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Interposition sleeve as treatment option for interprosthetic fractures of the femur: a biomechanical in vitro assessment

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Abstract
Purpose The number of patients having hip and knee arthroplasties on the ipsilateral leg is going to rise. In this regard, the prevalence of interprosthetic femoral fractures is going to increase further. The treatment of these fractures is difficult and sometimes it is impossible to perform an osteosynthesis because of worse bone quality. The goal of this study was to investigate the use of an interposition sleeve as an alternative treatment option for interprosthetic fractures with major bone loss.
Methods Six human cadaveric femurs were instrumented using cemented hip- and knee prosthesis. Interprosthetic fractures were induced during a four-point-bending test and then treated using the interposition sleeve. Afterwards the constructs were tested using the four-point-bending test again.
Results Load-to-failure of the construct before fracturing was significantly higher than after treatment with the interposition sleeve (10681 N vs. 5083 N; p=0.002). The failure mechanism of the femurs with the interposition sleeve was plastic deformation of the hip or knee prosthesis. The interposition sleeve did not fail in any specimen.
Conclusion The interposition sleeve is a valuable treatment option for interprosthetic fractures in situations in which osteosynthesis is impossible or insecure due to major bone defects. However, fracture healing should be preferred whenever possible.

Keywords Interprosthetic fractures · Periprosthetic fractures · Total femur replacement · Interposition sleeve · Femoral fractures

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Introduction

Fractures involving arthroplasties often represent a major challenge for orthopaedic trauma surgeons. Since the number of implanted hip (THA) and knee prostheses (TKA) continues to rise, there are increasingly more patients having both arthroplasties on the ipsilateral leg. In this regard, the prevalence of peri- and interprosthetic femoral fractures is going to increase further [7, 11, 12].

The incidence of periprosthetic fractures in THA ranges from 0.1 to 18 % [7], while the incidence of periprosthetic fractures in TKA is approximately 0.3 to 5.5 % [16]. The exact incidence of interprosthetic femoral fractures is rarely described: Kenny et al. described an incidence of 1.25 %, with four cases among a total of 320 limbs [5]; Sah et al. observed 22 patients in four years at two institutions [18]; Hou et al. published 13 cases within six years [4]; and Platzer et al. reported 24 cases in 16 years [15]. An increased risk is observed after revision surgeries [1]. The rising number of hip and especially knee joint replacements will inevitably lead to a growing incidence in the future [6].

Because there is no separate classification, interprosthetic femoral fractures are usually classified as periprosthetic fractures of the hip or the knee joint. The most popular classification for periprosthetic fractures in THA is the Vancouver classification; periprosthetic fractures in TKA are classified according to the Rorabeck, Su, or SoFCOT classifications. All of these classifications are based on the fracture side and the fixation status of the prosthesis. Along with the interprosthetic distance and bone stock, these are the decisive factors during treatment planning for interprosthetic femoral fractures.

Treatment of such fractures between two stemmed prostheses is challenging. Possible options include cerclage wires, non-locking and locking plates, bone allografts, revision of the prostheses, and total femur replacement. In case of stable hip and knee prostheses, an angular stabilized plate osteosynthesis appears to be the treatment of choice [10, 13, 19, 20]. In cases of severely damaged bone stock, open reduction with internal plate fixation may be impossible and a total femur replacement should be considered as a last resort [3]. However, it is very demanding and should be limited to specialized centres.

This in vitro biomechanical study aimed to evaluate a custom-made interposition device that might be an additional treatment option for interprosthetic femoral fractures in cases of two-stemmed implants and severe damage of the bone stock, in which plating is insecure or impossible.

Materials and methods

Approval for this study was granted by the local ethics committee.

A total of six human cadaveric femurs were included in this study. They were collected from three female and three male donors, aged 56 years and older (average age, 65.7 years; SD 6.9; range, 56–73 years). The specimens were removed postmortem at the local Institute of Forensic Medicine and stored at −20 °C. Computed tomography scans were performed on all specimens for instrumentation planning.

After thawing the fresh-frozen specimens overnight at room temperature, the soft tissue was removed. Next, the medullary canals were prepared for hip and knee prosthesis implantation. Cemented Lubinus Classic Plus hip prostheses (Link, Hamburg, Germany) and the Endo Modell M modular knee prostheses with different stem lengths (Link, Hamburg, Germany) were used for implantation. Hip stem sizes differed depending on the bone dimensions: we used one small, four medium, and one large hip stem. A cement stopper (PE cement stopper, Smith & Nephew, Memphis, USA) was implanted 10 mm distal to the hip and 10 mm proximal to the knee prostheses. The Optipac System with Refobacin R bone cement (Biomet Inc., Warsaw, USA) was used for cementation. Based on the computed tomography data, the stem lengths of the knee prostheses were adjusted to achieve an interprosthetic distance of 35 mm (defined as the distance between the two stem tips). Distances were checked by fluoroscopy during preparation and optimized by varying the resection level or implantation depth if needed. After the implantation of both prostheses, the femurs were embedded in aluminium pots at their proximal and distal ends using polyurethane (Ureol FC 53, Gößl & Pfaff, Karlskron, Germany).

Interprosthetic fractures were generated with a four-point bending setup, applying a constant moment between the support points and omitting transverse forces. Prior studies have shown that this loading condition can be used to produce interprosthetic fractures [17]. Therefore, this setup on a servohydraulic testing machine (MTS 858.2, MTS Systems, Eden Praire, MN, USA) was used to generate the fractures and to test the interposition sleeve. The femur was placed on the outer two supports and loaded with a constant bending moment according to Eq. (1) between the middle two supports (Fig. 1).

$$M = \frac{F}{2} \times \frac{l_1 - l_2}{2}; l = \frac{l_1 - l_2}{2} = 8cm \quad (1)$$

l_1: distance between the outer supports; l_2: distance between the inner supports; F: applied force; l: lever arm length. The load was applied with a constant speed of 0.1 mm/s.

Fracture treatment was performed using a custom-made interposition sleeve (Link, Hamburg, Germany) (Fig. 2). The implant is in the market and can be ordered as custom-made implant from the manufacturer. Surrounding bone and cement were removed circumferential to the area of the distal hip stem and the proximal knee stem (Fig. 3). Next, the stems were cleaned and cemented into the interposition sleeve using Refobacin R bone cement (Biomet Inc., Warsaw, USA). Grub screws were used for additional fixation (Fig. 4). After treatment, femurs were tested again using the four-point-bending setup.

Statistical analysis was performed using the software package IBM SPSS Statistics 21. Given the sample size,

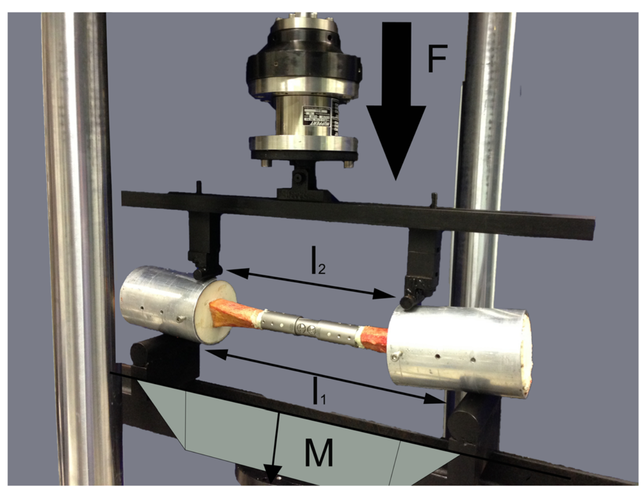

Fig. 1 Biomechanical testing setup. Specimens were loaded with a constant bending moment between the inner supports. *l1* distance between the outer supports, *l2* distance between the inner supports, *F* applied force, *M* bending moment

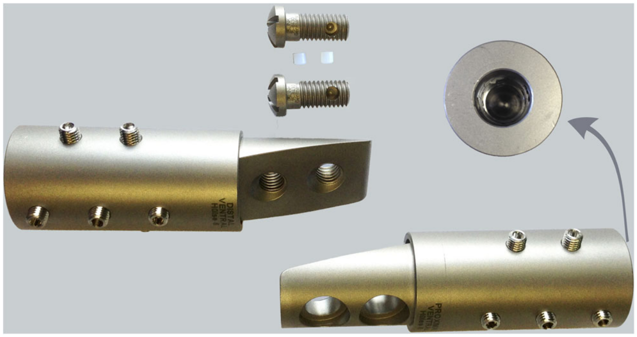

Fig. 2 The custom-made interposition device (Link, Hamburg, Germany) consists of two sleeves for the stems. The connection bridge is adapted to the interprosthetic distance and connects the two sleeves using two screws

nonparametric analyses (Mann–Whitney-U) were performed to compare the failure loads as well as the stiffness before and after treatment with the interposition sleeve. The stiffness of each construct was determined using a linear regression to determine the slope of the load–displacement curves. The type I error probability was set to α=0.05 for all tests.

Results

Fractures between the hip and the knee stem could be produced in all specimens while the implants remained well fixed to the bone. The mean fracture strength was 10681 N (SD, 3032; range, 5832–14387). The mean maximum bending moment was 427 Nm (SD, 121; range, 233–575). The mean stiffness of the specimens before fracturing was 742.66 N/mm (SD, 168.63; range, 558.62–1033.9).

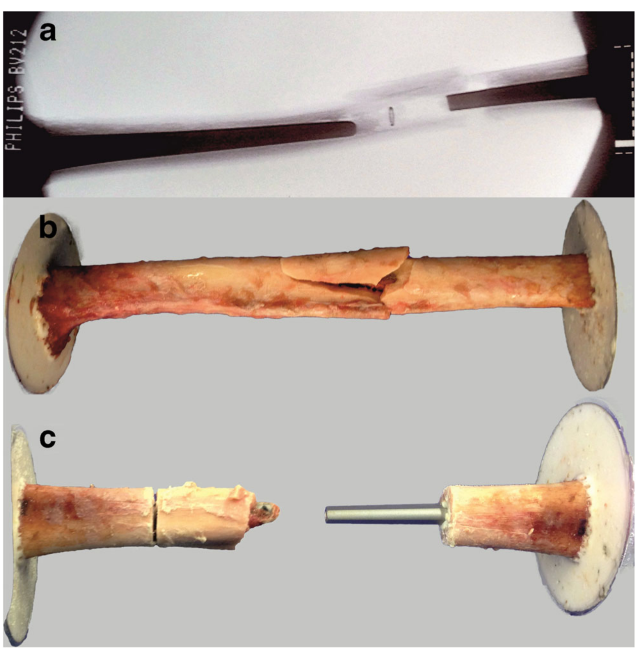

Fig. 3 An anteroposterior femur X-ray showing an interprosthetic fracture (**a**). A specimen with an interprosthetic fracture before preparation (**b**). To implant the interposition nail, the surrounding bone and cement were removed from the distal and proximal stems, respectively (**c**)

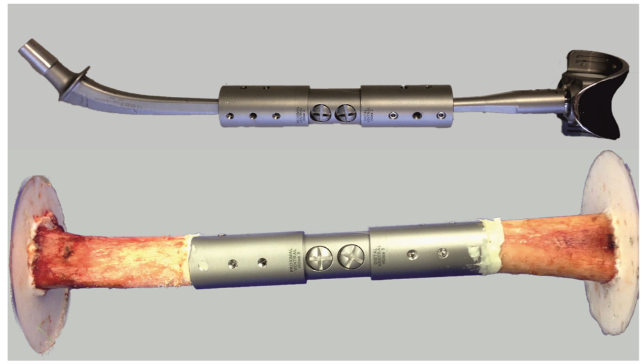

Fig. 4 The stems of hip and knee prostheses were fixed to the sleeves using bone cement and grub screws

After treatment with the interposition sleeve, failure was defined as plastic deformation of the construct, which was observed in the force-displacement diagram. Deformation was seen at the stem of the hip prosthesis in five specimens (small and medium hip stems) and at the stem of the knee prosthesis in one specimen (large hip stem) (Fig. 5). The interposition device did not fail in any case.

The mean force to failure after treatment with the interposition sleeve was 5083 N (SD, 953; range, 3175–5680) and the mean maximum bending moment was 203 Nm (SD, 38.12; range, 127–227.21). These forces were significantly lesser than the load required to create the interprosthetic fractures (p=0.002). The dimensions of the prosthetic stems were decisive for the magnitude: the lowest force to failure was observed with the small hip stem (3175 N), while the specimen with the large hip stem showed the highest value (5680 N). Mean stiffness after treatment was 585.94 N/mm (SD, 79.23; range, 502.6–717.22). The construct with the large hip stem showed the highest stiffness (717.22 N/mm).

Fig. 5 An anteroposterior femur X-ray and specimen after testing. Plastic deformation occurred at the stem of the hip prosthesis (*left side*)

The stiffness before fracturing and after treatment showed the same trend as the required failure forces but there was no significance (p=0.066).

Discussion

The treatment of interprosthetic fractures of the femur is very complex and surgically demanding. It is challenging, even when both prostheses are stable and the bone stock between and around the prostheses is of high quality. In these cases, a locked plate osteosynthesis is recommended [13, 19, 20].

In cases of short interprosthetic gap sizes and severe damage to the bone stock or in cases of failed plate osteosynthesis after interprosthetic fractures, a total femur replacement appears to be the last choice before disarticulation at the hip [3]. Despite the associated disadvantages (removal of most or all host bone, poor attachment of the soft tissue, and high perioperative morbidity), the main advantage of total femur replacement is immediate stability, which allows early post-operative mobilisation [14].

The interposition sleeve can be used to treat interprosthetic fractures, particularly the specific fractures described above. Because it is immediately stable after implantation, it has the advantage of early postoperative mobilisation, but is not as invasive as a total femur replacement. Citak et al. published four cases of interposition sleeve treatment and indicated that it is a valuable treatment option for interprosthetic femoral fractures [2]. Based on a mean follow-up period of eight years (range, 0.5–16), they saw one case with aseptic loosening, but no other complications requiring revision surgery. The biomechanical properties of this interposition sleeve treatment were determined in this study. The strength of the interposition sleeve construct is limited by the stiffness and strength of the stems of the implanted hip and knee prostheses. The interprosthetic fracture strength was significantly higher than the failure strength after interposition sleeve treatment, which indicates that fracture healing should be the goal whenever possible. The interposition sleeve is intended for special cases of poor bone quality in which fracture healing is insecure or impossible.

Comparing the load to failure of the interposition sleeve to that of other treatment options yields similar results. Lehmann et al. published different biomechanical studies regarding interprosthetic fractures and treatment options using exactly the same biomechanical testing setup as this study [8, 9]. Their results show a load to failure of 5020 N (SD, 639) for a combination of hip prosthesis, retrograde nail, and lateral compression plate; 4591 N (SD, 690) for the same combination with additional osteotomy simulating an interprosthetic fracture; and 6335 N (SD, 3529) for a combination with a hip prosthesis and long distal locking plate.

The stiffness of the construct with the interposition device was lower than the stiffness of the femurs before fracturing (trend). Although this fact appears to be controversial considering the stiff implants, mechanically it can be explained easily: the bending stiffness depends on the E-modulus of the material and the moment of inertia of the construct. Because the moment of inertia rises with the fourth power of the radius, the stiffness of the bone (with its large radius compared with the prosthetic stems) is higher, despite its lower E-modulus.

This study is subject to certain limitations. A biomechanical in vitro study is not able to completely simulate all in vivo conditions. Because of the use of specimens and the removal of soft tissues, the muscles and ligaments did not contribute to stability. Furthermore, the use of human bone specimens leads to a small sample size and might lead to a greater variation of the results due to different bone dimensions and qualities compared to composite models. However, human bone specimens are much more appropriate to simulate in vivo conditions compared to composite bones. The four-point bending test considers only a few trauma mechanisms (e.g., lateral falls). However, it was appropriate to create an interprosthetic fracture and to test the interposition sleeve under the same conditions. The comparison of fracture-strength and force to failure is somehow limited because the fracture strength depends on the bone quality, while the force to failure depends almost exclusively on the implants. On the other hand, it shows that fracture healing should be attempted whenever possible. No fatigue testing was performed. The long-term endurance of the construct mainly depends on the interface of the cement prosthesis. This study only evaluates the implant behaviour under laboratory conditions. Further investigation with respect to the implantation procedure, blood loss during operation, and long-term stability, for example, has to be performed in a clinical study.

In conclusion, the interposition sleeve is a valuable treatment option for interprosthetic fractures in which osteosynthesis is impossible or insecure owing to major bone defects. It shows adequate biomechanical properties for immediate stability and early postoperative mobilisation. However, fracture healing should be preferred, whenever possible.

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Conflict of interest I (we) certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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