Analysis of trans-sacral corridors in stabilization of fractures of the pelvic ring

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Abstract
Percutaneous screw fixation combined with pelvic reduction is a surgical technique used to stabilize fractures of the posterior pelvic ring. This is the standard surgical treatment of unstable posterior pelvic ring injuries. The primary goal of this treatment is an anatomic reduction and stable fixation. This has been shown to reduce pain and improve the patients' long-term well-being. The aim of this analysis was to determine the possible screw lengths and the positioning of the screws in the S1 and S2 sacral segments. A population of 697 pelvises from the Stryker Orthopaedic Modeling and Analytics database were analyzed. The dimensions of the S1 and S2 screw corridors were determined and after assessing for sacral dysmorphism, the correct screw placement was chosen to determine the necessary screw length for surgical treatment. The measurements of the screw lengths show a Gaussian distribution for the analyzed population. The percentage of dysmorphic pelvises for the S1 screw corridor was 31.3% and for the S2 corridor 8%. Average screw length for S1 was 163.8 ± 16.2 mm and for the S2 137.3 ± 9.5 mm. The results show that the S1/S2 axis cannot be used for a trans-sacral screw placement in every patient. The study shows that intraosseous screw corridors are present in 68.7% of the patients in the S1 position and in 92% at the S2 level where an intended implant can be placed fully intraosseous.

KEYWORDS
dysmorphism, percutaneous screw fixation, S1/S2 screw corridor, screw length, trans-sacral corridors

Abbreviations: CT, computer tomography; S1, sacral 1; S2, sacral 2; SAAT, Stryker Anatomy Analysis Tool; SOMA, Stryker Orthopaedic Modeling and Analytics.

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1 | INTRODUCTION

Pelvic ring injuries are relatively rare and account for approximately 3% of all fractures.1,2 However, in patients with multiple injuries as a result of high energy trauma, nearly 25% of cases involve the pelvic ring.3,4 In older patients, pelvic injuries frequently occur due to poor bone quality, resulting in low energy related injury mechanism.5 The incidence of pelvic ring fractures in older people is 90/100,000 and it is increasing due to demographic changes.6 The standard surgical procedure for stabilizing posterior pelvic ring fractures is fixation of the bone with percutaneous screws. Several studies have shown that in addition, the reduction and surgical stabilization of iliosacral joint disruptions can positively affect the outcome of the surgical treatment, that is, the anatomical reduction has a beneficial effect on the long-term well-being of the patients.4

Multiple screws and screws which traverse the trans-sacral corridor, the contralateral iliosacral joint or contralateral iliac cortex are used to improve stability of the pelvis and thereby result in successful outcomes.5 Such surgical treatments can be technically demanding in patients with a presence of dysmorphic anatomy who have narrow screw corridors S1 and S2.6 The relatively high prevalence of sacral dysmorphism in the general population introduces a high risk of cortical breach with resultant neurovascular damage.7 The knowledge of the dysmorphism of the sacrum is therefore crucial for the safe placement of screws.5 This aspect of the surgery has already been addressed in several earlier studies.8-14 However, conclusions from these studies are in part controversial. Thus, we performed a more detailed analysis with 697 specimen (272 females; 425 males) to evaluate the anatomy in the S1/S2 region to find the best placement corridor for screws to best surgically stabilize fractured pelvic ring structures.

The subject of the present study is to investigate (i) whether it is possible to place a trans-sacral screw in either S1 or S2 in all patients, (ii) to explore the maximum suitable screw lengths as well as (iii) to find the optimal positioning of the screws for the trans-sacral placement in the S1 and S2 corridor and (iv) to determine whether there is a gender difference with respect to dysmorphism of the sacrum. We show that an optimal trans-sacral placement in the S1 and S2 corridors can be achieved by a perpendicular screw position to the iliosacral joint, thereby avoiding extraosseous screw malposition.

2 | METHODS

The study was performed in compliance with the Helsinki Declaration and approved by the ethics committee of the University Medical Center Göttingen (Approval No.: AN 11/11/20).

2.1 | Stryker Orthopaedic Modeling and Analytics (SOMA) database

This study utilized a pre-existing SOMA database (Stryker Trauma GmbH). This database contains complete computer tomography (CT) data of 697 human pelvic cadavers (mean age, 58.8 (range, 18-93 years)) listed as three-dimensional templates.15 Two hundred seventy-two patients (39%) were females and 425 (61%) were males. Population differences in bone morphology, bone density, and implant fit for the purposes of research and development can be assessed using SOMA.15 Three-dimensional surface models were created based on CT scans from the SOMA database acquired exclusively for medical indications: polytrauma (20%), CT angiography (70%), and others (10%). Pelvises with pathologies (fractures, tumors), pelvic ring deformity, hip dysplasia, and pelvic implant in situ were excluded from the study.

2.2 | Stryker Anatomy Analysis Tool (SAAT)

We used SAAT to analyze shape variation of bones, and to capture geometric measurements such as bone density of the patients. Using this tool, the lengths of both S1 and S2 screw corridors were measured after identifying dysmorphic anatomy and the correct screw placement was chosen to determine the necessary screw length. The S1 screw axis was determined with the help of a frontal and a transverse reference plane. These planes were set with reference to the sacral foramina distally, the spinal canal dorsally and the ventral cortex of the sacrum. The distances to these reference elements were chosen to best fit the template bone in SAAT, and adjusted for the 25 biggest pelvises of the population, which were the most interesting specimen for the study. For the S2 screw axis the workflow in SAAT was the same as for the S1 axis described above with the axis determined in the frontal plane between S1 and S2 sacral foramina.

2.3 | Physiological or dysmorphic anatomy

To make a reliable length measurement of a trans-sacral screw, normal anatomy of the sacrum (see Figure 1A,B) and dysmorphic anatomy (see Figure 1C,D) had to be differentiated. A dysmorphic anatomy of the sacrum is indicated by a malformed and ellipsoid superior sacral segment, which significantly limits the area available for screw placement. Also, the inclination of the alarum is more pronounced in these patients and accompanied by a prominent anterior cranial alarium indentation. This oblique dysmorphic alar osteology makes trans-sacral screw fixation difficult.6 Usually if a dysmorphic anatomy is present, the S1 axis cannot be used for a perpendicular trans-sacral screw placement. In these cases, screws must be inserted from slightly dorsally because the perpendicular insertion of the screw to the opposite side is not possible. If this is not appreciated, a screw could either pass into a sacral foramen or into the sacral canal or even comes out of the bony pelvis and enters the pelvic cavity. All of these scenarios need to be avoided (see Figure 1C,D). To differentiate between a normal and a dysmorphic sacrum, additional intersection points of the screw canal were established with the ilium. If these intersection points were lying on the inside of the pelvis, a dysmorphic
The sacrum was present. If the additional intersection points were identical with those established for length measurement on the outside of the pelvis, the respective pelvis was considered to exhibit a normal anatomy with no intersection of the screw corridor inside the pelvis (see Figure 1). Using SAAT algorithm, the length of portion of the screw cylinder that emerges from the bone medially between the two os ilium bones was measured. Due to the algorithm, it is possible that this test value is either 0 mm or equal to the length measured in S1 in case the screw runs completely in the bone. Collectively, a pelvis is classified as dysmorphic if this value is greater than 5 mm and differs by more than 5 mm from the length measured in S1 and S2.

### 2.4 Screw length measurements and placement

For measuring the screw length, the intersection points of the axis and the outer pelvic surface/shape were established. The distance between these two points was then measured for both the S1 axis and the S2 axis. For pelvises rated as normal, the distance between the intersection points measured on the S1 axis was considered as screw length, whereas for pelvises rated as dysmorphic, the distance measured on the S2 axis was considered as screw length (see Figure 2). In the clinical settings for the screw placement a screw diameter of 8 mm was used with a safety distance between screw and foramen of the sacrum of 1 mm. The total screw corridor diameter was 10 mm with a safety distance of 1 mm.
circumferentially and a screw diameter of 8 mm. Screw positioning was perpendicular to the sacroiliac joint (see Figures 1 and 2).

2.5 | Statistics

Statistical analysis was performed using the D’Agostino-Pearson test to check for normal distribution. All data are presented as mean values ± SD, except when noted differently in the result section. The significance calculation was based on the two-sample t test and the significance level was set to α = 5%. Furthermore, the confidence interval was set to 95%. For all statistical tests, the statistics software Graphpad Prism 8 (version 8.1.1 for mac) was used.

3 | RESULTS

A pre-existing SOMA database containing datasets of the pelvises of 697 patients (mean age, 58.8 (range, 18–93 years); 272 females and 425 males) were examined. Figure 3 and Table 1 show the age range and the gender distribution of the patients.

3.1 | S1 and S2 screw corridor levels

Figure 4 shows the results of the distribution of dysmorphic anatomy and a normal pelvic structure for the S1 and S2 screw corridors with a diameter of 8 mm and a safety distance of 1 mm. Figure 4A shows the number of patients with percutaneous screw fixation for S1 and S2 corridors divided into normal anatomic structure and anatomical dysmorphism. There is a statistical difference between the two groups for both screw implantation in position of the S1 corridor (**p < 0.0016) and the S2 corridor (****p < 0.0001).

In Figure 4A, the data for a safety distance of 1 mm indicate that 68.7% for the S1 corridor have a normal structure of the pelvis, whereas 31.3% show a dysmorphic structure. For the S2 screw corridor, 641 of 697 examined pelvises (92%) have a normal structure, whereas 8% show a dysmorphic structure of the pelvis (Figure 4A). In very few cases (n = 9; 1.9%) we found critical corridors at both levels S1 and S2. Thus, in these cases, regular screw implantations were not feasible or clearly more difficult to perform.

In the area of pelvic anatomy, male patients showed dysmorphic pelvic structure at the level of S1 in 24% of the cases whereas the dysmorphic status in females was almost twice as high, that is, in 43% of the cases (see Figure 4B and Table 1). This result was statistically significant (**p = 0.00016). In the S2 corridor, the dysmorphism in males was only 5%. In females, this portion was almost three times higher, namely 13% (**p = 0.041).

| TABLE 1   | Gender distribution |
|-----------|---------------------|
| Number of female patients | 272 |
| Percent of female patients (%) | 39 |
| Number of male patients | 425 |
| Percent of male patients (%) | 61 |
| Ratio (males/females) | 1.6 |
| Dysmorphism female patients S1 corridor (%) | 43 |
| Dysmorphism female patients S2 corridor (%) | 13 |
| Dysmorphism male patients S1 corridor (%) | 24 |
| Dysmorphism male patients S2 corridor (%) | 5 |

**FIGURE 3** Age and gender distribution of the study group age distribution of the patient collective (n = 697); red bars show the number of females (n = 272), and blue bars males (n = 425) and their age distribution. Number of patients shown on the y axis. Age of patients shown on the x axis [Color figure can be viewed at wileyonlinelibrary.com]
3.2 | Distribution and measured S1 and S2 screw lengths

Figure 5 shows the distribution of the measured screw lengths which exhibit a Gaussian distribution. The majority of screws had a length of 150 mm (n = 103), followed by 145 mm (n = 92), 155 mm (n = 85), 160 mm (n = 79), and 140 mm (n = 77). In addition, screw lengths of 165 mm (n = 61), 135 mm (n = 55), and 170 mm (n = 41) were observed. The screw lengths of the remaining n ≤ 28 patients were found with a maximum of 237 mm along the trans-sacral S1 corridor and minimum of 130 mm. These numbers give rise to a mean value of 163.8 ± 16.2 mm. The maximum screw lengths of the trans-sacral S2 corridor was 169.3 mm and the minimum was 96.7 mm with a mean value of 137.3 ± 9.5 mm (see Table 2 above).

3.3 | Gender differences

Figure 6 shows the distribution of the measured screw lengths with respect to gender. The distributions show a Gaussian distribution for both sexes. For the female gender (Figure 6A), the majority of screws had a length of 150 mm (n = 55; 7.9%), followed by 145 mm (n = 45; 6.5%), 140 mm (n = 34; 4.9%), 135 mm (n = 34; 4.9%), 160 mm (n = 30; 4.3%), and 155 mm (n = 25; 3.6%), respectively. In addition, screw lengths of 165 mm (n = 21; 3%), 170 mm (n = 7; 1%), and 130 mm (n = 7; 1%) were observed. Screw lengths of the remaining patients (n = 14; 2%) were found with a maximum of 185 mm along the S1 trans-sacral corridor and a minimum of 125 mm. The overall mean value was 161.1 ± 15.2 mm. The maximum screw length of the trans-sacral S2 corridor was 169.3 mm and a minimum of 112.6 mm (mean value: 138.4 ± 9.2 mm) with a mean value of 161.5 ± 15.2 mm.

In contrast, the majority of screws in male patients (Figure 6B) had a length of 155 mm (n = 60; 8.6%), followed by 160 mm (n = 49; 7%), 150 mm (n = 48; 6.9%), 145 mm (n = 47; 6.7%), 140 mm (n = 43; 6.2%), and 165 mm (n = 40; 5.7%). In addition, screw lengths of 170 mm (n = 34; 4.9%), 175 mm (n = 23; 3.3%), and 135 mm (n = 21; 3%) were observed. Screw lengths of the remaining n ≤ 60 patients had a maximum length of 210 mm.
along the S1 trans-sacral corridor and a minimum length of 120 mm with a mean value of 165.5 ± 16.6 mm. The maximum screw length of the trans-sacral S2 corridor was 162.0 mm and the minimum was 96.7 mm. The overall mean value was 136.7 ± 9.6 mm.

### 4 | DISCUSSION

Reduction of fractures with dislocations and percutaneous insertion of trans-sacral screws is a common surgical procedure to stabilize injuries of the posterior pelvic ring. Percutaneous screw fixation of the posterior pelvic ring is used for many injuries, including high-speed trauma in young patients but also in elderly osteoporotic injuries. It has recently been shown that anatomical reduction of the iliosacral joint is important when considering the functional outcome and wellbeing of patients.

This study on CT scans of 697 patients indicates that iliac corridors corresponding to prevalent trans-sacral corridors were observed. The complex anatomical structure of the sacrum and the high individual variability require reliable and easy to use measurement for preoperative planning. Relevant limitations exist for the different measurement techniques, resulting in variable information concerning the corridor size values, in particular for the ellipsoid shaped S1 osseous corridor. Furthermore, osseous screw corridors of different pelvises were analyzed with respect to the predetermined trans-sacral S1- or S2-corridors and a starting point of the corridor axis on the posterior iliac crest. The recent results of Gras et al. on placement of percutaneous screw implantation in posterior pelvic ring

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**TABLE 2** Overview of the data on screw lengths from the entire studied population

| Description       | Mean       | Minimum | Maximum | Median | p value       |
|-------------------|------------|---------|---------|--------|--------------|
| Screw length S1 [mm] ±SD | 163.8 ± 16.2 | 130     | 237     | 161.5  | <0.0001 (****p) |
| Screw length S2 [mm] ±SD | 137.3 ± 9.5 | 96.7    | 169.3   | 137.2  | <0.0001 (****p) |

**FIGURE 6** Gender distribution of screw length. (A) Screw length distribution of the female patients (n = 272) and (B) for the male patients (n = 425). Frequency of screws [n] is shown on the y axis, screw lengths [mm] on the x axis [Color figure can be viewed at wileyonlinelibrary.com]
fractures are consistent with a recommended 65° drill direction in the horizontal plane.

With the selected safety distance of 1 mm from the foramen of the os sacrum, different results of dysmorphism were obtained with respect to earlier reports. For a safety distance of 1 mm, comparable with the data provided by Gras et al.,9 using a screw diameter of 7.3 mm. We used screws with a slightly larger diameter of 8 mm for the S1 corridor. It resulted in 31.3% patients showing dysmorphic anatomy of the pelvis, a value that is higher than the 24% reported by Gras et al.9 It has to be noted that in the report of Gras et al.,9 no differentiation into S1 or S2 anatomical dysmorphism was made. This difference of the analysis makes a direct comparison with our results very difficult. For example, Gras et al.9 reported that screw implantation at S1 corridor was not possible in 12% of the cases, whereas it was always possible to perform percutaneous screw implantation at S2 corridor as reported by Wagner et al.,10 who provide a statistical model for the S1 trans-sacral corridor. The 3D models by Wagner et al.,10 were reconstructed from CT scans of the pelvis of 92 Europeans and 64 Japanese (n = 156). In these models, a corridor of <12 mm was considered critical for trans-sacral implant positioning, and a corridor of <8 mm was considered impossible. In particular a safe placing of the trans-sacral screws in the S1 corridor was impossible in 26%, whereas a placement of such screws was always possible in the S2 corridor.10

We also found that the dysmorphic structure of the pelvis makes a completely intraosseous screw position nearly impossible. The results for the S2 corridor, with a safety distance of 1 mm to the foramen of the sacrum, show a dysmorphic anatomy of the pelvis in 8% of the patients. Thus, the dysmorphic structure of the pelvis makes a completely intraosseous screw position impossible in these cases. Gras et al.9 also describe the prevalence of corresponding intraosseous corridors at the S1 or S2 level in 88% of patients and that implantation was always possible at the level of S2. In our comprehensive study, the numbers of those patients who are suitable for a trans-sacral screw fixation are with 68.7% for S1 and 92% for S2 much lower than reported by Gras et al.9 who studied a much lower number of patients (84 patients) (n = 156) and did not differentiate between S1 and S2 anatomical dysmorphism.9 Wagner et al.,10,11 reported significantly lower numbers with respect to secure screw implantations as revealed by our present study. They investigated also where cortical damage can occur when an S1 screw was not properly placed. They reported that in their patient population without pelvic fractures (n = 156), 7.3 mm diameter trans-sacral implants were virtually positioned with and without a surrounding 12 mm diameter safety zone. Fifty-one percent of pelvises accommodated trans-sacral implants in S1 with a safe zone. Seventy-eight percent provided sufficient space for a trans-sacral implant in S2, with the inclusion of a safety zone.

Using the statistical surface model of the S1 trans-sacral corridor, including the adjacent parts of the iliac bones, which was developed from CT scans of 20 intact adult pelvises revealed that the diameter of the screw channels can be reliably taken as the main criteria for the surgically available corridor.12 They concluded that a distinct pattern of bone mass distribution with lower density, especially in the sacral alae, is an important determinant of the trans-sacral corridor dimension on level S1 which represents the limiting factor for safe screw placement.12

However, our results concerning the maximum screw lengths of the trans-sacral S1 corridor was 237 mm and the minimum screw lengths was 130 (mean value, 163.8 ± 16.2 mm) were almost identical with those reported by Gras et al.9 (mean value: 164 ± 12.9 mm).

Furthermore, in our study the maximum and minimal screw lengths of the trans-sacral S2 corridor were 169.3 and 96.7 mm, respectively, with a mean value of 137.3 ± 9.5 mm. Comparing these values with the literature9 which shows a mean of 142 ± 10.2 mm, these data are also comparable. These results show that implantation of percutaneous trans-sacral screws is not always possible at the S1 and S2 level (see Figure 5). Trans-sacral screws of 8 mm diameter can safely be placed at the S1 level in almost 70% of patients and at the S2 level in approximately 92% of patients.

According to Bastian et al.,16 a secure and optimal placement of percutaneous cannulated screws with at least 7 mm in diameter was not feasible in the majority of patients. Therefore, thoughtful preoperative planning of screw placement using CT scans is strongly advisable to identify secure pathways of a more optimal direction for the screw placement in terms of the biomechanics of the fixation. This notion underlines the clinical relevance of our study, which mainly relates to a patient population with a safe screw corridor at S1 and S2. The significantly higher prevalence of dysmorphic pelvic anatomy of females as compared to males came as a surprise, since our finding concerning both the difference and the distribution of longer screws for the male pelvis is in contrast to the earlier report of Balling,17 showing only a slight and nonsignificant difference in sacral anatomy in a cohort of some 200 patients. Our study, with 697 patients elutes to the fact that screw implantation is a more difficult task in women as compared to men.

Our study has some limitations. They concern, for example, the data on anatomy and trans-sacral screw corridors related to patients with noninjured pelvices. A fractured and displaced pelvis makes screw implantation more difficult. It has previously been documented that if pelvic fracture or dislocation is not reduced it is far more difficult to accurately insert a trans-sacral screw safely.18 The reason for using healthy human pelvises in our study was to obtain representative data in relation to different age groups and genders.

This study focuses on the prevalence of trans-sacral screw corridors of the pelvis to enable surgical therapy. Despite its limitation the results clearly demonstrate that the prevalence of corresponding intraosseous trans-sacral screw corridors are present in 68.7% of patients at the S1 level and in 92% at the S2 level for an intended 8 mm fully intraosseous implant.
CONCLUSION

This study shows that it is possible to safely implant an 8 mm trans-sacral screw in almost 70% of patients at the S1 level and in 92% of patients at the S2 level. The mean rans-sacral screw length at the S1 level is 163.8 mm and at the S2 level 137.3 mm and, in contrast to an earlier study gender specific differences were observed. Our findings are important during preoperative planning and when considering which implants need to be utilized to provide optimum fixation in both elderly and younger patients with injuries of the posterior pelvic ring. It is not possible to insert a trans-sacral screw in all patients and in this group of patients' alternative methods of fixation should be employed.

ACKNOWLEDGMENT

This study was funded by Stryker Trauma GmbH. Open access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTERESTS

Matthias Paulisch and Tobias Blüchel are employees of Stryker GmbH. The remaining authors report no financial and nonfinancial conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization: Wolfgang Lehmann and Mehool R. Acharya. Methodology: Katharina Jäckle and Wolfgang Lehmann. Validation: Katharina Jäckle and Wolfgang Lehmann. Formal analysis: Katharina Jäckle and Wolfgang Lehmann. Investigation: Katharina Jäckle. Resources: Wolfgang Lehmann. Data curation: Katharina Jäckle, Tobias Blüchel, and Matthias Paulisch. Writing—original draft preparation: Katharina Jäckle, Wolfgang Lehmann, and Mehool R. Acharya. Writing—review and editing: Katharina Jäckle, Christopher Spering, Matthias Paulisch, Tobias Blüchel, Marc-Pascal Meier, Mark-Tilmann Seitz, Mehool R. Acharya, and Wolfgang Lehmann. Visualization: Katharina Jäckle and Wolfgang Lehmann. Supervision: Wolfgang Lehmann. Project administration: Katharina Jäckle and Wolfgang Lehmann. All authors have read and agreed to the published version of the manuscript.

ETHICS STATEMENT

The present study was approved by the ethics committee of the University Medical Center Göttingen (Approval No.: AN 11/11/20). “Additional informed consent was obtained from all individual participants for whom identifying information is included in this article.” Written informed consent will be obtained from all participants.

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REFERENCES

1. Ruchholtz S, Wirtz DC. Kapitel 9—Beckengürtel und untere Extremität: 9.1 Hüfte. Oberschenkel. 9.1.1 Frakturen des Beckens. In: Kalbe P., Tegtmeyer K., eds. Essentials—Intensivkurs zur Weiterbildung: Orthopädie und Unfallchirurgie. 2nd ed. Georg Thieme Verlag; 2013. https://doi.org/10.1055/b-0034-62265
2. Zeckey C, Wolf F, Keppler A, Kammerlander C, Böcker W, Helfen T. Diagnostik und Therapie von Extremitätenverletzungen bei Polytraumapatienten. Intensivmedizin Up2Date. 2018;14(03):307-326. https://doi.org/10.1055/s-0043-122428
3. Eckardt H, Egger A, Hasler RM, et al. Good functional outcome in patients suffering fragility fractures of the pelvis treated with percutaneous screw stabilisation: assessment of complications and factors influencing outcome. Injury. 2017;48:2017-2723. https://doi.org/10.1016/j.injury.2017.11.002
4. Jäckle K, Spering C, Seitz T, et al. Anatomic reduction of the sacroiliac joint in unstable pelvic ring injuries and its correlation with functional outcome. [published online ahead of print June 10, 2020]. Eur J Trauma Emerg Surg. 2020. https://doi.org/10.1007/s00068-020-01504-z
5. Mehling I, Hessmann MH, Rommens PM. Stabilization of fatigue fractures of the dorsal pelvis with a trans-sacral bar. Operative technique and outcome. Injury. 2011;43(2012):446-451. https://doi.org/10.1016/j.injury.2011.08.005
6. Miller AN, Routt ML Jr. Variations in sacral morphology and implications for iliosacral screw fixation. J Am Acad Orthop Surg. 2012;2012(20):8-16.
7. Kaiser SP, Gardner MJ, Liu J, Routt ML Jr., Morshed S. Anatomic determinants of sacral dysmorphism and implications for safe iliosacral screw placement. J Bone Joint Surg Am. 2014;2014(96):e120.
8. Teo AQA, Yik JH, Jin Keat SN, Murphy DP, O’Neill GK. Accuracy of sacroiliac screw placement with and without intraoperative navigation and clinical application of the sacral dysmorphism score. Injury. 2018;49(7):1302-1306. https://doi.org/10.1016/j.injury.2018.05.027
9. Gras F, Hillmann S, Rausch S, Klos K, Hofmann GO, Marintschev I. Biomorphometric analysis of ilio-sacro-ilialic corridors for an intra-osseous implant to fix posterior pelvic ring fractures. J Orthop Res. 2015;33(2015):2060. https://doi.org/10.1002/jor.22754
10. Wagner D, Kamer L, Sawaguchi T, et al. Critical dimensions of trans-sacral corridors assessed by 3D CT models: relevance for implant positioning in fractures of the sacrum. J Orthop Res. 2017;35(11):2577-2584. https://doi.org/10.1002/jor.23554
11. Wagner D, Kamer L, Sawaguchi T, et al. Space available for trans-sacral implants to treat fractures of the pelvis assessed by virtual implant positioning. Arch Orthop Trauma Surg. 2019;139(10):1385-1391. https://doi.org/10.1007/s00402-019-02304-9
12. Wagner D, Kamer L, Rommens PM, Sawaguchi T, Geoff Richards R, Nosher H. 3D statistical modelling techniques to investigate the anatomy of the sacrum, its bone mass distribution, and the trans-sacral corridors. J Orthop Res. 2014;32(11):1543-1548. https://doi.org/10.1002/jor.22667
13. Trikha V, Gaba S, Kumar A, Mittal S, Kumar A. Safe corridor for iliosacral and trans-sacral screw placement in Indian population: a preliminary CT based anatomical study. J Clin Orthop Trauma. 2019;10(2):427-431. https://doi.org/10.1016/j.jocot.2018.01.007
14. Kamer L, Nosher H, Arand C, Handrich K, Rommens PM, Wagner D. Artificial intelligence and CT-based 3D statistical modeling to assess transsacral corridors and plan implant positioning. [published online ahead of print February 15, 2021]. J Orthop Res. 1–12. https://doi.org/10.1002/jor.25010
15. Schmidt W, LiArno S, Khlopas A, Peterisk A, Mont MA. Stryker Orthopaedic Modeling and Analytics (SOMA): a review. Surg Technol Int. 2018;32:315-324.
16. Bastian JD, Jost J, Cullmann JL, Aghayev E, Keel MJB, Benneker LM. Percutaneous screw fixation of the iliosacral joint: optimal screw pathways are frequently not completely intraosseous. Injury. 2015;46(10):2003-2009. https://doi.org/10.1016/j.injury.2015.06.044
17. Balling H. Gender-associated differences in sacral morphology do not affect feasibility rates of transsacral screw insertion. Radio-anatomic investigation based on pelvic cross-sectional imaging of 200 individuals. *Spine*. 2020;145(7):421-430. https://doi.org/10.1097/BRS.0000000000003293

18. Reilly MC, Bono CM, Litkouhi B, Sirkin M, Behrens FF. The effect of sacral fracture malreduction on the safe placement of iliosacral screws. *J Orthop Trauma*. 2003;17(2):88-94. https://doi.org/10.1097/00005131-200302000-00002

**How to cite this article:** Jäckle K, Paulisch M, Blüchel T, et al. Analysis of trans-sacral corridors in stabilization of fractures of the pelvic ring. *J Orthop Res*. 2022;40:1194-1202. https://doi.org/10.1002/jor.25144