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Safe Zones in Hip-Implant Designs to Resist Dislocation

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RESEARCH ARTICLE

Safe zones in hip-implant designs to resist dislocation

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Abstract: Major contributing parameters to hip implant dislocation include preoperative, intra-operative and post-operative factors. Implant geometry are design as well as non-design related. Femoral and acetabular component design features causing dislocation and/or resisting it are elucidated. Twelve implants were designed during this investigation were analyzed for dislocation resistance. A safe zone, establishes combinations of implant dimensions, was analyzed for all the 12 implants where implants were dislocation resistant. Head diameters between 26 mm to 32 mm, neck diameters closer to 14 mm, and neck angle between 25 to 35º were examined to be the safest ranges for hip implant designs.

Keywords: geometrical factors, safe zone, neck diameter, neck angle, dislocation

1 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. Design related parameters are femoral head diameter, stem neck diameter, stem length, stem neck angle, and acetabular cup liner thickness. The efficiency of an implant may be increased by optimizing design related parameters. Non-design related factors include femoral component and acetabular component orientation that surgeons take in to account in surgery.

Long-term performance of a hip implant requires ability to resist dislocation. This behavior is classified in three categories: preoperative, intraoperative, and postoperative factors. Preoperative factors include patient demography including age, sex, weight and side of operation along with surgeon's experience, primary causes of dislocation and several surgical approaches. Major contributing parameters to dislocation include femoral and acetabular component deficiencies and depicted as intraoperative factors. Orientation of prosthetic component found highly significant affecting the dislocation. Postoperative factors include dislocation mechanisms, time of dislocation, and significance of revision surgery and recurrent dislocations. Dislocation mechanisms include three classified types of dislocation: anterior, superior and posterior dislocation. Time of dislocation observed as either early or late with respect to time after surgery.

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 include head diameter, neck diameter, neck angle, and cup thickness and stable range of motion, all of which determine the risk of dislocation.

2 Clinical prameters

2.1 Acetabular component

Acetabular cup circumference helps properly hold the femoral head and allows appropriate range of motion by reducing chances of dislocation [3, 6–8]. Acetabular cup liner thickness was also reported as a significant factor affecting contact stresses and wear between acetabular cup and femoral head surfaces [9, 10]. *In vitro* wear of acetabular cup liner is a multi-factorial process which is greatly affected by acetabular design factors as well as its anatomical orientation [11, 12].

Improper inclination of acetabular cup was found a common cause of dislocation due to too anteverted or too vertical placement [13]. Table 1 shows an analysis of 112 dislocations due to defects in acetabular cup orientation. Amongst all hip instability, 31% of the cases had cups too vertical and 29.5% too retroverted placed. An increase in dislocation rate occurred with the cup anteverted above 15±10º or placed vertical above 40±10º [13].

Table 1 Dislocations with acetabular component orientation, amongst all hip instability cases, cups were examined with 31% too vertical and 29.5% too retroverted placement [13].

Acetabular Cup Placement	Early Dislocations	Late Dislocations	Total	
			No.	%*
Loose	8	5	13	11.6
Too Anteverted	20	13	33	29.5
Too Retroverted	10	3	13	11.6
Too Vertical	17	18	35	31.3
Too Superior	11	6	17	15.2
Too Inferior	1	0	1	0.9
Total	67	45	112	

Note: * Numbers in % columns show percentages of total dislocation cases

An *in vitro* study [14] examined effects of prosthetic component orientation on offered RoM. With increase in acetabular and femoral anteversion, flexion and internal rotation movements found to increase; however, it restricts external rotation and adduction movements with extended hip prosthesis.

As shown in Figure 1, among all total hip dislocations, 90% of the cases evaluated with 50º or more inclination angle with horizontal axis for acetabular component [15]. Subsequently, 35% of these cases examined were with the revision dislocations. The cup inclinations showed higher rate of failure for 20 to 60º. Above 60º of cup inclination, the dislocations found were less frequently occurring than the primary dislocations. The recommended vertical inclination of cup was 40 to 40±10º and anteversion 15±10º [8].

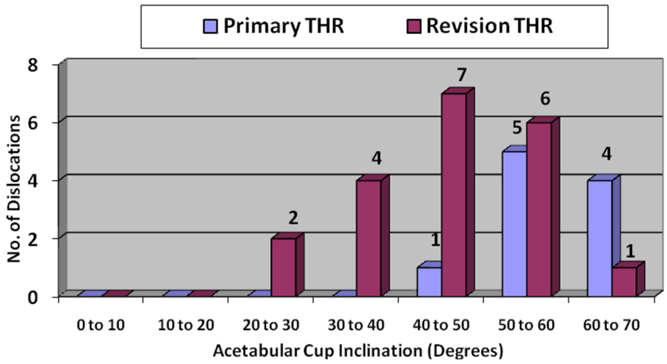

Figure 1 Acetabular Cup Inclinations in Primary and Revision THRs, amongst all total hip dislocations, 90% of the cases were evaluated with 50 degrees or more inclination angle with horizontal axis for acetabular component [13].

2.2 Femoral components

Dislocations due to defective femoral component found to be significant in THR. Major factors contributing to femoral component deficiency include femoral head size, head-neck ratio, proper stem fixation, and stem orientation [16]. Smaller head diameters found to be more significant resulting in not only dislocation but also recurrent dislocation as compared to large head diameters [16–18]. Since, larger head diameter increases allowable RoM and needs to travel large amount of distance to get dislocated, it is examined with comparatively less risk of dislocation [18–20].

Another study [21] reported the rate of instability in hip implants using several surgical approaches. Prosthetic hip implantation using anterior approach showed 2.6% instability in 22 mm head diameter compared to 1.3% and 1.2% in 28 mm and 32 mm head diameters, respectively. Using posterior approach, less difference noticed between 22 mm (68% of all dislocations) and 28 mm (60% of all dislocations). However, 32 mm femoral head had 3.5% higher stability compared to other two head diameters [21].

Femoral stem orientation proved to be a significant factor affecting dislocation rate. Table 2 describes correlation of different stem orientation with dislocation cases [13]. Hip dislocations are found more sensitive to too anteverted or too retroverted stems as compared to stem loosening or femoral shaft fractures. Too anteverted and too retroverted stem orientations were respectively 44.9% and 22.4% contributing to all recorded hip dislocations. Stem loosening with 12.2% and femoral shaft fractures with 14.3% were observed relatively less contributing to all dislocations caused by femoral component defects. An uncommon case was examined with complete femoral stem migration from the femoral shaft due to femoral component loosening [22].

Table 2 Dislocations with femoral component orientation, hip dislocations are found more sensitive to too anteverted or too retroverted stems as compared to stem loosening or femoral shaft fractures [13].

Femoral Placement	Early Dislocations	Late Dislocations	Total	
			No.	%*
Loose	5	1	6	12.2
Too Anteverted	17	5	22	44.9
Too Retroverted	10	1	11	22.4
Too much Neck removed	3	0	3	6.1
Femoral Shaft Fracture	7	0	7	14.3
Total	42	7	49	

Note: * Numbers in % columns show percentages of total dislocation cases

In order to reduce the stresses on the stem area after prosthetic hip implantation, several studies have been reported on the stress analysis of femoral stems [23, 24]. Higher stress levels at the proximal stem area may result in fatigue failure of femoral component [23]. Cyclic stress distribution and body weight plays an important role in fatigue failure of stem [23]. To reduce the risks of dislocation due to femoral stem defects, a study has been reported investigating an innovative design of cervico-trochanteric stemless prosthesis replacing the traditional stem-type prosthesis [25]. A review of unusual case studies [26–28] examined femoral heads completely disengaged from stem necks due to excessive force applied during closed reduction of dislocated femoral components.

3 Materials and methods

SolidWorks 2008 SP 2.1 was used to create the hip implant models. The design details, geometrical parameters for each of the implants are summarized in Figure 2 and Table 3. One of the implants was donated by TRIDENT™ acetabular System by Stryker Howmedica, Osteonics. ANSYS 11.0 was used to create solid models, mesh and stress analysis. All implants were analyzed using the material properties of stainless steel, SS 316L. The properties inserted were Young's modulus 209 GPa, Poisson's ratio, 0.3, and density of the material, 7800 kg/m^3. Results from the finite element analysis were used to develop safe design estimates, those combinations of parameters were entered in zone, called safe zone. The following sections perform the analysis of safe zones for all the 12 implants. The implant geometrical dimensions within these zones provide dislocation resistant implants and considered to be most safe.

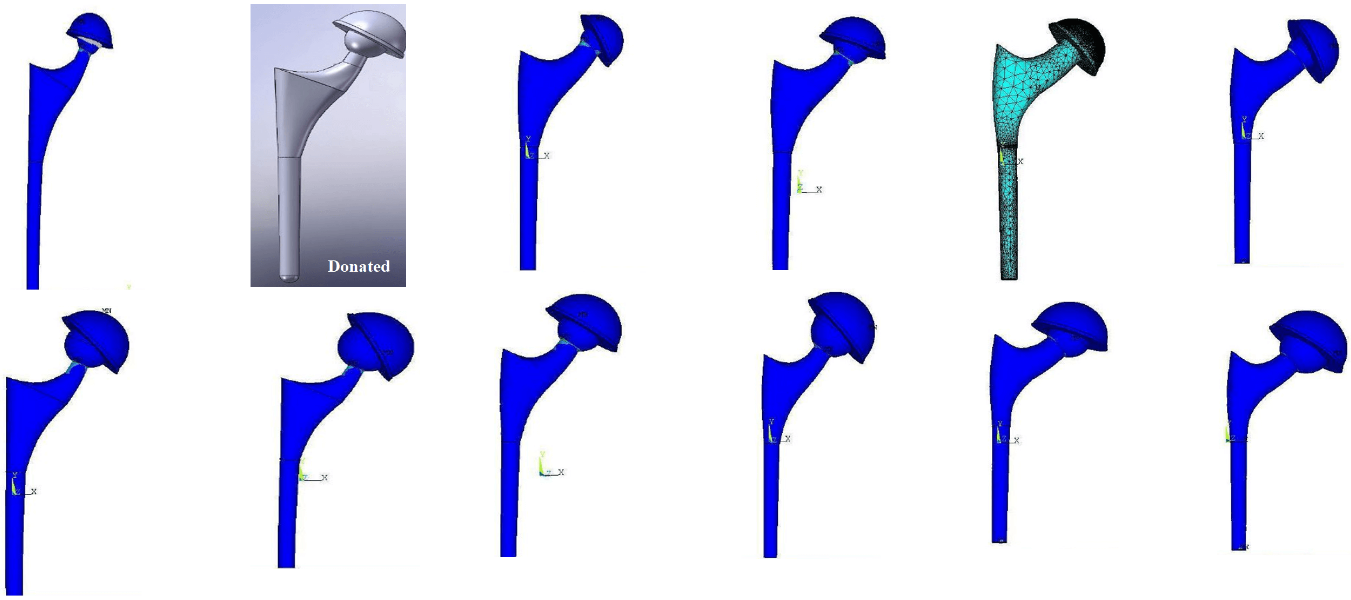

Figure 2 Hip implant designs used in the research

Table 3 Classification of Hip Models based on the selected design related as well as non-design related parameters

Models	Head Diameter (mm)	Neck Diameter (mm)	Head/Neck Ratio	Neck Angle (deg)	Cup Thickness (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

Note: The ranges for all geometrical parameters are also included.

4 Safe zones

The range of selected design and non-design related parameters that provide a hip implant maximum stability is called the *Safe Zone*. The selected parameters were analyzed statistically using the FEA results. Based on the performance of these factors, five different safe zones were determined for hip implants which included head diameter, neck diameter and neck angle as design parameters; while cup anatomical inclination and cup anteversion as non-design parameters.

Several combinations of head and neck diameters were evaluated to define a safe zone in order to reduce the risk of dislocation. Figure 3 shows safe zone for all combinations of head and neck diameters. Head diameter below 26 mm and above 32 mm was examined particularly for higher risk of hip instability. Neck diameters above 10 mm as well as below 18 mm showed lowest von Mises stress. The optimum performance was for neck diameter of 14 mm.

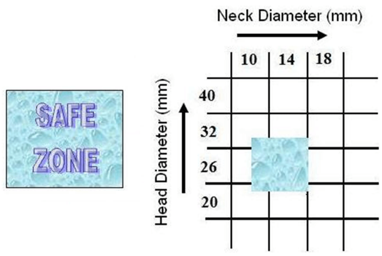

Figure 3 Safe zone for combinations of different head diameters and neck diameters, head diameter below 26 mm and above 32 mm was examined with higher risk of hip instability.

A similar safe zone was examined for combinations of head diameters and neck angles (Figure 4). The safe range for head diameters were from 26 mm to 32 mm. The range of examination for neck angle was from 25 to 50º from vertical axis. The safe zone was considered as neck angle between 25 to 35º. The best combination of both design parameters was evaluated as 26 mm of head diameter and 35º of neck angle.

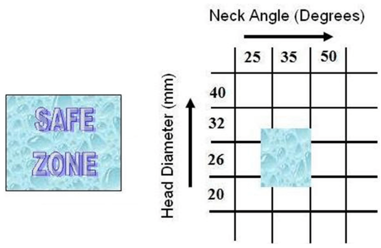

Figure 4 Safe zone for combinations of different head diameters and neck angles. Safe zone was considered as head diameters from 26 mm to 32 mm, and neck angles between 25 to 35º.

An analysis of ranges of head diameters, neck diameters and neck angles was used to define a safe area which included all three design parameter at the same time. Figure 5 shows the safe zone for all three selected parameters. Head diameters between 26 mm to 32 mm, neck diameters closer to 14 mm, and neck angle between 25 to 35º were examined to be the safest ranges for hip implant designs.

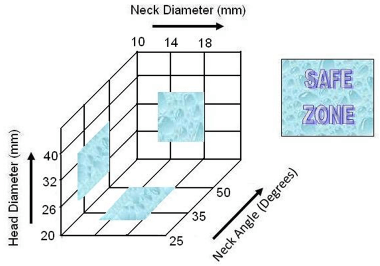

Figure 5 Safe zone for combinations of different head diameters, neck diameters and neck angles, head diameters between 26 mm to 32 mm, neck diameters between closer to 14 mm, and neck angle between 25 to 35º were examined to be safest ranges for individual performances of these parameters.

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. Figure 6 defines a safe zone for all combinations of head diameters and cup anatomical inclinations. The head diameters between 26 mm to 32 mm were defined as secured region for femoral head designs. A selected range for evaluation of cup anatomical inclination was from 20 to 65º from horizontal axis. The risk area was examined for cup inclinations below 35º as well as above 50º; while, safe zone was described as cup inclination between 35 and 50º. A study by McCollum and Gray [29] determined similar safe range of 30 to 50º for cup inclination.

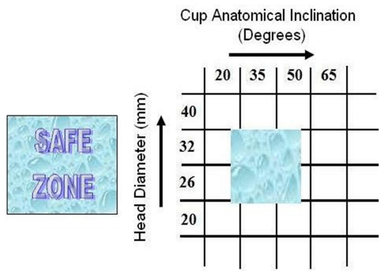

Figure 6 Safe zone for combinations of different head diameters and cup anatomical inclinations, the head diameters between 26 mm to 32 mm were defined as secured region for femoral head designs. The risk area was examined for cup inclinations below 35 as well as above 50º; while, safe zone was described as cup inclination between 35 and 50º.

A significant influence of acetabular component orientation has been attributed to the increased rate of dislocation. Too anteverted or too retroverted cup inclination is more likely to cause anterior and posterior dislocation, respectively. The safe range of cup inclination with horizontal axis was found between 35 and 50º which was similar to safe range of 40 to 45º predicted by Widmer and Zurfluh [3]. Increase in cup inclination above 50º was considered as a risk factor highly increasing the chances of dislocation. Cup anteversion was evaluated in correlation with the cup anatomical inclination in Figure 7. Cup anteversions above 15º was found highly sensitive to dislocation. The safe range of cup anteversion was examined between 5 and 15º.

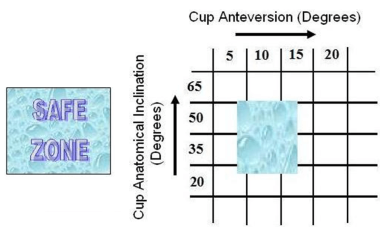

Figure 7 Safe zone for combinations of different cup anatomical inclinations and cup anteversions, cup anteversions above 15º was found highly sensitive to dislocation, the safe range of cup anteversion was examined between 5 and 15º.

Similar study by Scifert et al. [30] showed 47.6 MPa of von Mises stresses for 60º of cup inclination with 25º of cup anteversion compared to 44.25 MPa of von Mises stresses for 45º of cup inclination and 15º of cup anteversion. Figure 8 was developed to combine the safe areas observed for combinations of hip implant design and non-design related parameters used in this study.

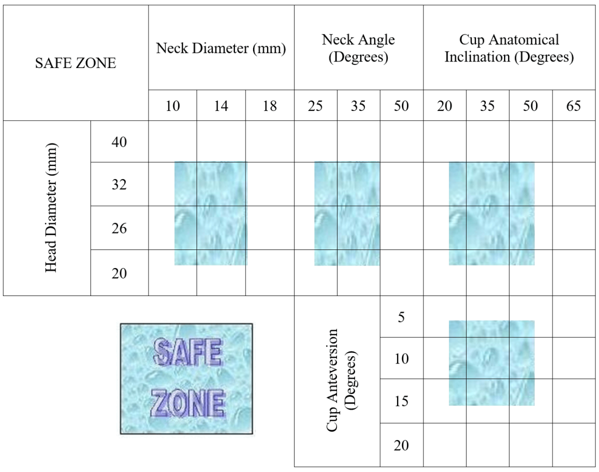

Figure 8 Safe Zones for combinations of hip design and non-design related parameters. For head diameters from 26 mm to 32 mm, neck diameters closer to 14 mm and below 18 mm, neck angles between 25 to 35º, cup anatomical inclination from 35 to 50º and cup anteversion below 20º were found within safe ranges for a stable hip implant design.

5 Discussion

Dislocations due to malposition of the implant may be one of the dominating mode by which dislocations occur. Numerous factors contribute to the etiology of the dislocation, as pointed out early in this paper it will be a difficult task to study this subject based on individual parameters and their influence in singular mode. Interacting implant parameters together with hip anatomy is rarely studied. However, literature reveals what found in this paper that safe zones involving 35-50º of inclination angle of the cup and 5-15º anteversion angle of the cup.

Significant differences in the direction of dislocation reported in the literature with an increase in activity levels, particularly when it exceeded the RoM of a prosthetic hip. Hip implants rotate beyond its ranges, thereby causes dislocation. Anterior dislocations are due to leg rotations external or too abducted, femoral component disengaging causes the superior dislocation, and when the leg is too flexed. Anterior dislocations are lower than posterior and superior dislocations. Internally rotated hip when forced to hyper flex, posterior dislocation occurs. Actions such as getting up from a low chair or bent to pick up an object from the ground are the most common activities leading to dislocations.

Impingement between neck and acetabular component can be reduced by evaluating appropriate neck length as well as neck diameter [8]. Increase in neck length provided higher RoM reducing chances of primary impingement of neck with the outer rim of acetabular cup [20]. Smaller Neck cross-section was observed with higher ranges of motion and also with reduced possibility of impingement between femoral neck and outer rim of acetabular cup [31]. Conversely, smaller neck diameters may produce higher stresses at contact area between femoral head and neck. Hip implants with higher neck diameters help provide comparatively higher contact area with femoral head reducing contact stresses; however they may limit allowable ROM. Several combinations of femoral neck and head diameters are succinctly examined in the present study.

6 Conclusions

Several combinations of geometrical parameters were evaluated to define safe zones in order to reduce the risk of dislocation. Safe zones were efficiently defined based on the performances of the design related as well as acetabular component orientation related factors.

(1) Head sizes with 26 mm or larger diameters were found within safe range when examined for contact stresses.

(2) Head diameters between 26 mm to 32 mm, neck diameters closer to 14 mm, and neck angle between 25 degrees to 35 degrees were examined to be the safest ranges for hip implant designs.

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