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BIOMECHANICS

Short stems have lower load at failure than double-wedged stems in a cadaveric cementless fracture model

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Objectives

Periprosthetic femoral fractures (PFFs) have a higher incidence with cementless stems. The highest incidence among various cementless stem types was observed with double-wedged stems. Short stems have been introduced as a bone-preserving alternative with a higher incidence of PFF in some studies. The purpose of this study was a direct load-to-failure comparison of a double-wedged cementless stem and a short cementless stem in a cadaveric fracture model.

Methods

Eight hips from four human cadaveric specimens (age mean 76 years (60 to 89)) and eight fourth-generation composite femurs were used. None of the cadaveric specimens had compromised quality (mean T value 0.4 (-1.0 to 5.7)). Each specimen from a pair randomly received either a double-wedged stem or a short stem. A materials testing machine was used for lateral load-to-failure test of up to a maximal load of 5000 N.

Results

Mean load at failure of the double-wedged stem was 2540 N (1845 to 2995) and 1867 N (1135 to 2345) for the short stem ($p < 0.001$). All specimens showed the same fracture pattern, consistent with a Vancouver B2 fracture. The double-wedged stem was able to sustain a higher load than its short-stemmed counterpart in all cases. Failure force was not correlated to the bone mineral density ($p = 0.718$).

Conclusion

Short stems have a significantly lower primary load at failure compared with double-wedged stems in both cadaveric and composite specimens. Surgeons should consider this biomechanical property when deciding on the use of short femoral stem.

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Article focus

- The aim of this study was to determine the load-to-failure force of two types of cementless stems.

Key messages

- Short stems have a significantly lower load at failure than standard stems.
- This study provides the surgeon with information on stem properties, especially in the early phase.

Strengths and limitations

- This is the first ever direct comparison of these types of stems.
- This can be applied only in the early operative phase, prior to bone ingrowth.

Introduction

Periprosthetic femoral fractures (PFFs) have tremendous adverse effects on patients after total hip arthroplasty (THA). It is a grave complication that in most cases requires complex revision surgery.[1]

A recent literature review has shown that cementless stems have a higher incidence of PFF.[2] The predisposing factors for an intraoperative PFF include osteoporosis, rheumatoid arthritis, surgical technique, and press-fit components. More importantly, cementless

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stems remain a risk for PFF in the postoperative phase. Other factors in the postoperative phase include female sex, with the risk as high as double compared with men,[3] and post-traumatic and rheumatoid osteoarthritis.[4]

In the clinical setting, using the classification system described by Khanuja et al,[5] the stems with the highest incidence of PFFs are the single-wedge/type 1 and a double-wedge/type 2 cementless stem with type 2 stems at a somewhat higher risk.[2] These stems are also the most commonly used.[2] Type 3 stems are tapered in a round, rectangular, or conical form. Type 4 are cylindrical stems[6] and type 5 are modular stems,[2] more commonly used for revisions.[7] Anatomical or type 6 stems have been introduced as bone-preserving alternatives to other stem types with proximal metaphyseal fixation and the distal curve.[8] These stems have been found to be both very safe when used in patients with good proximal femoral bone,[9] but also to have a relatively higher incidence of PFFs when newly introduced.[10]

In the biomechanical setting, these stems have been reported to have low micromotion, comparable to type 2 stems.[11-13] Shortening the stem improves the proximal load at the expense of bone stress.[14,15] One biomechanical study reported anatomical stems having a similar load-to-failure force to those of type 2 stems.[16] This study concludes that short-stemmed prostheses do not constitute a higher fracture risk, although the forces observed were different. The biomechanical results are not consistent with the clinical findings for these two stems, especially considering that undersizing has been shown to increase micromotions.[17] Since one-third of all postoperative falls occur in the first year postoperatively,[18] identifying the primary stability for different stem types is very important. It is also crucial to undertake all possible steps in reduction of PFF rate, as it is better to prevent them than to cure them.[19]

The purpose of this study was to evaluate the direct load-to-failure force of type 2 and type 6 stem in a biomechanical setting. It was hypothesized that type 2 stems would be able to sustain higher loads.

Materials and Methods

Study design and specimen preparation. The study was approved by the ethics boards of the authors' institutions (163/17, 2 November 2017) prior to commencement. Before commencement, a trial run with fourth-generation composite femurs (Sawbones; Pacific Research Laboratories, Inc., Vashon, Washington) was performed for the power analysis to determine the number of cadaveric femur pairs necessary to find a statistical difference. With an alpha value of 0.05 and a power value of 0.8, the number of cadaveric pairs was four.

The femurs were donated by the authors' institute for anatomy. All donors provided written consent by their own freewill for the use of their body for research purposes. The specimens originated from four male adults with a mean age of 78 years (68 to 89).

The paired femurs were obtained from human cadavers and embalmed with a solution consisting of 96% ethanol and 2% formaldehyde. During perfusion, approximately 15 l of the solution was passed through the femoral artery. The human cadavers were stored for at least one year before use. All specimens were thawed at room temperature before testing.

To exclude damage related to pre-existing fractures or osteolyses, all specimens were examined for integrity via a clinical examination and a radiological examination using a C-arm unit. The surrounding soft tissue was stripped from the specimens. Bones were then wrapped in moist towels using the aforementioned embalming solution and stored in a cooling chamber at 4°C to avoid drying artefacts.

Additionally, four pairs of fourth-generation composite femurs, two pairs of model 3403 and two pairs of model 3406 (Sawbones), were used for the testing.

Femoral stems. The implants compared in this study were the cementless type 2 Polarstem (Smith & Nephew, Baar, Switzerland) and cementless type 6 Nanos stem (Smith & Nephew). Polarstem is a double-tapered femoral stem with 180 µm of titanium (Ti)-plasma spray combined with 50 µm of hydroxyapatite coating with fixation occurring on the calcar and metaphysis. The cementless version is a Ti alloy (Ti-6Al-4V ISO 5832-3) and comes in 12 sizes for the standard offset and 10 sizes for the lateral offset. In this study, standard 135° angle was used. The Nanos stem is a Ti alloy (Ti-6Al-4V ISO 5832-3) coated with calcium phosphate on approximately 75% of its surface and is manufactured in ten sizes. It is wedged in the sagittal and coronal plane with a curved distal end, providing a cortical multipoint contact and loading on both the calcar region and proximal lateral cortex.[20]

The implantation was performed according to the manufacturer's operating manual and using the original instruments. The same technique was used for cadaveric and for composite specimens, with the femoral stems placed in 20° of anteversion with a goal of combined anteversion to within the safe zone.[21] The trials were implanted until press-fit was secured and controlled radiologically. The final implant was again radiologically controlled for the correct position, as well as exclusion of a periprosthetic fracture occurring during implantation. A polyethylene component with an inner diameter of 32 mm was used as the acetabulum (Reflection; Smith & Nephew). It was fixed with cement and screws in 45° inclination and 10° of anteversion. A 32 mm ceramic head was implanted on the femoral component. The distal femoral fixation was placed at 400 mm distal from the resection using a screw clamp to prevent axial rotation of the specimen. Proximally, a joint was created by inserting the ceramic head into the created acetabulum. As the

Fig. 1

Photograph showing the biomechanical setting for producing a periprosthetic femoral fracture.

final result, the femoral mechanical axis was set parallel to the ground.

Bone mineral density assessment. Peripheral quantitative CT (pQCT) measurements were used to record bone mineral density (BMD) of the cadaveric specimens. For the pQCT measurements, a Stratec XCT Research SA instrument was used (Stratec Medizintechnik GmbH, Pforzheim, Germany). Measurements of BMD were performed at the femoral neck region.

Load-to-failure assessment. Each specimen was tested with load to failure on an Instron 5566 universal testing machine (Instron, Darmstadt, Germany), shown in Figure 1, by using a protocol from a previous study.[22] A 30 mm diameter cylinder was attached to the testing machined and used to apply force axially. The test sequence started at 5 N force with the cylinder positioned directly over the greater trochanter. The load was continuously raised at a velocity of 3 N per second. Criteria for discontinuation of testing was a premature rotation of the femur (fixation failure) or occurrence of a fracture (final result). The data were collected at 100 ms intervals using the instrument-specific Bluehill Software (Instron) and the loading cycles were not interrupted, as it has been shown that prolonged cycling may compromise bone quality further.[23] Load at failure (N) and time (seconds) were recorded.

Statistical analysis. The difference in force between implants was statistically analyzed using the paired Student's *t*-test, and the correlation of force and BMD was analyzed using the Pearson's correlation. Statistical significance was set at $p < 0.05$.

Table I. Results for cadaveric specimens

Pair number	Stem*	Implant size	Bone mineral density, mg/cm²	Load at failure, N
1	Polarstem	5	778.5	1845
	Nanos	6	681.9	1334
2	Polarstem	3	937.6	2302
	Nanos	3	859.1	1479
3	Polarstem	1	777.0	1851
	Nanos	1	1648	1135
4	Polarstem	4	1109.2	2788
	Nanos	4	652.0	1845

*All produced by Smith & Nephew, Baar, Switzerland

Table II. Results for composite specimens

Pair number	Stem*	Implant size	Density, PCF	Load at failure, N
1	Polarstem	1	17	2858
	Nanos	1	17	2267
2	Polarstem	1	17	2790
	Nanos	1	17	2181
3	Polarstem	3	17	2995
	Nanos	3	17	2344
4	Polarstem	3	17	2888
	Nanos	3	17	2345

*All produced by Smith & Nephew, Baar, Switzerland
PCF, pounds per cubic foot

Results

Implants used as well as individual forces are reported in Tables I and II. Figures 2 and 3 depict a radiograph of a preloaded and a fractured Polarstem and Nanos, respectively.

Bone mineral density. Mean bone mineral density of the tested femurs was 930.4 mg/cm² (SD 324.7; 652 to 1109.2). None of the specimens were of compromised bone quality compared with the corresponding reference value (T value range -1.1 to 5.7).

Load at failure. A fracture was produced consistently in all specimens. Mean load at failure of the type 2 stem in a cadaveric specimen was 2196.5 N (SD 448.7; 1845 to 2788). Mean load at failure of the type 6 stem in a cadaveric specimen was 1448.2 N (SD 299.7; 1135 to 1845). Composite specimens showed a higher mean load at failure than cadaveric specimens, 2882 N for type 2 stem (2790 to 2995) and 2284 N (2181 to 2345) for type 6 stem. All specimens suffered a fracture of the medial wall on the level of the prosthesis, extending distal of the prosthesis, corresponding to a Vancouver B2 type fracture. The tapered stem was able to sustain a higher load than its short-stemmed counterpart in all eight pairs. The Type 2 stem had a significantly higher load-at-failure force in cadaveric specimens ($p = 0.002$), in composite specimens ($p < 0.001$) and overall ($p < 0.001$). For cadaveric specimens, BMD did not correlate to load-at-failure force ($p = 0.718$).

Discussion

This study demonstrated the increased load at failure of a type 2 tapered stem compared with a type 6 short stem in a biomechanical setting.

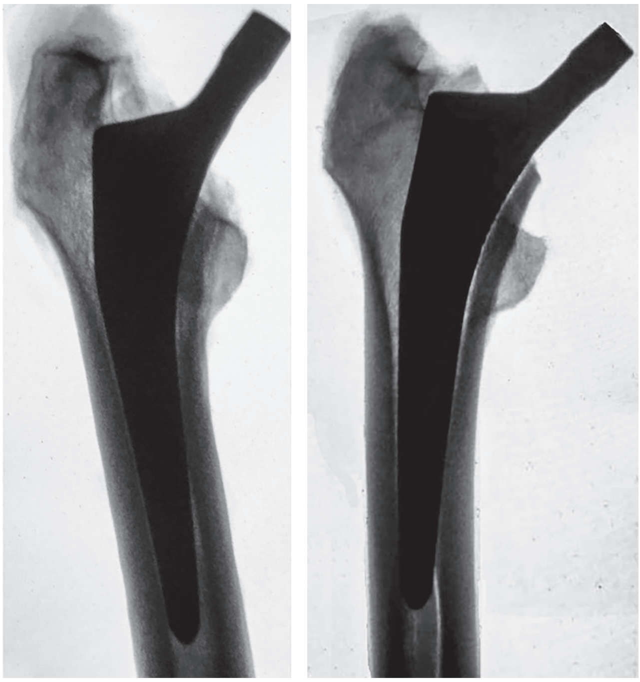

Fig. 2a Fig. 2b

a) Anteroposterior view of a specimen with an implanted type 2 stem; b) anteroposterior view of a fractured specimen with an implanted type 2 stem.

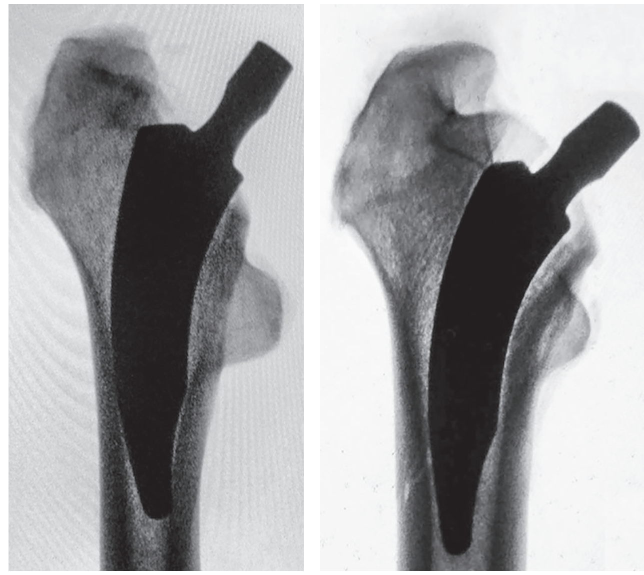

Fig. 3a Fig. 3b

a) Anteroposterior view of a specimen with an implanted type 6 stem; b) anteroposterior view of a fractured specimen with an implanted type 6 stem.

The only other biomechanical study in the literature that we could identify that compares these two types of stems is the study by Jakubowitz et al.[16] The researchers found higher maximum forces in the type 6 Mayo stem (Zimmer Biomet, Warsaw, Indiana) in 30% of cases compared with the type 2 CLS stem (Zimmer Biomet).[16] However, the mean force was higher in the type 2 stem. The increased plasma-sprayed coating area of a stem has been shown to increase the load-bearing capacity,[24] which could contribute to the different findings between this study and the one by Jakubowitz et al,[16] since both the area and the thickness of the coating are different between the CLS and Polarstem. Studies that have labelled a stem simply as 'short', which would include some type I stems,[5] have suggested similar biomechanical properties in terms of micromotion.[11,25] As noted by Carli et al,[2] it is important to state not only the implant used in the study, but also the classification used, since short stems also have a classification system.[26] Short stems have various performance results in biomechanical studies,[27] with data suggesting that more research is needed.[26] Cement mantle thickness also plays a crucial role. Takahashi et al[28] have demonstrated that a thicker cement mantle results in greater stem and cement subsidence even in biomechanical settings, as have Numata et al.[29] In our study, the cement mantle created was as per manufactured broach size.

In clinical settings, the type 2 stem shows a decreased fracture risk compared with the type 6 stem consistently in a number of studies.[9,10,30,31] Thien et al[30] reported a hazard ratio for a PFF within two years after surgery for the type 6 ABG I and II stem (Stryker Orthopaedics, Mahwah, New Jersey) at 1.61, the highest in the cohort, compared with 0.47 for the type 2 Corail (DePuy Synthes, Raynham, Massachusetts) stem. The incidence of PFF was 0.59% for the type 6 stem and 0.28% for the type 2 stem. van der Wal et al[31] reported an incidence of PFF with a type 6 ABG stem at 2.2%. Van Eynde et al[10] reported an incidence of PFF at 2.89 for a type 2 Profile Stem (DePuy Synthes) *versus* 9.35% for a type 6 Image stem (Smith & Nephew, London and Hull, United Kingdom). Finally, Taunton et al[9] compared a type 6 APR stem (Zimmer Biomet) with three different type 2 stems: ProxiLock HA (Zimmer Biomet), Summit (DePuy Synthes), and Secur-Fit HA (Stryker). The type 6 stem had a PFF incidence of 0.29% *versus* 1.66% for ProxiLock HA, but also 0.24% for Summit and 0.16% for Secur-Fit HA. The authors provided no explanation for a comparatively higher PFF incidence of the ProxiLock stem. A study[32] comparing a standard type 2 version and its shortened type 2 counterpart (Taperloc and Taperloc Microplasty) found no difference in fixation after two years. There were no PFFs reported, and fixation was defined as stem subsidence. Another study comparing the same two stems[33] for PFFs found that the shorter version had a higher incidence of PFFs. Interestingly, a study on 216 type 6 stems Optmys (Mathys, Bettlach, Switzerland) found no periprosthetic fractures regardless of the postoperative caput-collum-diaphysis angle.[34] A study comparing Metha Stems (Braun Aesculap, Tuttlingen, Germany) found an overall PFF rate at 0.4% at ten-year follow-up with a 0.9%

implant failure rate.[35] The data on modular stems is even less consistent and can be misleading.[36] A similar approach to interpreting various studies is also advised.

The lower load at failure shown in this study and the higher incidence of PFF in clinical studies suggest that the increased stability remains after the bone ingrowth phase. An explanation of this is increased stress shielding of shorter stems and subsequent loss of BMD in that area.[15]

Although this study has clinical implications for short stems after the bone ingrowth phase, the lack of it in this biomechanical study will always be a limitation.[2] These results are still significant, however, as the immediate postoperative phase remains a clinically relevant period, with registry data showing a PFF rate of 2.1% at fewer than or equal to 90 days postoperatively.[37] The short stem used in this study does not have a curvature in the frontal plane; however, due to its short design and neck-sparing resection properties, it was classified as a type 6 stem. This study also does not fully account for soft-tissue contributions due to the stripping of soft tissue and, therefore, it cannot precisely determine the biomechanical effect of the implant in a patient, where soft tissue is present. Another bias that was uncontrolled for was the lack of consideration of the dominant side of the specimen donor. The lower number of cadaveric specimens was augmented with the use of an additional four pairs of composite specimens, delivering results in the same consistency. The composite specimens used in this study have been shown to be biomechanically equivalent to cadaveric specimens of non-compromised bone quality, again, used in this study.[38,39] Finally, embalmed and not fresh frozen specimens were used for the study. It has been shown, however, that the stability between these two fixation techniques for femoral cadaveric specimens is very similar.[40] Due to a wide standard of biomechanical testing, a direct comparison with another stem would be possible by using the exact same set-up.[41]

In conclusion, short stems have a significantly lower primary load at failure compared with double-wedged stems in both cadaveric and composite specimens. Surgeons should consider this biomechanical property when deciding on the use of short femoral stem.

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Author contributions

- A. Klasan: Devised the study, Conducted the experiment, Analyzed the data, Wrote the manuscript.
- M. Bäumlein: Conducted the experiment, Analyzed the data.
- P. Dworschak: Conducted the experiment, Wrote the manuscript.
- C. Bliemel: Supervised the experiment, Reviewed the manuscript.
- T. Neri: Analyzed the data, Reviewed the manuscript.
- M. D. Schofer: Reviewed the manuscript.
- T. J. Heyse: Senior supervisor of the study, Devised the study, Reviewed the manuscript.

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Conflict of interest statement

- M. D. Schofer reports personal fees from Smith & Nephew and DePuy Synthes, not related to this study. T. J. Heyse reports grants and personal fees from Zimmer Biomet, as well as grants, personal fees, and consultancy fees from Smith & Nephew, not related to this study.

Ethical review statement

- The study was approved by the ethics boards of the authors' institutions (163/17, 2 November 2017) prior to commencement.