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ORIGINAL PAPER

Periacetabular osteotomy through the pararectus approach: technical feasibility and control of fragment mobility by a validated surgical navigation system in a cadaver experiment

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Abstract
Purpose The pararectus approach has been validated for managing acetabular fractures. We hypothesised it might be an alternative approach for performing periacetabular osteotomy (PAO).
Methods Using four cadaver specimens, we randomly performed PAO through either the pararectus or a modified Smith-Petersen (SP) approach. We assessed technical feasibility and safety. Furthermore, we controlled fragment mobility using a surgical navigation system and compared mobility between approaches. The navigation system's accuracy was tested by cross-examination with validated preoperative planning software.
Results The pararectus approach is technically feasible, allowing for adequate exposure, safe osteotomies and excellent control of structures at risk. Fragment mobility is equal to that achieved through the SP approach. Validation of these measurements yielded a mean difference of less <1 mm without statistical significance.
Conclusion Experimental data suggests the pararectus approach might be an alternative approach for performing PAO. Clinical validation is necessary to confirm these promising preliminary results.

Keywords Pelvis · Osteotomy · Pararectus approach · Surgical navigation · Joint preservation · Hip

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Introduction

Periacetabular osteotomy (PAO) allows for reorientation of the acetabulum, with large correction possibilities [1, 2]. Several surgical approaches for performing PAO have been introduced [1, 3–7]. A goal common to all approaches is to provide sufficient exposure for conducting osteotomies and acetabular reorientation while at the same time minimsing access morbidity [3]. Known complications include minor and major nerve injuries (lateral cutaneous femoral, femoral and sciatic nerve), vascular injuries (iliac vessels, corona mortis), as well as intra-articular osteotomy and accidental posterior column transection [8–11].

The pararectus approach has been developed and validated for managing acetabular fractures from inside the pelvis [12]. It permits excellent access to the anterior column and the quadrilateral plate. In this study, we hypothesised that it might also qualify for intrapelvic conduction of PAO. The purpose of this study was to create an experimental cadaver setup for:

(1) Assessing surgical feasibility of the pararectus approach for performing PAO
(2) Intraoperative assessment of fragment mobility compared with a modified Smith-Petersen (SP) approach controlled by a surgical navigation system
(3) Accuracy assessment of measurements obtained by the navigation system

Material and methods

Surgical technique and experimental setup

Computed tomography (CT) scans of four cadaver pelvises (Thiel fixated) were obtained, and 3D models were

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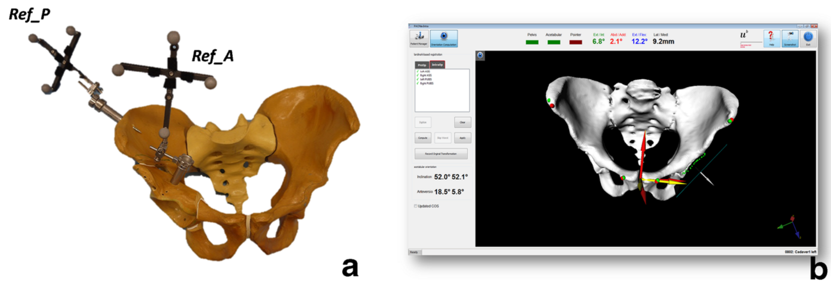

Fig. 1 Intraoperative periacetabular osteotomy (PAO) surgical navigation **a** Intraoperatively, two dynamic reference bases (DRBs) with reflective spheres are attached to both the pelvis (*Ref_P*) and the later acetabular fragment (*Ref_A*). **b**Navigation application providing all necessary data regarding acetabular orientation

reconstructed using image segmentation software (AMIRA, Visualization Sciences Group, USA). The specimens were placed in a supine position and a pelvic dynamic reference base (DRB) equipped with passively light-emitting spheres was fixed at the iliac crest. Randomly one hip of each specimen was treated with a PAO through a modified Smith-Petersen approach and as traditionally described by Ganz et al. [1]. The other hip was operated through the pararectus approach according to Keel et al. [12]. Using this approach, PAOs were performed from inside the pelvis, which is demanding for assessing technical feasibility and identifying structures at risk. After mobilisation of the acetabulum through either approach, the fragment was equipped with another dynamic reference base for reorientation tracking purposes (Fig. 1). For all acetabula, maximum fragment mobility was assessed using the classic maneuvres in flexion/extension, internal and external rotation and abduction and adduction, controlled by a previously validated surgical navigation algorithm [13]. Maximum mobility per parameter, as well as changes in acetabular version and inclination, was compared between these two approaches. Fragment fixation was performed using 3.5-mm cortical screws in a traditional manner for hips in which a modified Smith-Petersen approach was used. Alternative screw corridors were evaluated through the pararectus approach. Postoperative X-rays were performed to assess screw position.

Navigation workflow and mathematical background

As with every navigation procedure, our methodology employed a virtual object (VO—the 3D model of the pelvis) and a surgical object (SO—the true specimen). Different coordinate systems were defined:

- Virtual 3D computer model of the pelvis (VO)
- Anterior pelvic plane (APP) on this model
- True intraoperative anatomic specimen (SO)
- APP on this true intraoperative anatomic specimen
- DRBs used to code for pelvic and acetabular bone on the true specimen

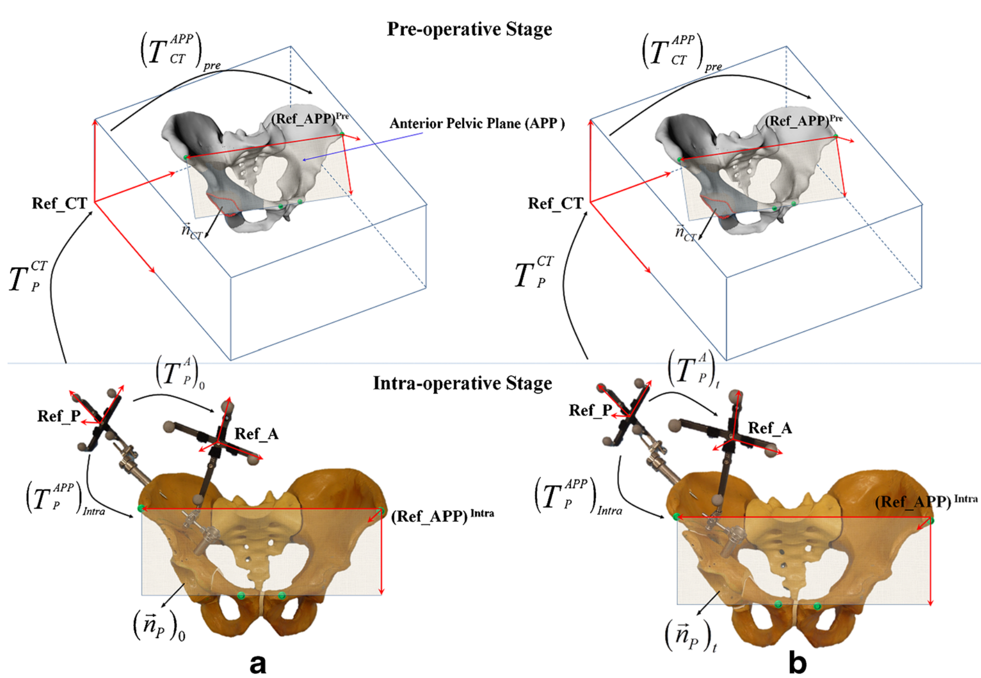

Fig. 2 Precise estimation of acetabular position: **a** estimation of acetabula orientation $(\vec{n}_{APP})^{0}_{Intra}$ in the native position before fragment reorientation; **b** estimation of acetabula orientation $(\vec{n}_{APP})^{t}_{Intra}$ during fragment reorientation

The purpose of surgical navigation is to unite all of these coordinate systems and to present a virtual scenery to the surgeon, which resembles the real surgical scenario. The relationship between SO and VO is established by the navigation system with the help of a registration process. In order to link virtual representation of the patient (in our case, 3D model of the pelvis) and actual patient anatomy (in our case, cadaver specimen), the surgeon can use a digitiser pointer recognised by the navigation system to point out true anatomic landmarks, which can also be recognised on the 3D model (paired points), in our case, the anterior pelvic plane marked by the anterior superior iliac spines and pubic tubercles. Furthermore, so-called dynamic reference bases are used to communicate with the navigation system. Each reference base also defines its own coordinate system. By attaching a reference base to each SO to be represented in the virtual scene, the navigation system is able to identify the relative positions and the spatial orientation between those SOs (in our case, the acetabular bone and the pelvic bone) by computing transformations between coordinate systems of the reference bases.

We used a passively light-emitting optical navigation system, a Windows-based software programme that uses a preoperative planning module to assess acetabular reorientation by defining classic parameters of acetabular geometry [13]. Furthermore, the system allows for intraoperative tracking of acetabular DRB excursion in relation to a pelvic DRB to

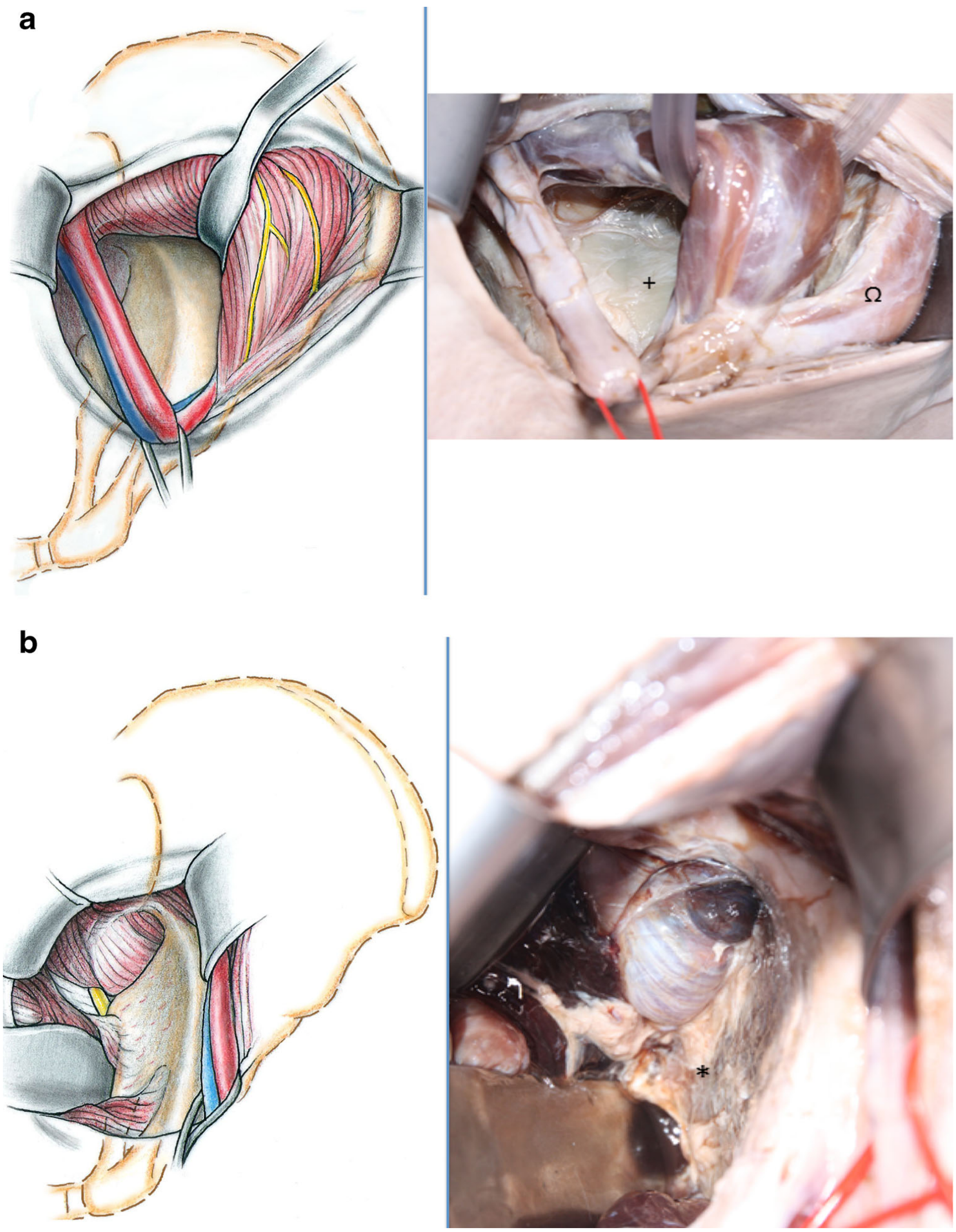

Fig. 3 Deep dissection using the pararectus approach. After identifying the external iliac artery and vein, the vascular bundle can be mobilised by retraction with a vessel loop. Lateral dissection leads to mobilisation of iliacus and psoas muscles, which are also marked and controlled by a silastic loop, including and protecting the ilioinguinal, femoral, lateral femoral cutaneous and genitofemoral nerves (**a**). Ultimately, after dissection is completed, full access to the iliac crest (Ω), pelvic rim, quadrilateral plate (+) and entire aspect of the acetabulum is shown. Placement of retractors around the ischial spine (*) allows visualisation of the piriformis muscle and fossa as well as the exiting sciatic nerve (**b**). The posterior column can be nicely visualised

quantify fragment mobility (Fig. 1b). Moreover, it employs automated detection of the acetabular rim [14] to calculate acetabular inclination and anteversion with respect to the APP [15]. Preoperatively, all related coordinate systems are defined (Fig. 2) on the virtual 3D model, with Ref_CT representing the preoperative CT data coordinate system of the surface model, which is necessary for automated detection of the acetabular rim. $(\mathrm{Ref\_APP})^{\mathrm{Pre}}$ represents the local coordinate system established on the APP, which is defined manually by choosing four landmarks [left and right anterior-superior iliac spine (ASIS) and left and right pubic tubercle]. Using the acetabular rim points extracted in the Ref_CT acetabular version, and inclination can be calculated in relation to $(\mathrm{Ref\_APP})^{\mathrm{Pre}}$.

Intraoperatively, Ref_P represents the pelvic coordinate system defined on the pelvic DRB, while Ref_A represents the intraoperative acetabulum coordinate system defined on acetabular DRB (Fig. 1a). The intraoperative APP coordinate system is defined by intraoperative paired-point matching [16] of the above-named landmarks and is represented by $(\mathrm{Ref\_APP})^{\mathrm{Intra}}$. Mathematical workflow of the navigation process is as follows:

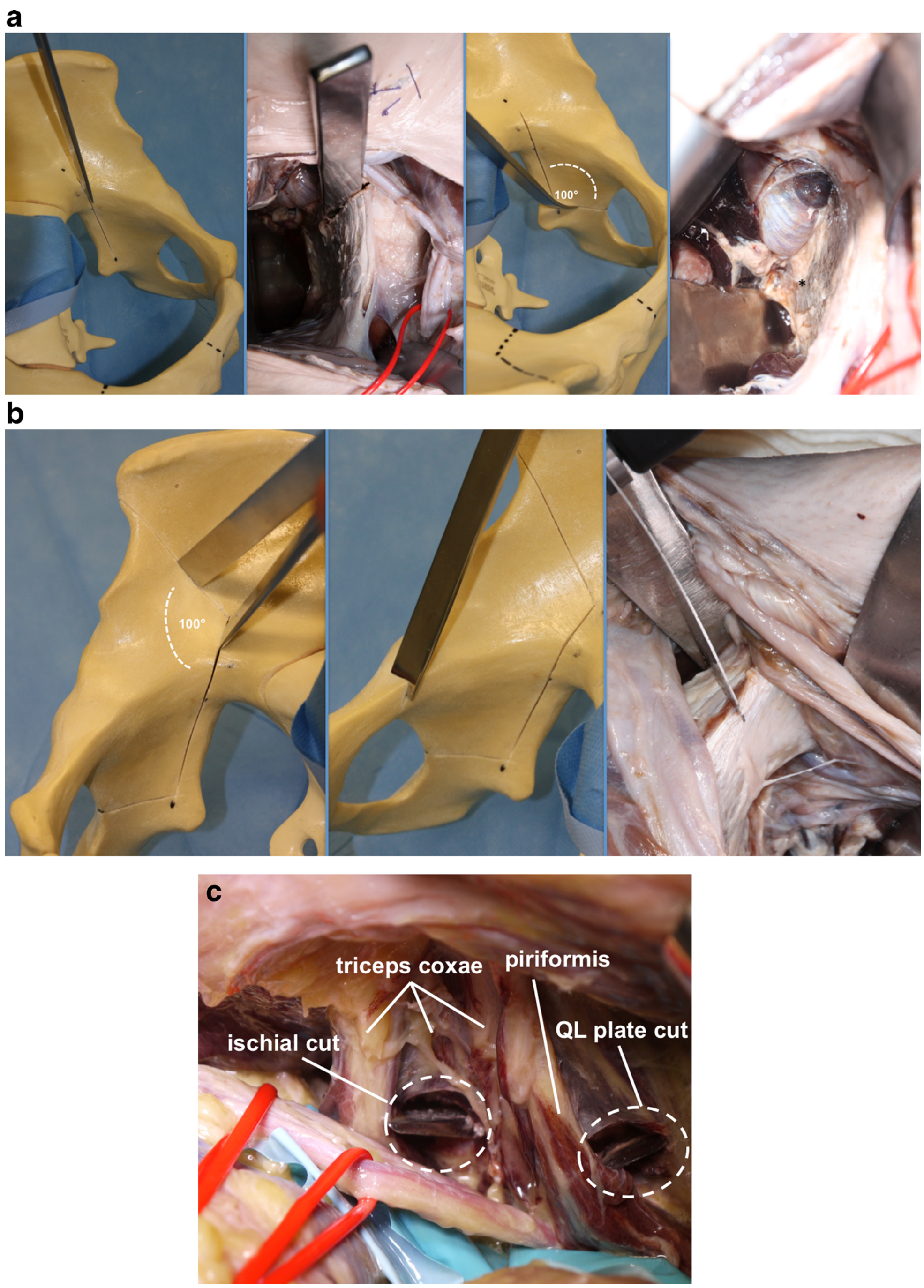

Fig. 4 Inside-out osteotomies. The first limb is directed behind the quadrilateral plate along the posterior column, with lateral retraction of vessels and Iliopsoas muscle (**a**). The second limb is the ischial cut under visual control, which is a 100°-angled cut with retractor positioned in the lesser notch (**a**). The third limb is a roof-shaped 100°-angled cut, which can optionally be completed using a short counterincision at the level of the anterior-superior iliac spine (ASIS) (**b**). Finally, the fourth limb is the pubic cut medial to the eminentia under protection of the obturator vascular nerve bundle (**b**). While the above-mentioned structures are under full visual control during the intervention, the sciatic nerve remains at risk during inside-out cuts, shown by an exemplary dissection of the Kocher–Langenbeck interval (**c**)

Step 1:

In order to register Ref_CT to Ref_P, DRBs are fixed, and a paired-point matching is performed before osteotomies and acetabular fragment tracking (Fig. 1a). The transformation $(T_P^{APP})_{Intra}$ between Ref_P and $(\text{Ref\_APP})^{\text{Intra}}$ can be calculated by Eq.(1).

$$(T_P^{APP})_{Intra} = (T_{CT}^{APP})_{\text{Pre}} \cdot T_P^{CT} \tag{1}$$

where T_P^{CT} is the rigid transformation between Ref_P and Ref_CT derived from paired-point matching; $(T_{CT}^{APP})_{Pre}$ is the transformation between Ref_CT and $(\text{Ref\_APP})^{\text{Pre}}$.

Step 2:

Before the fragment is moved, a snapshot of the neutral positional relationship $(T_A^P)0$ between Ref_A and Ref_P is recorded (Fig. 2a). At this moment, acetabular orientation $\left(\overrightarrow{n}_{APP}\right)^0_{Intra}$ with respect to $(\text{Ref\_APP})^{\text{Intra}}$ can be estimated by the following equation (Fig. 2):

$$\left(\overrightarrow{n}_{APP}\right)^0_{Intra} = (T_P^{APP})_{Intra}\cdot\left(\overrightarrow{n}_P\right)_0 = (T_P^{APP})_{Intra}\cdot(T^A{}_P)_0\cdot(T_{CT}^P)\cdot\overrightarrow{n}_{CT} \tag{2}$$

where $\overrightarrow{n}_{CT}$ denotes acetabular orientation measured in the Ref_CT preoperatively. Eq. 2 indicates that one can first compute acetabular orientation $\left(\overrightarrow{n}_P\right)_0$ with respect to Ref_P and then transform it to $(\text{Ref\_APP})^{\text{Intra}}$ through a transformation train.

Step 3:

Fragment mobility is measured by the navigation system, which records the instantaneous positional relationship $(T_A^P)_t$ between Ref_A and Ref_P. The neutral positional relationship $(T_A^P)_0$ obtained from Step 2 is used to calculate acetabular orientation $\left(\overrightarrow{n}_P\right)_t$ with respect to Ref_P during motion. The instantaneous acetabular orientation $\left(\overrightarrow{n}_{APP}\right)^t_{Intra}$ with respect to $(\text{Ref\_APP})^{\text{Intra}}$ can be calculated using the following equation (Fig. 2b):

$$\cdot\left(\overrightarrow{n}_{APP}\right)^t_{Intra} = (T_P^{APP})_{Intra}\cdot\left(\overrightarrow{n}_P\right)_t = (T_P^{APP})_{Intra}\cdot(T_A^P)_t\cdot(T_P^A)_0\cdot T_{CT}^P\cdot\overrightarrow{n}_{CT} \tag{3}$$

Eq. 3 indicates that one can first compute the instantaneous acetabular orientation $\left(\overrightarrow{n}_P\right)_t$ with respect to Ref_P and then transform it to $(\text{Ref\_APP})^{\text{Intra}}$ through a transformation train.

Step 4: The $\left(\overrightarrow{n}_{APP}\right)^0_{Intra}$ and the $\left(\overrightarrow{n}_{APP}\right)^t_{Intra}$ can then be decomposed into three motion components (extension/flexion, external rotation/internal rotation and abduction/adduction) along x-, y- and z axes of $(\text{Ref\_APP})^{\text{Intra}}$.

Accuracy assessment of intraoperative navigation

Postoperatively, in order to assess the accuracy of intraoperative measurements for the different rotation components, the stored values for acetabular version and inclination associated with each rotation component were entered into the preoperative planning module. Based on the entered values for version and inclination, the planning module virtually calculated the corresponding motion components named above, enabling direct comparison with the intraoperatively measured motions.

Statistical analysis

For comparison of fragment mobility between the two approaches, median values (range) for motion patterns were calculated. For comparison of intraoperatively measured values

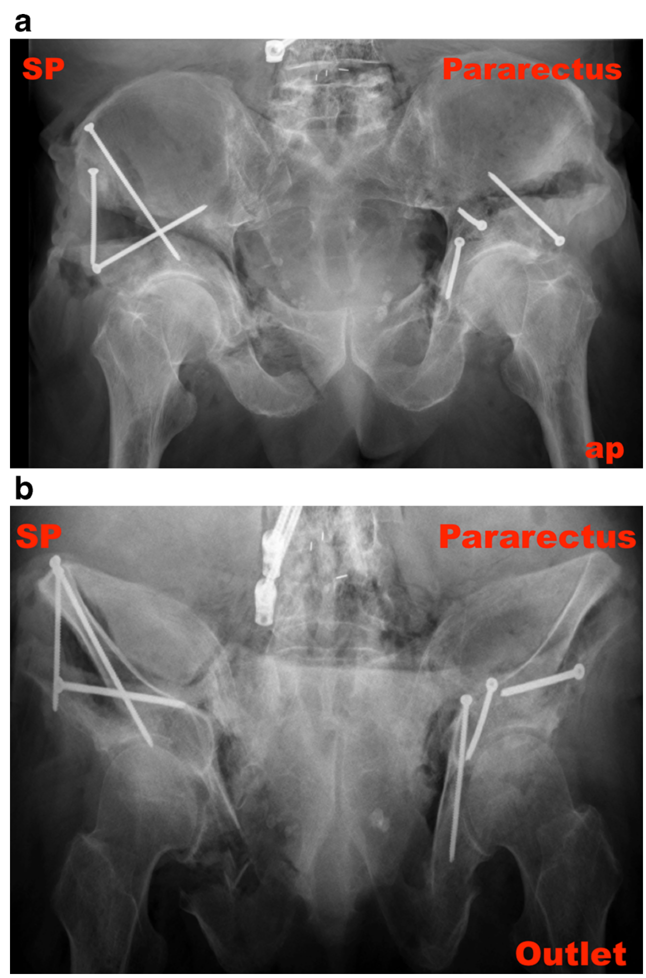

Fig. 5 Fragment fixation is depicted on an anteroposterior and outlet pelvis X-ray. The right hip was operated through a modified Smith-Petersen (SP) approach and the left hip through the pararectus approach, in which new screw trajectories were evaluated. Finally, safe corridors were determined for one screw into the posterior column through the infra-acetabular bone corridor, whereas two other screws found reliable purchase within the supra-acetabular bone stock

Table 1 Comparison of fragment mobility between modified Smith-Petersen (SP) and pararectus approaches

Parameter	Median (range)	
	Pararectus approach (*n*=4)	Modified Smith-Petersen approach (*n*=4)
Extension (°)	21 (13–27)	20 (14–32)
Internal Rotation (°)	10 (10–29)	11 (8–22)
External Rotation (°)	33 (20–37)	25 (11–44)

and values calculated by the planning module, we confirmed normal distribution using a Kolmogorov–Smirnov test and assessed significance by employing an independent *t* test.

Results

The pararectus approach proved feasible for conducting a PAO. After deep surgical dissection and external iliac vessel identification, obturator neurovascular bundle and spermatic cord, these structures can retracted together with the Iliopsoas muscle, providing full exposure of the quadrilateral surface and ischial spine (Fig. 3). Subsequent osteotomies are performed using an inside-out technique (Fig. 4). Safe screw corridors for acetabular fragment fixation were found (Fig. 5). For both approaches, no intra-articular penetrations or transections of posterior columns occurred.

Fragment mobility assessed by the navigation system showed similar results for both approaches when comparing median and range of all measurements (Table 1).

Accuracy comparison of the intraoperative navigation and values computed by the planning module showed a maximum difference of 1° with consistently low standard deviations (SDs) for all tested motion components (Table 2). Values for all motion components showed no significant difference.

Discussion

We investigated the pararectus approach as an alternative for performing PAO. In a cadaver experiment, we assessed technical feasibility, providing a stepwise technique description. Creating an acetabular fragment using inside-out osteotomies was achieved uneventfully. Fragment mobility was equal to the mobility achieved with the modified SP approach, and measurements can be considered accurate, since intraoperative navigation and computerised simulation of fragment reorientation yielded values without statistically significant difference.

Our study has limitations. As in general with cadaver experiments and technique descriptions, the case number is low, compromising statistic rigidity of data analysis. Addressing this, firstly we depicted median instead of mean values to compare fragment mobility, assuming a skewed data distribution and the median to be more robust and thus better suited for depicting a central tendency. Secondly, comparing intraoperative navigation data and values calculated by the planning application showed a maximum mean difference of 1°, with consistently low SDs for all tested motion components. Even though statistic rigidity of the applied tests could be debated, a submillimeter accuracy represents a reassuring result.

The second limitation might be that the pararectus approach has not been used clinically to perform PAO. However, it is a frequently used technique in our hands for open reduction and internal fixation (ORIF) of acetabular fractures involving the anterior column. It has been thoroughly evaluated, and both experimental and clinical data on five cadavers and 48 patients showed excellent applicability and safety of this technique as well as good clinical outcome [12, 17]. Based on this data and on experience from underlying experiments, clinical application of this technique can be considered feasible.

Table 2 Comparison of intraoperative navigation data for acetabular motion and motion data simulated by validated preoperative planning application

	Side	External rotation (°)			Internal rotation (°)			Flexion (°)		
		Intraoperative	Simulation	Δ	Intraoperative	Simulation	Δ	Intraoperative	Simulation	Δ
Cadaver 1	L	19.7	18.3	1.4	29.2	27	2.2	17.4	16.7	0.7
	R	43.9	43.2	0.7	22.4	21.7	0.7	32.2	32.6	0.4
Cadaver 2	L	22.5	24.5	2.0	13.7	13.2	0.5	17.5	19.2	1.7
	R	30.2	31	0.8	10.0	11.0	1.0	13.0	13.6	0.6
Cadaver 3	L	26.9	26.2	0.7	4.1	4.6	0.5	13.8	12.8	1.0
	R	35.1	34.8	0.3	10.2	10.0	0.2	24.6	23.7	0.9
Cadaver 4	L	11.2	11.7	0.5	8.0	7.7	0.3	21.5	22.3	0.8
	R	36.5	35.7	0.8	10.3	10.6	0.3	27.3	25.7	1.6
Mean±SD (range)		28.3±10.4 (11–44)	28.2±10.1 (12–43)	0.9±0.5 (0–2)	13.5±8.3 (4–29)	13.2±7.5 (5–27)	0.7±0.7 (0–2)	20.9±6.8 (13–32)	20.8±6.6 (13–33)	1.0±0.5 (0–2)
P value		0.943			0.793			0.962		

SD standard deviation

Another possible limitation is the typical source of error associated with application of surgical navigation to orthopaedic procedures. Inaccuracies can occur during 3D model generation and the matching procedure, which in our study was reduced to a paired point matching to define the anterior pelvic plane and a previously validated automated detection of the acetabular rim [14]. We believe that taking these errors into account, accuracy of the procedure can still be considered acceptable due to the consistency of data acquired.

One other downside to the pararectus approach is that in concomitant cam impingement [8], compared with the modified SP approach, anterior arthrotomy for anterior offset correction is not possible. This might require a second arthroscopic procedure in order to correct the deformity.

Several surgical approaches for performing PAO have been introduced [1, 3–7] (Ilioinguinal, SP, modified SP, two-incision technique using Toennis approach and transartorial approach) differing mostly in their invasiveness. Summarising the knowledge derived from the literature, the traditional approaches were all more invasive and hence associated with significantly higher access morbidity (blood loss, complications, time to access, hospital stay, etc.). The advantage was excellent exposure for performing osteotomies, reorientation and fragment-fixation possibilities [3, 6, 11]. In contrast to this, the minimally invasive approach—although favourable results have been reported [6, 7], might be associated with limited reorientation and fixation possibilities as well as underestimation of intraoperative blood loss. Compared with all these approaches, the pararectus approach provides excellent access to the ischium and quadrilateral plate, allowing execution of inside-out osteotomies without the need for external pelvic muscle detachment. Fragment mobility is equal to the modified SP approach, confirmed by a sophisticated 3D assessment using a surgical navigation system. The approach uses the full potential of PAO, allowing for an acetabular fragment free from any soft tissue restraints. Fixation with 3.5-mm cortical screws is possible; furthermore, additional application of low-profile reconstruction plates is easy, as shown in ORIF of acetabular fractures [12, 17].

Finally, the pararectus approach offers excellent possibilities for managing complications. Hussel et al. [3] described vascular injury as the most devastating complication during PAO. The pararectus approach allows for control of all important vessels prone to injury during PAO, such as external and internal iliac vessels, obturator vessels and corona mortis, of which the latter can be a cause of profound bleeding during PAO. Furthermore, a potential decrease in nerve injury, especially to the femoral nerve and lateral cutaneous femoral nerve, is expected. It must be stated, however, that with this technique, the sciatic nerve remains at risk during ischium osteotomy.

Conclusions

The pararectus approach might be an alternative for performing PAO, as it provides safe access, good correction possibilities and enhanced management of possible complications. Clinical evaluation of this approach, otherwise already validated for performing acetabular fracture reconstruction, is needed to confirm these promising preliminary results.

Conflict of interest The authors declare that they have no conflict of interest.

Research involving human participants and IRB approval All studies were approved by the appropriate institutional and/or national research ethics committee and were performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

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