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ORIGINAL STUDY

Shear force in the femoral neck affects clinical outcome of total hip arthroplasty

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Case-reports of broken modular femoral necks have implied increased shear loading as the main culprit. The study aim was to determine whether total hip endoprostheses with modular femoral necks produced larger magnitudes of shear force, smaller leg length discrepancy and better WOMAC score in comparison to nonmodular implants. A single-surgeon series of unilateral uncemented primary total hip arthroplasties (50 modular ProfemurZ and 52 nonmodular Zweymüller) was compared retrospectively in hip force magnitudes computed with a previously validated static biomechanical model, radiographic changes before/after total hip arthroplasty, leg lengths and WOMAC. Modular implants ProfemurZ on average had larger shear force magnitudes in the femoral neck than nonmodular Zweymüller, but there was no significant difference in leg-length discrepancy or WOMAC score. In multivariate regression (adjusted for implant type, gender, age, BMI, leg length discrepancy) increase in shear force magnitude was an independent predictor of better WOMAC score, regardless of the implant type.

Keywords: shear force ; modular femoral neck ; clinical outcome ; total hip arthroplasty.

INTRODUCTION

Development of modular femoral necks with junction at the base of the neck was supposed to provide easier achievement of leg length equality, offset restoration and hip stability at total hip arthroplasty *(2,31)*, but most studies found no significant difference between modular femoral necks (MFN) and nonmodular femoral necks (NMFN) in the planning phase or clinical setting *(6,10,14)*. Individual case-reports on MFN initially warned of the risk of serious catastrophic complications due to corrosion, fretting and neck fracture at the neck-stem junction *(36)* and an increasing number of similar clinical reports followed until the long varus/valgus femoral neck of one of the most popular MFN implants -Profemur® Z- was eventually recalled by FDA in 2015 *(34)*. As early as in 2010 it has been pointed out that long necks may contribute to a greater risk of MFN fracture due to proportionally larger bending stress and shear stress *(3)*, but biomechanical analyses of shear loading have only been done on case-to case basis *(3,15)*.

So far there has been no study published that would analyze shear loading of MFN in comparison to endoprostheses with NMFN on a larger number

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of patients. Research on MFN hip reconstruction has been concentrating mostly on radiographic changes, e.g. center of rotation, femoral offset and anteversion, leg length discrepancy *(6,10,31,32)*, but radiographic parameters do not have direct correlation clinical THA outcome *(26,33)*. Mathematical models have been developed lately that enable estimation of hip forces from pelvic radiographic parameters *(1,17,20,24)* or with mechanical testing of cadaver femora *(9)*, but so far only few studies on a limited number of subjects have analyzed the biomechanical consequences of leg lengthening *(23)* or changed hip geometry at THA *(19,35)*. Even if MFN cause larger shear stresses from conventional endoprostheses, it is not clear what impact these changes may have on subjective clinical outcome of THA. The question therefore arises whether assessment of hip joint forces with a biomechanical model *(1,17,20,21,24,29)* could better explain the cumulative impact of pelvic geometry changes on the final clinical THA outcome than analysis of radiographic parameters alone.

We asked whether the use of MFN resulted in: a) larger shear force, compressive force and abductor-muscle force around the hip joint ; b) smaller postoperative leg-length discrepancy after THA ; c) lower incidence of self-perceived postoperative LLD and d) better clinical outcome with WOMAC score in comparison to NMFN. Further we ascertained the impact of hip forces (shear, compressive, abductor) on postoperative WOMAC score after adjustment for implant type (MFN or NMFN), radiographic changes at THA (medialization and distalization of the center of rotation, femoral offset and femoral cranialization) and postoperative LLD.

MATERIALS AND METHODS

The study protocol was approved by the National Medical Ethics Committee of the Republic of Slovenia on June 11, 2013, case No.# 77/06/13, and all participants signed an informed consent form to participate. The retrospective case-control study included patients with unilateral uncemented primary THA who were operated by a single experienced surgeon in a single institution in the period between January 1, 2004, and September 30, 2011. Until June 1, 2009, our institution policy was to implant uncemented non-modular Zweymüller femoral stems in all patients younger than 75 years. After a short transition period of three months, from September 1, 2009 onwards the default femoral implant for subjects below 75 years at the institution was changed to uncemented modular Wright ProfemurZ. The use of modular or non-modular femoral necks in the studied population was therefore pseudorandomized since it was only based on implant availability at the date of surgical treatment and was not biased by patient characteristics or surgeon's preference. Out of 630 primary and revision THA performed by this surgeon in the selected time period, 121 patients had either modular ProfemurZ femoral stem or nonmodular Zweymüller femoral stem implanted. Further we excluded from the study 16 patients with radiographs of insufficient quality, 2 patients who had postoperative luxations, 2 patients with deep infection and one patient with perioperative neurological lesion. Eventually, 102 patients met the inclusion criteria of the study (50 patients with modular femoral stem ProfemurZ-Wright and 52 with nonmodular femoral stem Zweymüller-EndoPlus). All patients were operated through the lateral transgluteal approach in the supine position. Preoperative planning was performed by the operating surgeon and LLD was adjusted intraoperatively by comparing the position of patellae and malleoli. The wound was drained for 24 hours, the single dose cephazolin preoperative antibiotic prophylaxis was used and each patient received four weeks of low-molecular-weight-heparin postoperative antithrombotic prophylaxis. Patients were mobilized with crutches and partial weight-bearing on the postoperative day 1, full weight-bearing was allowed 6 weeks later. In the course of follow-up, none of the included study subjects suffered any additional implant related complication or breakage.

Preoperative and postoperative clinical assessment was performed with the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC score 3.1-VAS©) with 24 items on pain, stiffness and physical function *(4)*. The mean follow-up interval between total hip arthroplasty and postoperative evaluation with WOMAC score was

5.6 ± 1.7 years. The scores of 24 items (VAS range of 0–100 mm) were summed to total WOMAC score (range 0-2400 mm, higher score corresponds to worse clinical status) *(4)*. In the postoperative questionnaire we included an additional question "Do you feel that after THA Your legs are equally long?" to which the patients responded either "YES" or "NO".

Radiographic analysis of preoperative/postoperative radiographs was performed after magnifi-cation adjustment with circular radioopaque marker or the implanted femoral head. LLD was evaluated in each patient preoperatively/postoperatively by measuring the vertical distance between the inter-teardrop line and lesser trochanters on pelvic anterior-posterior radiographs *(30)*. In addition, preoperative/postoperative radiographs were superimposed to measure the shift of the center of rotation (medialization/distalization) in the coordinate system of pelvis and the shift of the femoral head center (offset increase/cranialization) in the coordinate system of femur. Measurements were performed with the nearest reading of 1 mm.

Biomechanical computations of the resultant hip force (F_R) with its shear component (F_S) and compressive component (F_C) and the required abductor-muscle force (F_{ABD}) in one-legged stance (Figure 1) were based on the mathematical model of 3-D anatomical data of pelvic muscle attachment points *(1,17,20,24)*. The model has been previously validated in normal and dysplastic hips *(24)*, Perthes' disease *(20)* and hips with implanted endoprostheses *(21,29)*. The input parameters of the mathematical model (Figure 1) include five measurements from anterior-posterior pelvic radiograph: the interhip distance L, the pelvic height H, the pelvic width laterally from the femoral head center C and the coordinates of the insertion point of abductors on the greater trochanter (T_X, T_Z). In order to correctly determine the femoral coordinates (T_X, T_Z), femoral neck anteversion is computed by comparing the projected caput-collum-diaphyseal (CCD) angle from a 2-D radiograph with the known true CCD angle of the implanted femoral component, whereby the angle of femoral neck anteversion HR equals $\cos(HR) = \tan(CCD_{IMPLANT} - 90º) / \tan(CCD_{PROJECTED} - 90º)$ (*22*). Anteversion of femora on preoperative radiographs is considered either equal to postoperative anteversion (in implanted femoral components with neutral version) or the known version of the implanted femoral component is subtracted from the postoperative measurement. In this paper the magnitudes of hip forces are reported normalized to the body weight (F_S/W_B, F_C/W_B, F_{ABD}/W_B) in order to enable comparison between patients.

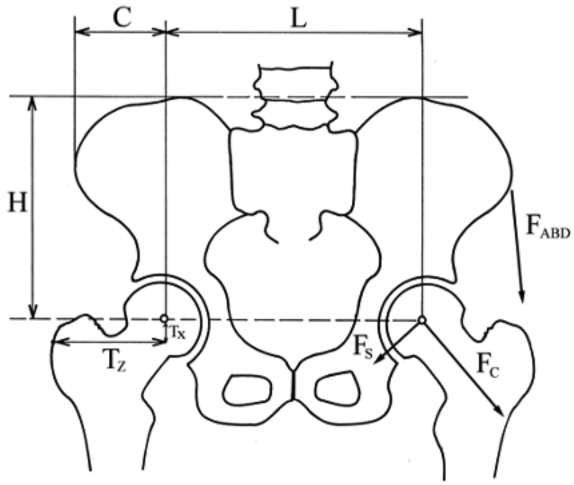

Figure 1. — Left side of the image shows the input parameters (L, H, C, T_X, T_Z) of the mathematical model of one-legged stance based on 3-D anatomical data of pelvic muscle attachment points and patient-specific pelvic shape data derived from planar pelvic anterior-posterior radiograph of each patient. Right side of the image shows the computed output parameters: two perpendicular components of the resultant hip joint force (shear component F_S is perpendicular to the femoral neck; compressive component F_C is parallel to the femoral neck) and the required abductor muscle force F_{ABD}. Adapted from *(17,24)*..

Differences between means were evaluated with the two-tailed Mann-Whitney U-test for unpaired samples. The difference in proportions between groups was tested with the Fisher's exact test. The impact of changes in radiographic parameters (medialization/distalization of the center of rotation, femoral offset increase and head cranialization) and covariates (implant type, gender, age, BMI, postoperative LLD) on postoperative WOMAC score was evaluated with the multivariate ordinal regression model. The impact of perioperative changes in hip forces (F_S/W_B, F_C/W_B, F_{ABD}/W_B) and covariates (implant type, gender, age, BMI, postoperative LLD) on postoperative WOMAC score was evaluated with three separate multivariate ordinal regression models for each of the forces. Statistical significance was set at $P \leq 0.05$. Sample sizes were determined with a priori power analysis.

The effect size for comparison of means with the two-tailed Mann -Whitney U test was com-puted from the minimal clinically-detectable LLD (> 5 mm) and from the standard deviation of LLD (8 mm) in THA population of the previous methodological study *(18)*. For $\alpha = 0.05$ and power $(1 - \beta) = 0.80$, the required minimal sample size for comparison of means was 44 subjects in each group (minimal total sample size 88 subjects). Sample size for ordinal regression models (fixed model, 4 tested predictors, 9 total predictors) was computed from $f^2 = 0.16$ that corresponds to the expected medium effect size *(11)*. For $\alpha = 0.05$ and power $(1 - \beta) = 0.80$, the required minimal total sample size for linear regression model was 80 subjects. Statistical analyses were performed with SPSS 17.0 for Windows (SPSS Inc, Chicago, IL), Microsoft Office Excel 2010 (Microsoft Inc, Redmond, WA), and GPower 3.1.5 *(11)*.

RESULTS

Prior to THA there was no statistically significant difference between patients who were implanted modular femoral necks ProfemurZ-Wright (MFN) and nonmodular femoral necks Zweymüller-EndoPlus (NMFN) in terms of gender, age, BMI, preoperative LLD, magnitudes of hip forces (F_S/W_B, F_C/W_B and F_{ABD}/W_B) or preoperative WOMAC score (Table 1).

After THA, the shear force F_S/W_B increased significantly in the MFN group and remained unchanged in the NMFN group ($p = 0.01$). There was no significant difference between the two groups in the mean postoperative LLD, the proportion of self-perceived LLD or the mean postoperative WOMAC score. Postoperative magnitudes of the

Table 1. — Demographic data, preoperative assessment and postoperative assessment for the patient group with modular (50 subjects) versus nonmodular femoral necks (52 subjects)

	Modular femoral neck	Nonmodular femoral neck	p-value
DEMOGRAPHIC DATA			
Gender	26 F / 24 M	26 F / 26 M	0.85
Operated leg	27 right / 23 left	27 right / 25 left	0.85
Age at operation (years)	62.4 ± 12.2	59.5 ± 10.2	0.22
Body mass index (kg/m^2)	28.4 ± 4.1	27.5 ± 4.5	0.46
PREOPERATIVE ASSESSMENT			
Preoperative LLD (mm)	6 ± 6	7 ± 5	0.14
To-be-operated leg longer	5 patients out of 50	12 patients out of 52	0.11
Shear resultant hip force F_S/W_B (-)	1.48 ± 0.22	1.50 ± 0.21	0.71
Compressive resultant hip force F_C/W_B (-)	2.17 ± 0.42	2.21 ± 0.40	0.63
Abductor-muscle force F_{ABD}/W_B (-)	1.83 ± 0.32	1.87 ± 0.30	0.53
Preoperative WOMAC (mm)	1770 ± 420	1990 ± 380	0.16
POSTOPERATIVE ASSESSMENT			
Center of rotation medialization (mm)	9 ± 6	9 ± 8	0.50
Center of rotation distalization (mm)	3 ± 6	4 ± 6	0.52
Femoral head offset increase (mm)	3 ± 9	6 ± 9	0.08
Femoral head cranialization (mm)	9 ± 7	2 ± 7	0.01*
Postoperative LLD (mm)	8 ± 10	7 ± 5	0.13
Shear resultant hip force F_S/W_B (-)	1.69 ± 0.26	1.51 ± 0.25	0.01*
Compressive resultant hip force F_C/W_B (-)	1.75 ± 0.62	1.70 ± 0.86	0.74
Abductor-muscle force F_{ABD}/W_B (-)	1.69 ± 0.21	1.61 ± 0.18	0.06
Postoperative WOMAC (mm)	290 ± 340	360 ± 480	0.88
Self-perceived postoperative LLD	19 yes / 31 no	24 yes / 28 no	0.43

Results are shown as absolute numbers of subjects or as mean ± standard deviation. P-values ≤ 0.05 are marked with an asterisk (*).

Table 2. — The combined data of 102 patients (50 modular + 52 nonmodular femoral necks) in the ordinal regression model with postoperative WOMAC score as the dependent variable and four radiographic parameters as input variables

	Estimate	95% Confidence Interval	p-value
Threshold WOMAC ≤ 150			
150 < WOMAC ≤ 300	5.27	1.04 to 9.49	0.01*
300 < WOMAC ≤ 450	5.96	1.69 to 10.23	< 0.01*
450 < WOMAC ≤ 600	6.24	1.96 to 10.53	< 0.01*
600 < WOMAC	6.73	2.41 to 11.05	< 0.01*
Radiographic parameters			
Center of rotation medialization	- 0.05	- 0.14 to 0.05	0.34
Center of rotation distalization	- 0.02	- 0.11 to 0.08	0.75
Femoral offset increase	0.02	- 0.05 to 0.08	0.64
Femoral head cranialization	- 0.06	- 0.14 to 0.02	0.11
Factors/covariates			
Implant Modular	0.02	- 1.12 to 1.16	0.97
Nonmodular			
Gender Female	0.22	- 0.70 to 1.14	0.64
Male			
Age at operation	0.04	- 0.01 to 0.09	0.08
Body Mass Index	0.08	- 0.03 to 0.19	0.14
Postoperative LLD	0.09	0.00 to 0.19	0.05*

Nagelkerke pseudo $R^2 = 0.23$, $p = 0.02$. P-values ≤ 0.05 are marked with an asterisk (*).

Table 3. — The combined data of 102 patients (50 modular + 52 nonmodular femoral necks) in the ordinal regression model with postoperative WOMAC score as the dependent variable and perioperative increase of shear force F_S/W_B as input variable

	Estimate	95% Confidence Interval	p-value
Threshold WOMAC ≤ 150			
150 < WOMAC ≤ 300	5.48	1.36 to 9.61	0.01
300 < WOMAC ≤ 450	6.18	2.00 to 10.35	< 0.01*
450 < WOMAC ≤ 600	6.47	2.27 to 10.66	< 0.01*
600 < WOMAC	6.98	2.76 to 11.21	< 0.01*
Biomechanical parameter			
Perioperative increase of F_S/W_B	- 3.42	- 5.81 to - 1.03	< 0.01*
Factors and covariates			
Implant Modular	- 0.18	- 1.20 to 0.83	0.73
Nonmodular			
Gender Female	0.06	- 0.84 to 0.96	0.90
Male			
Age at operation	0.04	- 0.01 to 0.08	0.14
Body Mass Index	0.10	- 0.01 to 0.21	0.08
Postoperative LLD	0.12	0.03 to 0.20	0.01*

Nagelkerke pseudo $R^2 = 0.27$, $p < 0.01$. P-values ≤ 0.05 are marked with an asterisk (*).

abductor force F_{ABD}/W_B and the compressive hip force F_C/W_B were similarly reduced in both MFN and NMFN (Table 1). Changes in radiographic parameters (medialization and distalization of the center of rotation, femoral offset increase and head cranialization) did not have any significant impact on postoperative WOMAC (Table 2).

Increase of the shear force F_S/W_B and lower postoperative trochanteric LLD were independent predictors of lower postoperative WOMAC score, i.e. better clinical outcome, regardless of the implant type (Table 3). On the other hand, compressive hip force F_C/W_B and abductor force F_{ABD}/W_B did not show any significant correlation with THA outcome in multivariate ordinal regression models after adjustment for implant type, gender, age, BMI and postoperative LLD.

DISCUSSION

Estimated joint forces in the presented study confirm previous case-report findings of increased shear loading in MFN *(3)*, reduced magnitudes of the required abductor force F_{ABD} and reduced compressive force F_C after THA *(28)*. In this regard, the presented analysis of generally increased F_S in MFN is in accordance with observed catastrophic events of long necks in obese patients *(36)*. While previous studies mostly focused on metallurgic problems of increased shear loading, our results have shown independent correlation between increase of F_S and better clinical outcome with postoperative WOMAC score, regardless of the implant type used. Clinical predictive value of the shear force F_S was considerable although changes in femoral head cranialization, offset and the center of rotation as individual variables had no significant independent impact. The observed correlation between shear force and better mid-term clinical outcome should be interpreted with caution because increased shear might influence bone loss and femoral component loosening after long-term follow-up *(9)* : it might turn out that increased shear force offers mid-term clinical advantage and long-term biomechanical disadvantage. All these findings emphasize the importance of considering the entire geometry of hip and pelvis in biomechanical analysis rather than relying on morphological measurements only (e.g. offset or abductor-muscle lever arm) *(6,10,31,33)*. To the knowledge of the authors this is the first study to compare shear loading, postoperative LLD and clinical outcome in a series of patients with modular and nonmodular femoral necks.

We note several limitations of the presented retrospective study. We did not use full-leg radiographs to assess LLD or CT / MRI to assess muscle attachment points because they were not taken in the routine clinical setting and for ethical reasons we did not additionally expose subjects to unnecessary radiation. To improve the accuracy, we used the interteardrop line as the reference line for pelvic horizontality as it has been shown to have excellent agreement with leg-length measurements on full-length radiographs *(25)*. The error of the presented mathematical model used for computation of hip forces amounts to approximately 10% *(24)*. Methodology only enabled assessment of static one-legged stance and did not account for different body positions or dynamic activities. Nevertheless, the advantage of presented methodology is that all subjects were compared in the same body position, which provides better comparison between different individuals than dynamic measurements.

While the presented biomechanical analysis was conducted on two-dimensional (2D) planar pelvic radiographs, biomechanical analyses of hip forces in MFN and NMFN have also been done with more complex three-dimensional (3D) models, but only in limited series on a small number of patients. Such analyses have so far been performed for research purposes only and biomechanical modelling has not become part of clinical hip arthroplasty practice in spite of widely available 3D imaging. Some biomechanical studies have claimed load transfer and stress shielding in the proximal femur primarily depend on the stem length without significant effect of femoral neck offset and orientation *(13)*, other studies found no significant impact of stem length on stress-shielding *(5)*. Research focus on the neck-stem junction of MFN implants identified off-axis impaction *(12)* and femoral neck notching with anteverted neck and extended offset *(16)* as possible biomechanical culprits of corrosion implant failure *(27)*. Modular femoral necks may have contributed to better understanding of the importance of femoral geometry restoration, but most recent studies on this topic concur with our findings that clinical benefits for patients are minimal or none *(6,7,8)*. Consequently, routine usage of modular neck femoral stems in total hip arthroplasty is not advised and such implants should only be used in in cases that cannot be reconstructed with the nonmodular option *(7,8)*.

In conclusion, magnitudes of shear forces are on average higher in modular femoral necks (MFN) than in NMFN, but MFN do not offer any general advantage in terms of leg-length restoration, offset restoration or clinical outcome. Orthopaedic surgeon cannot rely on MFN *per se* to automatically achieve better fine-tuning of LLD or hip joint forces. Increase in the shear component of the resultant hip force is an independent predictor of better mid-term clinical outcome regardless of the femoral neck modularity.

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