The influence of head and neck geometry on stability of total hip replacement

A mechanical test study

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Background Dislocation after replacement may be caused by poor implant design or positioning, or by the surgical approach taken. We evaluated the influence of head and neck design on range of motion and stability (with respect to risk of dislocation) in total hip endoprostheses.

Material and methods Using a test device, we determined the stability afforded by different head sizes and neck geometries for various implant positions.

Results Increasing head diameter led to an enhancement of range of motion as well as resistance against subluxation, and thus to improved stability in any movement combination and implant orientation. Smaller femoral heads were associated with increased risk of dislocation, especially in a poor implant position such as retroversion, and steep positioning of the cup. Skirted metal or mushroom-shaped ceramic heads had a reduced range of motion until impingement of approx. 20°, as compared to spherical standard heads. Furthermore, after identical joint loading, skirted heads dislocated more readily than standard heads with corresponding diameters.

Interpretation To obtain sufficient joint mobility and stability, neck geometry and implant position should be considered when choosing the femoral head size.

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Instability and dislocation of total hip replacement (THR) represent serious complications and, second to aseptic loosening, are the most common reasons for revision (Robbins et al. 2001, Beaule et al. 2002). Woo and Morrey (1982), Gächter (1989) and Morrey (1992) pointed out several risk factors for dislocation (Table 1). Some implant designs easily cause prosthetic impingement and the risk of such can be accentuated by malpositioning. Poor implant positioning is responsible for about one-third of all dislocations (Morrey 1992, Lavernia et al. 1998). Technical failure in the surgical approach is a significant factor for the risk of dislocation (Kohn et al. 1997).

The correlation between stability (regarding ease of dislocation) of THR and head diameter is controversial (Sanchez-Sotelo and Berry 2001). The original Charnley concept had small heads with a diameter of 22 mm (Charnley and Cupic 1973). However, different trends including 26 mm, 28 mm and 32 mm heads have been seen during the past three decades (Kelley et al. 1998). Callaghan et al. (2001) found an increased risk of dislocation associated with 22-mm modular heads (13%) as compared to 28-mm heads (6%) in primary total hip replacements between 1970 and 1996.

To evaluate the causal factors of THR dislocation, the kinetic parameters must be considered. In this experimental study we investigated the influence of femoral head and neck design on range of motion, resisting moment and stability of THR.

Table 1. Selected risk factors for instability of total hip replacement (Woo and Morrey 1982, Gächter 1989, Morrey 1992)

Related to impingement	Independent of impingement
Implant design head size, head-neck ratio, neck length Implant position Bony and soft-tissue impingement osteophytes, poor femoral offset Interposition of bone cement	Soft-tissue tension poor offset and position of hip centre, insufficient tissue balance, avulsion of abductor muscles and trochanter Surgical approach Neurological disorders

Material and methods

We used a test device (Bader et al. 2004) (Figure 1) to determine the stability and occurrence of dislocation in different head and neck designs. Both the range of motion until impingement and the range of motion until dislocation were measured. In addition, the torque (resisting moment) in subluxation against levering the femoral head out of the cup was recorded. Movements associated with dislocation (Kummer et al. 1999) were carried out under dry environmental conditions and at room temperature.

We examined standard total hip implants. The acetabular cup (CL socket, outside diameter 56 mm; ESKA Implants, Lübeck, Germany) had a modular construction. The cup was embedded into the acetabular implant fixture by epoxy resin. The opening plane of the cup was flush and centrically aligned towards the acetabular implant fixture. By a formfitted link with the implant fixture, a reproducible positioning of the embedded cup in a lateral inclination (abduction) angle of 30°, 45° and 60° as well as angles of 0° up to ± 30° for retroversion and anteversion of the cup could be achieved. The centre of rotation of the fixture was aligned to the opening plane of the acetabular cup. We tested liners made of polyethylene with inside diameters of 22 mm, 28 mm, 32 mm or 36 mm. All liners (inserts) had a slightly advanced rim, resulting in a shift of the centre of rotation of the articulating femoral head towards the dome of the cup. The internal edge of the liners was rounded off slightly (radius approx. 0.5 mm).

Spherical metal heads with 22-mm, 28-mm, 32-mm and 36-mm diameters, which articulated with the corresponding liners, were fixed onto a cemented stem (C-Hüftstiel simplex, ESKA Implants). The stem exhibited a collar as well as a taper 12–14 on a cylindrical neck with 14 mm diameter. The stem was also embedded in epoxy resin into a special fixture, which permitted variation of the torsion angle (retro- or antetorsion). For variation of the femoral neck design, we used a skirted head (so-called XL head) with 28-mm head diameter and 19.1-mm neck diameter, and also a mushroom-shaped ceramic head of 32 mm diameter.

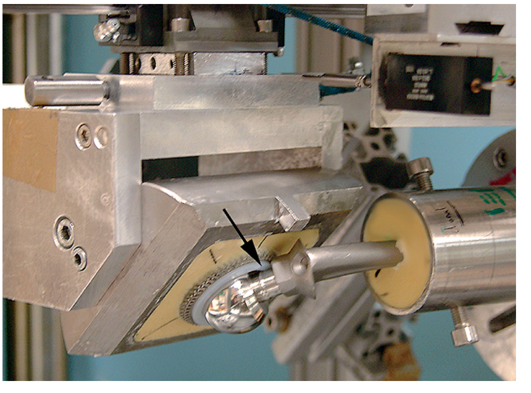

Figure 1. Detailed view of the test device in configuration for examination of internal and external rotation movements combined with 90° flexion and 0° adduction. Modular acetabular cup with polyethylene insert in articulation with 36-mm metal head. Prosthetic impingement (arrow) at the cranial-ventral edge of the cup and subluxation in the internal rotation movement.

The data recorded were evaluated statistically by an analysis of variance with several factors using the software package SPSS, version 11.5 (SPSS Inc., Chicago, USA). The LSD (least significance difference) test was used as a post-hoc test. All tests were two-sided. The degree of significance was assessed at 5%.

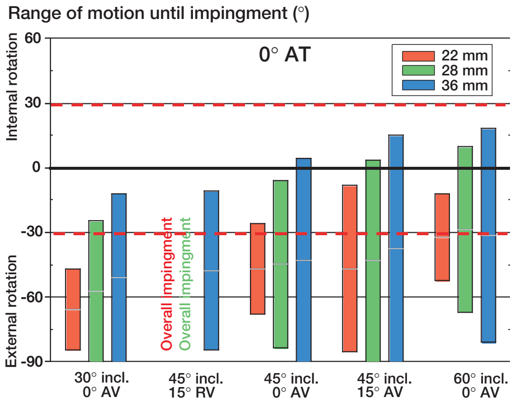

Figure 2. Overall range of motion until impingement (ROM_{Imp}) for the internal and external rotation movement in combination with 90° flexion and 0° adduction, using different femoral head diameters (22 mm, 28 mm and 36 mm). Implant position: cup inclination 30°, 60° and 45° with cup version (15° retroversion (RV), 0°, 15° and 30° anteversion (AV)), antetorsion of the femoral stem always 0°. The columns show the impingement-free interval in the internal and external rotation movements for the femoral stem (up to ± 90°). The dashed lines show the physiological range of motion for the above-mentioned movements (according to Genoud et al. 2000).

Results

Head design

In all movement combinations examined, larger heads showed a clear increase in the range of motion until impingement (ROM_{Imp}) ($p < 0.001$) (Figure 2). In the case of a flat-positioned acetabular cup (30° inclination) without anteversion and/or without antetorsion of the stem, no sufficient range of motion until impingement could be realized in the movement internal rotation at leg position 90° flexion and 0° adduction for all head sizes tested (Figure 2). By increasing the cup inclination angle (45° or 60°), larger ROM_{Imp} values for internal rotation were recorded (Figure 2). However, in a generally agreed "optimal cup position", i.e. 45° inclination and 15° anteversion, the entire physiological range of motion could not be achieved without antetorsion of the stem.

The cup version substantially affects the ROM until impingement and the ROM until dislocation. For example, with a steep-positioned and retroverted cup (60° inclination and 15° retroversion) no stable situation in 90° flexion and 0° adduction could be achieved using the 22-mm head. At a cup inclination angle of 45°, an impingement-free interval could not be obtained with the 22-mm and 28-mm heads, whereas the 36-mm head permitted a limited movement interval without impingement in external rotation at the above-mentioned implant position. By increasing cup anteversion, the ROM_{Imp} values for internal and external rotation were clearly raised, with small head diameters gaining the most (Figure 2).

Table 2. Range of motion until dislocation (ROM_{Lux}) for internal rotation movements in combination with 90° flexion and 0° adduction, using different femoral head diameters. Implant position: inclination and anteversion angles of the acetabular cup (45° inclination, 0°, 15° and 30° anteversion (AV) and 15° retroversion (RV)), antetorsion of the femoral stem with taper 12/14 always 0°. Values are mean (SD)

Cup version	22 mm	28 mm	36 mm
15° RV	–2° (1.2°)	21° (0.8°)	22° (3.5°)
0° AV	25° (1.2°)	43° (0.1°)	40° (0.2°)
15° AV	45° (0.2°)	54° (0.9°)	53° (0.3°)
30° AV	52° (0.7°)	… [a]	66° (0.3°)

mean: mean value (n = 3), SD standard deviation
[a] no typical dislocation

The maximum range of motion until dislocation (ROM_{Lux}) for internal rotation combined with 90° flexion and 0° adduction was less with the 22-mm head than with the 28-mm, 32-mm or 36-mm heads ($p < 0.001$). Moreover, differences in the ROM_{Lux} between the 28-mm, 32-mm and 36-mm heads were influenced by the cup position (Tables 2 and 3). By forward rotation of the cup (anteversion), dislocation in the posterior direction was delayed. Retroversion resulted in partly unstable conditions and early dislocation, respectively (Tables 2 and 3). In poor implant position, i.e. retroversion of the cup or retrotorsion of the stem, the 36-mm head led to higher ROM_{Lux} values compared to the 28-mm head ($p = 0.003$). Earlier posterior dislocation occurred with all head diameters in the case of a flat-positioned cup (30° inclination) compared to 45° inclination, each with a cup anteversion angle of 0° ($p < 0.001$). However, steeper cup position (60° inclination) led to earlier dislocation in the above-mentioned movement using the 22-mm head ($p = 0.023$) (Table 3).

An increase in the maximum resisting moment (RM_{Sublux}) was recorded for internal and external

Table 3. Maximum resisting moment in subluxation (RM_{Sublux}) and range of motion until dislocation (ROM_{Lux}) for internal rotation movements in combination with 90° flexion and 0° adduction, using different femoral head diameters (22-mm, 28-mm, 32-mm and 36-mm spherical head with taper 12/14) and neck geometries (28-mm skirted (XL) head and 32-mm mushroom-shaped (m-s) ceramic head). Implant position: inclination and anteversion angles of the acetabular cup (60° inclination, 0° and 30° anteversion (AV) and 15° retroversion (RV)), antetorsion of the femoral stem always 0°

Head-neck design		15° RV mean (SD)	0° AV mean (SD)	30° AV mean (SD)
22 mm 12/14	RM_{Sublux}	unstable	0.9 (0.04) Nm	2.8 (0.2) Nm
	ROM_{Lux}	unstable	22° (1.2)	67° (0.9)
28 mm 12/14	RM_{Sublux}	0.5 (0.1) Nm	1.6 (0.1) Nm	3.7 (0.1) Nm
	ROM_{Lux}	12° (0.6)	47° (0.5)	78° (1.7)
28 mm XL	RM_{Sublux}	unstable	0.8 (0.1) Nm	3.6 (0.1) Nm
	ROM_{Lux}	unstable	26° (0.8)	73° (0,6)
32 mm 12/14	RM_{Sublux}	0.7 (0.1) Nm	1.8 (0.1) Nm	4.6 (0.1) Nm
	ROM_{Lux}	15° (0.7)	44° (0.8)	75° (0.8)
32 mm m-s	RM_{Sublux}	unstable	0.2 (0.02) Nm	3.3 (0.1) Nm
	ROM_{Lux}	unstable	14° (0.2)	66° (0.5)
36 mm 12/14	RM_{Sublux}	0.9 (0.1) Nm	2.3 (0.1) Nm	6.7 (0.1) Nm
	ROM_{Lux}	17° (0.8)	48° (0.2)	82° (0.6)

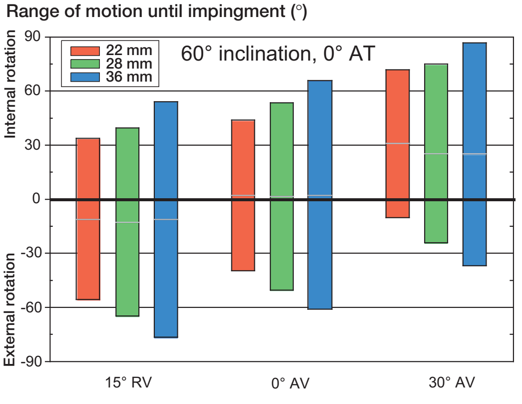

Figure 3. Overall range of motion until impingement (ROM_{Imp}) for the internal and external rotation movement in combination with 10° extension and 15° adduction using different femoral head diameters (22 mm, 28 mm or 36 mm). Implant position: cup version (15° retroversion (RV), 0° and 30° anteversion (AV)), cup inclination always 60°, antetorsion of the femoral stem always 0°. The columns show the impingement-free interval in the internal and external rotation movements for the femoral stem (up to ± 90°).

rotation movements using larger head diameters ($p < 0.001$) (Table 3). In general, we found higher values for resisting moment in cases where there was low inclination angle of the cup.

In the external and internal rotation movements combined with 10° extension and 15° adduction leg position, a steep-positioned cup (60° inclination) in combination with pronounced anteversion of 30° or stem antetorsion caused a distinct restriction of the ROM_{Imp} for external rotation (Figure 3). Dislocation in the anterior direction can occur after posterior impingement. In the above-mentioned leg position, anterior dislocation was favored by the reduced torque due to pronounced cup anteversion.

Neck geometry

Modifications of the neck geometry affected the range of motion of THR substantially. Thus, the use of a skirted head (XL head) or a mushroom-shaped ceramic head led to a clear reduction of the ROM until impingement (ROM_{Imp}) for internal and external rotation ($p < 0.001$), in comparison to the spherical standard head with identical head diameter of 28 mm and 32 mm, respectively (Figure 4). For example, in the neutral position of the leg, i.e. 0° flexion/extension and 0° abduction/adduction, or in the 10° extension and 15° adduction position, the ROM_{Imp} was reduced on average by up to 20° for the single rotational movements using skirted heads.

At internal rotation in 90° flexion and 0° adduction, contact of the prosthetic neck with the edge of the cup appeared over the entire measured range of movement for nearly all implant positions using

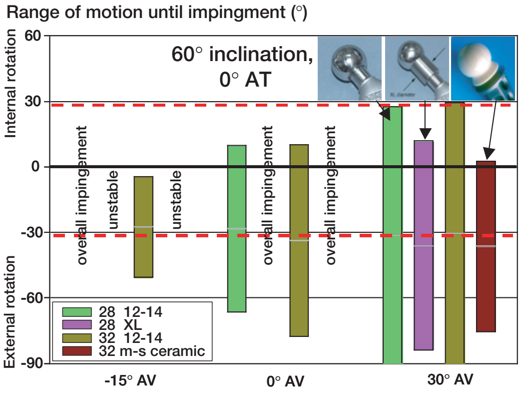

Figure 4. Overall range of motion until impingement (ROM_{Imp}) for the internal and external rotation movement in combination with 90° flexion and 0° adduction using different femoral head diameters (28-mm and 32-mm spherical head with taper 12/14) and neck geometries (28-mm skirted (XL) head and 32-mm mushroom-shaped (m-s) ceramic head). Implant position: cup version (15° retroversion (RV), 0° and 30° anteversion (AV)), cup inclination always 60°, antetorsion of the femoral stem always 0°. The columns show the impingement-free interval in the internal and external rotation movements for the femoral stem (up to ± 90°). The dashed lines show the physiological range of motion for the above-mentioned movements (according to Genoud et al. 2000).

the skirted metal head and the mushroom-shaped ceramic head, in contrast to the corresponding standard heads (Figure 4). Furthermore, with a steep-positioned and retroverted cup, no stable articulation could be achieved with the skirted metal head and the mushroom-shaped ceramic head (Figure 4). Under identical joint loading, lower resisting moments were recorded for these heads than for the spherical standard heads ($p < 0.001$) (Table 3).

In addition, the range of motion until dislocation (ROM_{Lux}) was lower for the 28-mm XL head and the 32-mm mushroom-shaped ceramic head than for the 28-mm and 32-mm standard head, respectively ($p = 0.02$). For example, differences in the ROM_{Lux} of more than 20° were observed in the case of 60° inclination and 0° anteversion of the cup and 0° antetorsion of the stem (Table 3).

Discussion

Head diameter and neck geometry are important for postoperative mobility and the risk of dislocation after THR (McCollum and Gray 1990, Scifert et al. 1998, Bartz et al. 2000, Bader et al. 2002, Burroughs et al. 2002, Byström et al. 2003). In several studies, the ROM until impingement was calculated from known implant geometries and orientations (Lavernia et al. 1998, Kummer et al. 1999, Bader et. al. 2002). According to Lavernia et al. (1998), the implant position has substantial influence on the risk of dislocation. Lewinnek et al. (1978) described a safe zone for the cup position, with an inclination of 40° ± 10° and anteversion of 15° ± 10°.

In the present study, we have demonstrated that an increased head diameter leads to an increase in the range of motion until impingement (ROM_{Imp}), as well as in the range of motion until dislocation (ROM_{Lux}) and the resisting moment in subluxation. Using a 22-mm spherical head, early posterior dislocation or complete instability of the artificial joint may occur if the implant is unfavorably positioned (e.g. 60° inclination and 15° retroversion). Even with an optimal implant position, the 22-mm head provides less than the physiological ROM, which can lead to an increased risk of impingement and dislocation. In the tests, dislocation occurred clearly later using the 28-mm and 36-mm heads, independently of the adjusted inclination and anteversion angle. This is similar to the results of a clinical study showing a lower dislocation rate with 28-mm heads than with 22-mm heads (Kelley et al. 1998).

With adequate implant positions, we found no differences between the 28-mm, 32-mm and 36-mm femoral heads in the range of motion until dislocation occurred. However, the 36-mm head led to an increased stability in the case of less optimal cup orientation, i.e. steep and retroverted position. Using the 22-mm head, the contact of the femoral neck with the rim of the cup (prosthetic impingement) is responsible for dislocation. With larger heads, a different mechanism of dislocation can be observed. Support of the stem collar by the embedding material of the acetabular cup leads to leverage of the femoral head. This corresponds to the so-called bone-to-bone impingement, i.e. contact of the trochanter at the peri-acetabular pelvic bone. This mode of impingement may occur during extreme movement excursions before prosthetic impingement (Bartz et al. 2000).

In an experimental study on human specimens, Bartz et al. (2000) found no significant differences in the range of motion between femoral heads of 32 mm and of 28 mm diameter, since in the case of the 32-mm head, the hip mobility was limited by a bony impingement. However, in that investigation the cup position was optimal, i.e. 45° inclination and 20° anteversion (Bartz et al. 2000). In our study, larger femoral heads, e.g. 32-mm and 36-mm heads as compared to the 28-mm head, can even increase the ROM_{Lux} in the case of a poor implant position such as retroversion of the cup and/or retrotorsion of the stem. In agreement with our results, Scifert et al. (1998) calculated increased ROM_{Lux} and resisting moments with larger head diameter in a finite element analysis.

Recently introduced implant combinations of large metal heads (36-mm or 40-mm) in combination with cross-linked polyethylene liners potentially result in higher stability regarding dislocation, with reasonable wear (Muratoglu et al. 2001, Robbins et al. 2001, Burroughs et al. 2002). Beaule et al. (2002) reported good clinical outcome with the so-called “jumbo femoral heads” (head diameter between 40 mm and 50 mm). After an average follow-up of 7 years, no further post-operative dislocation occurred in 10 of 11 patients who had been revised due to recurrent total hip dislocation. According to Harris (2001), larger head diameters such as 38 mm or 48 mm, apart from significantly increasing the range of motion, also provide the benefit of simple balancing of the femoral offset. Therefore, correction of the offset can be performed intraoperatively without movement-restricting skirted heads (Harris 2001).

To avoid early impingement, it seems that the ratio between femoral head and neck diameter should be greater than 2:1 (Bader et al. 2002). If small head diameters are necessary for technical reasons in surgery, such as a small acetabulum, these should be combined with a stem having a reduced taper and neck diameter. Moreover, considering the variation and inaccuracy of cup positioning intraoperatively, a more precise implant positioning is required. In a clinical study, after a total of 50 total hip replacements Hassan et al. (1998) observed that 21 cups were outside of the safe zone defined by Lewinnek et al. (1978). Skirted heads, which clearly reduce the maximum range of motion and may therefore increase the risk of dislocation, should only be used in exceptional cases. The use of mushroom-shaped ceramic heads should generally be discontinued, since in addition to the restriction of the range of motion, there is a risk of implant breakage.

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No competing interests declared.

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