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HIP

Prophylactic cable prevents tapered titanium stem subsidence with 2 cm of stem-cortical engagement in a cadaveric model

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Aims

When performing revision total hip arthroplasty using diaphyseal-engaging titanium tapered stems (TTS), the recommended 3 to 4 cm of stem-cortical diaphyseal contact may not be available. In challenging cases such as these with only 2 cm of contact, can sufficient axial stability be achieved and what is the benefit of a prophylactic cable? This study sought to determine, first, whether a prophylactic cable allows for sufficient axial stability when the contact length is 2 cm, and second, if differing TTS taper angles (2° vs 3.5°) impact these results.

Methods

A biomechanical matched-pair cadaveric study was designed using six matched pairs of human fresh cadaveric femora prepared so that 2 cm of diaphyseal bone engaged with 2° (right femora) or 3.5° (left femora) TTS. Before impaction, three matched pairs received a single 100 lb-tensioned prophylactic beaded cable; the remaining three matched pairs received no cable adjuncts. Specimens underwent stepwise axial loading to 2600 N or until failure, defined as stem subsidence > 5 mm.

Results

All specimens without cable adjuncts (6/6 femora) failed during axial testing, while all specimens with a prophylactic cable (6/6) successfully resisted axial load, regardless of taper angle. In total, four of the failed specimens experienced proximal longitudinal fractures, three of which occurred with the higher 3.5° TTS. One fracture occurred in a 3.5° TTS with a prophylactic cable yet passed axial testing, subsiding < 5 mm. Among specimens with a prophylactic cable, the 3.5° TTS resulted in lower mean subsidence (0.5 mm (SD 0.8)) compared with the 2° TTS (2.4 mm (SD 1.8)).

Conclusion

A single prophylactic beaded cable dramatically improved initial axial stability when stem-cortex contact length was 2 cm. All implants failed secondary to fracture or subsidence > 5 mm when a prophylactic cable was not used. A higher taper angle appears to decrease the magnitude of subsidence but increased the fracture risk. The fracture risk was mitigated by the use of a prophylactic cable.

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Introduction

While total hip arthroplasty (THA) is a durable procedure with excellent clinical outcomes, femoral component failures do occur and require revision surgery. The most common indications for femoral component revision include periprosthetic joint infection, aseptic loosening, and periprosthetic fracture. Less commonly, hip instability, implant recall, and stem subsidence with associated leg length discrepancy are also culprits for failed THA.[1-3] Many of these revision indications are associated with varying amounts of femoral bone loss.[4] Several studies on titanium tapered

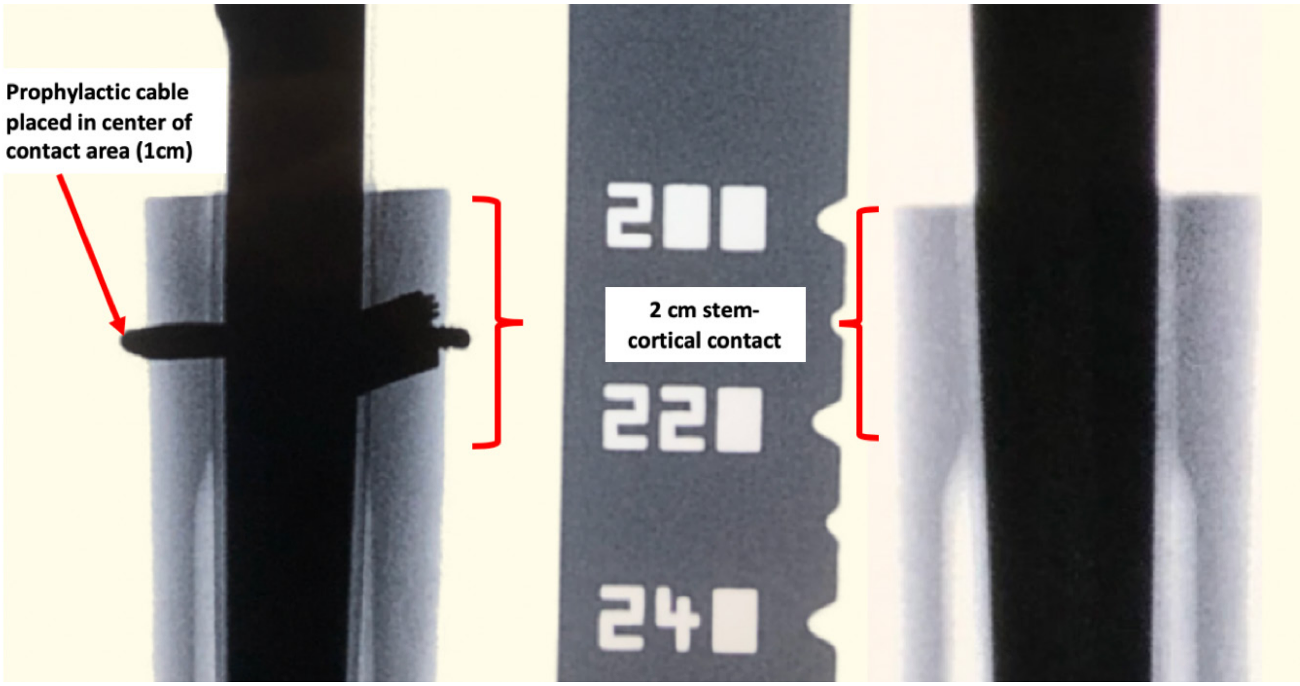

Fig. 1

Representative fluoroscopy images of specimens prepared with 2 cm of stem-cortical contact and a prophylactic beaded cable (left) and without a cable (right).

stems (TTS) have reported excellent implant survivorship with relatively low rates of stem subsidence;[5-7] for this reason, the TTS is now the workhorse implant design used in contemporary femoral component revision.

The Paprosky classification on femoral bone loss was developed nearly three decades ago and helped guide implant selection based on amount of femoral bone stock available for stem fixation.[8] However, the classification system was based on the use of cylindrical porous-coated stems which required a minimum of 4 cm of interference "scratch" for long-term fixation. In contrast, TTS have been used successfully in Paprosky 3B (less than 4 cm of diaphyseal bone), and even Paprosky type 4 (stove pipe) femora with good results.[9,10] Despite this, the minimum amount of contact length required for reproducible implant fixation of a TTS implant is still debated. In order to address this open issue, we previously studied the minimum contact length required to achieve immediate axial stability.[11] In this cadaveric biomechanical study that incorporated two contemporary TTS commonly used in revision THA, 3 to 4 cm of contact was established as the minimum threshold required for stability. Contact of 2 cm was found to be insufficient, resulting in uncontrolled subsidence or femoral fracture.

However, all of these femora were prepared without a prophylactic cable. Cables and wires have been historically used as an adjunctive intraoperative fixation option and have been shown to reduce hoop stress generated in the host femoral bone during axial loading.[12,13] Thus, the primary aim of this study was to test in a cadaveric biomechanical model whether the addition of a prophylactic cable to a Paprosky 3B femur with 2 cm of available contact length prevents TTS subsidence during immediate initial axial loading. A secondary aim was to determine whether and how different spline taper angles (2° vs 3.5°) affect axial stability in our model. We hypothesized that the addition of a prophylactic cable and a higher spline taper angle would prevent subsidence.

Methods

A cadaveric biomechanical model we previously developed was used to assess axial stability of revision TTS.[11] A total of 12 human fresh anatomical cadaveric femora (six matched pairs) were obtained for stem implantation and axial stability testing. The inclusion criteria of the specimens were female sex and age > 60 years. The exclusion criteria were history of smoking, previous fragility fracture, gross anatomical deformity of the femur, prior trauma to the femur, history of malignancy, previous surgery to the femur, and known history of metabolic disease or osteoporosis. All eligible specimens underwent preliminary visual inspection and plain radiograph imaging to confirm absence of grossly decreased bone density and pre-existing cortical diaphyseal defects. Specimens that cleared initial screening then underwent CT imaging, and specimens with femoral canal diameters > 22 mm or cortical thickness < 5 mm were excluded to ensure that specimens would not fracture during over-reaming.

Table I. Donor demographics for the six matched pairs of femora prepared with 2 cm of titanium tapered stem-cortical contact.

Specimen ID	Age, yrs	BMI, kg/m²
Femora implanted without prophylactic cables		
1	78	40.5
2	73	33.9
3	86	70.7
Femora implanted with prophylactic cables		
4	62	34.0
5	64	32.8
6	64	34.7

Two types of TTS, both with eight splines in the axial cross-section, were used. Restoration Modular (Stryker, USA) revision hip stems, with 2° spline taper, were implanted in the right-sided femora and Alteon (Exactech, USA) revision hip stems, with 3.5° spline taper, were implanted in the left-sided femora. Other than taper angle, the two TTS designs were similar, but did have slightly different surface finish roughness values and spline geometries (4.5 to 5 µm and sharp splines for the 2° TTS vs 5 µm to 11 µm and flat splines for the 3.5° TTS). Additionally, the 2° TTS is a modular stem while the 3.5° TTS is monoblock, resulting in slightly different lengths of the final implant construct (225 mm vs 195 mm from the centre of rotation to the distal tip, respectively).

Matched pairs of specimens were then randomized, with three matched pairs assigned to each of two comparison groups: 2 cm of stem-cortical contact with no cable adjunct compared with femora with 2 cm of available stem-cortical contact length with the addition of a single prophylactic cable.

All specimens were prepared with identical, standardized methodology to achieve 2 cm of stem-cortical contact following stem implantation. First, the proximal femur was resected at the metadiaphyseal junction following identification of this anatomical landmark on preliminary fluoroscopy. The distal end of the femur was resected to leave a 15 cm-long bone segment, representing the diaphysis and isthmus. Starting at the proximal end of this bone segment, a 2 cm region was measured and marked to serve as the stem-cortical contact zone. Then, the femora were over-reamed in a retrograde fashion 1 to 2 mm greater than the diameter of the proximal femoral canal. The over-reaming terminated at the border of the 2 cm contact zone, leaving only those 2 cm of bone preserved and ensuring no stem-cortical contact could occur distally.

Next, for the three matched pairs assigned to the adjunct comparison group, a prophylactic Dall-Miles Vitallium beaded cable (Stryker) was placed in the centre of the 2 cm contact zone (1 cm past the proximal bone cut) and tensioned to 445 N (100 lbf). The proximal femur was prepared for all specimens using stem-specific instrumentation. Any additional retrograde over-reaming required to maintain a 1 to 2 mm difference from the proximal femoral canal was then performed. This was followed by implantation of the stems by a single fellowship-trained arthroplasty surgeon (TDT) as per standard surgical technique. Finally, verification of the desired 2 cm of stem-cortical contact was performed using fluoroscopy (Figure 1). Absence of three-point contact was confirmed via direct visualization of the distal stem through the open distal end of the canal.

The prepared specimens were potted in epoxy (Bondo; 3M, USA) as previously described.[11] Axial stability testing was performed using a custom loading fixture with applied axial load along the long axis of the stem using a servo-hydraulic material testing system (8800; MTS, USA). Following a previously published loading protocol, load was applied in a stepwise fashion starting at 50 N until a maximum of 2,600 N was reached or progressive subsidence past 5 mm without an endpoint occurred.[14] Subsidence was determined with retroreflective markers tracking the relative motion of the stem to the bone, as previously described.[11]

Endpoints measured included load to 1 and 5 mm of subsidence, maximum load reached, and subsidence at maximum load. Subsidence > 5 mm was defined as clinically significant subsidence, and hence failure, under the axial load testing based on previous clinical studies.[3,15-17] Grossly evident longitudinal fractures were documented.

Results

Demographic and implant characteristics. Specimen donor demographic information is listed in Table I. The diameters of implanted stems were within 1 mm between the left and right femora comprising every matched pair.

Axial stability testing. All six specimens (three matched pairs) that did not receive a prophylactic cable adjunct failed axial load testing, subsiding > 5 mm (Table II). In contrast, all six specimens (three matched pairs) that received a prophylactic cable successfully resisted testing, subsiding < 5 mm. For two specimens with cables, subsidence was negligible (0 mm or 0.1 mm) even at the maximum load tested of 2,600 N. Both were implanted with the 3.5° taper stem.

Of the six specimens without cables, three developed grossly evident longitudinal cortical fracture originating proximally (Table II). On the other hand, of the six specimens reinforced with a prophylactic cable, one also developed a longitudinal cortical fracture, but subsidence was just 1.4 mm. The fracture extended approximately the full length of the 2 cm stem-cortical contact length, past the prophylactic cable positioned in the middle of that contact zone (Figure 2).

Spline taper angle comparisons. Of the specimens with an adjunctive prophylactic cable, those that were implanted with the 2° spline taper stem subsided 1.3 to 4.5 mm,

Table II. Subsidence and fracture in femora prepared with 2 cm of stem-cortex contact with or without prophylactic cables upon stepwise axial load testing to 2600 N.

Spline taper angle, °	Stem size, mm	Load to 1 mm subsidence, N	Load to 5 mm subsidence, N	Maximum load, N	Subsidence at maximum load, N	Testing result	Fracture
Without prophylactic cable							
2	16	1,850	2,400	2,600	10.6	Failed	No
2	16	1,350	1,750	2,550	20.4	Failed	Yes
2	15	1,550	1,550	2,600	19.4	Failed	No
3.5	16	1,600	2,350	2,450	18.6	Failed	Yes
3.5	16	1,300	1,400	2,350	28.6	Failed	Yes
3.5	15	1,800	1,800	2,600	5.4	Failed	No
Without prophylactic cable							
2	15	1,850	N/A	2,600	1.5	Passed	No
2	15	1,950	N/A	2,600	4.5	Passed	No
2	15	2,400	N/A	2,600	1.3	Passed	No
3.5	16	N/A	N/A	2,600	0.0	Passed	No
3.5	15	N/A	N/A	2,600	0.1	Passed	No
3.5	14	2,400	N/A	2,600	1.4	Passed	Yes

N/A, not applicable.

while those implanted with the 3.5° spline taper stem subsided 0.0 to 1.4 mm. Comparisons of spline taper angle could not be made in the specimens without cables, as all of those failed with subsidence > 5 mm, leading to unreliable absolute subsidence measurements.

Of the three femora implanted with the 3.5° spline taper stem without prophylactic cables, two developed longitudinal cortical fractures during axial load testing, as did one of the femora implanted with the 3.5° spline taper stem with a prophylactic cable. Of the six specimens implanted with the 2° spline taper stem, only one, which had no cable, developed a longitudinal cortical fracture.

Discussion

In our cadaveric model, the addition of a single prophylactic cable to an implant with 2 cm of stem-cortical contact conferred excellent immediate axial stability. All six specimens without the cables failed, with subsidence > 5 mm, and three of them fractured. In contrast, none of the implants with prophylactic cables failed under axial loading, despite one that fractured. Additionally, subsidence due to axial loading was not impacted by different TTS spline angles, with no discrepancies in success or failure within any matched pair. However, fractures occurred more frequently in femora implanted with the higher 3.5° spline taper angle TTS when prophylactic cables were not used. Conversely, in specimens with a prophylactic cable, less subsidence occurred in the femora implanted with the higher 3.5° spline taper angle TTS compared with the 2° spline taper angle TTS.

Our finding that prophylactic cables prevented subsidence of TTS under axial load, despite only 2 cm of stem-cortical contact, suggests that a TTS is viable when used in conjunction with a cable adjunct in this clinical scenario. Previously, we used this cadaveric model to establish 3 cm to 4 cm as the minimum stem-cortical contact required to resist axial loading when TTS are used without prophylactic cables in revision THA.[11] Clinical studies have similarly concluded that 4 cm of host bone-stem contact is necessary for adequate stability, albeit with cylindrical stems rather than the TTS studied here.[8] In biomechanical studies of torsional stability of cylindrical stems, 3 to 4 cm of contact have been recommended as the minimum threshold for stability.[18] However, in the setting of revision THA, 3 cm of stem-cortical contact is not always possible due to inadequate bone stock. Our study suggests that prophylactic cabling is effective in preventing subsidence when stem-cortex contact length is limited to 2 cm. Cabling may also be the ideal prophylactic option, as Herzwurm et al[19] demonstrated a significantly greater increase in tolerable microstrain under axial load compared with controls when prophylactic 2 mm chrome-cobalt cables were used than when 18-gauge cerclage wires were used. However, a cerclage wire could still be a viable alternative based on evidence elsewhere in the literature. Notably, a recent biomechanical cadaveric study applying combined axial and torsional load reported that prophylactic cerclage wires significantly increased the required torsion and energy to failure compared with unwired controls.[12]

Previous studies have demonstrated the effects of taper angle, surface roughness, and spline geometry on stem subsidence.[20-23] We examined whether those design features affected subsidence in a cadaveric fracture model. Of the four specimens that fractured, three were implanted with the 3.5° spline TTS, but in femora treated with prophylactic cables (and which therefore did not fail), the amount of subsidence was lower in the femora implanted with the 3.5° spline TTS than in those implanted with the 2° spline TTS. These findings

Fig. 2

Lone specimen prepared with 2 cm of stem-cortical contact and a prophylactic cable that experienced a longitudinal proximal fracture (highlighted with blue dye in red bracket area of the figure). Fracture length was approximately 2 cm long and extended past the prophylactic cable. Subsidence at maximum axial load of 2,600 N was 1.4 mm.

are likely attributable to the greater axial resistance (N/mm) provided by higher taper angle TTS, which has been demonstrated previously.[20] However, in our particular scenario with significantly deficient host bone, this higher axial resistance may come at a cost by exceeding the hoop stress tolerable by the femoral cortex, resulting in longitudinal cortical fractures. Because prophylactic cables increase tolerable microstrain under axial load, as discussed earlier, their primary benefit seen in this study may be attributable to their mitigation of fracture risk and, in one case, prevention of stem subsidence > 5 mm despite a longitudinal fracture. Although definitive conclusions cannot be made in the setting of the limited sample size, these findings support future studies to elucidate the scenarios in which differences between spline taper angles result in clinically meaningful differences.

Limitations. This study has several limitations. First, due to the rigour of specimen selection criteria, this study was limited to a total of 12 cadaveric specimens. However, our primary conclusion, supporting the use of a prophylactic cable with a TTS when only 2 cm of stem-cortex contact exists, remains compelling due to the stark contrast in success rates. Next, despite the randomization process, specimens that received a prophylactic cable belonged to younger donors with higher BMIs. However, donors were carefully screened for both comorbidities and via preliminary imaging to attain a homogenous group of specimens with regard to bone quality. Additionally, none of the donors was underweight and, with higher BMIs associated with benefits to bone mineral density, any potential impact of age difference on outcomes was likely mitigated.[24] Finally, a cadaveric biomechanical model is intrinsically limited in only being able to assess immediate construct stability. Clinical studies are required to supplement these findings with long-term outcomes which incorporate biological bone on-growth into the stem under real-world loading conditions.

In conclusion, this cadaveric biomechanical study investigated TTS fixation in cases of extreme femoral bone loss (2 cm of available stem-cortical contact). The addition of a single prophylactic cable produced superior immediate axial stability. In the absence of a prophylactic cable, an increased taper angle did not improve initial axial stability but increased the fracture risk. Adding a prophylactic cable decreased the fracture risk for the stems with a larger taper angle and improved the axial stability for both stem designs.

We detected no difference in the proportion of failures under axial load (subsidence > 5 mm) between a 2° and 3.5° spline TTS for 2 cm of stem-cortical contact with a cable, but mean subsidence was lower with the 3.5° spline TTS design. Our findings support future clinical studies to determine the possible in vivo efficacy of adding prophylactic cables to TTS to prevent subsidence and eventual loosening or instability when only 2 cm of stem-cortical contact is possible.

Take home message

- When performing revision total hip arthroplasty, significant proximal femoral bone loss is often encountered.
- In severe cases with less than 2 cm of stem-cortical diaphyseal contact, a prophylactic cable improves stem-cortex stability and may help mitigate risk of failure from stem subsidence and/or cortical fracture.

References

1. **Springer BD**, **Fehring TK**, **Griffin WL**, **Odum SM**, **Masonis JL**. Why revision total hip arthroplasty fails. *Clin Orthop Relat Res*. 2009;467(1):166–173.
2. **Kenney C**, **Dick S**, **Lea J**, **Liu J**, **Ebraheim NA**. A systematic review of the causes of failure of Revision Total Hip Arthroplasty. *J Orthop*. 2019;16(5):393–395.
3. **Clair AJ**, **Gabor JA**, **Patel KS**, **Friedlander S**, **Deshmukh AJ**, **Schwarzkopf R**. Subsidence following revision total hip arthroplasty using modular and monolithic components. *J Arthroplasty*. 2020;35(6S):S299–S303.
4. **Sheth NP**, **Nelson CL**, **Paprosky WG**. Femoral bone loss in revision total hip arthroplasty: evaluation and management. *J Am Acad Orthop Surg*. 2013;21(10):601–612.
5. **Streit MR**, **Lehner B**, **Peitgen DS**, **et al**. What Is the long-term (27- to 32-year) survivorship of an uncemented tapered titanium femoral component and survival in patients younger than 50 years? *Clin Orthop Relat Res*. 2020;478(6):1283–1291.

6. **Streit MR**, **Innmann MM**, **Merle C**, **Bruckner T**, **Aldinger PR**, **Gotterbarm T**. Long-term (20- to 25-year) results of an uncemented tapered titanium femoral component and factors affecting survivorship. *Clin Orthop Relat Res*. 2013;471(10):3262–3269.
7. **Saunders PRJ**, **Shaw DA**, **Sidharthan SK**, **Siney PD**, **Young SK**, **Board TN**. Survivorship and radiological analysis of a monoblock, hydroxyapatite-coated titanium stem in revision hip arthroplasty. *J Arthroplasty*. 2020;35(6):1678–1685.
8. **Paprosky WG**, **Greidanus NV**, **Antoniou J**. Minimum 10-year-results of extensively porous-coated stems in revision hip arthroplasty. *Clin Orthop Relat Res*. 1999;369(369):230–242.
9. **Rodriguez JA**, **Deshmukh AJ**, **Robinson J**, **et al**. Reproducible fixation with a tapered, fluted, modular, titanium stem in revision hip arthroplasty at 8-15 years follow-up. *J Arthroplasty*. 2014;29(9 Suppl):214–218.
10. **Wirtz DC**, **Gravius S**, **Ascherl R**, **et al**. Uncemented femoral revision arthroplasty using a modular tapered, fluted titanium stem: 5- to 16-year results of 163 cases. *Acta Orthop*. 2014;85(6):562–569.
11. **Gkiatas I**, **Malahias M-A**, **Xiang W**, **et al**. How does contact length impact titanium tapered splined stem stability: a biomechanical matched pair cadaveric study. *J Arthroplasty*. 2021;36(9):3333–3339.
12. **Waligora AC**, **Owen JR**, **Wayne JS**, **Hess SR**, **Golladay GJ**, **Jiranek WA**. The effect of prophylactic cerclage wires in primary total hip arthroplasty: a biomechanical study. *J Arthroplasty*. 2017;32(6):2023–2027.
13. **Kuster LS**, **Marshall D**, **Fässler C**, **Duff SJ**, **Hayes A**, **Kuster MS**. Can prophylactic cables stop crack propagation in revision arthroplasty: a biomechanical study. *J Arthroplasty*. 2019;34(5):987–990.
14. **Russell RD**, **Pierce W**, **Huo MH**. Tapered vs cylindrical stem fixation in a model of femoral bone deficiency in revision total hip arthroplasty. *J Arthroplasty*. 2016;31(6):1352–1355.
15. **Loudon JR**, **Older MW**. Subsidence of the femoral component related to long-term outcome of hip replacement. *J Bone Joint Surg Br*. 1989;71-B(4):624–628.
16. **Callaghan JJ**, **Salvati EA**, **Pellicci PM**, **Wilson PD**, **Ranawat CS**. Results of revision for mechanical failure after cemented total hip replacement. *J Bone Joint Surg Am*. 1985;67-A:1074–1085.
17. **Ries C**, **Boese CK**, **Dietrich F**, **Miehlke W**, **Heisel C**. Femoral stem subsidence in cementless total hip arthroplasty: a retrospective single-centre study. *Int Orthop*. 2019;43(2):307–314.
18. **Meneghini RM**, **Hallab NJ**, **Berger RA**, **Jacobs JJ**, **Paprosky WG**, **Rosenberg AG**. Stem diameter and rotational stability in revision total hip arthroplasty: a biomechanical analysis. *J Orthop Surg Res*. 2006;1(1):5.
19. **Herzwurm PJ**, **Walsh J**, **Pettine KA**, **Ebert FR**. Prophylactic cerclage: a method of preventing femur fracture in uncemented total hip arthroplasty. *Orthopedics*. 1992;15(2):143–146.
20. **Pierson JL**, **Small SR**, **Rodriguez JA**, **Kang MN**, **Glassman AH**. The effect of taper angle and spline geometry on the initial stability of tapered, splined modular titanium stems. *J Arthroplasty*. 2015;30(7):1254–1259.
21. **Kaneuji A**, **Yamada K**, **Hirosaki K**, **Takano M**, **Matsumoto T**. Stem subsidence of polished and rough double-taper stems: in vitro mechanical effects on the cement-bone interface. *Acta Orthop*. 2009;80(3):270–276.
22. **Norman TL**, **Thyagarajan G**, **Saligrama VC**, **Gruen TA**, **Blaha JD**. Stem surface roughness alters creep induced subsidence and "taper-lock" in a cemented femoral hip prosthesis. *J Biomech*. 2001;34(10):1325–1333.
23. **Verdonschot N**, **Huiskes R**. Surface roughness of debonded straight-tapered stems in cemented THA reduces subsidence but not cement damage. *Biomaterials*. 1998;19(19):1773–1779.
24. **Xiang B-Y**, **Huang W**, **Zhou G-Q**, **Hu N**, **Chen H**, **Chen C**. Body mass index and the risk of low bone mass–related fractures in women compared with men. *Medicine (Baltimore)*. 2017;96(12):e5290.

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