sampling areas being palpated on the left side for each registration. To reproduce identical sampling areas, 8 lines were drawn on the surface of the sawbone and points were acquired along these lines. For each registration, the coordinates $X_{i\ \mathrm{trans\ DRB}}$, $Y_{i\ \mathrm{trans\ DRB}}$ and $Z_{i\ \mathrm{trans\ DRB}}$ of 10 CP_is were obtained, with 7 of these CP_is being located on the left and 3 on the right hemi-pelvis, and global accuracy error was calculated using Equation 1.

Two matched sets were determined to study the relationship between global accuracy error and the DRB position. The only change between the two sets was the position of the DRB; the same initialization points (ASIS, AIIS and PT on the left hemi-pelvis) and the same 8 sampling surface areas on the left side were used, following the same lines as before. In set 1 the DRB was fixed in the right iliac wing (contralateral to the sampling surface area), while in set 2 the DRB was fixed in the left iliac wing (ipsilateral). For each DRB location, 6 registrations were determined, and the coordinates $X_{i\ \mathrm{trans\ DRB}}$, $Y_{i\ \mathrm{trans\ DRB}}$ and $Z_{i\ \mathrm{trans\ DRB}}$ of 10 CP_is were obtained for each registration, 7 of the CP_is being located on the left and 3 on the right hemi-pelvis. The global accuracy error was calculated as described previously.

To evaluate the influence of sampling surface area on the global accuracy error, 7 zones were defined for an ilio-inguinal approach. The surface available for palpation was progressively enlarged from zones 1 to 7 (Figures 2 and 3). The DRB location (contralateral) and the 3 initialization points (ipsilateral ASIS, AIIS and PT) were identical. For each sampling surface area, 10 registrations were determined, with 10 CP_is for each registration. The global accuracy error was calculated using Equation 2.

Statistical analysis was performed using SPSS 15.0 for Windows (SPSS, Inc., Chicago, IL) to examine the differences in global accuracy error with respect to initialization point position, DRB position and intraoperative sampling surface area. Initially, the distribution of each variable was tested for normality using the Kolmogorov test. Differences in global accuracy error between groups were analyzed by analysis of variance (ANOVA) followed by the Bonferroni test for multigroup comparison. Homogeneity of variance was tested with Levene's test. The global accuracy error was computed in logarithm to respect the homoscedasticity condition.

Results

The RMS for the 20 CP_is was 0.35 mm, which was identical to the published RMS of the localizer. No significant differences in global accuracy error were found between the three sets of initialization points.

The global accuracy error decreased when the DRB was located on the contralateral side (set 1), being 2.07 ± 0.11 mm with the DRB on the contralateral side versus 2.58 ± 0.24 mm with the DRB on the ipsilateral side (Figure 4). As the sampling surface area was progressively expanded from sets 1 to 6, the accuracy improved significantly (Figure 5), with global accuracy error decreasing from 2.54 ± 0.42 mm for set 1 to 1.31 ± 0.14 mm for set 6. The difference in global accuracy errors for sets 1 (2.54 ± 0.42 mm) and 2 (2.20 ± 0.28 mm) was not significant, although the result for set 3 (1.70 ± 0.25 mm) was significantly

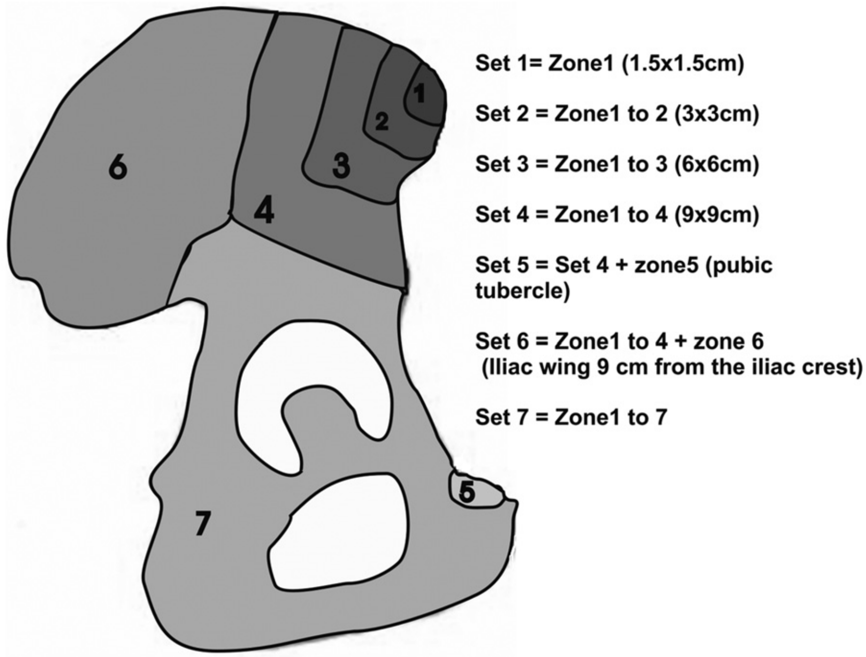

Figure 2. Seven sets of sampling surface areas were tested. The surface available for palpation was progressively enlarged from sets 1 to 7.

lower than that for sets 1 or 2. The global accuracy error for set 4 was 1.46 ± 0.17 mm, with no significant accuracy improvement compared to set 3. The global accuracy errors further decreased to 1.38 ± 0.18 mm for set 5 and 1.31 ± 0.14 mm for set 6, which was significantly different from the result obtained for set 3 but not from that for set 4. When the entire iliac bone was used for palpation (set 7), the global accuracy error increased to 1.50 ± 0.21 mm, which was not significantly different from that obtained for set 6.

Discussion

The purpose of this study was to evaluate the effect of initialization point location (ipsi- or contralateral), DRB location (ipsi- or contralateral) and sampling surface area on global accuracy error in computer-assisted pelvic surgery (using an ilio-inguinal approach), and to find a clinically acceptable trade-off between accuracy and surgical invasiveness. From this study, it is recommended that the DRB be located on the opposite side. Extending the approach posteriorly and including the whole working area in the sampling surface area, if possible, are also helpful.

Accuracy is critical in CT-based image guided surgery, and different factors can affect it. For instance, decreased slice thickness of the CT [7] and decreased reconstruction pitch improve accuracy. In the pelvis, expanding the sampling surface area influences accuracy, as was previously shown using a postero-lateral approach [8]. The surface model threshold is also an important parameter. In this study, we used a sawbone without soft tissues and an optimal threshold was chosen. The absence of soft tissues on the sawbone is one limitation of our model; in the operating room, soft tissues covering the bony surface can render the palpation less precise.

The initialization points did not significantly influence the registration accuracy. It is easier to palpate initialization points on the ipsilateral iliac wing (in the working area), and there is no advantage in using an additional contralateral approach to palpate the initialization point. These three points only grossly orient the pelvis to accelerate the surface-based matching process. In the case of mis-palpation, the global accuracy error was not significantly different.

In contrast, the DRB location had a significant influence on registration accuracy. Based on our results, the DRB should ideally be placed far from the working sampling area. There is also an advantage in performing a percutaneous approach and inserting the DRB on the contralateral iliac wing, as this significantly decreases global accuracy error. When the DRB is located far from the navigation pointer, and hence from the points

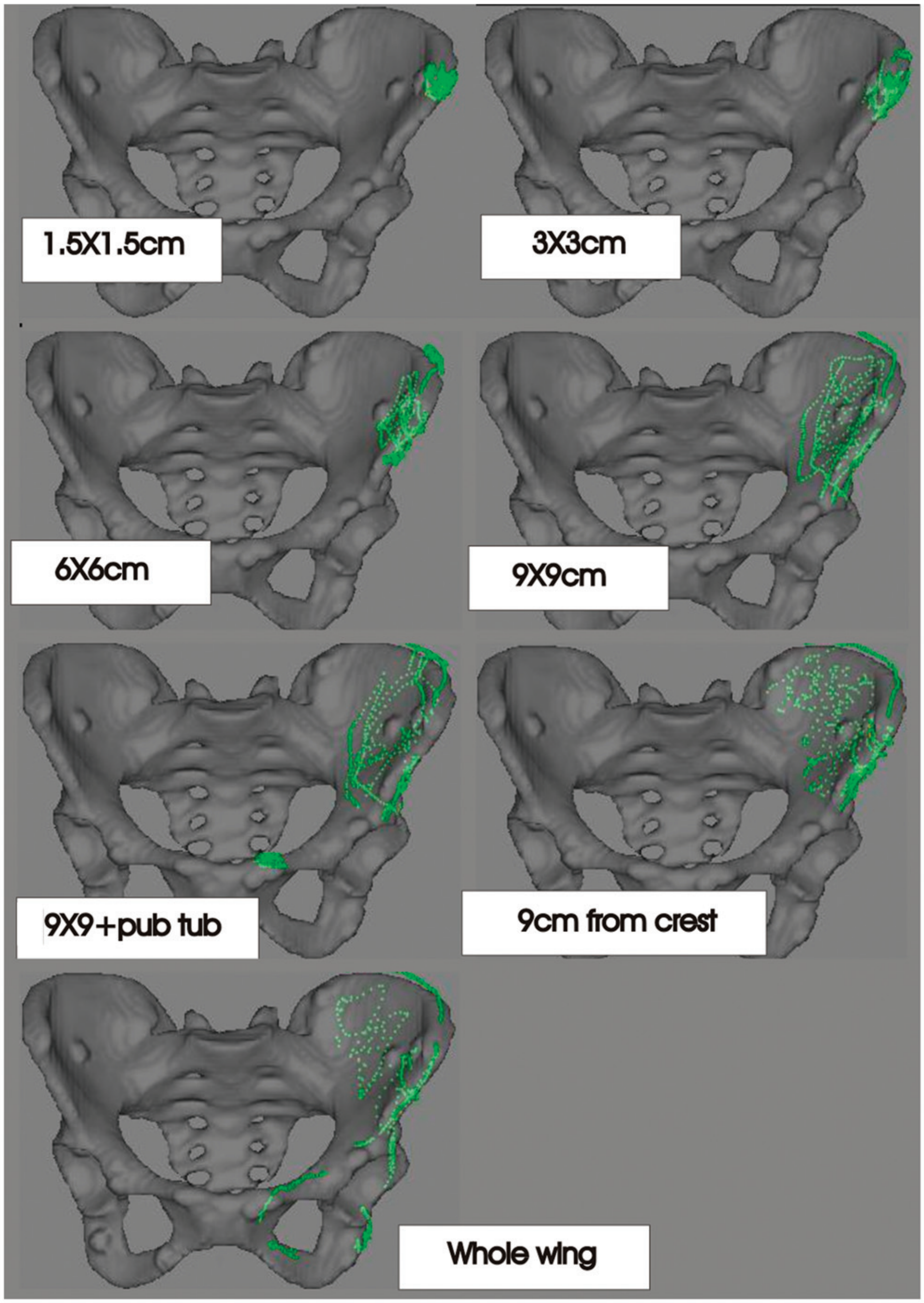

Figure 3. Screenshots of the acquired sampling surface areas from sets 1 to 7.

being acquired, all the distances are proportionally larger. This thereby proportionally minimizes the influence of the optical localizer error (0.35 mm). However, if the DRB is placed close to the sampling area, then the optical localizer error has more impact.

The accuracy increased from sets 1 to 6 as the sampling surface area was expanded. Furthermore, extending an ilio-inguinal approach to the posterior may be useful, since it decreased global accuracy error in our experiment. In the case of a larger sampling surface area, the position of the pelvis calculated by the computer is more precise. However, the sampling of distant zones on the entire iliac bone did not result in further accuracy improvement, but rather in a deterioration; global accuracy error underwent a slight but insignificant increase from 1.31 to 1.5 mm. The same

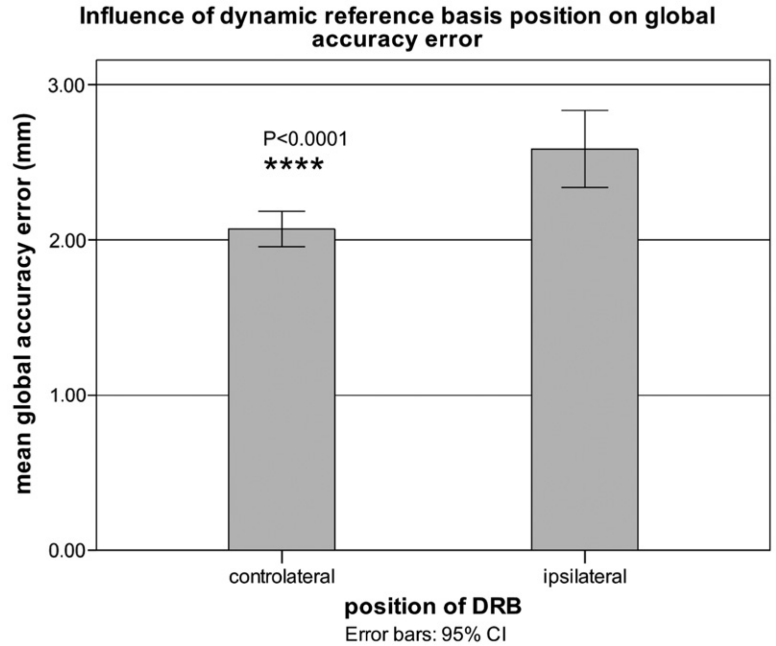

Figure 4. The influence of the DRB position on the global accuracy error: this error decreased when the DRB was located on the contralateral side.

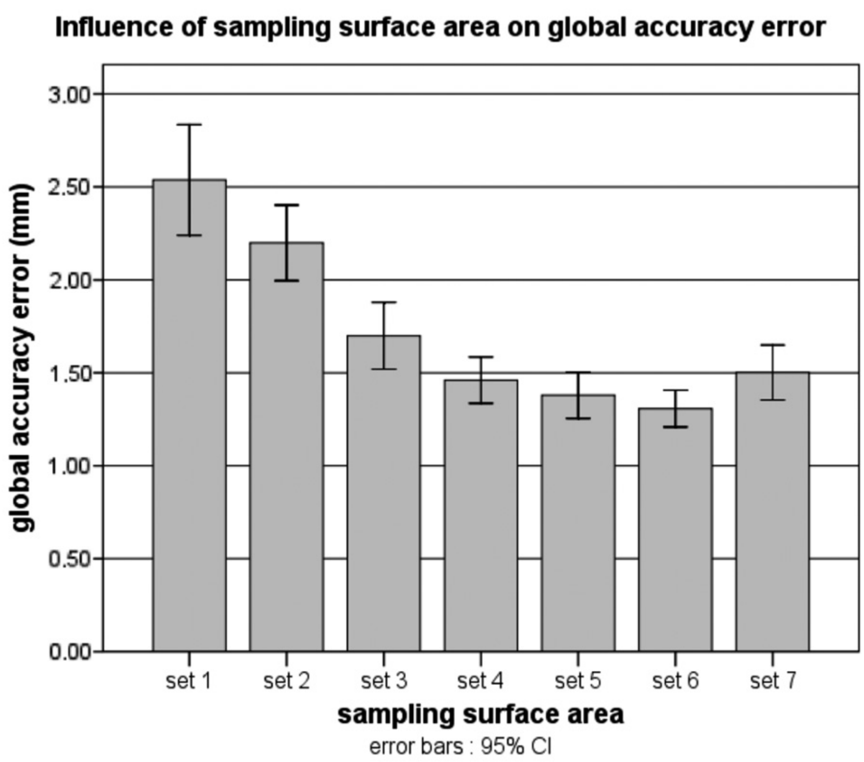

Figure 5. The influence of sampling surface area on the global accuracy error: this error decreased from 2.54 ± 0.42 mm for set 1 to 1.31 ± 0.14 mm for set 6.

phenomenon, in which accuracy of registration was decreased by expanding the sampling surface area, was previously reported in the spine [11] and pelvis [8]. In the latter case, using a postero-lateral approach, Sugano et al. found that the position error was higher when the iliac crest was palpated with an additional skin incision. This may occur because the density of the

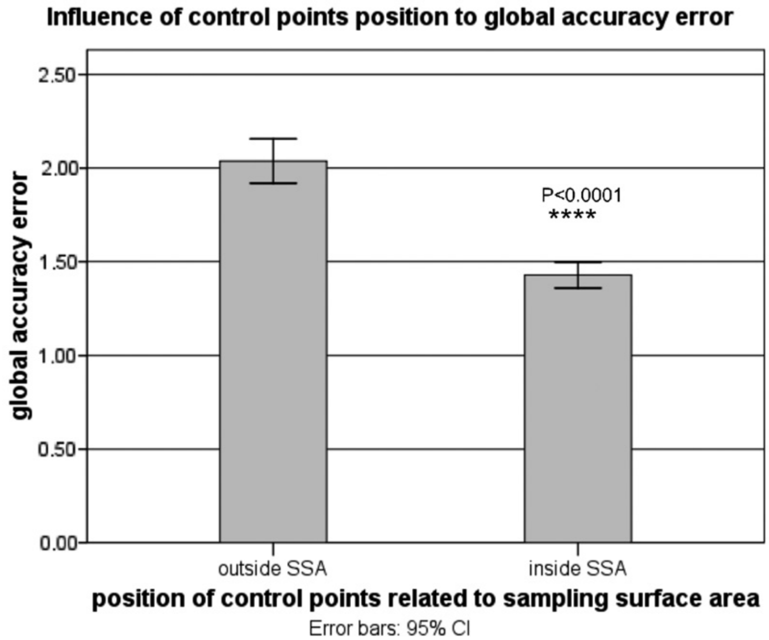

Figure 6. The influence of the position of control points (CP_is) on the global accuracy error. The "inside SSA" bar represents the CP_is included in the sampling surface area, and the "outside SSA" bar represents those distant from the sampling surface area. Accuracy is better when a surgeon works within the sampling volume as opposed to outside this volume.

sampling points decreases as the extent of the sampling surface area increases.

To investigate the target registration accuracy instead of the global registration accuracy, we can separately consider the CP_is included in the sampling surface area (inside) and those at a distant from it (outside). The difference between the inside and outside CP_is was highly significant (Figure 6).

The global accuracy error is the sum of the localization, alignment and optical localizer errors. The localization error is due to inaccurate acquisition of CP_is in the CT-scan coordinate system. As the slice thickness was 1.3 mm, locating a CP_i with high precision was not possible, leading to a constant bias for some points. The alignment error is due to the computer, as it calculates the transformation to match the pelvis from the DRB coordinate system to the CT-scan coordinate system, and could be minimized by enlarging the sampling surface area. The relative importance of the optical localizer error (RMS = 0.35 mm) could be minimized by placing the DRB far away from the working zone.

In conclusion, during a computer-assisted pelvic procedure using an ilio-inguinal approach, it is recommended that the DRB be located on the opposite side. Extending the approach posteriorly is useful, but extension to the ischium or ischiopubic ramus confers no benefit. It is also helpful to include the entire working area in the sampling surface area, if possible.

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