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# Three-dimensional computed tomography evaluation of anterior cruciate ligament footprint for anatomic single-bundle reconstruction

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**Abstract**
*Purpose* Femoral and tibial footprint coordinates have been well studied in double-bundle anterior cruciate ligament (ACL) reconstruction. However, in a single-bundle reconstruction approach, the central coordinate of femoral and tibial footprints have not been determined. The purpose of this study was to describe the central point locations of the ACL footprints visualized by three-dimensional computed tomography (3D CT) images and analysed by the quadrant method.
*Methods* Eight cadaveric knees were dissected, and the central points of ACL femoral and tibial footprints were marked and analysed using 3D CT images.
*Results* In the present study, the means (and standard deviation) of ACL femoral footprint dimensions were in the ventral–dorsal plane and in the cranial–caudal plane $9.4 \pm 0.8$ and $15.6 \pm 0.9$ mm, respectively. In the tibial side, the means of ACL footprint dimensions were in the anterior–posterior and in the medial–lateral $18.5 \pm 1.9$ and $15.5 \pm 1.0$ mm, respectively. In the tomographic analyses, the means of femoral central location coordinates in the ventral–dorsal ($y$) and in the cranial–caudal ($x$) axes were $35.3 \pm 4.5$ and $30.0 \pm 1.6$ %, respectively. The means of tibial central location coordinates were in the anterior–posterior ($y$) and in the medial–lateral ($x$) axes, respectively: $40.5 \pm 5.3$ and $50.2 \pm 1.3$ %, respectively.
*Conclusions* These computed tomographic coordinates might help future studies as a reference on ACL single-bundle anatomic reconstruction, with respect to the management of ACL revision surgery or in symptomatic patients after ACL reconstruction. Improvements in three-dimensional image acquisition could facilitate its intraoperative applicability in the coming years.

**Keywords** Anterior cruciate ligament reconstruction · Anatomy · Knee joint

This study was carried out at Universidade Federal de Minas Gerais, Orthopaedic and Post-Graduation Surgery Department, Minas Gerais, Brazil, and at Hospital Felício Rocho, Minas Gerais, Brazil.

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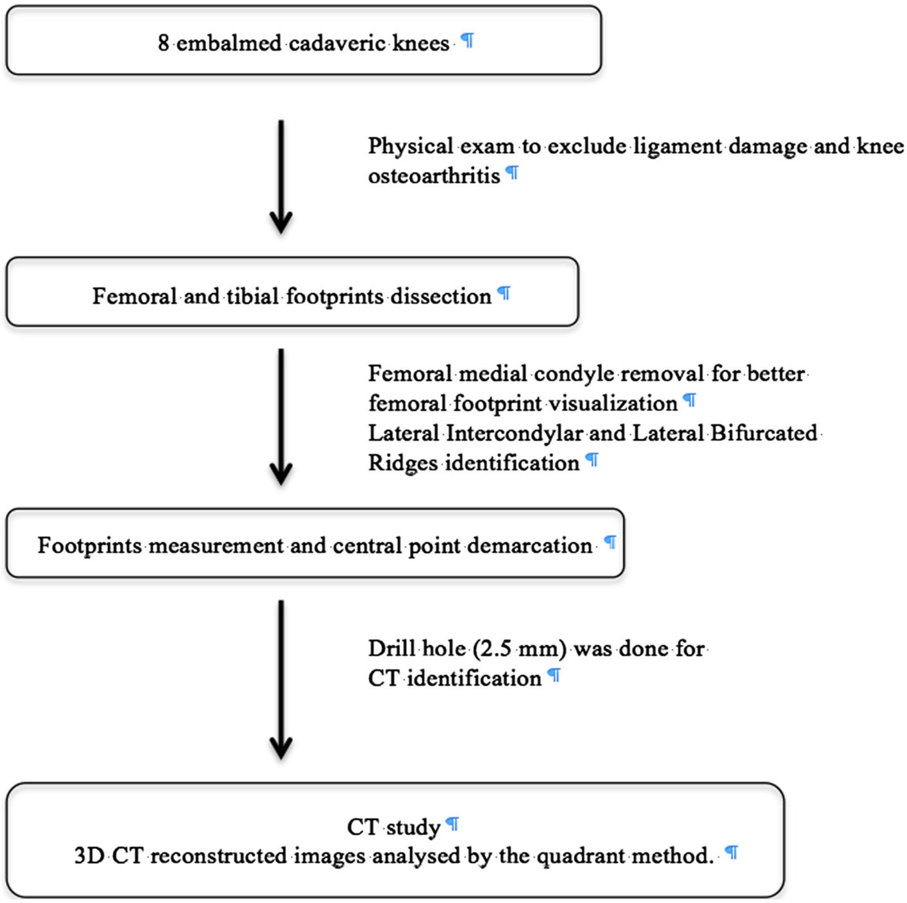
## Introduction

A comprehensive understanding of anterior cruciate ligament (ACL) anatomy is critical to its successful treatment [40]. Many studies have detailed the anatomy and functions of both anteromedial (AM) and posterolateral (PL) bundles [10, 12, 27]. Despite this, single-bundle reconstruction technique continues to play a major role in clinical practice. Anatomic reconstruction aims to reestablish femoral and tibial footprints by restoring their biomechanical and kinematic functions [13]. Yasuda et al. [40] described anatomic ACL reconstruction as tunnels being placed in the centre of the native femoral and tibial insertion sites, regardless of whether a single- or double-bundle technique has been used. Van Eck et al. [38] defined ACL anatomic reconstruction as functional restoration of its native dimensions, collagen orientation, and insertion sites. Likewise, Fu et al. [8] defined it as the restoration of at least 60–80 % of the native ACL footprint.

**Fig. 1** Flow chart: patients included Materials and methods summary




Recent transition from transtibial to transportal technique has introduced new challenges [18]. The radiographic parameters and surgical applicability of previous evaluation criteria have been changed over time [31]. Khalfayan et al. [15] described radiographic parameters to evaluate tunnel position in the traditional transtibial technique. However, these parameters lead to a posterior tunnel placement in the tibia and a high (anterior) tunnel placement in the femur—the so-called non-anatomical position [9, 18, 41]. Indeed, radiographic exams are limited in visualizing both the intercondylar anatomy and tunnel placement due to their two-dimensional inherent characteristics [17].

Computed tomography (CT) provides three-dimensional reconstructed images, thereby improving footprint visualization [7]. Lorenz et al. [21] and Forsythe et al. [7] proposed tomographic criteria for tunnel creation in double-bundle reconstruction technique, but landmarks for single-bundle reconstruction technique, i.e. single femoral and tibial footprint central point, were not well established.

Since tomographic ACL single central coordinate had not been described until now, we intended to study the femoral and tibial footprints utilizing 3D CT images, which could be useful in clinical terms for better positioning ACL graft by the anatomic single-bundle technique.

## Materials and methods

The Fig. 1 below summarizes the study methods. Eight embalmed non-paired human cadaveric knees (five men and three women, five right knees, mean age 52 ± 13.4 years, range 22–65 years) were carefully dissected by three of the authors and their ACL femoral and tibial centres demarcated. Each knee was examined to establish ACL integrity and to exclude osteoarthritis.

All knee structures were removed except for the ACL and articular cartilage surface. After identification, the ACL was sectioned in its midsubstance. The footprint was identified, and its boundaries were then marked [12]. The medial femoral condyle was removed with an oscillating saw to improve femoral visualization [33, 42] (Fig. 2a).

The AM and PL bundles were not divided intentionally. In the lateral femoral condyle, the lateral intercondylar ridge and the lateral bifurcated ridge [6] were sought in all knees. The following reference points of the tibial ACL insertion site were defined for all measurements: the anterior border of the tibial insertion of the AM bundle; the posterior border of the tibial insertion of the PL bundle; the medial border of the tibial insertion of the AM bundle, which is mainly the AM rim of the articular surface of the

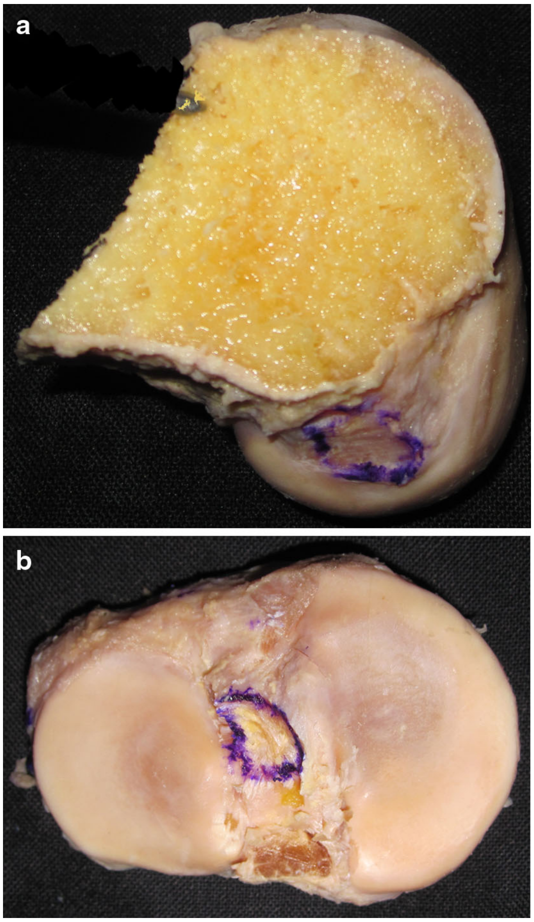



**Fig. 2** **a** Femoral and **b** tibial footprints: the measurement was done in the inner board of demarcation. Note that in the femoral side, the medial femoral condyle was removed to improve visualization

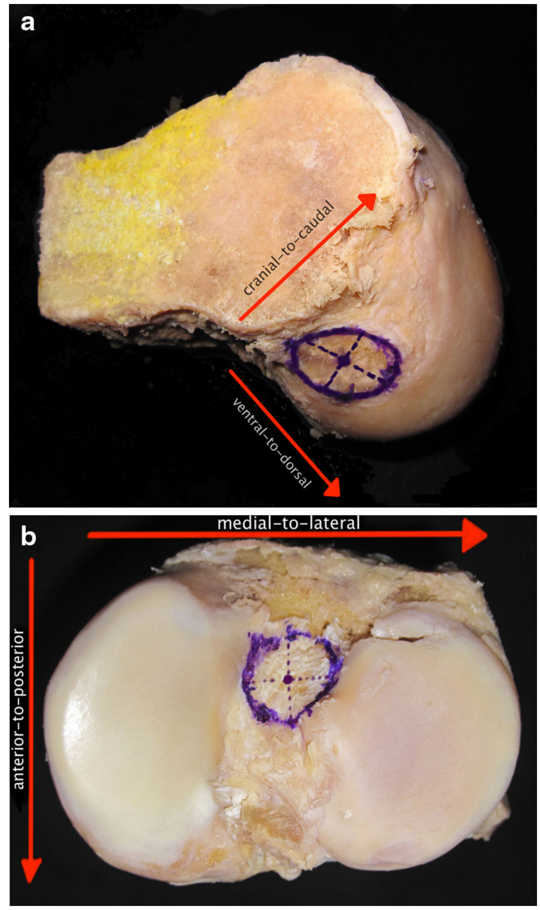



**Fig. 3** Central point location in femur and in tibia. Cranial–caudal ($x$) and ventral–dorsal ($y$) planes were used in femur (**a**), and medial–lateral ($x$) and anterior–posterior ($y$) planes were used in tibia (**b**). The central point was found as intersection point of two perpendicular planes

medial tibial condyle along the intercondylar area; and the lateral border of the tibial insertion of the PL bundle, which is mainly the anterolateral rim of the articular surface of the lateral tibial condyle [33].

The footprint dimensions were measured three times with a ruler by three of the authors (three times per person in two different occasions). Measurements in the footprint area were done according with two-planar orthogonal orientation to find a central point location. In the femur, the cranial–caudal ($x$) and ventral–dorsal ($y$) planes were used, and the intersection point between these planes was marked as the central point in each knee. In the tibia, medial–lateral ($x$) and anterior–posterior ($y$) planes were used, and the intersection point between theses planes was referred as the central point, as shown in Fig. 3. The footprint centre was then perforated with a drill bit (2.5 mm) to one-inch depth, which could be visualized by the CT study.

Computed tomography analyses were done in all knees. Multislice CT technology (Aquilion—Toshiba Medical Systems®) with 4-slice multidetector helical acquisition in 1.25-mm sections and pitch 3.0 and spacing of 0.6 mm was used. Three hundred slices were done in each knee, and three-dimensional reconstruction images were created by volume-rendering software (Aquarius Workstation® software—TeraRecon, Inc.). After 3D reconstruction process, the femoral medial condyle was removed for better visualization of the ACL femoral footprint [7]. In the tibial side, a true superior tibial plateau view was obtained. All analyses were performed using image software (OsiriX® v.4.0 32 bit) [21, 30].

After 3D-CT reconstruction images were created, two-dimensional quadrant method analysis was used [1, 21]. Central femoral footprint coordinates were calculated using the VDa and Cca positions, as shown in Fig. 4a. The tibial study followed the criteria described by Tsukada et al. [37]. The anterior–posterior axis position was calculated as percentage of the distance from the anterior border of the tibial plateau to the aperture tibial centre (APa position), while the medial–lateral axes position was calculated as

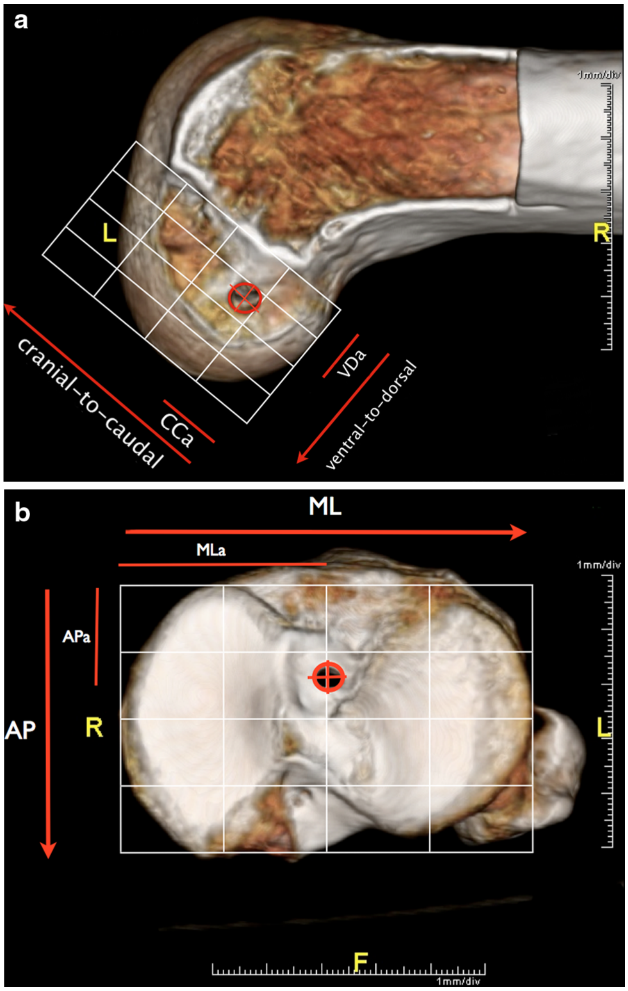



**Fig. 4** Three-dimensional tomographic view of the femoral (**a**) and tibial (**b**) centre aperture. Cca and VDa distance show the central point in femur. As well, MLa and APa distances represent the tibial central point

percentage of the distance from medial border of the tibial plateau to the tibial aperture centre (MLa position), as shown in Fig. 4b.

Details of the project were previously submitted to and approved by the Institution Review Board.

### Statistical analysis

The intraclass correlation coefficient (ICC) with 95 % confidence interval was calculated for the diameter measurement analysis. For this study, the coefficient represents the consistency between the three author's measurements of the cadaveric knees. Probability level of <0.05 was used as the criterion of significance. All analyses were carried out using the PASW software (version 18, Inc., Chicago, IL).

**Table 1** Interobserver and intraobserver agreement in the femoral and tibial footprint measurements

| | Footprint area (mm) | Intraobserver | | Interobserver | |
|---|---|---|---|---|---|
| | | ICC | Confidence interval (95 %) | ICC | Confidence interval (95 %) |
| Femur | | | | | |
| Ventral–dorsal | 9.4 ± 0.8 | 0.80 | 0.50–0.95 | 0.83 | 0.70–0.95 |
| Cranial–caudal | 15.6 ± 0.9 | 0.95 | 0.85–0.99 | 0.95 | 0.93–0.96 |
| Tibia | | | | | |
| Anterior–posterior | 18.5 ± 1.9 | 0.95 | 0.83–0.99 | 0.98 | 0.97–0.98 |
| Medial–lateral | 15.5 ± 1.0 | 0.91 | 0.75–0.98 | 0.91 | 0.85–0.96 |

## Results

Table 1 depicts the femoral and tibial footprint measurements. The footprint shape found in the femoral side was the oval type, while in the tibial side, seven knees were classified as oval and one as triangular. In the lateral femoral condyle, the lateral intercondylar ridge was identified in all knees, while the lateral bifurcated ridge was observed only in four knees. The intraclass correlation coefficient values were good for all measurements, in the femur but also in the tibia. The lowest ICC score of 0.80 was found in the ventral–dorsal ($y$) femoral axis.

Table 2 depicts the femoral and tibial coordinates in the two orthogonal axes. The percentage represents the footprint centre location in the grid. The ACL double-bundle values found in the literature are also shown.

## Discussion

The most important finding of this study was to describe tomographic coordinates that represent a unique and central location of ACL femoral and tibial footprints. These findings could allow the surgeon to define the right tunnel placement in ACL reconstruction, trying to correlate success or failure of the procedure with this positioning. Theses findings could also be helpful in ACL revision cases.

Anatomic single-bundle ACL technique is a reliable and reproducible approach in ACL reconstruction [26]. Although ACL double-bundle reconstruction leads to advantages in anatomical and biomechanical terms, concerns about clinical benefits still remain [2, 3, 36]. The authors agree with the functional importance of the two bundles, but single-bundle technique still plays a major role in ACL reconstruction in clinical practice.

**Table 2** Overview of reference points found in this study and its comparison with double-bundle studies (as %)

| Author | Study | Femur | | | | Tibia | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | AM ($x$)[a] | PL ($x$)[a] | AM ($y$)[b] | PL ($y$)[b] | AM ($x$) | PL ($x$) | AM ($y$) | PL ($y$) |
| Present study | Single bundle | 30.0 (1.6) | | 35.3 (4.5) | | 50.2 (1.3) | | 40.5 (5.3) | |
| Tsukata et al. [37] | Double bundle | 25.9 | 34.8 | 17.8 | 42.1 | 46.5 | 51.2 | 37.6 | 50.1 |
| Lorenz et al. [21] | Double bundle | 21 | 27 | 22 | 45 | 48 | 50 | 41 | 52 |
| Colombet et al. [4] | Double bundle | 26.4 | 32.3 | 25.3 | 47.6 | – | – | – | – |
| Forsythe et al. [7] | Double bundle | 21.7 | 35.1 | 33.2 | 55.3 | – | – | – | – |
| Zantop et al.[c] [42] | Double bundle | 18.5 | 29.3 | 22.3 | 53.6 | – | – | – | – |

[a] Results show the cranial–caudal orientation ($x$)

[b] Results show the ventral–dorsal orientation ($y$)

[c] Tibial measurements were not shown because authors utilized a different quantification method, as described by Stäubli and Rauschning [34]

An accurate evaluation of the native ACL anatomy is critical for achieving anatomic ACL reconstruction. Favourable clinical outcomes could be impaired by a non-anatomic graft placement [20]. In a cadaveric knee model, Ho et al. [10] showed that a central anatomic single-bundle ACL reconstruction where tunnels are centred in the tibial and femoral insertion sites can restore normal anterior translation under anterior and rotational loads applied at 30° and 60° of knee flexion. Anatomical ACL reconstruction, either single-bundle or double-bundle technique, could provide better knee kinematics than non-anatomic reconstruction [16].

In the present study, the ACL femoral footprint dimensions were 9.4 ± 0.8 in ventral–dorsal plane and 15.6 ± 0.9 mm in cranial–caudal plane. Kopf et al. [19] in a literature review showed that ACL femoral footprint could vary from 7 to 13 mm in the ventral–dorsal orientation, and from 12 to 23 mm in the cranial–caudal orientation. These founds could be explained by gender, body size, and ethnic variations.

In the tibial side, the ACL tibial footprint dimensions were 18.5 ± 1.9 (anterior–posterior) and 15.5 ± 1.0 mm (medial–lateral). Ferretti et al. [5] in a 3D laser scan analysis of tibial plateau in eight non-paired cadaveric knees found length (anterior–posterior) and width (medial–lateral) values of 18.1 ± 2.8 and 10.7 ± 1.9 mm, respectively. Tállay et al. [35] found similar values in ACL tibial dimensions in anterior–posterior (19.5 ± 2.6 mm) and in medial–lateral (10.3 ± 1.9 mm) axes. Collombet et al. [4] found a broader ACL tibial area (length 17.6 ± 2.1 mm and width 12.7 ± 2.7 mm), values that most resemble the present study. The oval-shaped pattern of the tibial footprint was present in seven (87.5 %) knees in our study. This find was very similar to a previous anatomical study [12]. Nevertheless, Ferretti et al. [5] found oval ACL tibial footprint shape only in four knees, while triangular ACL tibial footprint shape was seen in four knees.

The development of anatomical reconstruction concept created new landmarks for ACL reconstruction, such as residual footprint tissue or bony ridge landmarks, which could be useful during surgery for precise femoral and tibial tunnels positioning [6, 29]. Evaluation with imaging methods intraoperatively has been used for several years, even before the concept of anatomical ACL reconstruction. However, reference points used previously lost their value due to changes in positioning of the tunnels brought with new technique [11, 15, 25, 28].

Definition of ACL anatomic position by two-dimensional image is questionable, mainly at the femoral side [14]. Since radiographic measurement is largely influenced by rotation and angulation, 3D-CT reconstructed image analysis is preferable to assess the intercondylar notch geometry even by the two-dimensional quadrant method [22]. Van Eck et al. [39] studied the influence of rotation of the femur on estimates of the position of the femoral ACL tunnel aperture relative to Blumensaat's line in a true lateral radiographic view. For double-bundle reconstruction patients, valgus malalignment of more than 10° significantly altered tunnel position estimates by true lateral radiographic study. For non-anatomic single-bundle reconstruction patients, internal rotation malalignment of more than 10° significantly altered tunnel position estimates by the same method.

Comparing our coordinate findings with double-bundle studies, similar results could be observed. Tsukada et al. [37] studied ACL insertion sites anatomy in thirty-six cadaveric knees. In this open anatomic study, the means of AM and PL bundles were very similar to our results. As well, in a tomographic study, Lorenz et al. [21] reported results very similar to ours except for a more posterior tibial central point location (41 % AM bundle and 52 % PL bundle in the anterior–posterior tibial axis). Using the quadrant method analysis in eight cadaveric knees, Forsythe et al. [7] found coordinates very similar to the central points of AM and PL bundles found in the present study.

Although intraoperative availability of three-dimensional image acquisition is still limited, 3D navigation system can provide such image, although controversies exist about its applicability in ACL reconstruction [23]. Moreover, cone-beam 3D CT image acquisition has been described in brain and spinal surgery, improving image quality with safe dose radiation [32, 43]. This technology could be useful in ACL reconstructions in the coming future, providing 3D image information for better surgical decision-making. Indeed, the authors believe that these tomographic landmarks could also be useful for other scenarios, such as for preoperative planning in ACL revision surgery or for evaluation whether anatomical reconstruction was accomplished or not in patients with symptoms after ACL reconstruction.

The main limitation of this study was a small sample with only 8 knees. However, our sample had similar features than others cadaveric and tomographic studies [5, 7, 21]. Moreover, previous double-bundle anatomic studies have been conducted using fresh knee specimens [5, 7, 12, 21]. In the present study, no alterations were perceived in anatomic characteristics with respect to the embalming process [24]. In the author's opinion, this could be worrisome in studies that assess the joint biomechanics or kinematics but not in this anatomic investigation.

## Conclusions

This study describes computed tomographic coordinates by the quadrant method analysis for tunnel positioning for ACL anatomic single-bundle reconstruction technique. These computed tomographic coordinates might help future studies as a reference on ACL single-bundle anatomic reconstruction, with respect to management of ACL revision surgery or in symptomatic patients after ACL reconstruction. Three-dimensional image acquisition could facilitate its intraoperative applicability in the coming years.

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

**Disclaimer** No author or related institution has received any financial benefit from research in this study.

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