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Biomechanical analysis of a short femoral stem used in revision total hip replacement of a standard femoral stem

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Short-stem total hip arthroplasty (SHA) has become popular because it preserves femoral bone stock and enables the use of short femoral stems in revision total hip arthroplasty (THA). However, no study has evaluated whether a short stem in revision THA, replacing a standard stem, can provide adequate primary stability to facilitate osseous integration. In this biomechanical study, a metaphyseal anchoring SHA (Tri-Lock BPS) stem and a standard THA (Corail) stem were implanted into ten composite femurs and loaded dynamically from 300 to 1700 N with 1 Hz. Primary stability was estimated using three-dimensional (3D) micromotions at five points around the bone–implant interface. A revision scenario was then established by removing the standard stem and implanting the same Tri-Lock BPS stem, with subsequent measurements of 3D micromotions. In the primary scenario, no significant differences in 3D micromotions were noted between the short and standard stems at most of the test points. Compared with the Corail group, the Tri-Lock BPS group presented significantly greater 3D micromotions only at the lateral point of the distal femur (P5: Tri-Lock BPS 32.9 ± 7.54 µm vs. Corail 25.1 ± 4.32 µm; $p = 0.011$). In the revision scenario, no significant differences in the 3D micromotions were noted between the primary and revision Tri-Lock BPS stems at all test points. Our results show that the SHA (Tri-Lock BPS) offers good primary stability, which is similar to that of the standard THA (Corail). The Tri-Lock BPS stem obtained comparable stability in this revision scenario as in the primary scenario; therefore, it can be assumed that the Corail standard stem can safely be revised with a Tri-Lock BPS short stem.

Keywords Total hip replacement, Short stem, Revision, 3-dimensional micromotion, Primary stability

Short-stem total hip arthroplasty (SHA) has gained increasing popularity in recent years because it is a bone-conserving procedure for more active or younger patients undergoing total hip arthroplasty[1,2]. Various design-specific short stems with individualized anchorage types have been introduced[3,4], and the excellent outcomes of the first SHA have been revealed in multiple studies[4–7]. Compared with a standard cementless stem in conventional total hip arthroplasty (THA), a short cementless stem may have benefits in terms of lower stress shielding with a reduction in proximal bone remodelling[8,9], bone preservation[3,10], minimally invasive surgical techniques with a reduction in soft tissue disruption[11,12], and ease of revision surgery[13,14]. An additional advantage is that it allows the use of a short stem as a revision prosthesis, preserving critical bone for hip revision, particularly in younger patients who may need further revision[15,16].

However, to date, evidence that short-stem implants can be safely used as revision prostheses in THA is lacking. Only a few reports have described the clinical outcomes of the use of short stems as a revision femoral implant[15,16]. There are also some case reports on the revision of fractured stems with the benefits of avoiding distal cement removal in the femoral canal, reducing surgical time and blood loss, and allowing easier femoral revision[17–19]. However, no study has yet demonstrated that a stable anchorage of a cementless short stem with

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sufficient stability can be acquired in such a revision scenario. The major reason for the absence of evidence is that most short implants have only been used in recent years; in particular, long-term follow-up of short stems with noteworthy data as a revision component is not currently available[4,15,16]. In light of this, it seems highly necessary to assess the biomechanical stability of a short stem when it is applied in revision THA procedures and this is also the novel concept in this study because there are no other studies focusing on this topic.

The stability of an implant depends on a combination of primary stability (mechanical stability) and secondary stability (biological stability). Primary stability may affect the implant–bone interface condition and thus influence the mechanical stimuli for bone remodelling in the resurfaced femur[20]. The primary stability of a prosthetic implant may be defined as the three-dimensional motion at the interface between pairs of points consisting of the layer of bone-forming cells closest to the implant and their corresponding point on the prosthetic surface. Two different types of motion can be characterized: reversible movement of the implant under a cycle of loading (termed micromotion) and irreversible movement of the implant within the femoral canal over time (termed migration)[21]. In cementless total hip arthroplasty (THA), primary stability is required to avoid micromotion and aseptic loosening, the main reason for early revision[22]. Insufficient primary stability with high micromotion greater than 150 µm may lead to fibrous tissue at the bone–implant interface and consequently cause implant failure or loosening[23,24]. Thus, we chose immediate biomechanical stability to predict long-term effects.

Therefore, the present biomechanical analysis aimed to assess whether aseptic failure of a standard THA stem can safely be reversed using a short SHA stem. We assumed that a cementless short SHA stem has the ability to provide adequate primary stability in such a revision situation to allow osseous implant integration (Fig. 1 and 2).

Results

All the implantations and measurement procedures were successfully conducted. The 3D micromotion values at all the test points for both the primary and revision scenarios were less than the threshold value for osteointegration of 150 µm (PMID). The 3D micromotion results are shown in Figs. 4 and 5.

Primary implantation (Tri-lock BPS and Corail)

In the primary scenario, no significant differences in 3D micromotions were observed between the Corail and Tri-Lock BPS stems for most of the points: proximal points P1 (percentage value of the difference = 9.8%; $p = 0.306$) and P2 (percentage value of the difference = 0.8%; $p = 0.951$), middle point P3 (percentage value of the difference = 11.4%; $p = 0.269$), and distal points P4 (percentage value of the difference = 17.7%; $p = 0.156$) and P5 (percentage value of the difference = 23.1%; $p = 0.016$) (Figs. 3 and 4). The Tri-Lock group revealed significantly higher 3D micromotions than those of Corail group only in the distal part at P5 (P5: Tri-Lock 32.9 ± 8.2 µm vs. Corail 25.1 ± 4.3 µm; percentage value of the difference = 23.1%; $p = 0.016$) (Figs. 4 and 5).

Revision scenario (tri-lock BPS and tri-lock BPS revision stem)

In the revision scenario, no significant differences in 3D micromotion were noted between the primary Tri-Lock and Tri-Lock as revision stems at any of the test points: proximal points P1 (percentage value of the difference = 14.4%; $p = 0.141$) and P2 (percentage value of the difference = 12.9%; $p = 0.292$), middle point P3 (percentage value of the difference = 12.5%; $p = 0.134$), and distal points P4 (percentage value of the difference = 17.9%; $p = 0.239$) and P5 (percentage value of the difference = 2.2%; $p = 0.887$) (Figs. 4 and 5).

Discussion

This in vitro study provides the biomechanical rationale that aseptic failure of a standard THA stem can be safely reversed with a short SHA stem. The results indicate that the micromotions of the Tri-Lock BPS stem utilized to revise the standard stem are comparable to those of the Tri-Lock BPS stem used in the primary scenario. Moreover, the acquired data demonstrate a stable revision scenario that provides sufficient primary stability for good osseous integration of implants.

An evaluation of the primary scenarios of the Tri-Lock BPS SHA and Corail THA revealed sufficient primary stability. The Tri-Lock BPS short stem revealed 3D micromotions under the threshold value of 150 µm, which is considered an important prerequisite for osseous integration[23]. Pilliar et al. and Jasty et al. reported that implants subjected to more than 150 micrometres of motion were surrounded by dense fibrous tissue, resulting in aseptic loosening of the cementless implant[23,24]. These results are consistent with previous biomechanical studies showing desirable primary stability for Tri-Lock stems[25,26]. Tatani et al. used the digital image correlation (DIC) technique for analyzing the strain distribution of Tri-Lock BPS implant, and found that DIC technique was a good preclinical evaluation tool of the biomechanical behavior induced by implants and also identified its potential for experimental FE model validation. Additionally, Tri-Lock BPS implant can reduce the stress shielding in the distal region of femur[27]. The available clinical data with medium-term follow-up further support these biomechanical data. Guo et al. evaluated 84 Tri-Lock BPS SHAs after a mean of four years and reported no occurrence of aseptic loosening of the implants[28]. A retrospective outcome review reported a revision rate of 0.8% after a mean of 8 years in a cohort of 2,040 Tri-Lock BPS SHAs[7].

The good primary stability of the Corail THA found in this study is consistent with the findings of previous studies[29,30]. Kistler et al.[29] and Glismann et al.[30] conducted in vitro biomechanical studies and demonstrated sufficient primary stability of the coronary stem in THA with 3D micromotions less than 150 µm. The good biomechanical stability is consistent with the excellent long-term survival of this stem, which has been reported in multiple studies[31–33]. According to a retrospective study performed by Vidalain JP[31], the survival rate of patients treated with the Corail stem was 96.4% after 23 years. Almeida et al.[32] reported no aseptic loosening of

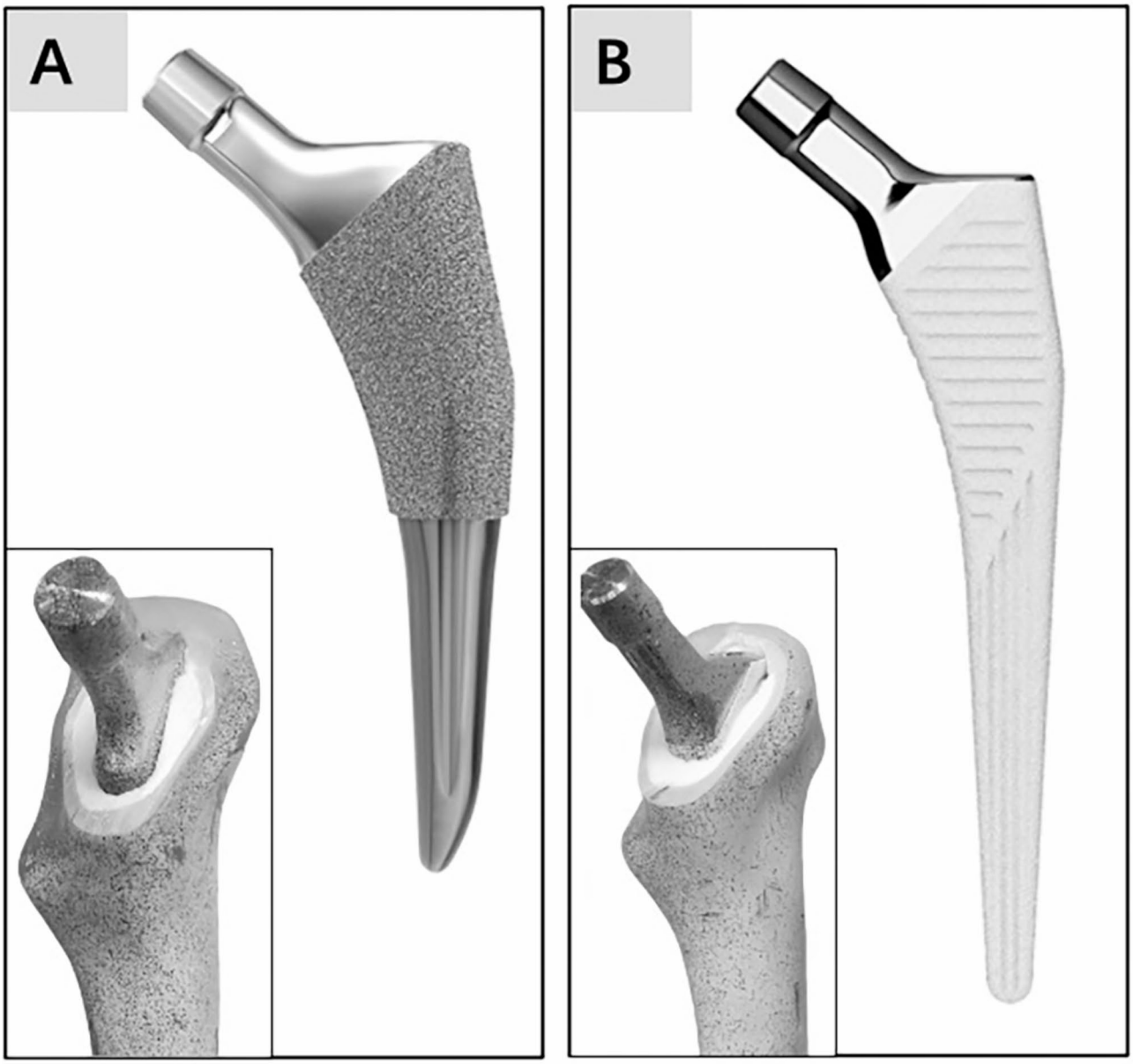

Fig. 1. (**A**) Implantation of the metaphyseal anchored SHA stem (Tri-Lock BPS, DePuy Synthes) and (**B**) implantation of the standard THA stem (Corail, no collar, DePuy Synthes).

the femoral component in a series of 301 coronary THA procedures after 16.9 years. Louboutin et al. evaluated 133 Corail THAs after a mean of 12 years and reported 98% stem survival for revision due to aseptic loosening[33].

Revising the Corail standard implant with the Tri-Lock BPS stem as a revision implant revealed no significant differences in 3D micromotions between the revision and primary Tri-Lock BPS settings at any of the tested points. This result supports the assumption that adequate bone stock is reserved in the metaphyseal femur to anchor a metaphyseal anchoring Tri-Lock BPS implant in a revision after aseptic failure of coronary THA. However, it is important to note that this in vitro analysis is only responsible for cases without the occurrence of large defects in the bone stock or bone fractures after removing the coronary stem.

A comparison of the present biomechanical results with clinical data is challenging because, to our knowledge, only a few clinical studies have described the outcome of revision procedures using short stems as a femoral component[15,16]. Mauch et al.[15] evaluated 31 patients utilizing Optimys short stems for revision THA after a mean of 2.3 years and revealed that stem fixation was stable in all patients without aseptic loosening. Liu et al. evaluated 381 Tri-Lock BPS SHAs after a mean of 5.9 years and reported a low aseptic loosening rate of the femoral stem (96.8%). There are also case reports on the revision of fractured stems using short femoral stems, which reported a radiologically stable, well-fixed implant in SHAs after 2 to 3.5 years[17–19]. Although good clinical efficacy is associated with our biomechanical results, long-term clinical and radiological follow-up is needed to draw a definite conclusion.

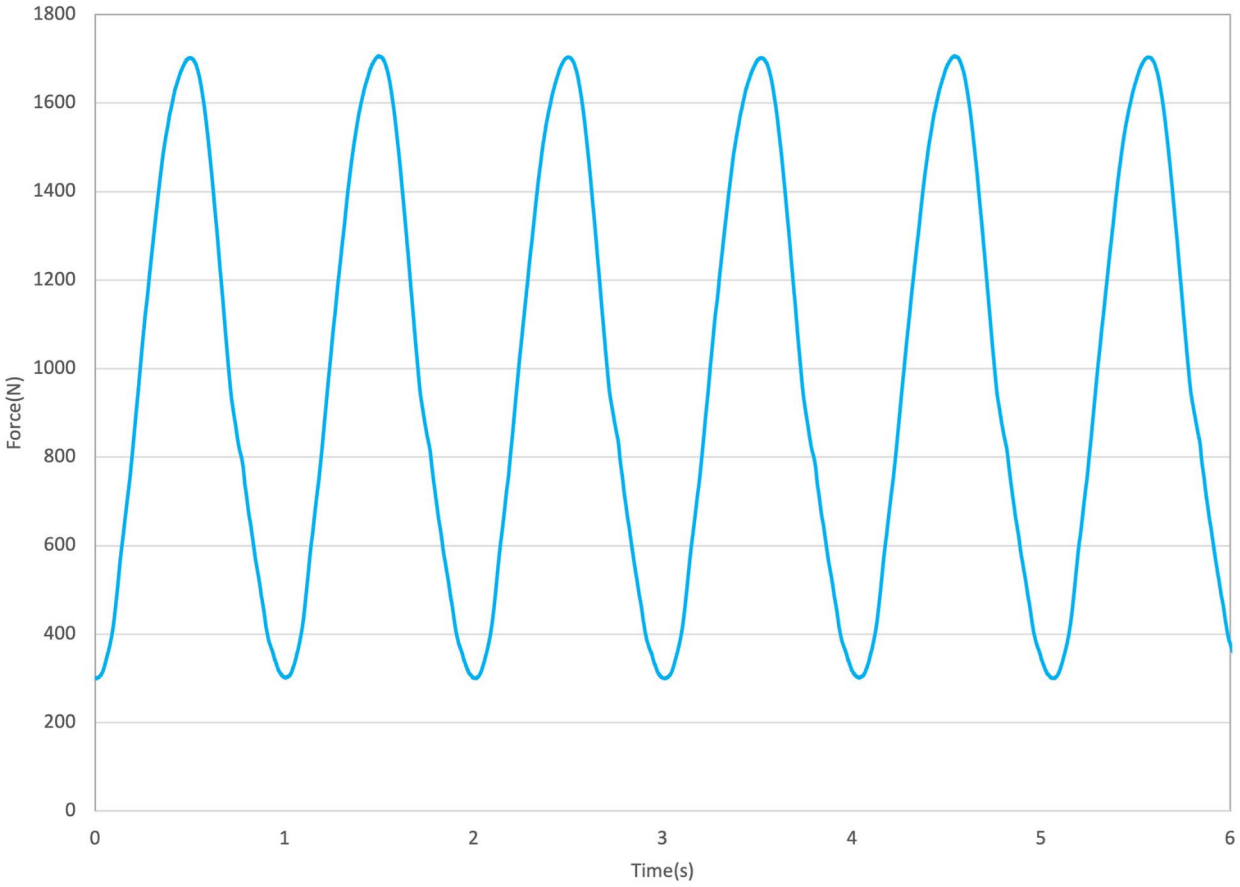

Fig. 2. The load profile of the setup.

Further limitations of the present study must be discussed. First, composite sawbones were chosen rather than cadaveric bones. The absolute micromotion values obtained from the mechanical testing of sawbones are not equal to those of in vitro cadaveric models, which might imitate superior in vitro behaviour. However, the use of composite bone is considered an effective method for exploring the biomechanical characteristics of implanted femurs with a uniform structure and highly reproducible results[34,35]. Second, the femoral stems are cementless implants that require osseous integration, whereas the present study focused only on primary fixation and did not consider long-term biological fixation. Finally, the in vitro biomechanical studies do not completely represent the in vivo scenario because the sawbones highly mimic human bones but not human bones, thus, the results should be further verified in a clinical setting.

Conclusions

The results of this study demonstrate that the metaphyseal anchored Tri-Lock BPS SHA provides good primary stability comparable to that of conventional Corail THA. The data also suggest that in a revision scenario, the conventional Corail stem can be safely revised with a cementless Tri-Lock BPS stem and acquire similar primary stability as a Tri-Lock BPS stem in a primary scenario. However, it is also worth noting that this study only provides a biomechanical analysis, and the results should be verified in a clinical setting.

Materials and methods

Implants

For standard THA, a cementless proximal anchored Corail standard stem (Corail, DePuy Synthes, Warsaw, Indiana, USA) with good long-term clinical results was used (corail size 13,135°, no collar) (Fig. 1)[36,37]. The stem is straight with a stepped geometry and collarless with the concept of proximal anchorage. It has a proximal trapezoidal cross-section and a tapered distal stem with a fully hydroxyapatite-coated (150 micron thickness) nonporous forged titanium alloy stem.

For SHA, a metaphyseal anchored Tri-Lock BPS short stem (Tri-Lock Bone Preservation Stem, DePuy Synthes, Warsaw, Indiana, USA) was evaluated (Tri-Lock BPS size 6, 135°) (Fig. 1). The rationale for choosing this stem is that although the high-offset Tri-Lock BPS short stem has been widely used, few studies have explored its biomechanical results[38]. The stem is a cementless, bone preservation stem that is a tapered wedge and collarless

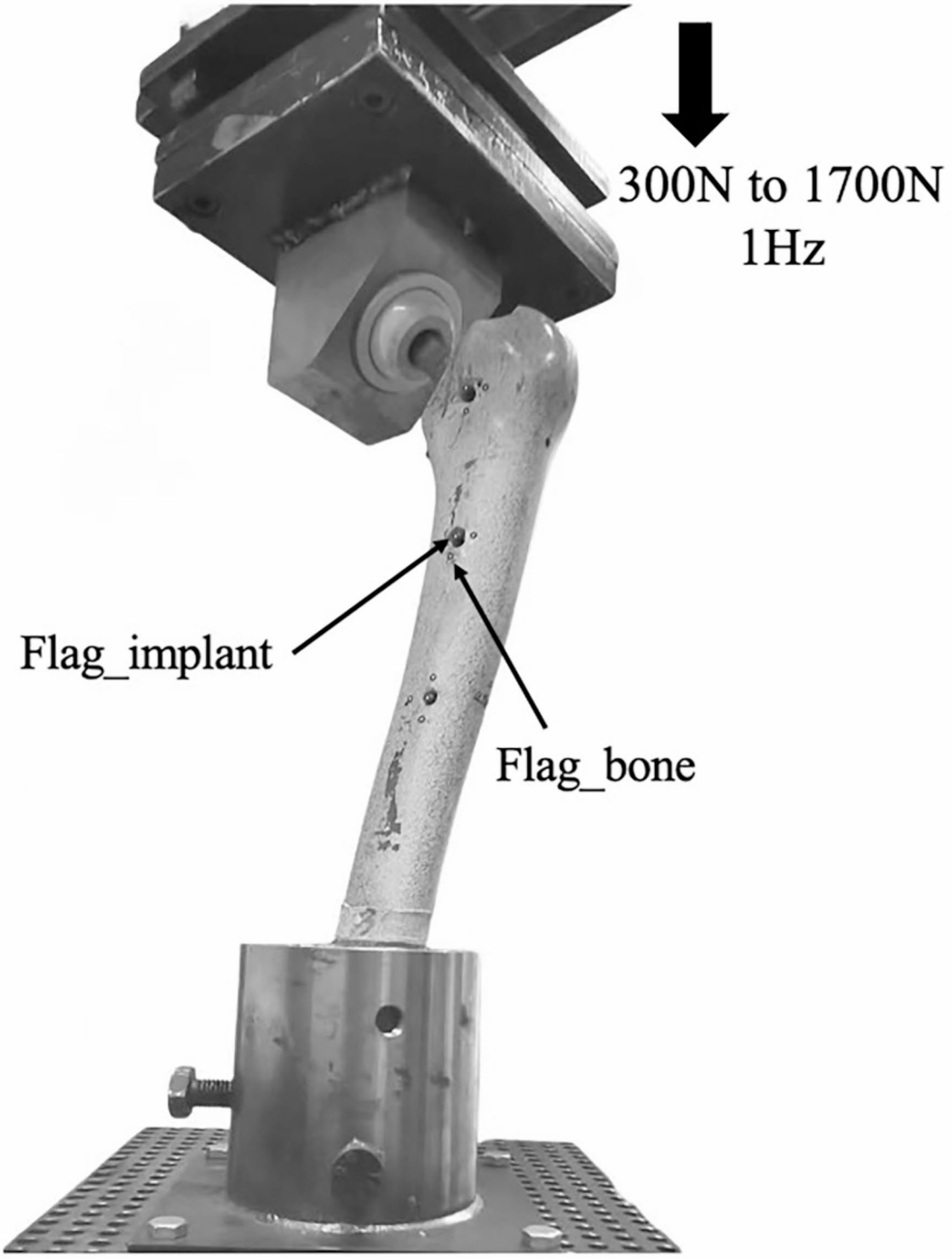

Fig. 3. Setup configuration for measuring 3D micromotions at the bone–implant interface.

and based on the concept of metaphyseal anchorage[10,39]. The distal part is polished, and the proximal part has a highly porous and roughened coating (Gription).

Specimen preparation

Both cementless implants, the Corail THA and Tri-Lock BPS SHA, were implanted without cement in ten composite femurs (Model 3406, left side, Size L, Sawbones Pacific Research Laboratories, USA). All the implantations were performed by a senior orthopaedic surgeon specializing in hip arthroplasty under fluoroscopy

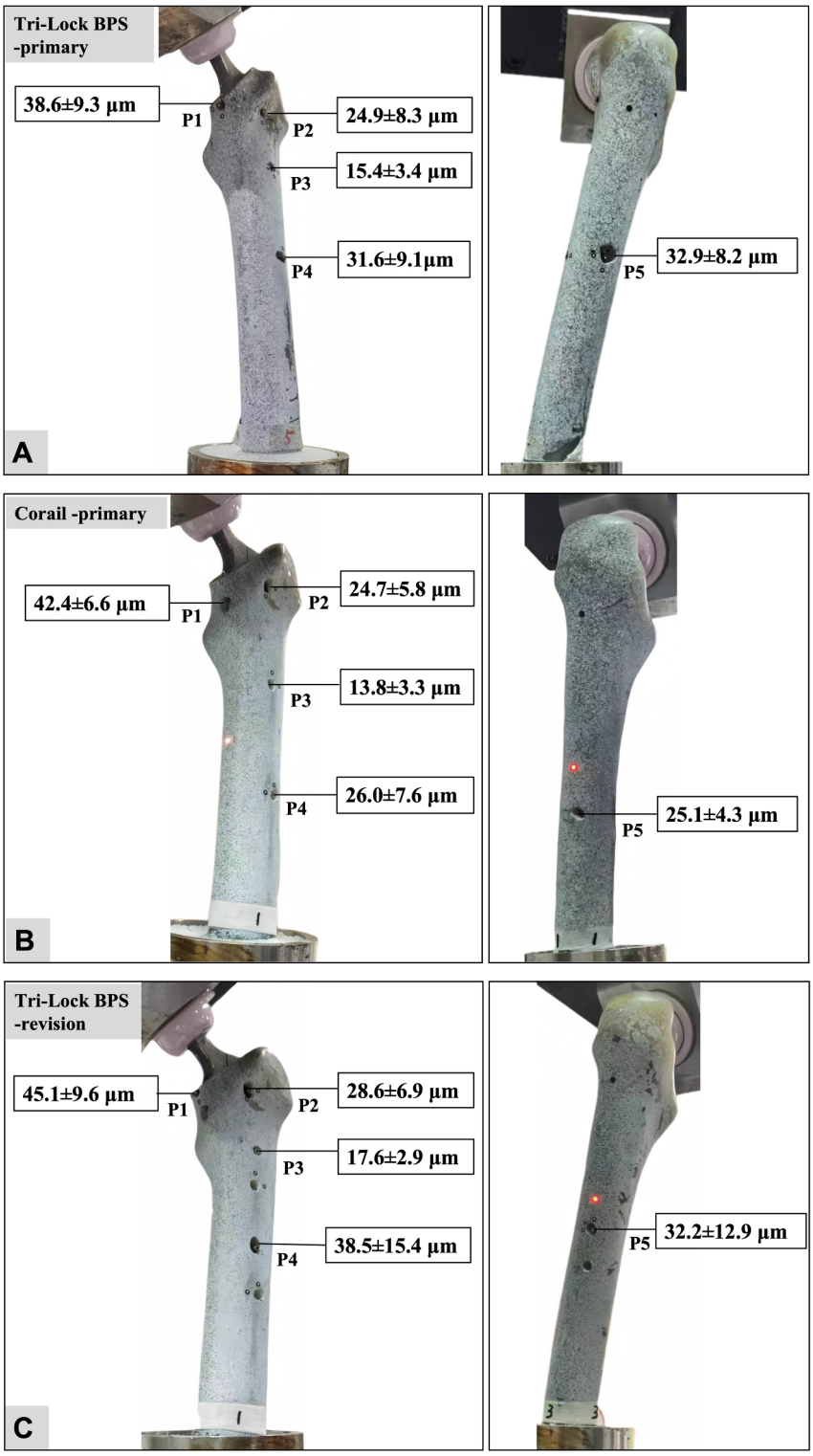

Fig. 4. 3D micromotions determined for (**A**) the primary situation of the Tri-Lock BPS short stem (Tri-Lock BPS primary), (**B**) the primary situation of the Corail standard stem (Corail primary), and (**C**) the revision of the Corail standard stem with a Tri-Lock BPS short stem (Tri-Lock BPS revision). Measurements were registered at 5 points: P1 = medial-proximal, P2 = ventral-proximal, P3 = ventral-median, P4 = ventral-distal, and P5 = lateral-distal.

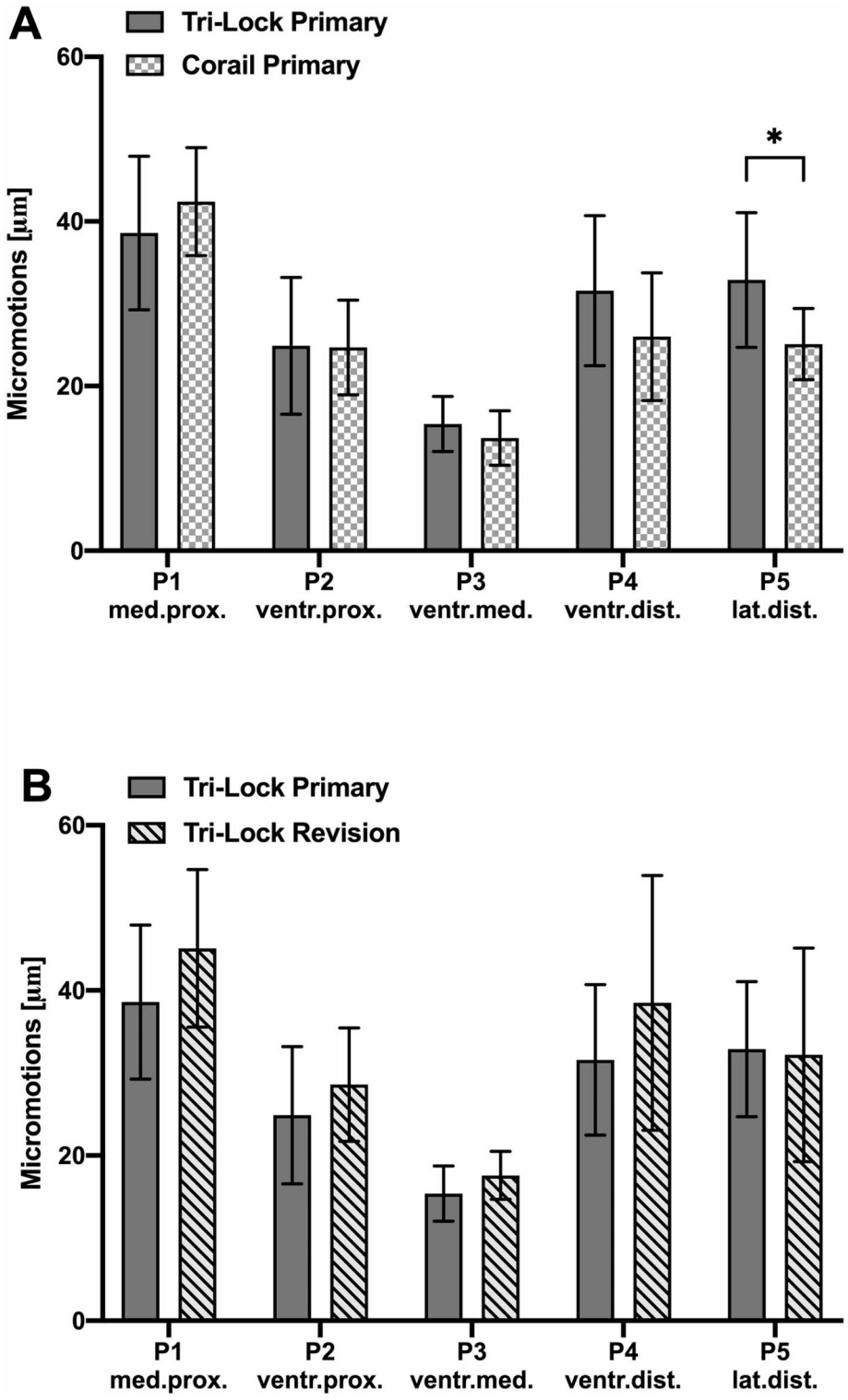

Fig. 5. Direct comparison of the 3D micromotions for the 5 points. (**A**) Tri-Lock BPS-primary vs. Corail-primary stem. (**B**) Tri-Lock BPS-primary vs. Tri-Lock BPS-revision stem. Significantly higher 3D micromotions were not registered for the Tri-Lock BPS revision stem after revision of the Corail standard stem. The asterisk (*) indicates a significant difference from Tri-Lock BPS-primary ($p < 0.05$).

according to the manufacturer's instructions (Fig. 1). The composite femur was cut 20 cm below the trochanter minor and then firmly embedded in a metal pot (Technovit 3040, Merck, Darmstadt, Germany). To imitate a physiological loading condition in light of the in vitro data from Bergman et al., all the samples were located at an adduction angle of 16° (coronal plane) and a flexion angle of 9° (sagittal plane)[40]. All the tests were conducted utilizing a ceramic head with a medium length and a 32 mm diameter.

Loading procedure

All the tests for measuring the primary stability were conducted under the same loading conditions. To obtain physiological adapted loading conditions, the test parameters were adjusted to the in vivo measurements of a patient with a bodyweight of about 70 kg, walking on level ground[40,41]. A sinusoid dynamic load with an amplitude between 300 and 1700 N at a frequency of 1 Hz was applied similar to former studies described by Fottner et al.[42] (Fig. 2). The force was generated using an MTS 809 hydraulic testing machine (MTS Systems Corporation, MN USA) (Fig. 3). These physiological loading conditions were also utilized in previous studies, as we described previously[43,44]. To avoid transverse shear stress, the load was applied to the ceramic head (32 mm, size M) utilizing a ceramic liner mounted on an x–y table. The implants were all preconditioned under the designed loading pattern for 10 min (600 cycles) before the first measurement.

Micromotion registration

To determine the primary stability of the implants, 3D micromotions were detected using an optical 3D motion tracking system (ARAMIS Professional 6 M, GOM GmbH, Braunschweig, Germany). Therefore, the marker flag was attached to a metal rod (Flag_implant) that was securely affixed to the implant and transferred the micromotions from the bone–implant interface to the flags through drilling holes on the sawbones, and the relative marker flags (Flag_bone) were attached to the composite femur along the edges of the holes to detect the relative bone–implant micromotion (Fig. 3). The marker flags attached to the metal ring and the relative marker flags attached to the composite femur were at the same level as the test point, thus enabling the reduction of errors from bone deformation. The micromotion measurement were conducted by analyzed the relative displacement between flag_implant and flag_bone. The calculation of relative movement at the bone–implant interface was performed along each coordinate axis (x, y and z) and subsequently converted into 3D micromotion[45,46]. The samples were preloaded, and every single point was tested for 30 cycles (30 s) during dynamic loading. The time point chosen for the micromotion measurement was at the maximum loading time. The data for each test point were an average of 30 cycles and were considered micromotions[44,45].

Primary setting (Tri-lock BPS and Corail stem)

In the primary implantation setting, the 3D micromotions were measured at 5 measurement points (P1-5) for both stems, which were located at three different levels of the composite femur, including 1 on the medial side (P1: medial-proximal), 3 on the ventral side (P2: ventral-proximal, P3: ventral-median and P4: ventral-distal) and 1 on the lateral side (P5: lateral-distal) (Fig. 4A–C). The proximal registrations P1 and P2 were placed at the level of the trochanter minor. The distal registrations P4 and P5 were positioned approximately 1 cm above the tip of the stem. The middle registration P3 was positioned medianly between the proximal and distal levels. Owing to the different sizes and shapes of the short and standard implants, the points of the standard THA and SHA do not have identical locations.

Revision setting (tri-lock BPS and tri-lock BPS revision stem)

For the revision setting, the coronary standard stem of THA was removed after all 3D micromotions were tested. The composite femur was then prepared for the Tri-Lock BPS short stem as a revision stem. The preparation was conducted as described in the primary Tri-Lock BPS scenario with an osteotomy, stepwise broach, and implantation of the same Tri-Lock BPS stem (size 6). All the tests for the revision Tri-Lock BPS (Tri-Lock BPS-revision) stem were performed under the same set of procedures as those of the primary Tri-Lock BPS stem with identical test points.

Statistics and analysis

The data are presented as the means ± standard deviations (SDs). GraphPad Prism 5 (GraphPad Software, Inc., La Jolla California, USA) was used for the statistical calculations and graphs. After evaluation for normality using the Shapiro–Wilk test, an unpaired Student's t test was performed to compare the Corail vs. Tri-Lock stems in the primary scenario and the Tri-Lock-primary vs. Tri-Lock-revision stems in the revision scenario. A p value < 0.05 was considered to denote significance.

Data availability

Data are available from the corresponding author upon reasonable request.

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Author contributions

YSG made the study conception and design; YSG. ZW. YC, XH, FL and DL made acquisition, analysis and/or interpretation of data; YSG made drafting/revision of the work for intellectual content and context; YSG prepared Figs. 1, 2, 3 and 4; YSG, ZW, XH, FL, JL, HZ and DL made final approval and overall responsibility for the published work. All authors read and approved the final manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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