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Prediction of the drilling path to surgically pin the femoral neck from the spatial location of pelvic and femoral anatomical landmarks: A cadaver validation study

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ABSTRACT

Several clinical applications rely on accurate guiding information when drilling along the femoral neck (e.g., pin insertion in case of neck fracture). Currently, applications rely on real-time X-ray imaging, which results in irradiation issues for the surgeon conducting the operation. The goal of this paper was to develop an X-ray-free method that would allow for a pathway to be drilled between the lateral aspect of the femoral diaphysis (the so-called piercing point), the femoral neck and the head centres. The method is based on on-the-fly computational predictions relying on a biomechanical database that includes morphological data related to the femoral neck and head and various palpable anatomical landmarks located on the pelvis and the femoral bone. From the spatial location of the anatomical landmarks, scalable multiple regressions allow for the prediction of the most optimal drilling pathway. The method has been entirely validated using *in vitro* experiments that reproduce surgical conditions. Further, a surgical ancillary prototype that integrates the method of guiding the pin drilling has been developed and used during *in vitro* and *in situ* validation using nine hip joints. Pin insertion was controlled after drilling using medical imaging and show successful result for each of the nine trials. The mean accuracy of the estimated hip joint centre and neck orientation was 6.0 ± 2.8 mm and 7.1 ± 3.8°, respectively.

1. Introduction

Several clinical applications rely on accurately locating specific anatomical features that are found on the proximal aspect of the femoral bone. For example, guiding information must be available when pinning along the femoral neck [1] or drilling to reach the femoral head, e.g., in the case of hip joint osteonecrosis [2]. Currently, fluoroscopy is probably the most common method used to perform this evaluation in a surgical setting [3,4]. X-ray irradiation of surgeons and patients is, however, still a concern, and alternatives to reduce X-ray exposure are requested by the field [5–7]. Such methods depend on medical imaging equipment, which may not be available in many parts of the world (e.g., Central Africa) [8].

The hip joint is typically assumed to be a ball-and-socket joint centred on the femoral head centre (FHC) or coinciding with the centre of the acetabulum [9]. Two common methods are available to define the hip joint centre (HJC): one predictive approach uses morphology-based regression equations estimated from specific anatomical landmarks (ALs) [10,11], and another approach is based on functional calibration when the HJC location is determined from movements during the calibration trials [12].

Functional methods have been recognized as the most accurate HJC location methods; however, despite their usefulness, they have some practical drawbacks. Indeed, they require particular motion patterns that are often too complex for patients showing limited joint range [13] or who are lying on an operating table prior to surgery. Morphological methods seem to be more appropriate for surgical settings because the patient can remain at rest even while anaesthetized during palpation. A recent study reported that manual palpation using ALs might achieve satisfactory accuracy [14].

This paper presents a novel computational method based on a morphological bone database and AL manual palpation procedure to predict the relevant guiding data that are used to control the surgical ancillary. Repeatability of the virtual palpation was performed for *in vivo* data. The adopted multiple regression approach

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Table 1
Anatomical landmarks included in the database. Palpated ALs are indicated in bold (Van Sint Jan [23]). The other ALs have been estimated. LACC, RACC: left and right acetabulum centres, respectively. RFHC: femoral head centre. RFNC, RFMM: femoral neck centres using two methods (from the one-sheet hyperboloid and circle fitting, respectively). RFDP: position of the estimated drilling point in the greater trochanter area.

	1	2	3	4	5	6	7	8
Pelvis	**LIAS**	**LIPS**	**RIAS**	**RIPS**	**RIIT**	LIIT	LACC	RACC
Femur	**RFTC**	**RFLE**	**RFME**	RFHC	RFNC	RFMM	RFDP	

is based on the modification of a previously published method [15]. We aimed to estimate the feasibility and the accuracy of the developed prediction method and femoral neck drilling for *in vitro* application. The method has been applied in this paper to drill a surgical pin within the femoral neck up to the femoral head centre without the need of medical imaging on the subject undergoing the procedure because of on-the-fly multiple regression procedures. Validation of the approximated drilling pathway was performed *in vitro* and *in situ* using nine hip joints.

2. Materials and methods

The computational database for the method was built from data collected from 57 cadavers obtained from the ULB Body Donation department that is an officially recognized academic structure for research and pedagogical activities. X-ray control by two of the authors and senior orthopaedic surgeons (J.P. and M.R.) confirmed that the lower limbs of the donors had no bone disorders or osteosynthesis material that could lead to artefacts during CT imaging nor did they have any joint-related disorders. CT imaging was performed on the lower limbs of all of the donors.

2.1. Data collection for building the computational database

For each donor, CT datasets were obtained from above the iliac crests to below the joint space of both knees (CT specifications: Siemens SOMATOM, helical mode, slice thickness: 1 mm for the pelvis area and for both femoral epiphyses and 10 mm for the femoral diaphysis). After segmentation (Amira 5.4.3, FEI Visualization Sciences Group, France), 3D models of the specimen's pelvis and two femoral bones were obtained [16]. Virtual palpation was then performed following strict definitions to ensure the reproducibility of the palpation results [17,18]. Virtual palpation allowed for the collection of the spatial coordinates of 8 key ALs from both hip joints of each available specimen; these key ALs included 5 pelvic and 3 femoral ALs (highlighted in Table 1). Supplementary ALs were virtually palpated on the surface of the acetabulum, the femoral head and the neck surfaces to further characterize these surfaces using geometrical shape approximation [15].

2.2. Data processing

Several data processing steps were taken to unify the collected data (using custom-made software developed in MATLAB v2013a, the Mathworks, Inc., USA). The left hip joint data were mirrored before transformation [15] to double the database size, which eventually included 114 hip joints. At first, all of the ALs and bone model vertices were converted to a pelvic local coordinate system (LCS), which was defined according to ISB recommendations [19] (Fig. 1). The pelvic LCS was based on four pelvic ALs (1–4 in Table 1). Then, the supplementary ALs (i.e., 3D bone model vertices related to the area of interest) were processed to fit quadric surfaces (ellipsoid or one-sheet hyperboloid) and to obtain computational models of the acetabulum, the femoral head and the femoral neck [15,20]. The femoral head and the acetabulum were also fitted using a spherical representation for comparison with the quadric surfaces. The centre of the fitted surfaces was then determined (RACC, RFHC and RFNC for the acetabulum, the head and the neck, respectively) (Fig. 1). The poses of all of the hip joints available in the database were transformed using rigid transformations towards the same joint orientation [21]. Such a hip joint pose adjustment was also important to allow database bone poses transformation to currently estimated ones and for the further use of similarity criteria for AL clouds to implement weighted multiple regressions [22], which are used hereafter in this paper. For each specimen, the fitting quality was assessed by comparing the distance of the obtained quadric surfaces with the original 3D bone models. The distance was estimated as mean from distances between 3D bone vertices and their orthogonal projections on the fitted quadric surface [15]. It must be stressed that the database content (i.e., the hip pose of bone models) can be transformed to any pose, for example, the hip orientation showed by a patient on an operating table. This was important for further application of the method in surgical practice.

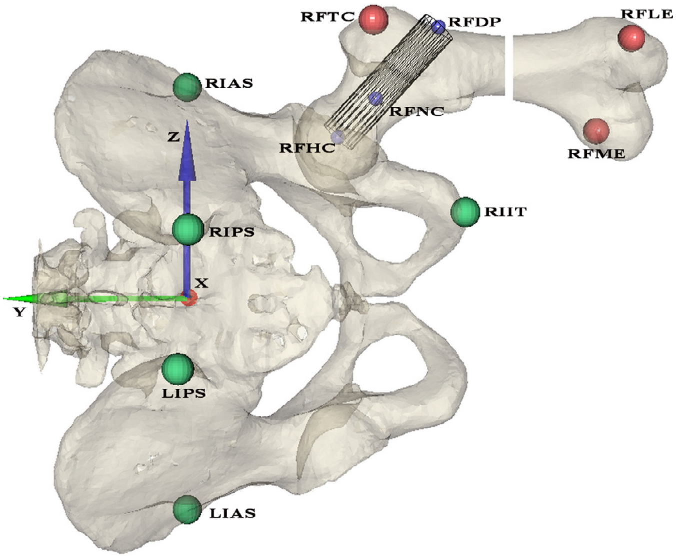

Fig. 1. Pelvis and right femur in the pelvic LCS (posterior view, all of the bone models were rendered transparent). The 5 pelvic and 3 femoral ALs used in this paper to predict values of the femoral head centre (RFHC, R for right) and the femoral drilling point (RFDP) are also visible. The femoral neck centre (RFNC) is used to control the drilling pathway to remains within the femoral neck. The transparent cylindrical mesh shows the maximum prediction error of the drilling pathway between the RFDP and the RFHC (see text for explanations). R/L_IAS: anterosuperior iliac spine; R/L_IPS: posterosuperior iliac spine; RIIT: ischial tuberosity; RFLE: lateral epicondyle; RFME: medial epicondyle; RFTC: centre of greater trochanter (Van Sint Jan [23]).

2.3. Prediction method

A numerical approach based on similarity criteria and weighted multiple regressions [22] was used with eight available key ALs from the pelvic and femoral bones as defined in the reference pose (see Fig. 1; additionally, there are more details available in the *supplementary materials 1*). The adjusted database AL clouds were processed to predict RFHC, RFNC and RFDP using multiple regressions. For all of the predicted values, a systematic leave-one-out (LOO) cross validation was performed with the available database specimens to evaluate the *in vitro* prediction accuracy of the method [15].