The morphology of the proximal femur in the very elderly

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Abstract

Introduction. The population of the very elderly (i.e. ≥80 years of age) is growing rapidly due to demographic changes, an increased life expectancy, in particular. As a consequence, a 170% increase in the number of performed total hip arthroplasties (THAs) is projected for the next decades. Previous studies described the age-related changes in the morphology of the proximal femur, however, almost exclusively in subjects <80 years of age and using 2D X-rays. In THA the emphasis lies on reconstruction of the center of rotation (CoR) in order to preserve leg length, leg rotation and muscle tension (more precise: lever arm). The present study focuses on the reconstruction of the center of rotation (CoR) in the very elderly, with emphasis on the neck-shaft angle (NSA), the femoral neck anteversion angle (FNAA) and the mediolateral offset (ML offset). Furthermore, the effect of patient demographics such as gender, length and weight on the internal and external morphology of the proximal femur, the relationships between dimensions and angles on the proximal femur, and the effect of the internal morphology of the femoral canal on parameters describing the external geometry of the proximal femur were investigated.

Methods. Ninety very elderly subjects (avg. 84.2 ± 3.6 years, range 80-105 years, 50M/40F) got a high-resolution CT-scan of their right femur (voxel size 1x1x1mm). Cortical bone models were derived from these scans using a specialized threshold algorithm in Materialise Mimics v10 and were further processed in Inus Technology Rapidform 2006. In order to classify the proximal femoral canal shape in stovepipe, normal or champagne flute the canal flare index (CFI) was measured according to Noble et al.

Results. Compared to previous studies, the mean NSA (125.1 ± 5.5) and FNAA (10.0 ± 5.6) values found in the present study did not show notable differences. Based on the coronal CFI, the studied femora can be divided into stovepipe (23.3%) and non-stovepipe (76.7%).

This percentage of stovepipe shaped proximal femoral canals is high compared to literature about younger populations. There are no differences in the external geometry between femora with a stovepipe or a non-stovepipe shaped canal. Furthermore, the FHD and the $CoR\text{-}LT_{absolute}$ proved to be positively correlated (r=0.449) in the current study, the $CoR\text{-}LT_{absolute}$/FHD-ratio showed to be 1.17. The distance between the lesser trochanter and the center of rotation was both absolute (59.54 ± 5.76mm vs. 54.85 ± 6.31mm) and vertical (44.37 ± 6.77mm vs. 38.95 ± 7.41mm) larger in males than in females.
Discussion. Based on the current study, no alternations in the external geometry of the current hip stem have to be made for an optimal elderly hip stem. However, due to advanced osteoporosis, this population of very elderly subjects contained more stovepipe shaped proximal canals based on their CFI, than younger populations. This has implications for hip stem design in the elderly. Namely, the proximal canal in which the hip stem is fixated is widened, while the external morphology remains the same. A hip stem with a thicker part for fixating in the shaft and the same external features as the currently used hip stem seems thus optimal in the very elderly (≥80yrs). Furthermore, a new equation for determining the head height, based on the diameter of the femoral head is suggested, which may be useful in hemiarthroplasty.

Keywords
Proximal femur, morphology, elderly, hip arthroplasty, THA, three-dimensional, 3D analysis, neck-shaft angle, femoral neck anteversion.

Introduction
Total hip arthroplasty (THA) is widely used in patients suffering from osteoarthritis and aims to regain the patients' mobility and to relieve the patients' pain. According to the LROI (Landelijke Registratie Orthopedische Implantaten) 23,815 total hip arthroplasties (THAs) were performed in the Netherlands in 2012 (1). The average age of patients undergoing THA in that year was 70 years (1). Due to demographic changes, the population of the elderly is growing rapidly, in particular because of a higher life expectancy. As a consequence, a 170% increase in THAs is expected for the next decades (2). It is known that malpositioning of components during THA is a major cause of adverse outcomes (3). Therefore, one of the main goals during the THA procedure is a careful reconstruction of the center of rotation (CoR) (3). Prostheses with a well reconstructed CoR will preserve leg length, leg rotation and muscle tension (more precise: lever arm). Orthopaedic surgeons aspire to do so by pre-operative templating, which plays an important role in the success of THA (2, 4). In this way the artificial hip resembles the real morphology of the anatomic

hip joint before surgery. According to Noble et al. critical knowledge of the morphology of the proximal femur and the predictability of key femoral dimensions is needed for the ultimate success in THA (5).
The morphology of the proximal femur is described by several authors (2, 3, 5-13). This is done by measuring external parameters like dimensions and angles between defined reference points and lines on the proximal femur. For example: the neck-shaft angle (NSA) (5-13), the femoral neck anteversion angle (FNAA) (6-9, 12) and the mediolateral offset (ML offset) (5, 10, 12), are parameters in which the location of the CoR is involved. These variables should resemble the real proximal femur in hip stem design and implantation. An orthopaedic surgeon performing an uncemented THA namely, has only limited control over the femoral part of the THA, this is because the position of the stem is dictated by the morphology of the proximal femoral canal (16).
Besides external parameters, also internal parameters of the proximal femur, like the width and the shape of the proximal femoral canal have been described previously. It is known that proximal femoral canal width and shape change during the aging process (5, 11). Knowledge of the internal morphology is essential for achieving adequate and durable primary fixation of uncemented hip stems in the proximal femoral canal.
Nevertheless, it is possible to design cementless components that fit the average femur fairly well (5, 10). However, the assumptions then made are that the external proximal femur does not change with age or gender. However, there are some effects of age and gender on the morphology of the proximal femur earlier reported (10, 12, 17). Noble et al. showed that the NSA is smaller in older people (10), which was confirmed by Maruyama et al. in female subjects (12). Unnanunta et al. reported a higher NSA and a higher ML offset in males (17), this was also found by Maruyama et al (12).
Current uncemented hip stem designs are based on a population aged much younger than 80 years of age. Despite the growing relevance of the latter age group, hip stems are designed with the assumption that aging has no effect on the morphology of the proximal femur (10). Most research towards proximal femoral morphology is done on populations aged 50-70 years of age (5-8, 10, 12, 13). Rubin et al. investigated a relative older population with a mean age of 82 years (range 70-95 years). This small population (n=32) had a lower NSA when compared to younger populations described by others. However, the same study concluded that their measurements, which were performed on 2D radiographs, only gave a rough estimation when compared to anatomical measurements (11).
Based on these findings it is expected that the morphology of the proximal femur keeps changing while aging, which suggests that a special elderly hip stem design is needed for optimal THA. Therefore, the primary aim of this study was to assess the external geometry of

the proximal femur, by the use of 3D models in a large population, aged 80 years and older. This study emphasized in particular on the position of the CoR. The secondary aims were to investigate 1) the effect of patient demographics such as gender, length and weight on the internal and external morphology of the proximal femur, 2) the relationships between dimensions and angles on the proximal femur, and 3) the effect of the internal morphology of the femoral canal on parameters describing the external geometry of the proximal femur. Finally, it is investigated whether the frequently made assumption stating that the CoR is located on the femoral neck axis (FNA), is correct in the elderly above 80 years of age.

Methods

Subjects

This study included 90 very elderly subjects above 80 years of age (avg. 84.2 ± 3.6 years, range 80-105 years, 51M/40F). Bodyweight and height were 69.8kg (SD 11.1kg) and 167.7cm (SD 9.1cm) respectively. Patients with a bone metabolic disorder or previous hip surgery were excluded from this study.

Construction 3D model

All subjects underwent a CT-scan of their right femur for a non-orthopedic medical complaint, in which the right femur was an addition or an extension to the prescribed scan. The CT-scanner used was a Siemens Sensation Open scanner (Siemens AG, Erlangen, Germany) with a scan field view of 500mm and a pixel size of 0.98x0.98mm. The slice thickness of the scan was set on 1mm. The 90 high-resolution CT-scans (voxel size 1x1x1mm) were loaded into Materialise Mimics™ (version 10.01, Materialise, Leuven, Belgium). With this software the femoral cortex is segmented from soft tissue, the tibia and the acetabulum. This cortical bone segmentation is done by carefully selecting a threshold based on Hounsfield Units (HU).

Parameters based on measurements

All measurements were done on the obtained 3D models.

Canal flare index (CFI)

The CFI is defined as the ratio between the width at the level 20mm proximal to the lesser trochanter (LT) and the width at the isthmus (5). Following previously published procedures in Mimics (5, 10). The CFI was measured in both the coronal and sagittal plane at the abovementioned levels. According to the work of Noble et al. a $CFI_{coronal}$ ≤3.0 was labeled 'stovepipe', between 3.0 and 4.7 was considered 'normal' and ≥4.7 was considered 'champagne flute' (5).

After measuring the CFI, the 3D models of the femur were loaded into Rapidform 2006 (Inus Technology, Rock Hill, South Carolina, USA) to define points, to create planes and 3D geometric objects and to perform measurements (fig. 1).

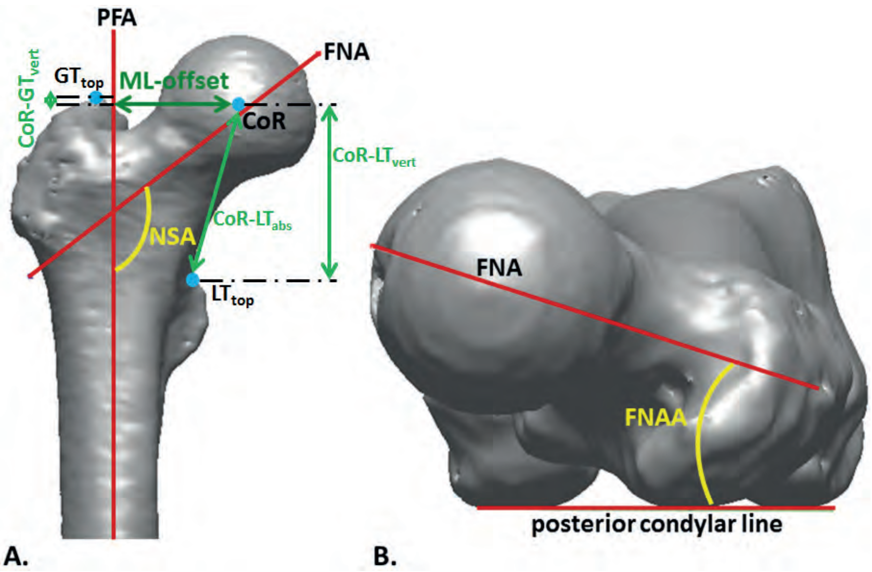

Figure 1. Overview of axes, reference points and investigated parameters in Rapidform. Showing the proximal femur axis (PFA), femur neck axis (FNA), posterior condylar line (PCA), Center of rotation (CoR), Neck-shaft angle (NSA), the Femoral neck anteversion angle (FNAA), the mediolateral offset (ML offset), the greater trochanter top (GT_{top}) and the lesser trochanter top (LT_{top}). Additionally, the vertical distance between the greater trochanter top and the center of rotation ($CoR\text{-}GT_{vert}$) and the vertical distance between the lesser trochanter top and the center of rotation ($CoR\text{-}LT_{vert}$) is shown. Furthermore, the absolute distance between the lesser trochanter top and the center of rotation ($CoR\text{-}LT_{abs}$) is displayed. A. Coronal view. B. Transversal view from cranial to caudal.

Femoral head diameter (FHD) and femoral head center (Center of rotation, CoR)

The diameter of the femoral head (FHD) and the center of rotation(CoR) were obtained by fitting a sphere around the femoral head. Fitting the sphere was done by marking at least 75% of the total surface of the femoral head. Pits and non-spherical areas (such as the attachment of the ligamentum capitis femoris) could influence the size and position of the sphere and therefore these regions were excluded from the spherical construction.

The diameter of this sphere was defined as the femoral head diameter (FHD) and the center of this sphere was defined as the center of rotation (CoR).

Proximal femur axis (PFA)

The determination of the position of the proximal femur axis (PFA) was based on the method of Maruyama et al. (12). The cortex of the proximal femur was marked with its proximal margin distal to the lesser trochanter and its distal margin at approximately 35% of the total length of the femur, excluding the linea aspera on the posterior side. Around this marked region a cylinder was fitted, subsequently a XYZ-coordinate was based on this cylinder. Along this coordinate the femur was divided into 20 parts between the most proximal point of the greater trochanter and the most distal point on the femoral condyles. Between 25% and 35% of this total length, the cortex was sliced every 5mm. Circles were fitted around these curves. The centroids of these circles were used to fit a vector, which served as the PFA.

Femoral neck axis (FNA)

The reconstruction of the FNA was based on the method described as the golden standard for reconstructing the FNA in the work of Sugano et al. (22). The isthmus of the femoral neck was marked 360° around and a circle was fitted. The vector perpendicular to this circle was used as a first approximation of the true FNA. Along this vector, between the femoral head and the greater trochanter, slices with a 1mm intervention were made. Around these curves, circles were fitted, subsequently a vector was fitted on the centroids of these circles in order to construct the FNA. Along this vector the femoral neck was sliced every 1mm between the femoral head and the greater trochanter. Based on these curves, circles were made. Based on the centroids of these circles a new vector was constructed. This process of fitting new circles along the previously created vector was repeated 10 times on average for each case. The number of iterations depended on the SD between subsequent measurements of both the NSA and the FNAA, when these were ≤1.5°, the mean NSA and FNAA were calculated. The drawn vector which was the best representation of the mean was defined as the FNA.

Reference points relative to the center of rotation

In order to reconstruct the anatomical CoR during surgery, orthopedic surgeons may use reference points, such as the greater trochanter and the top of the lesser trochanter. Therefore the shortest distance between the CoR and the greater trochanter ($\text{CoR-GT}_{vertical}$) and the shortest distance between the lesser trochanter top and the CoR ($\text{CoR-LT}_{vertical}$)

were measured, both parallel to the PFA. This was done by creating a plane perpendicular to the PFA through the top of the greater trochanter. Furthermore, a plane perpendicular to the PFA and through the CoR was created. The distance between these two planes was measured. In case GT_{top} was proximal to CoR, the distance was listed negative. The same method was used for determining the vertical distance between the CoR and LT_{top}. Furthermore, the absolute distance between CoR and LT_{top} (CoR-$LT_{absolute}$) was measured.

Position of the femoral head center relative to the femoral neck axis

To reconstruct the FNA, the center of the femoral head (i.e. CoR) is a commonly used end point (5, 12, 23). To investigate whether the use of CoR as an end point is a proper way of reconstructing the FNA, the absolute distance between the FNA and CoR was measured.

Statistical analysis

All comparisons between groups (male vs. female, stovepipe vs. non-stovepipe) were statistically tested using independent-sample T-test (for normal distributed parameters) or Mann-Whitney U test (for non-normal distributed parameters). Correlations with demographics and between parameters were investigated using Pearson's r correlations. Statistical analysis was performed using IBM SPSS 21 statistics. The level of statistical significance was set at $p<0.05$.

Results

Gender

The total group of 90 subjects consisted of 40 females and 50 males. Male subjects were significantly taller (172.9 ± 7.0cm vs. 161.1 ± 6.9cm) and heavier (73.6 ± 9.4kg vs. 64.8 ± 11.2kg) than female subjects. The shape of the proximal femoral canal, quantified using the canal flare index (CFI), was only different in the sagittal plane and was significantly higher in male subjects than in female subjects (2.47 ± 0.45 vs. 2.18 ± 0.34). Furthermore, gender had an effect on the external morphology. Male subjects had a significantly larger femoral head diameter (FHD) compared to female subjects (51.55 ± 1.98mm vs. 46.06 ± 2.05mm). In addition, the distance between the lesser trochanter and the center of rotation was both absolute (59.54 ± 5.76mm vs. 54.85 ± 6.31mm) and vertical (44.37 ± 6.77mm vs. 38.95 ± 7.41mm) larger in males than females (Table 1).

Table 1. Demographics and values of internal and external measurements on the proximal femur displayed as mean ± SD and range for the total group and mean ± SD per gender. The p-values represent the significance of the effect of gender. A negative value for CoR-GT means that the CoR is distal to the level of the greater trochanter.

	Total Group (n=90)	Range	Female (n=40)	Male (n=50)	p-value
Age [yr]	84.20 ± 3.60	80.00 – 105.00	84.60 ± 2.90	83.80 ± 4.10	0.06
Length [cm]	167.70 ± 9.10	145.00 – 190.00	161.10 ± 6.90	172.90 ± 7.00	< 0.001
Weight [kg]	69.80 ± 11.10	40.00 – 95.00	64.80 ± 11.20	73.60 ± 9.40	< 0.01
FHD [mm]	49.11 ± 3.40	41.37 – 55.58	46.06 ± 2.05	51.55 ± 1.98	< 0.001
$CFI_{CORONAL}$	3.43 ± 0.57	2.20 – 5.31	3.41 ± 0.50	3.45 ± 0.63	0.70
$CFI_{SAGITTAL}$	2.34 ± 0.43	1.35 – 3.58	2.18 ± 0.34	2.47 ± 0.45	< 0.01
NSA [°]	125.10 ± 5.50	110.90 – 140.30	124.20 ± 6.00	125.90 ± 5.00	0.15
FNAA [°]	10.00 ± 5.60	1.00 – 23.40	11.20 ± 6.10	9.00 ± 5.10	0.07
ML offset [mm]	45.26 ± 5.64	26.45 – 59.54	44.18 ± 5.40	46.13 ± 5.73	0.10
CoR-LT vert. [mm]	41.96 ± 7.52	26.59 – 60.91	38.95 ± 7.41	44.37 ± 6.77	< 0.001
CoR-GT vert. [mm]	−11.21 ± 7.98	−23.19 – 22.79	−12.22 ± 7.17	−10.40 ± 8.56	0.32
Cor-LT absolute [mm]	57.46 ± 6.42	42.45 – 75.06	54.85 ± 6.31	59.54 ± 5.76	< 0.001

Comparison with literature

Compared to previous studies, the mean NSA and FNAA values found in the present study did not show notable differences (table 2).

Table 2. Comparing NSA and FNAA values from the present study with reference values in literature (mean±SD).

	Mean age [yrs]	n	Method	NSA [°]	FNAA [°]
Present study	84	90	CT	125.1 ± 5.5	10.0 ± 5.6
Rubin 1992	82	32	X-ray	122.9 ± 7.6	–
Dy 2012	74	22	CT	130.4 ± 4.6	9.2 ± 8.0
Noble 1988	70	200	X-ray	124.7 ± 7.4	–
Adam 2001	67	30	X-ray	123	26.5
Sugano 1999	67	32	X-ray	126.4 ± 7.3	–
Maruyama 2001	58	100	CT	125 ± 4.8	9.8 ± 8.5
Noble 1995	52	80	X-ray	125.4 ± 5.5	–
Anastopoulos 2010	51	22	CT	122.5	22.16
Mahaisavariya 2002	49	80	CT	125.4	10

Canal flare index

Based on the coronal CFI, the studied femora can be divided into stovepipe (n=21), normal (n=65) and champagne flute (n=4) shaped femora. The femora are divided into stovepipe (n=21) and non-stovepipe (n=69) based on the coronal CFI. It can be seen that there are no differences in age, length and weigth between the groups. Also the distribution of males and females is homogeneous. The sagittal CFI differs significantly between these groups. The stovepipe group showed a significant lower sagittal CFI than the non-stovepipe group (2.02 ± 0.36 vs. 2.43 ± 0.40). Furthermore, the absolute and the vertical distance between the lesser trochanter and the CoR was larger in the stovepipe shaped femora compared to the non-stovepipe shaped femora. (table 3)

Table 3. Subgroup demographics, internal and external measurements on the proximal femur for stovepipe and non-stovepipe shaped canal (mean ± SD). The p-values represent the significance of the effect of the shape of the proximal canal (stovepipe/ non-stovepipe). A negative value for CoR-GT means that the CoR is distal to the level of the greater trochanter.

	Stovepipe (CFI≤3) (n=21)	Non-stovepipe (CFI>3) (n=69)	p-value
Gender [#]	M:12 / F:9	M:38 / F:31	
Age [yr]	84.52 ± 5.55	84.09 ± 2.87	0.65
Length [cm]	167.95 ± 10.16	167.67 ± 8.78	0.91
Weight [kg]	70.52 ± 11.17	69.55 ± 11.15	0.97
FHD [mm]	49.36 ± 3.28	49.02 ± 3.45	0.70
$CFI_{CORONAL}$	2.76 ± 0.20	3.63 ± 0.49	< 0.001
$CFI_{SAGITTAL}$	2.02 ± 0.36	2.43 ± 0.40	< 0.001
NSA [°]	125.26 ± 5.67	125.09 ± 5.49	0.90
FNAA [°]	10.40 ± 6.16	9.84 ± 5.52	0.69
ML offset [mm]	45.80 ± 5.31	45.07 ± 5.76	0.58
CoR-LT vert. [mm]	45.24 ± 8.84	40.96 ± 6.84	0.02
CoR-GT vert. [mm]	−11.95 ± 4.79	−10.97 ± 8.74	0.89
Cor-LT absolute [mm]	60.50 ± 6.48	56.52 ± 6.15	0.01

Deviation from CoR relative to the FNA

The shortest distance between the CoR and the FNA was measured (avg. 2.30 ± 1.26 mm, range 0.13-8.48 mm).

Correlations

Significant correlations between the subjects' demographics and the measured parameters were found. Length and weight were positively correlated with the FHD (respectively r=0.769, r=0.531). A weak correlation was found between length and ML offset (r=0.231). The absolute and the vertical distance between the lesser trochanter were moderately correlated with length (respespectively r= 0.532, r=0.337) and weight (r=0.464, r=0.339). The FHD and the $CoR\text{-}LT_{absolute}$ proved to be positively correlated (r=0.449) in the current study. Furthermore, the $CoR\text{-}LT_{absolute}$/FHD-ratio showed to be 1.17.

Discussion

This study aimed to assess the morphology of the proximal femur in a population aged 80 years and older. The main focus was on the dimensions and angles commonly used in orthopaedic surgery for reconstruction of the CoR, namely the NSA, FNAA and ML offset. The femoral components of uncemented hip prosthesis are designed with the assumption that age and gender have no effects on the morphology of the proximal femur (10). In contrast to that, previous studies described changes according to ageing and differences in morphology due to gender. Unnanunta et al. showed that male subjects had a higher NSA and a higher ML offset (17), which is in accordance to Maruyama et al. (12). Noble et al. showed that NSA was significantly lower in elderly and that the FNAA tended to be lower in elderly subjects (10). Also Maruyama et al. showed a declination in NSA due to aging, but only in females (12).

Those previous studies only measured groups of younger subjects. Till now, no study was performed on a large group of very elderly subjects (>80yrs), using 3D analysis, which emphasizes the significance of the current study. Because of the high age of our population and the fact that the morphology changes with aging, deviating values were expected in our population relative to younger populations (5-13). However, the mean NSA and the mean FNAA found in this study corresponded with reference values of younger populations in the literature. The small differences found between our population and the younger populations could be due to the smaller sample size in the previous studies. This is suggested because previous studies on larger population groups showed almost identical NSA and FNAA values (5, 6, 10, 12), regardless of the younger age (i.e.70yrs (5), 58yrs (12), 52yrs (10), 49yrs (6)). This may imply that overall the NSA and FNAA are not notable influenced by aging after a certain age. However, another study in which an older population was investigated (i.e. 82yrs) showed a lower NSA compared to younger populations and the present study (11). This was in accordance with the effects of aging described before (10, 12, 17), but in contradiction with the present study. This can again be explained by the small population size of that particular study or can be due to the different method that was used (11). Rubin et al. used radiographs to measure the NSA, this is less accurate compared to the 3D models used in the present study (11). In 2D imaging the rotation of the subjects leg influences the AP-projection of the proximal femur and therefore the measurements in that plane (12). Therefore, the measured NSA in the study of Rubin et al. is less reliable due to the low accuracy of the method used. The suggestion that the NSA and FNAA are not notable influenced by aging after a certain age remains valid. But also this suggestion is not fully legitimate. For accurately describing the effects of aging on the in NSA and FNAA, it is needed to investigate these parameters on large

population groups consisting of all ages and both genders. This enables the showing of the development of the NSA and FNAA with aging.
In the present study no differences of NSA, FNAA or the ML offset were found between male and female subjects. However, males had a significantly larger femoral head diameter, which corresponds to previous studies (17). Also the distance between the CoR and the LT was larger in male subjects than in female subjects (both $CoR\text{-}LT_{vertical}$ and $CoR\text{-}LT_{absolute}$). The fact that men were significantly taller and heavier than women can partly explain the higher FHD and CoR-LT distance in the male population. Males are taller and will have larger femora and therefore a higher CoR-LT distance and larger FHD. In accordance with these results, Noble et al. showed a positive correlation (r=0.76) between the femoral length and the femoral head size. The FHD and the $CoR\text{-}LT_{absolute}$ proved to be positively correlated (r=0.449) in the current study. Furthermore, the $CoR\text{-}LT_{absolute}$/FHD-ratio showed to be 1.17. The $CoR\text{-}LT_{absolute}$/FHD-ratio was previously described by Sproul et al., who indicated that reconstruction of the head height in hemiarthrolasty can be predicted based on the head size ($CoR\text{-}LT_{absolute}$=1.035 x FHD) (24). However, they had a small sample size (n=34), a relative high number of males included and a population, which was relatively young (mean age: 62yrs) for hemiarthroplasty. Unnanuntana et al. also investigated the ratio between $CoR\text{-}LT_{absolute}$ and the FHD, he stated that $CoR\text{-}LT_{absolute}$=1.01 x FHD, which he had derived from a larger population (n=200). This population however, included only subjects younger than 40 years of age, which is an age group that is unlikely to suffer from a proximal femoral neck fracture, and if so, it is unlikely that patients in this age group would be treated by hemiarthroplasty. Because of the large population size (n=90) and the high mean age (84yrs, range 80 – 104rys) of the present study, the obtained ratio is suggested to be more useful in estimating the head height, based on femoral head diameter in hemiarthroplasty.
Based on the $CFI_{coronal}$, 23.3% of the study population had a stovepipe shaped proximal femoral canal. This in contrast to Noble et al, who used the same $CFI_{coronal}$ measurement, who showed that only 10% of the population had a stovepipe shaped proximal canal (5). This difference may be the result of advanced osteoporosis due to aging, because the population of Noble et al. was approximately 10 years younger. This effect of aging on CFI has previously been described (11). However, no correlation between age and the $CFI_{coronal}$ or the $CFI_{sagittal}$ was found in the present study. This might be explained by the small range in age of the studied population (80yrs-105yrs). Furthermore, the $CFI_{coronal}$ and the $CFI_{sagittal}$ showed a positive moderate correlation. This correlation shows that the same internal changes are occurring in every direction. However, only the $CFI_{sagittal}$ showed to be significantly lower in females. A lower CFI value in females represents the higher

prevalence of osteoporosis compared to males, which is well known (25). The results also show that the CoR-$LT_{absolute}$ and the CoR-$LT_{vertical}$ were larger in the femora with a stovepipe shaped canal. This can be explained by a limitation in the CFI measurement described by Nobel et al. (5). The CFI is the ratio of the width at the level 20mm proximal to the lesser trochanter divided by the width at isthmus level. At a small-sized femur the level 20 mm proximal to the lesser trochanter is relatively more proximally located compared to a normal-sized femur. At this relatively more proximal level, the femur is wider. This higher value divided by the same width at isthmus level will thus result in a higher CFI, indicating a non-stovepipe femur. Furthermore, the distance between the CoR and the LT is more likely to be small in a small-sized femur (which is also confirmed by the positive correlations found between length and the CoR-$LT_{absolute}$ and between length and CoR-$LT_{vertical}$). Therefore a smaller femur tends to have a higher CFI, a lower CoR-$LT_{absolute}$ and a lower CoR-$LT_{vertical}$, and vice versa. Therefore it is recommended to measure the width of the canal at a distance in a certain percentage of the total length above the LT instead of an absolute distance. This eliminates the effect of femur size on the CFI.

Many authors reconstruct the FNA based on the location of the CoR (5, 12, 23), although the CoR is not located on the FNA by definition. The results of this study show only a small deviation. This suggests that reconstruction of the FNA, based on the location of the CoR, is indeed an acceptable method.

Some limitations have to be considered. The statements based on comparisons with literature could be influenced by differences in used method or sample size. Furthermore, these comparisons could not be tested statistically. For more legitimate statements on the effect of aging in this population it remains necessary to investigate large population groups consisting of all ages and both genders. Additionally, the inter- and intravariability of the method used has not been investigated yet. This should be done in a future study to ensure the validity and accuracy of this relatively new method.

The small differences found in the NSA and FNAA between the present study and literature on younger subjects, suggest that NSA and FNAA are not affected by age. Based on the current study, no alternations in the external geometry of the current hip stem have to be made for an optimal elderly hip stem. This is the case when it is assumed that the current hip stems have an optimal design for the younger, previously investigated, populations. However, some internal changes in the proximal femur were reported. Due to advanced osteoporosis, this population of very elderly subjects contained more stovepipe shaped proximal canals based on their CFI, than previously described in younger populations (5). This has implications for hip stem design in the elderly. Namely, the proximal canal in which the hip stem is fixated is widened, while the external morphology remains the same. A hip stem with a thicker part for fixating in the shaft and the same external features, as the currently used hip stem seems thus optimal in the very elderly (≥80yrs). Furthermore, a new equation for determining the head height, based on the diameter of the femoral head is suggested. This may be useful in hemiarthroplasty. In addition, our study showed that the position of the CoR is located near to the FNA, which validates the used method to reconstruct the FNA based on the location of the CoR.

Role of the student

Hidde Veldman was an undergraduate student in Biomedical Sciences (major: Human Movement Sciences) when this study was performed. He worked closely together with (and under the supervision of) PhD-student drs. T. Boymans at AHORSE, which is the research foundation of the department Orthopaedic Surgery & Traumatology of the Atrium Medical Center Parkstad. Here he created 3D models of human femora out of 2D CT-scans. Furthermore, he performed the measurements on the 3D models and wrote a report about the results. He was daily supervised by dr. R. Senden, the research coordinator of AHORSE.

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