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Effect of Geometrical Parameter in Hip Implant Penetration, Contact Stress and Wear

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Abstract

Twelve hip implants designed during this investigation were tested for dislocation resistance. The finite element analyses were performed to determine the contact penetration, surface stress and sliding displacement. New prediction models were developed specific to the 12 hip implants to predict contact stress, penetration, and wear rate. Specific geometrical parameters when used in the model, the deterministic coefficient (R^2) of the regression fit increased from 97 to 100%. A safe zone, which establishes combinations of implant dimensions for dislocation resistance for 12 implants, was determined. Head diameters between 26-32 mm, neck diameter of 14 mm, and neck angle between 25-35º, cup inclination between 35-50º and cup ante version between 5-15º were examined to be the safest ranges for hip implant designs of this study

Keywords: Geometrical factors; Safe zone; Neck diameter; Neck angle; Dislocation

Introduction

Numerous parameters control the long-term performance of an artificial hip implant [1]. Geometrical parameters influence the performance of a hip implant [2] significantly. These geometrical parameters are design as well as non-design related parameters. The efficiency of an implant may be increased by optimizing design related parameters. Improper selection of geometrical design parameters of femoral and acetabular components significantly increases the rate of dislocation. Impingement between femoral neck and acetabular cup leads to dislocation, which can be avoided by using appropriate cup anatomical as well as femoral stem orientation [3-5]. Geometrical parameters such as head diameter, neck diameter, neck angle and cup thickness determine the rate of dislocation which affects the stable range of motion of a hip implant. This paper investigated the effect of geometrical parameters on contact penetration and stresses, and wear in 12 hip implants designed during this effort. New prediction models were developed to predict contact stresses, contact penetration and wear rate. An effort was made to define safe zones; which establishes boundary conditions of geometrical parameters as to where an implant is expected to be more efficient against dislocation [3-8].

Materials and Methods

SolidWorks 2008 SP 2.1 software was used to create the hip implant models in parasolid format (para). One of the implants was donated by TRIDENT™ acetabular System by Stryker Howmedica, Osteonics. Four different head diameters of 20, 26, 32 and 40 mm were combined with three other stems to develop all 12 different models. Three neck diameters of 10, 14 and 18 mm were used in this study. Head to neck ratio (R) defined as head diameter divided by neck diameter, ranged from 1.11 to 4. Neck angles used were 25, 35 and 50º from vertical axis. Except design parameters related to femoral component, three acetabular component parameters were used in the present research. Acetabular cup thicknesses varied from 9 to 11 mm. However, cup thickness was considered secondary to the cup orientation parameters. The cup was inclined at 20, 35, 50 and 65º from the horizontal axis. The cup was anteverted at 5, 10 and 20º from the top plane of the hip implant. The design details and geometrical parameters for each of the implants are summarized in Table 1 and Figure 1.

The parasolid (para) formatted hip assemblies created in solid works were imported into ANSYS for finite element analysis. An assembly named as Hip implant was defined with volumes using component names as stem, head and cup. Stainless steel (SS 316L) with elastic properties such as Young's modulus of 209 GPA, Poisson's ratio of 0.3, and density of 7800 kg/m3 were used to define the material characteristics of solid geometry. This study used 10-node 92 element for meshing irregular volumetric geometries, 3D Contact 174 element for characterizing 3D contact and 3D Target for characterizing contact sliding. The stem was defined as 3D Solid 92 element, head's articulating surface as 3D Contact 174 element and the cup's inner articulating surface as a 3D Target 170 element. Customized solution control was used for a static analysis. After load applied, the analysis type selected was based on the desired simulation characteristics. Static analysis was

Models	Head Diameter (mm)	Neck Diameter (mm)	Head/ Neck Ratio	Neck Angle (deg)	Cup Thick-ness (mm)	Cup Anatomical Inclination (deg)	Cup Ante-version (deg)
Ranges	**20-26-32-40**	**10-14-18**	**1.11-4**	**25-35-50**	**9-11**	**20-35-50-65**	**5-10-20**
1	20	10	2	25	9	20	5
2	26	10	2.6	25	9	35	5
3	32	10	3.2	25	9	50	5
4	40	10	4	25	9	65	5
5	20	14	1.43	35	9	65	10
6	26	14	1.86	35	9	20	10
7	32	14	2.29	35	11	35	10
8	40	14	2.86	35	11	50	10
9	20	18	1.11	50	11	50	20
10	26	18	1.44	50	1	65	20
11	32	18	1.78	50	11	20	20
12	40	18	2.22	50	11	35	20

Table 1: Classification of Hip Models based on the selected design related as well as non-design related parameters. The ranges for all geometrical parameters are also included.

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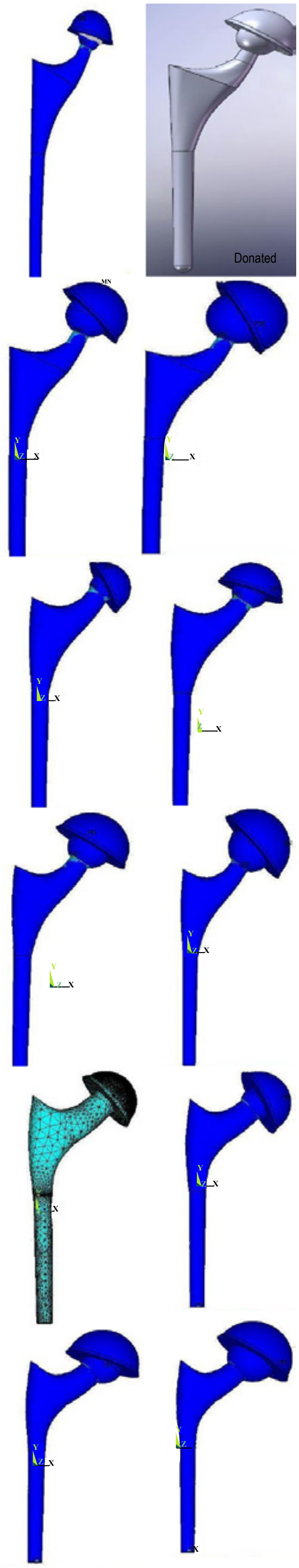

Figure 1: Hip implant designs used in the research

performed with large static displacements of nodes. Static analysis used in this study was time rate independent; which considered time duration as a loadstep counter and recognized the loadsteps and load substeps. The loadstep is a set of loads applied in the given time duration and load sub-step defines the time steps within a complete load-step at which the solutions were calculated for final display of results.

Results

Maximum stress

Figure 2 illustrates von Mises stress for Hip Model 1 after static load-step was applied. Similarly, the peak intensities of von Mises stresses were examined at the contact area between femoral head and femoral neck for all 12 hip models as indicated in Table 1. The range of von Mises stresses recorded was 0.65 to 1.73 MPa when a 100N force was applied. The von Mises stresses values change linearly, in the linear elastic regime. Majority of peak stress intensities were found at the contact surfaces between the head and the neck. A few models showed that highest stresses generated at the section of the stem connected with distal portion of the neck. Highest stresses at the stem were found in the hip models with higher neck angles. Since, individually recorded stress intensities show maximum stress behavior for entire hip model, they were referred as Maximum Stresses.

Contact stress

4.3Forces applied during present static analysis simulate ground reaction forces applied in a hip prosthesis in the Y-direction. These forces tend to move the femoral component towards acetabular component producing significant contact stresses [9-10]. Contact pair in the present study was defined as surface-to-surface contact. The forces exerted due to femoral head surfaces on acetabular liner were enlisted as contact stresses. The range of recorded contact stresses was from 1.16 MPa to 11.07 MPa; which were significantly higher compared to von Mises stresses listed previously. Contact stresses for all hip models achieved in this study are listed in Table 2

Contact penetration

4.4Contact penetration at the acetabular cup surfaces was determined. Penetration was observed between the contact surface of femoral head and the target surface of acetabular cup as shown in Table

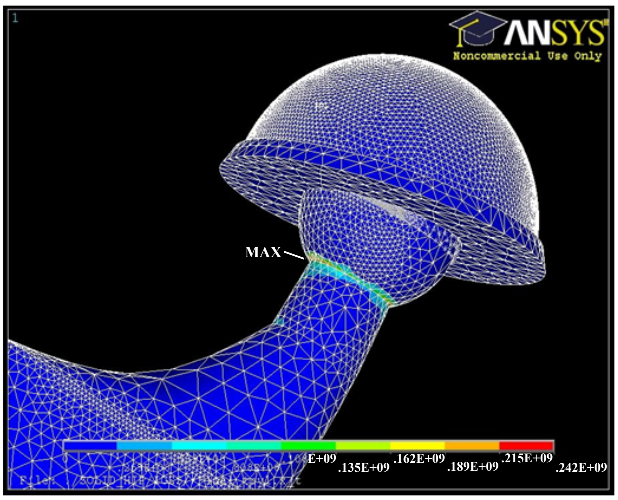

Figure 2: von Mises stresses plotted for static analysis of Hip Model 1.

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HIP MODEL	VON MISES STRESS (MPa)	HIP MODEL	VON MISES STRESS (MPa)
1	1.71	7	1.16
2	N/A	8	0.92
3	1.07	9	N/A
4	1.17	10	1.73
5	0.73	11	1.73
6	0.65	12	1.73

Table 2: Von Mises Stresses achieved from static analysis of all hip models.

3.The highest contact penetration was 0.3 mm to as low as 0.14 mm for all the hip models. Little or no penetration was found at the surface elements closer to the outer rim of acetabular cup which were unable to interact with contact surface of femoral head.

Sliding displacement

Vertical forces applied during the static analysis caused the femoral head to slide on the inner surface of the acetabular cup. The higher inclination angles of acetabular cup are more likely to induce higher sliding displacement of femoral contact surfaces. Table 4 describes results examined as sliding displacement for all hip models. The range of displacements reported was from 0.15 mm to 0.73 mm. Sliding displacement was believed to be dependent on the co-efficient of friction. The friction co-efficient applied during present static analysis was 0.1.

Discussion

Effects of geometrical parameters on maximum stress

5.2A common location of maximum von Mises stresses for all analyzed hip models was the contact area between femoral head and neck. Head diameter was found to significantly affecting the stability of a hip implant. Analysis in this study found higher stresses for head diameters above 26 mm. Lowest von Mises stress (0.65 MPa) was found for hip model#6 with 26 mm head diameter and 14 mm neck diameter as seen in Table 1. Hip models with 32 mm and 40 mm head diameters showed 10.9% and 6.7% higher mean stresses compared to hip models with 26 mm head diameters Figure 2a. Figure 2b shows a bar chart for mean maximum stresses corresponding to their head diameters. Highest and lowest mean stress values were found for 32 mm head diameter and 26 mm head diameter, respectively. In hip models with 26 mm head diameter-14mm neck diameter showed 48.9% lower stresses compared to 32 mm head diameter-14mm neck diameter. Smaller head diameters found to be more significant resulting in not only dislocation but also recurrent dislocation as compared to large head diameters [11-13]. Since large head diameters increases allowable range of motion and needs to travel longer distance to get dislocated, they render lower risk of dislocation [13-15]. Neck diameter was another geometrical parameter affecting the stability of hip models in this study. Table 5 shows considerable differences in the mean stresses for hip models when correlated with their neck diameters. Models with 14 mm neck diameters were examined with lowest mean stresses compared to 10 mm and 18 mm neck diameters. Three hip models with 18 mm neck diameter showed nearly 100% and 30.3% higher stresses as compared to 14 mm and 10 mm neck diameters, respectively; whereas mean stresses of four hip models with 14 mm neck diameter was found nearly 50% and 34.6% lower than hip models with 18 mm and 10 mm, respectively. With an increase in neck angle, the contact stresses were observed to be significantly higher. Hip implants with 25° of neck angle showed 23.7% lower mean stresses compared to those with 50°. Similarly, three hip models with 25° neck angles showed 52.8% higher mean stresses compared to 35° of neck angles. Three hip models with 50° neck angles showed 65.6% higher mean stresses compared to four hip models with 35° degrees of neck angles (Table 2). Similar behaviors were reported elsewhere [2-18]. All hip models with 50° of neck angles showed comparatively higher von Mises stresses regardless of the head diameter sizes combined in those models. Neck angle of 25° was evaluated with intermediate stress values with lowest stresses when combined with 32 mm head diameter and highest when combined with 20 mm head diameter. The best combination of all hip models was 26 mm head diameter and 35° neck angle with 14 mm neck diameter.

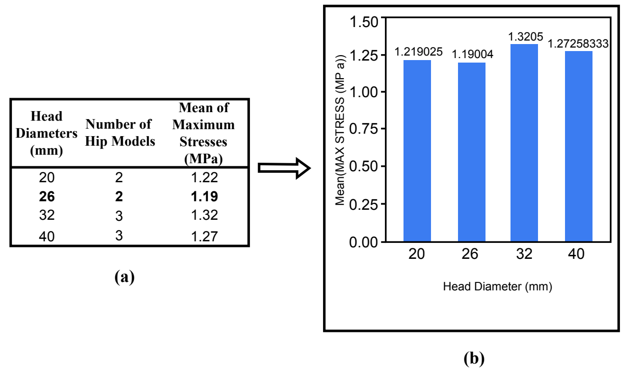

Figure 3: Head Diameter Vs Mean of von Mises stress. (a) Tabulated mean of von Mises stresses for all head diameters with analyzed number of hip models (b) Bar chart was plotted using One-way Anova. Mean stress value for 32 mm head diameter was highest of all analyzed hip models; whereas, the mean stress for 26 mm head diameter was found lowest of all series of hip models.

HIP MODEL	CONTACT STRESS (MPa)	HIP MODEL	CONTACT STRESS (MPa)
1	N/A	7	1.16
2	N/A	8	9.14
3	9.16	9	N/A
4	28.71	10	8.32
5	110.7	11	6.92
6	15.17	12	7.49

Table 3: Contact Stresses achieved from static analysis of all hip models.

HIP MODEL	CONTACT PENETRATION (mm)	HIP MODEL	CONTACT PENETRATION (mm)
1	N/A	7	0.2
2	N/A	8	0.21
3	0.187	9	N/A
4	0.2	10	0.21
5	0.3	11	0.14
6	0.193	12	0.191

Table 4: Contact Penetration achieved from static analysis of all hip models.

Effects of geometrical parameters on contact stress

Contact stress of articulating surface was significantly affected by the head and cup dimensions as well as their anatomical placements. All twelve models designed during the present analysis included 0.1 mm clearance between contact surfaces of femoral head and acetabular cup, since a study of wear rate [19] depicted 0.1 to 0.15 mm as safest range for clearance between articulating surfaces in order to achieve lower linear wear rate. Three hip models with 32 mm heads showed 51% lower mean contact stresses compared to 2 hip models with 26 mm head diameters. Heads with 40 mm diameter showed 28.8% higher stresses compared to heads with 26 mm diameter. Femoral heads with diameters above 40 mm can possibly lead towards higher contact stresses than 26 mm to 40 mm head diameters. Acetabular component orientation was examined in terms of cup anatomical inclination and contact stresses. Hip models with 35º inclination had 60.8% and 52.7% lower mean contact stresses compared to 20º and 50º of cup inclination, respectively. Cup inclination of 20º with horizontal axis showed 20.6% higher mean contact stresses than cup inclination of 50º. Since, mean contact stresses reported for hip models with cup inclination of 65º were not comparable to those below 50º, higher cup inclinations are believed to provide less hip stability. Lower peak contact stresses were observed for cup inclination below 50º when combined with 10 and 20º of cup anteversions. Hip models with cup anteversion as low as 5º failed to provide contact stress results for cup inclinations of 20 and 35º. Hip models with 10º cup anteversion showed least contact stresses compared to 20º when coupled with 35º of cup inclination. Peak contact stresses seemed to increase with cup inclination above 50º regardless of cup anteversion. Smaller amounts of acetabular and femoral component anteversion seem to provide higher contact area between articulating surface; however, these combinations may restrict the provided RoM [14-16].

Effects of geometrical parameters on contact penetration

The amount of penetration between femoral head and acetabular cup was recorded for all hip models. There was 7.2% increase in mean penetration observed for 32 mm head diameters compared to 26 mm head diameters. Similarly, 40 mm heads showed 12.1% higher mean penetration than 32 mm heads. Apart from head diameter, cup inclination was found to influence mean contact penetration. Cups inclined with 20º reproduced 16.2% lower mean contact penetration compared to those with 35º. Cups inclinations of 65º showed nearly 9% higher mean penetration relative to 50 and 35º, respectively.

Effects of geometrical parameters on contact sliding displacement

There was no significant correlation between mean contact sliding displacement and head diameters. Highest and lowest mean sliding displacement was found for hip models with 32mm and 40mm head diameters, respectively. Mean sliding displacement for hip models with 20mm and 26mm head diameters were not significantly different from one another. Sliding displacement was not found correlated to any other design parameters evaluated in this study.

Prediction model – contact stresses

The wear in hip implants occurs due to penetration of femoral head into the liner by repeated articulations. In the past, peers have predicted wear rate as a function of femoral head diameter, femoral head roughness, patient body weight and mechanical properties of ultra-high-molecular-weight polyethylene (UHMWPE) [19]. Prediction model was developed to define a relation between geometrical parameters such as HD, ND, and CI and contact stresses (CS). Head diameter controls the development of contact stress in implants. Two separate prediction equations were developed for contact stress prediction based on head diameter as discussed further.

Generic equation: A generic equation was derived to predict contact stresses (CS) correlating geometrical parameters such as head diameter (HD), neck diameter (ND) and cup anatomical inclination angle (CI) using HD as a continuous value.

$$CS = 90 - 2.62\ HD \quad 1.2\ ND + 0.73\ CI \qquad (1)$$

The above equation reproduces the contact stresses for head diameters ranging from 20 to 40 mm. The co-efficient for each significant parameter in the generic equation represents the weight of the individual factor contributing to the predicted contact stresses.

Specific equation: Similarly, when discrete values of HD are used in generic equation, it forms a specific equation as below:

CS = 36.15985 + Match [HD] + Match [ND] + Match [CI]…………….. (2)

The equation uses different coefficients for discrete values of HD, ND and CI. These coefficients are summarized as below.

Match [HD] = 20 mm » 73.35, 26 mm » -25.05, 32 mm » -29.30, 40 mm » -18.98,

Match [ND] = 10 mm » 8.22, 14 mm » -2.11, 18 mm » -6.107225

Match [CI] = 20º» 6.16, 35º» -3.57, 50º» -5.92, 65º » 3.3235875

To summarize, larger head diameter and neck diameters provide larger contact surfaces with acetabular liner leading to reduced contact stresses, whereas, higher cup inclination reduces the contact surfaces leading to increased contact stresses.

Prediction model-contact penetration

Contact penetrations determined during the analyses of twelve hip models (Table 4) were used to develop wear rate prediction equations. The linear wear rate (LWR) was found to be linearly dependent on penetration rate (dp/dt) as expressed below;

$$LWR = \frac{dP}{d\tau} \qquad (3)$$

Higher the penetration rate would increase the debris of particles resulting in increased wear rate. In the next section, contact penetration is predicted in terms of head diameter, contact stress and sliding displacement.

Generic equation: A generic equation was derived to predict contact penetration (CP) correlating head diameter (HD), contact stresses (CS) and sliding displacement (SD) using HD as a continuous value.

$$CP = 0.034 + 0.003\ HD + 0.002\ CS + 0.100\ SD \qquad (4)$$

The above equation reproduces the contact penetrations for head diameters ranging from 20 to 40 mm. The co-efficient for each significant parameter in the generic equation represents the weight of the individual factor contributing to the predicted contact penetrations. Contact penetration increases as the head diameter, contact stress and sliding displacement increases

Specific equation: Similarly when discrete values of HD are used in generic equation, it forms a specific equation as below:

$$CP = 0.177 + Match\ [HD] + 0.0003\ CS + 0.080\ SD \qquad (5)$$

Match [HD] = 20 mm » 7.96E-02; 26 mm » -5.46E-02; 32 mm » -2.95E-02, and 40 mm » 4.55E-03.

As seen above, when specific HD values (20mm, 26mm, 32mm and 40mm) were used, CP predicted by specific equation was found to be 3% more accurate than that derived from generic equation.

As seen in equation (3), higher the contact penetration, higher will be the linear wear rate. Hence, specific equation should be used to accurately predict contact penetration and resulting wear rate.

Safe zones: Based on statistical analysis derived from FEA results, five different safe zones corresponding to geometric parameters namely; head diameter, neck diameter, neck angle, cup inclination and cup anteversion, respectively, were determined in this study. A safe zone is a schematic illustration of hip implant geometrical parameters and

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combinations thereof that produce best clinical results and stability. Anatomical orientations of acetabular components were examined to reduce the occurrence of dislocation due to improper fixation angles. Cup anatomical inclination was found to be a significant factor affecting hip stability. Proper inclination of acetabular cup is believed to provide suitable holding of femoral head within the cup socket. Safe zone for stable RoM was determined for head diameters ranging from 26-32 mm, neck diameter 14mm, neck angle between 25-35°, cup inclination between 35-50° and cup anteversion between 5-15°. Figure 5 shows safe ranges of geometrical parameters.

Conclusions

Twelve hip implants designed during this effort were tested for dislocation resistance analytically. Finite element modeling examined the contact penetration, surface stress and sliding displacement. Hip models with 35° cup anatomical inclination provided lower contact stress than inclination of 20 and 50°. Higher cup inclinations make the joint unstable. Higher femoral head diameter, 32 mm or greater, increased the penetration, however, produced smaller sliding displacement. Sliding displacement was not dependent on other geometrical parameters, higher head diameters generated lower sliding displacements. Prediction models were able to correlate the contact stress, contact penetration. Contact penetration predicts the linear and volumetric wear rates clinically. Therefore, contact penetration prediction models may be used to determine the mass loss or wear of hip implant liners. A combination of geometrical parameters may produce safe and stable joint characteristic, it has been illustrated in safe zone diagrams.

HIP MODEL	SLIDING DISPLACEMENT (mm)	HIP MODEL	SLIDING DISPLACEMENT (mm)
1	N/A	7	0.73
2	N/A	8	0.15
3	0.1729	9	N/A
4	0.172	10	0.171
5	0.172	11	0.1709
6	N/A	12	0.173

Table 5: Sliding Displacement achieved from static analysis of all hip models.

Level of Neck Diameter (mm)	- Level of Neck Diameter (mm)	Difference of Mean Stresses	Difference Plot of Mean Stresses
18	14	0.87	
10	14	0.46	
18	10	0.41	

Table 6: Comparison of Neck Diameters with Maximum Stresses using Tukey-Kramer HSD method: Neck Diameter comparison using difference in the mean of maximum stresses.

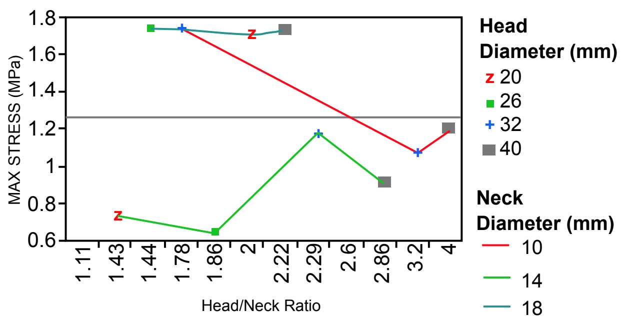

Figure 4: One-way analysis of maximum stress by H-N ratio with respect to head and neck diameters. The lowest peak stress was for hip model with H-N ratio of 1.86.

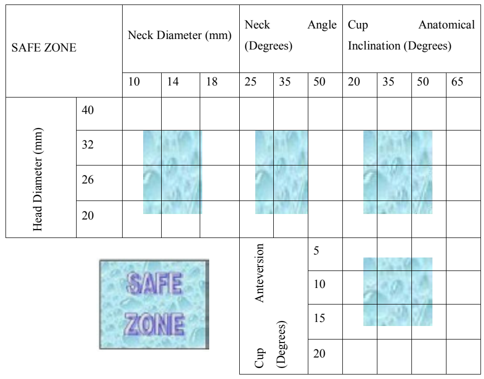

Figure 5: Safe Zones for combinations of hip design and non-design related parameters. For head diameters from 26 mm to 32 mm, neck diameters closer to 14 mm and below 18 mm, neck angles between 25 to 35°, cup anatomical inclination from 35 to 50° and cup anteversion below 20° were found within safe ranges for a stable hip implant design.

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