Research

Preserved Proximal Femoral Bone Stock Volume in Total Hip Arthroplasty Significantly Reduces the Risk for Periprosthetic Fractures. A Novel Modelling Technique and Preliminary Clinical Results

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Abstract:
Periprosthetic proximal femoral fractures (PPFFs) are one of the main causes for revision after total hip arthroplasty (THA), and are associated with some already known patient-/surgical-/implant-related risk factors. Despite the established increased risk of single and double-wedge femoral implants, the highest incidence in our institution has been observed with the anatomical cementless femoral component Anatomic Benoist Girard (ABG) II. The cumulative probability of PPFFs rose from 2.1% at 1 year to 6.5% at 10 years post-implantation, prompting comprehensive and multidisciplinary analysis. A novel parameter of preserved proximal femoral bone stock volume around implanted ABG II femoral stems (V_{PF}) and the modelling technique for its evaluation on the standing anteroposterior (AP) hip radiographs were introduced and estimated for each hip. Study was designed according to the standard protocol for matched case-control research. In the preliminary analysis, 5 age-/sex-/implant size-/surgeon-matched stratums, each comprising a case and 2 matched controls, were included. To calculate V_{PF}, a mathematical model was constructed by composing parts of rotational bodies and a prism, subject to geometrical parameters of the proximal femur that were assessed from radiographs. The mean value of V_{PF} in the group of cases was 141.6 ± 36.2 cm^3 and significantly lower compared to the mean volume of 254.2 ± 33.8 cm^3 in the control group ($P < 0.01$). Based on the preliminary results, the V_{PF} seems crucial for the PPFFs prevention. However, the mechanism of its effect works as a 'black box'. At this point, it can be hypothesized that insufficient bone stock from the implantation onwards interferes with adequate osseointegration by itself acutely and with increased stress shielding in the long term. The bone stock preservation should be emphasized and considered at all steps, starting from the preoperative planning. The novel parameter in THA, and the method for its evaluation were introduced and are further extensively analysed.

Keywords: Total Hip Arthroplasty, Periprosthetic Fracture, Bone Stock, Osseointegration, Stress Shielding

1. Introduction

Hip osteoarthritis (HOA) is an invalidating and prevalent disease with an estimated lifetime risk of symptomatic stage at around 25% (Katz et al., 2021; Murphy et al., 2010). Annually, more than 1 million total hip arthroplasties (THA) are performed worldwide with projections of further steady increase of primary as well as revision procedures (Ferguson et al., 2018). A number of factors, including the ageing population, the generalized demand for improved quality of life and functioning, along with the expansion of indications to the younger populations are governing the upscaling demand that has been proven insensitive even to the global economic downturns. In the next decades, a 2- to as much as 6-fold increase is projected by some studies (Shichman et al., 2023; Sloan et al., 2018).

As the incidence of primary THA continues to rise, the absolute burden of complications has increased with further growth being anticipated (Kurtz S et al., 2007; Schwartz AM et al., 2020). The periprosthetic fractures (PPFs) are one of the four most common reasons for revision after primary THA, the other three being infection, aseptic loosening and instability/dislocation (Smith PN et al., 2023). PPFs represent a complex orthopaedic pathology with significant patients' morbidity and mortality, and socio-economic implications. In more than 80% of cases, the mechanism of injury is a low-energy trauma, mainly fall from the standing height. Most of the PPFs affect the proximal femur (PPFFs), while acetabulum is involved in less than 10% of THA-related fractures (Abdel et al., 2015; Bozic et al., 2009; Patsiogiannis et al., 2021).

PPFFs are associated with some already known patient- (age, female sex, osteoporosis/osteopenia, neuromuscular diseases, cognitive disorders, Paget's disease, developmental hip dysplasia, rheumatoid arthritis), surgical- (malposition, extensive broaching), and implant-related (cementless, design/type, loosening, stress shielding) risk factors (Patsiogiannis et al., 2021; Singh et al., 2013). Despite the established increased risk of single and double-wedge femoral implants for PPFFs, the highest incidence in our institution has been observed with the anatomical cementless femoral component Anatomic Benoist Girard (ABG) II (Stryker Orthopaedics, Mahwah, NJ, USA), which is in line with some other studies in the literature (Carli et al., 2017; Catanach et al., 2015; Kropivšek et al., 2023; Mulford et al., 2022; Thien et al., 2014). The cumulative probability of PPFFs rose from 2.1% at 1 year to 6.5% at 10 years post-implantation, prompting comprehensive and multidisciplinary analysis (Kropivšek et al., 2023).

Given that, ultimately, it is the bone that fractures, and preserved bone stock is pivotal for revision procedures, the novel parameter of preserved proximal femoral bone stock volume around the implanted femoral stems (V_{PF}) has been hypothesized. The primary aim of the present study was to develop a practical and reliable method for the evaluation of this novel parameter on the widely available hip anterior-posterior (AP) radiographs, and to conduct a preliminary assessment of its validity.

2. Methods

2.1 Assessment of geometrical parameters

Geometrical parameters of the bone in contact with endoprosthesis were assessed from the standard hip AP radiographs. The images were available in DICOM format and measured by software Agfa HealthCare Enterprise Imaging (Agfa-Gevaert NV, Mortsel, Belgium). This software enabled measurements of lengths and delimited areas. The parameters x_N', x_M', x_L', $x'_{L\,LAT}$, x_N, x_M, x_L, $x_{L\,LAT}$, H_N, H_L and S that were used for calculation of respective volumes are depicted in **Figure 1**. As the magnifications of the images were not known, the parameter dimensions were scaled by considering the known diameter of the prosthesis femoral head.

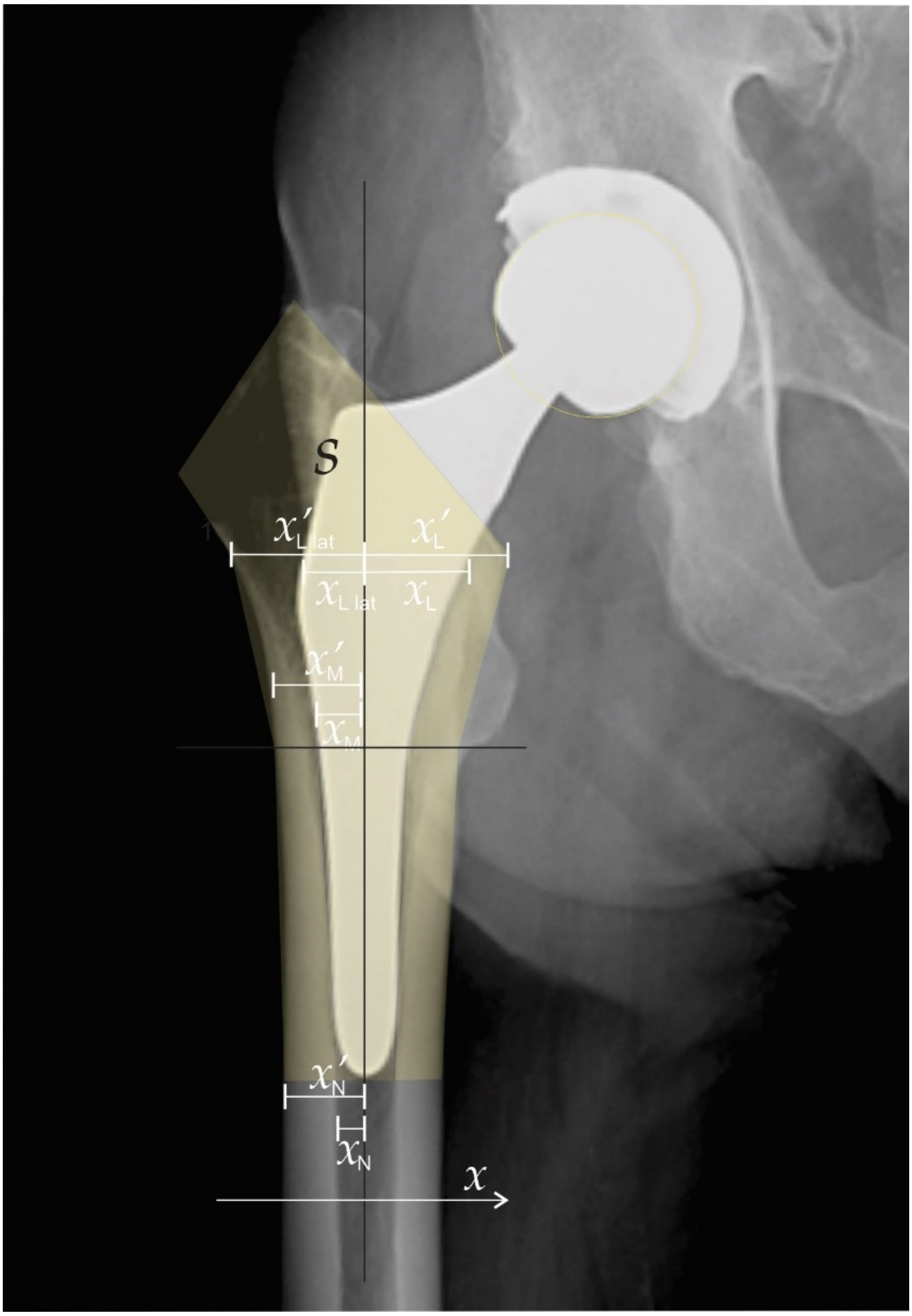

Figure 1. Geometrical parameters used as an input for the calculation of V_{PF} evaluation.

2.2 Evaluation of the V_{PF} parameter

V_{PF} is composed of hollow cut coni (modelling the bone of the femoral shaft in contact with the stem of the prosthesis) and a prism (modelling the remnants of the greater trochanter). In general, the volume of the conus with radius R at the base and height H is

$$V_{conus} = \pi R^2 H/3 \qquad (1)$$

and the volume of the conus cut at height h where the radius is r is

$$V_{cut\ conus} = \pi\ (R^2h + RrH + r^2h \quad , \qquad (2)$$

where

$$r = R\ (1 - h/H) \quad . \qquad (3)$$

Following Equation (2), at the lower part of the shaft the volume of the hollow cut conus is

$$V_1 = \pi\ (x_N'^2\ H_N + x'\ x_M' H_N + x_M'^2\ H_N)/3 \ \ -\ \ \pi\ (x_N^2\ H_N + x_N\ x_M H_N + x_M^2\ H_N)/3. \qquad (4)$$

In the middle part at the region of the smaller trochanter, the contour of the bone is considered asymmetric with respect to the axis along the shaft. The columns of the medial and the lateral halves are therefore calculated separately taking into account the differences between respective x_L and $x_{L\ LAT}$. The respective volumes are

$$V_2 = \pi\ (x_L'^2\ H_L + x_L'\ x_M' H_L + x_M'^2\ H_L)/6 \ \ -\ \ \pi\ (x_L^2\ H_L + x_L\ x_M H_L + x_L^2\ H_L)/6 \qquad (5)$$

and

$$V_{2\ LAT} = \pi\ (x'^2_{L\ LAT}\ H_L + x'_{L\ LAT}\ x_M' H_L + x_M'^2\ H_L)/6 \ \ -\ \ \pi\ (x_L^2\ H_L + x_L\ x_M H_L + x_M^2\ H_L)/6 \quad . \qquad (6)$$

It is considered that only half of each rotational body is contributing to the volume. The volume of the prism is calculated by

$$V_{prism} = 2\ S\ x_N' \quad , \qquad (7)$$

where S is the area of the prism assessed by delimiting its contours. The volume of the bone in contact with the prosthesis is

$$V_{PF} = V_1 + V_2 + V_{2\ LAT} + V_{prism} \quad . \qquad (8)$$

2.2 Subjects

The retrospective matched case-control study was conducted according to the standard protocol for this type of research. In the preliminary analysis, the patients with late PPFFs, minimum 1 year postoperatively, were enrolled from the observational cohort of all implanted primary total hip arthroplasties with uncemented ABG II femoral stem between January 1, 2012, and January 31, 2013, at a single tertiary hospital (University Medical Centre Ljubljana, Department of Orthopaedic Surgery, Ljubljana, Slovenia). Clinical investigational plan was approved by the National Medical Ethics Committee (permit No. 0120-605/2021/3). In the group of cases, 5 patients with late PPFFs were included. An example of PPFF around the ABG II femoral stem is represented in **Figure 2**. For each case, 2 controls matched for age, sex, implant size, and surgeon were found from the whole observational cohort: 1531 uncemented ABG II femoral stems implanted between January 1, 2012, and December 31, 2018. As a result, the control group of 10 patients was formed, and 5 matched stratums, each comprising a case and its 2 controls, were analysed. Patients' demographics, medical history, stress shielding (Engh Grading Scale) (Engh, et al. 1987), Canal Flare Index (CFI) (Noble PC, et al. 1988), and length of radiographic follow-up evaluation were documented (**Table 1**).

3.3 *Surgical intervention*

Patients were operated under spinal or general anesthesia, in the supine position with the direct lateral approach, or in the lateral decubitus position with the posterior approach to the hip joint. The cementless ABG II femoral stems were combined with either acetabular cup ABG II or acetabulum from another manufacturer. All surgical procedures were performed in the two operating rooms of the same operating suite of a single tertiary university hospital. Perioperative antibiotic prophylaxis, thromboembolic prophylaxis and postoperative rehabilitation protocol were uniform for all patients at a given time-point, but they have been changing between 2012 and 2018 in accordance with the national guidelines. The patients were followed from the initial primary total hip arthroplasty until the eventual outcome assessment on October 31, 2023.

Table 1. Demographics, medical history, and follow-up time of the radiographs' evaluation in both groups. Categorical variables are presented as frequencies (percentages), while continuous variables as mean (standard deviation). For comparison of both groups Student t test (continuous variables) or Chi square test (categorical variables) were applied.

Characteristic	All (n = 15)	Cases (n = 5)	Controls (n = 10)	Comparison (P values)
Age (years)	70.2 ± 5.0	68.2 ± 4.2	71.1 ± 5.3	0.31
Sex (n)				
Female	9 (60%)	3 (60%)	6 (60%)	1.0
Male	6 (40%)	2 (40%)	4 (40%)	
Height (m)	168.6 ± 8.9	168.6 ± 9.4	168.6 ± 9.1	1.0
Weight (kg)	78.3 ± 7.4	76.8 ± 7.0	79.1 ± 7.8	0.59
BMI (kg/m2)	27.7 ± 3.0	27.0 ± 1.7	28.0 ± 3.6	0.60
Follow-up (months)	59.7 ± 32.7	59.6± 35.2	59.7 ± 33.8	0.99
Osteoporosis (n)	2 (13%)	1 (20%)	1 (10%)	0.60
Stress shielding (Engh Grading Scale)	1.6 ± 1.0	2.6 ± 0.5	0.8 ± 0.4	0.01*
CFI	2.9 ± 0.4	2.8 ± 0.3	3.0 ± 0.4	0.58

CFI– Canal Flare Index, BMI – Body Mass Index, m – meter, kg – kilogram, kg/m2 – kilogram per square meter

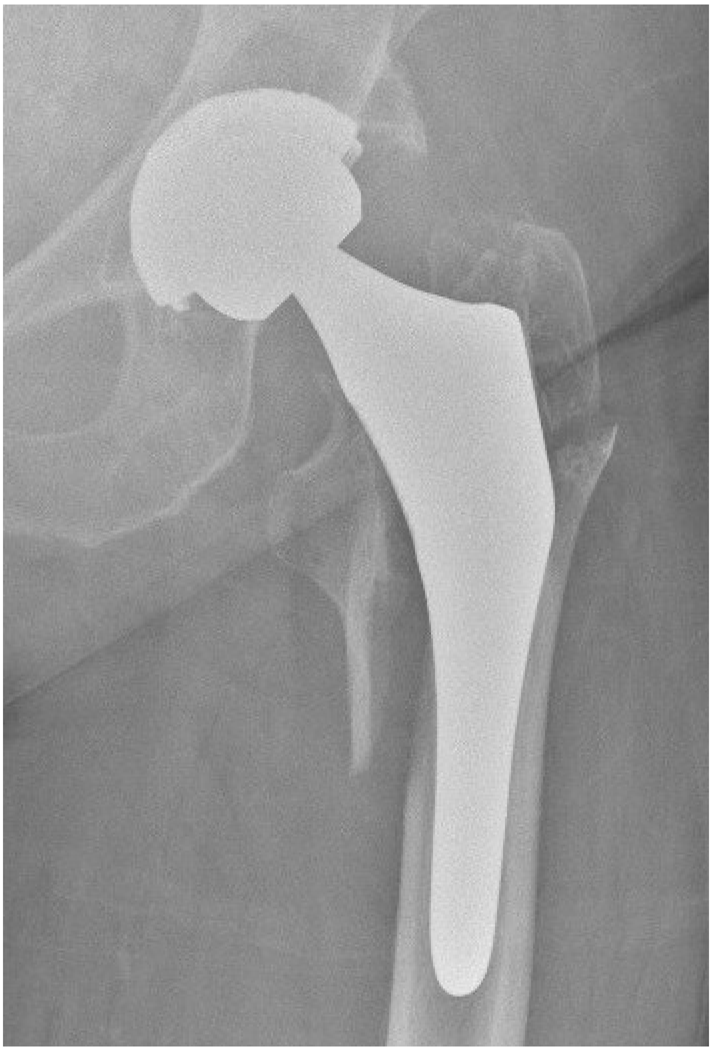

Figure 2. Case of PPFF around the ABG II femoral stem. Type B2 (unstable implant, sufficient bone stock) according to the Vancouver classification (Duncan CP et al., 1995) .

2.4 Statistical analysis

Descriptive statistical analysis was used to describe patients' demographics, medical history, stress shielding (Engh Grading Scale) (Engh et al., 1987), Canal Flare Index (CFI) (Noble et al., 1988), and length of radiographic follow-up evaluation. Continuous variables were presented as means with standard deviations (SD), and categorical variables as frequencies with corresponding percentages. For comparison of both groups either Student t test (continuous variables) or Chi square test (categorical variables) were applied. Statistical analysis was performed with SPSS (Version 25.0; IBM, Chicago, IL, USA). The level of statistical significance was set at $P < 0.05$.

3. Results

The mean value of V_{PF} in the group of cases was 141.6 ± 36.2 cm^3 and significantly lower compared to the mean value of 254.2 ± 33.8 cm^3 in the control group ($P < 0.01$). Moreover, in all 5 age-/sex-/implant size-/surgeon-matched stratums, the mean V_{PF} of both controls was lower than V_{PF} of the case (**Table 2**).

Table 2. V_{PF} in the 5 age-/sex-/implant size-/surgeon-matched stratums. In each stratum, the V_{PF} of the case (PPFF) and the mean V_{PF} with standard deviation of both controls are presented.

Stratum No.		V_{PF} (cm^3)
1	PPFF	90.0
	Controls mean	241.5 ± 1.6
2	PPFF	180.2
	Controls mean	280.1 ± 3.8
3	PPFF	118.5
	Controls mean	217.4 ± 27.3
4	PPFF	154.4
	Controls mean	239.3 ± 18.9
5	PPFF	165.0
	Controls mean	292.5 ± 12.1

V_{PF} – Volume of Preserved proximal Femoral bone stock around femoral stems, PPFF - Periprosthetic Proximal Femoral Fracture, cm^3 – cubic centim

4. Discussion

The present study introduces a novel method for the evaluation of preserved proximal femoral bone stock volume around the implanted femoral stems on the widely available hip AP radiographs. The preliminary results are promising.

Despite the longstanding awareness of the increasing incidence and consequences of PPFFs, and the rationale protective role of the preserved bone stock, no method for its evaluation, with the potential for routine clinical application, has been available. Interestingly, the research and development have been for decades intensively focused mainly on the artificial implants, their materials, composition, design, and other characteristics, while the local host environmental factors have remained mostly unaddressed (Burchard et al., 2023; Carli et al., 2017; Glassman et al., 2006; Huiskes et al., 1992; Rivière et al., 2018; Sumner et al., 1992).

The introduced modelling technique aims to tackle the increasing PPFFs problem, and proposes a novel V_{PF} parameter, which seems to significantly influence the risk of PPFFs and could be controlled to some degree. The method utilizes readily available standing hip AP radiographs that are part of every routine diagnostic assessment of patients with the indication for the primary THA. Moreover, its simplicity, quick learning curve, and time efficiency, taking only a few minutes after some examples measured, enable the surgeon to plan and control the bone stock preservation for every patient. Based on the preliminary results, the V_{PF} seems crucial for the PPFFs prevention. However, the mechanism of its effect works as a 'black box' (Mavčič et al., 2012). The interplay between the two well established risk factors, osseointegration and stress shielding, with this novel third parameter of the preserved bone stock could be proposed (Savio et al., 2022). Bone preservation supports initial stability and enhance osseointegration acutely, while reducing stress shielding and preventing loosening (ensuring stable osseointegration) in the long term. Therefore, the preserved bone stock volume may be considered as the common biological denominator of osseointegration and stress shielding. Moreover, the observed significant difference in the mean grades of stress shielding between the groups supports the proposed correlations. However, the constitutional law between these factors at interplay has not been fully established yet. Despite only the preliminary analysis being performed, the results clearly indicate the importance of considering bone stock preservation at all steps, starting from the preoperative planning.

5. Conclusion

The introduced method for V_{PF} evaluation demonstrated intuitive and promising results. Its wide availability, simplicity and significance promise the implementation into routine clinical practice. The novel parameter in THA, and the method for its evaluation were introduced and are further extensively analysed.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki. Clinical investigational plan was approved by the National Medical Ethics Committee (permit No. 0120- 605/2021/3).

Conflicts of Interest: The authors declare no conflict of interest.

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