JSES International 9 (2025) 212–218

Contents lists available at ScienceDirect

JSES International

journal homepage: www.jsesinternational.org

Short humeral stem in total shoulder arthroplasty does not jeopardize primary implant stability

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ARTICLE INFO

Keywords:
Shoulder prosthesis
Uncemented humeral component
Total shoulder arthroplasty (TSA)
Biomechanical test
Short-stem
Primary torsional stability
Implant micromotion
Pull-out

Level of evidence: Basic Science Study; Biomechanics

Background: The trend of the modern humeral components in total shoulder arthroplasty is toward shorter and shorter humeral stems. However, the question remains whether short uncemented stems can provide the same implant stability as long stems. This study aimed to evaluate and compare the torsional primary stability and the pull-out extraction force of both a long and a short version of the same stem.
Materials and methods: Ten humeral components (five long stems and five short stems) were press-fitted into ten synthetic composite humeri. A torsional load was applied to generate the most critical loading condition. The specimens were loaded with 100 cycles between 2 Nm and 10 Nm, at 1 Hz. A 3D Digital Image Correlation system was used to measure the relative displacement between the prosthesis and the host bone during the test. After completing the torsional test, the pull-out force was measured. Differences between the long and short stem on the biomechanical parameters (permanent migrations, inducible micromotion, and extraction force) were tested with the nonparametric Mann-Whitney test ($P < .05$).
Results: The main rotational inducible micromotion was around the craniocaudal axis. No significant differences were found between the rotational permanent migrations of the long and short stem around the craniocaudal ($P = .421$), anteroposterior ($P = .841$), and mediolateral axes ($P = .452$). No significant differences were found between the rotational inducible micromotions of the long and short stem around the craniocaudal ($P = .222$), anteroposterior ($P = .420$), and mediolateral axes ($P = .655$). No significant differences were found between the permanent translations of the long and short stem along the craniocaudal ($P = .341$), anteroposterior ($P = .420$), and mediolateral ($P = .429$) directions. No significant differences were found between the translations of the long and short stem in terms of inducible translation in the craniocaudal ($P = .547$), anteroposterior ($P = .999$), and mediolateral axes ($P = .285$). Similar extraction force ($P = .35$) was found.
Discussion and Conclusion: No statistically significant difference was found between the long-stem and short-stem implants. These results show that short uncemented stems can provide adequate primary mechanical stability. As the long-stem version of this stem is already clinically used, the present findings suggest that the short version can be reasonably expected to deliver similar outcomes in terms of implant stability.

Over the last few years, total shoulder arthroplasty, and especially the humeral component, has undergone substantial improvements.[9,15,26] Recent designs mostly rely on uncemented fixation, reporting satisfactory clinical outcomes.[20] However, complications after total shoulder replacement are observed in between 8% and 24% of cases.[27] While most complications involve the glenoid component, loosening of humeral stems, stress shielding, and periprosthetic fracture have also been reported.[1,5,16] Indeed, the trend in modern humeral components is toward shorter and shorter stems.[4,13] Shorter stems offer several advantages over the long ones. Firstly, the use of shorter and shorter stems enables a less-invasive soft-tissue-sparing surgical approach.[14] Short stems also grant preservation of bone stock, which is fundamental in case revision surgery is needed.[18] Moreover, short-stems can be expected to reduce stress shielding if compared to longer stems, thus reducing adverse bone remodeling.[3,13,24]

This is a biomechanical study involving solely synthetic bone models. No patients and no tissue was involved. So, ethics approval does not apply.

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https://doi.org/10.1016/j.jseint.2024.09.021
2666-6383/

However, the question remains whether short uncemented stems can provide the same implant stability as long stems. One of the main factors to achieve long-term fixation of an uncemented implant is the primary mechanical stability of the implant in the early postoperative period.

The micromotions of cemented stems under cyclic loading up to failure were tested by Cuff et al, focusing on the effects of proximal bone loss.[7] The effect of the stem length on the torsional stability was evaluated showing a similar mode of failure.[25] However, as they applied a monotonic ramp, their biomechanical study simulated the effect of a single overloading, while they did not address the effects of cyclic loading-unloading, which is the main factor associated with aseptic loosening. To the authors' best knowledge, no biomechanical study addressed the effect of the humeral stem length on the implant stability under a cyclic loading representative of the typical postoperative period.

Thus, this paper aims to evaluate if a short stem could be a reliable option instead of a long stem and if it can provide the same primary stability. In particular, i) the torsional primary stability and ii) the pull-out extraction force of both the short and long stem were measured and compared.

Materials and methods

Preparation of the humeri

Ten left synthetic composite humeri (medium Sawbones 4th generation, 3404 17 PCF; Pacific Research Labs, Vashon Island, WA, USA) were used to grant repeatability and reproducibility of the experiment and to enable a direct comparison between implant types. These humeri consist of a shell reinforced with short-glass fibers to mimic the mechanical properties of the cortical bone. The inner part is made of a polyurethane foam core designed to emulate the mechanical properties of the cancellous bone.[10] The mechanical properties of the materials of these models can be found in Matweb.[17]

The humeri were cut 150 mm from the greater tubercle, and their distal ends were embedded in an aluminum pot with acrylic cement (Restray NF, SPD Italia, Milano, Italy). The procedure, technique, and instrumentation used to implant both the long stems and the short stems were the same as those used in the operative setting and recommended by the manufacturer.

Implants

To compare the primary stability of the prototype short stem with the existing long-stem version (DIXI Shoulder System; Clover Orthopedics, Milan, Italy), five long-stems and five short stems were implanted in ten composite humeri, and tested:

- if the long-stem version of the DIXI stem is already clinically used. This device can be used both as an anatomical and as a reverse prosthesis. It is designed to achieve implant stability by filling the humeral metaphysis, and also by purchasing contact with the cortical bone in the endosteal canal, in the proximal portion of the humeral diaphysis. For this reason, the long-stem features a distal interchangeable part of different sizes (S, M, and L). The proximal part of the long stem is designed to fit the geometry of the metaphysis and is also available in different sizes.
- if the prototype short stem consisted of the very same proximal portion as the long-stem and featured a hemispherical distal tip (instead of the stem provided for the long stem). Thus, the stability of the short-stem prototype mainly relies on the support of the cancellous bone in the metaphyseal region of the humerus.

Both the long and short stems are computer numerical control-machined and are made of titanium alloy (Ti6Al4V), with a coating of titanium (Ti-Pore coating). The procedure, technique, and instrumentation used to implant both the long and the short stems were the same as those used in the operative setting and recommended by the manufacturer. The surgeons selected the optimal size of both the long and the short stems from a computed tomography scan of the composite bone. For the humeri used in this study, size 13 was chosen for the proximal component for both the long and the short stems. For the long stem, an S-size distal part was chosen to fit and fill the diameter of the humeral canal.

To implant the prosthesis with a 135° neck-shaft angle, the humeral head was cut (Fig. 1*A*) with a saw guided with a dedicated cutting mask similar to.[25] The proprietary reamers were then used on the medullary canal, followed by rasps of increasing size (diameter from 9 mm to 13 mm) (Fig. 1*B*). Finally, the stem was press-fitted into the bone using the stem holder (Fig. 1*C*).

The implants were CT-scanned to confirm that the stems adequately filled the metaphyseal region (both long and short stems) and the distal portion (long stems only) (Fig. 2).

Biomechanical cyclic test to assess the primary stability

Based on the shape of the humeral implant, loosening can be expected to occur with a rotation of the stem inside the medullary canal, similar to what happens in hip implants.[11,25] Indeed, the largest force component delivered to the humeral head and generating torsion around the long axis of the humerus is directed from the posterior toward the anterior.[2,31] While such loads were measured in patients implanted with anatomical prostheses, similar kinematics and loads can be expected for physiological motor tasks if a reverse prosthesis is used. Therefore, in this biomechanical study, a torsional load was applied, similar to previous biomechanical studies.[7,25] To generate the most critical loading condition, no axial compression was applied, as this would contribute to stabilizing the implant.

A multiaxial testing machine (Mod. MAS2-S; developed by MIB4.0, Bologna, Italy) equipped with 6 degrees of freedom load cell (HBM, Darmstadt, Germany), with a full scale of 150 Nm in torsion was used. The specimens were fully constrained distally, and torsion was applied proximally (Fig. 3) through a telescopic double cardan joint.

A preload of 2 Nm was applied. Then, the specimens were loaded with 100 sinusoidal cycles in load control between 2 Nm and 10 Nm, at 1 Hz. A 3D Digital Image Correlation system (Aramis Adjustable 12M; GOM, Zeiss, Germany) was used to measure the relative displacement between the prosthesis and the host bone throughout the cyclic torsional test. Images were acquired by 2 cameras (12 MegaPixels 4096 × 3000 pixels, 8 bit) equipped with high-quality 75 mm lenses (f 4.5; Titanar B, Schneider-Kreuznach, Germany). The distance between the specimens and the cameras was set to 1100 mm, with a field of view of 210 mm × 130 mm. A set of glossy, passive circular markers (type: 0.8 mm; GOM Aramis, Braunschweig, Germany) were glued on the prostheses and the humeri to track the prosthesis displacements with respect to the bone. Before each test, the digital image correlation system (DIC) was calibrated using a calibration target (type CP40/200/101296; GOM Aramis, Braunschweig, Germany). This procedure allowed to define the physical dimension of the measurement volume, the correction of the distortions due to lenses, and the compensation of the parallax effects.[22] In order to reduce the amount of data to be stored and analyzed, one cycle out of every ten cycles was acquired by the DIC system.

To quantify the systematic and random errors affecting the DIC-measured displacement, a zero-displacement analysis was

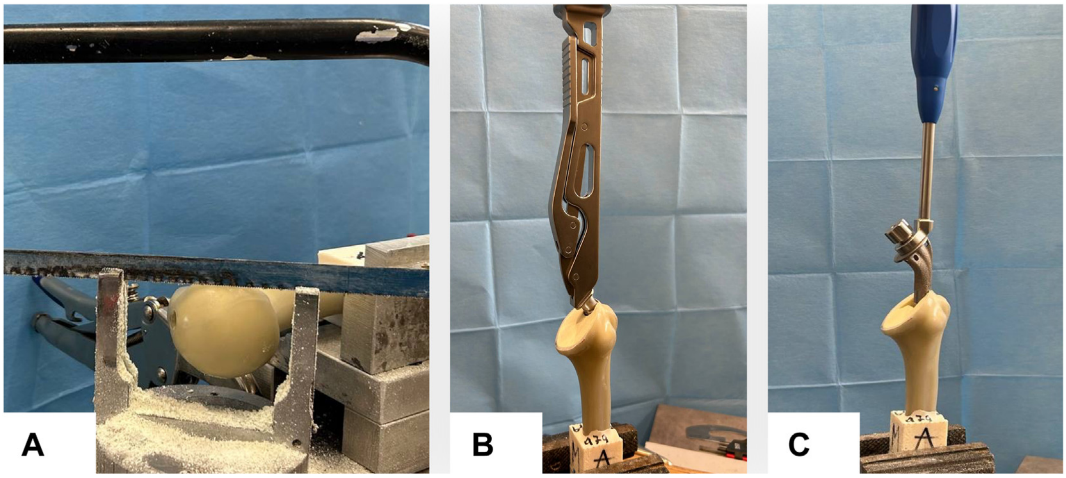

Figure 1 Overview of the preparation of the specimens. A similar procedure was used both for the long stems and for the short stems: (**A**) cutting of the humerus head with an angle of 135° from the humeral diaphysis; (**B**) rasping of the medullary canal; and (**C**) press-fit implantation of the stem.

Figure 2 Pictures of the stems used: long-stem on *Top* and short-stem at the *Bottom* (their length, in millimeters, is indicated). The two series of five humeri implanted with the long stem and with the short stems are shown, viewed from anterior. The radiographic images on the *Right* are mediolateral projections extracted from the computed tomography scans of a long stem (*Top*) and a short stem (*Bottom*) implant.

performed using a known configuration similar to Galteri et al[8] and Palanca et al.[21] Theoretically, this computation is expected to yield a null displacement. The actual displacement values derived from this computation (in three dimensions) provide an indicator of the intrinsic measurement uncertainties.

Based on the load applied, the largest expected component of motion would be the rotation in the direction of the applied torsional load. However, as secondary components of motions would likely occur, the spatial micromotions of the prosthesis with respect to the host bone were analyzed as the displacements (three components of rotations and three components of translation) between the prosthesis (tracked through the set of fiducial markers attached) and the proximal humerus (tracked through the set of markers on the bone) throughout the test. The DIC measurements were postprocessed with a dedicated script in MatLab (2021 Edition; MathWorks, Natick, MA, USA), which computed:

- The permanent migrations, as the difference between the position of the stem inside the bone at the end of the test and at the beginning of the test (in the unloaded condition);
- The inducible micromotion, as the difference between the position of the stem inside the bone at the load peak (10 Nm) and valley (2 Nm) of each cycle throughout the test.

Pull-out test

To measure the pull-out force, a tensile force was applied to the prosthesis after completing the torsional test. A uniaxial-servo-

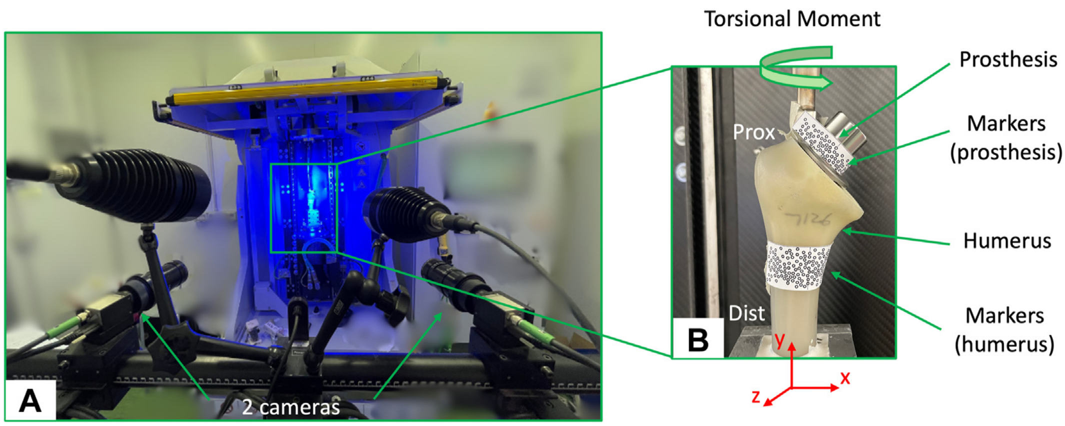

Figure 3 (**A**) Overview of the experimental setup for the torsional cyclic test: a multiaxial testing machine with 6-degrees of freedom load cell and a dedicated setup were used to apply torsion. The two cameras of the digital image correlation framed the medial, posterior, and lateral sides of the implanted specimen. (**B**) Detail of the implanted humerus: the markers to track motion are visible on the proximal portion of the humerus and on the proximal extremity of the prosthesis.

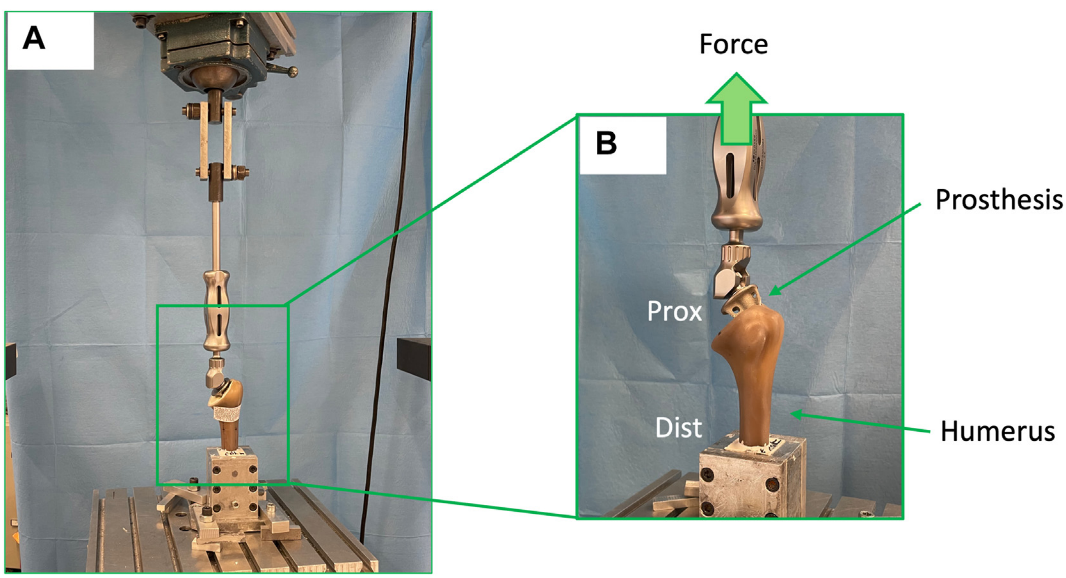

Figure 4 (**A**) Overview of the experimental setup of the pull-out test: a uniaxial-servo-hydraulic testing machine and a dedicated setup were used to apply an axial force through a spherical joint (*Top*), while the distal extremity was fully constrained. (**B**) Detail of the specimen while the stem was being pulled out.

hydraulic testing machine (8500, Instron, Wycombe, UK) was used to apply the load. The humeri were clamped distally (ensuring axial alignment). To ensure that a pure axial force was applied, the prostheses were attached to the actuator of the testing machine through a spherical joint (Fig. 4). The specimens were loaded in displacement control, with a constant rate of 0.1 mm/min. The force and displacement were recorded with a frequency of 100 Hz throughout the test. For each specimen, the pull-out extraction force was defined as the peak load recorded during the pull-out test.

Statistical analysis

Normality of the data was tested using Shapiro-Wilk statistic test. As the data did not follow a normal distribution, the difference between the long and short stem on the biomechanical parameters (i.e., for the permanent migrations, the inducible micromotions, and pull-out extraction force) was assessed with the nonparametric Mann-Whitney test. To assess if the micromotions significantly increased (loosening trend) or decreased (settling trend) or were stable, the significance of a linear regression was tested over the entire test. All the statistical analyses were performed using Prism (Prism 9.5.1; GraphPad Software, San Diego, CA, USA), with the level of significance set to 0.05.

Results

Measurement errors

The errors in measuring the implant-bone relative displacements and rotations introduced intrinsically by the DIC were estimated by measuring the roto-translation in the zero-displacement condition: any displacement and rotation value different from zero was accounted for as measurement error. The systematic error was less than 0.05° for the rotations and less than 2 micrometers for the displacements. The random error was less than 0.05° for the rotations and less than 10 micrometers for the translation. These errors

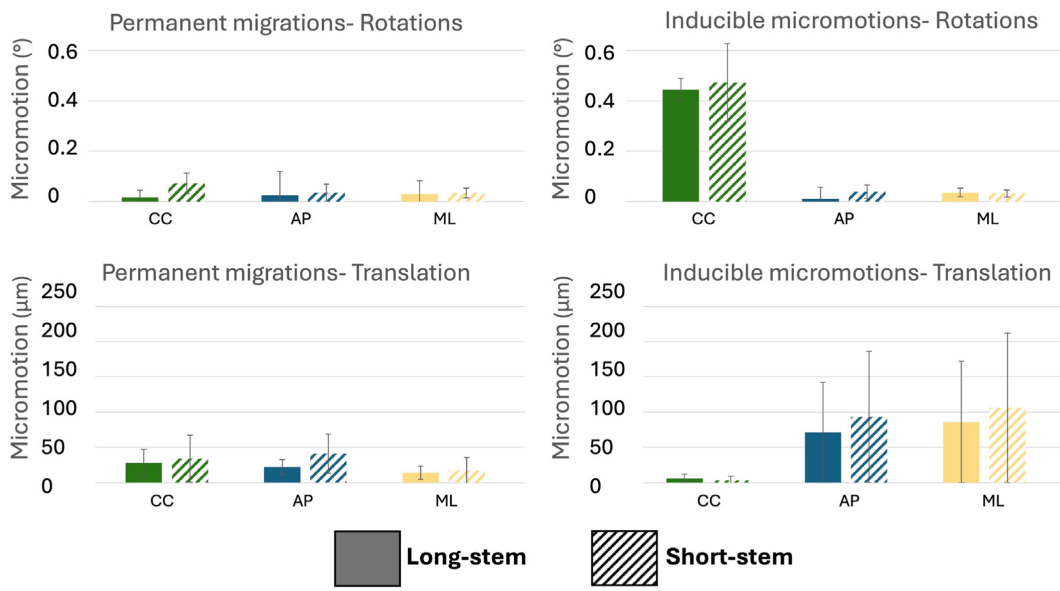

Figure 5 *Top*: Rotational stability in terms of permanent migrations and inducible micromotions around the craniocaudal, anteroposterior, and mediolateral axes for both the long and short stem (median and standard deviation of 5 specimens). *Bottom*: Translational stability in terms of permanent migrations and inducible micromotions along the craniocaudal, anteroposterior, and mediolateral axes for both the long and short stem (median and standard deviation of 5 specimens). No statistically significant difference was detected.

were one order of magnitude smaller than the threshold generally accepted for osteointegration (150 micrometers[23]). Thus, the analysis of the measurement errors confirmed that the test was suitable to discriminate between stable and unstable implants.

Primary stability under cyclic torsional load

Both for the long stem and for the short stem, the rotational permanent migrations did not exceed 0.13° (which is comparable with the measurement uncertainty of the DIC). No significant differences were found between the rotational permanent migrations of the long and short stem around the craniocaudal (P = .421), anteroposterior (P = .841), and mediolateral axes (P = .452) (Fig. 5). The main rotational inducible micromotion was around the craniocaudal axis (i.e., around the axis of application of the torque), while the other two components of rotation were lower than the measurement uncertainty of the DIC (Fig. 5). For the long stem, the rotational inducible micromotion around the craniocaudal axis was 0.45° ± 0.05° (median ± SD) while for the short-stem was 0.47° ± 0.1° (median ± SD). This difference was not statistically significant (P = .222). Similarly, no significant difference was found for the inducible rotations around the anteroposterior (P = .420) and mediolateral axes (P = .655).

For both the long stem and short stem, the analysis of the trend of the inducible rotations indicated generally either a stable trend over time (P = .063) or a decreasing trend ($P < .05$, micromotions reducing over the cycles, i.e., stabilizing, Fig. 6).

The translational permanent migrations for both the long stem and the short stem were smaller than 83 micrometers in all directions (Fig. 5). No significant differences were found between the permanent translations of long stem and short stem along craniocaudal (P = .341), anteroposterior (P = .420), and mediolateral (P = .429) directions. The largest translational inducible micromotions were observed along the anteroposterior and mediolateral axis, while inducible micromotions along the craniocaudal axis were lower (Fig. 5). No significant differences were found between the translations of long stem and short stem in terms of inducible micromotions in craniocaudal (P = .547), anteroposterior (P = .999), and mediolateral axes (P = .285).

Pull-out extraction force

Similar extraction force (P = .35) was found for the long stems (median ± SD = 1251 ± 220 N) and the short stems (1157 ± 319 N) (Fig. 7).

Discussion

Uncemented stems are becoming the gold standard in total shoulder arthroplasty. Short stems are becoming more common, as they allow to preserve bone stock and entail a less invasive surgical treatment. Despite the claimed benefits of short stems, there are some concerns about safety: the main question is whether short uncemented stems can provide the same implant stability as long stems.

From total hip and knee arthroplasty, it is clear that the early implant migration is a strong predictor for future aseptic loosening.[4] Thus, five long stems and five short stems were tested in the immediately postoperative condition, simulating the most critical loading scenario. To quantify the primary implant stability, torsional cyclic loads were applied, while Digital Image Correlation allowed to assess both the permanent migrations and the inducible micromotions between the prosthesis and the host bone, in the three components of rotation and three components of translation. Moreover, the pull-out extraction force was measured. While shoulder prostheses can be used both as anatomic and as reverse prostheses, the loading components transferred across the prosthetic shoulder joint do not depend on this detail. Therefore, the findings of this study apply to uncemented shoulder stems in general, independent of their use as part of an anatomic or reverse shoulder replacement.

The uncertainties affecting the DIC-measured permanent migrations and inducible micromotions were lower than those affecting radiostereometric analyses, which represents the standard for measuring micromotion of orthopedic implants *in vivo*.[28]

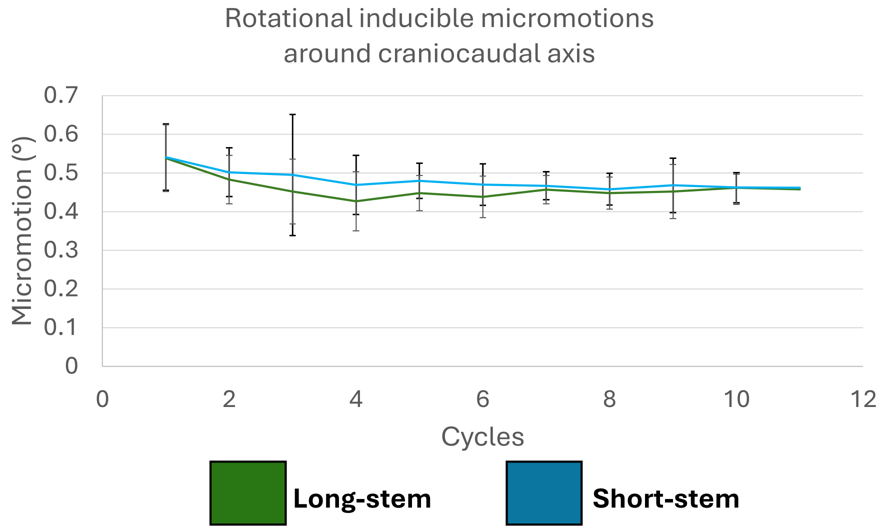

Figure 6 Trend of the rotational inducible micromotions over the cycles for a typical long stem (*Left*) and a typical short stem (*Right*). The three components of rotation (around the craniocaudal, anteroposterior, and mediolateral axes) are reported.

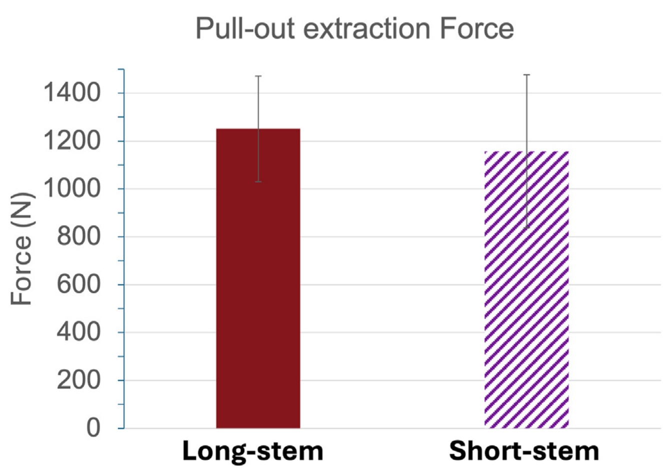

Figure 7 Comparison of the pull-out force of the long-stem and short-stem implants (median and standard deviation of the two groups).

This confirms that the sensitivity of the method presented here is sufficient to evaluate the primary stability.

The differences between the stability of the long-stem and short-stem implants were not statistically significant for all components of rotation and translation. Both the long-stem and short-stem implants granted adequate primary stability. In fact, both the permanent migrations and inducible micromotions did not exceed the threshold of 150 micrometers, which is commonly accepted for osteointegration.[23,29] Since no other similar biomechanical experiment about the primary torsional stability has been published, the relative rotation between the prosthesis and the bone can only be compared against the range found *in vivo*, with radiostereometric analysis.[4] A threshold for acceptable rotational migrations was defined as 2.00.[4] They[4] reported permanent rotations at 24 months (median of 24 implants) around the craniocaudal axis of 0.98°: this value is comparable to the values (0.45° for the long stems and 0.47° for the short stems, Fig. 5) from the present study. Similarly, they reported smaller rotations around the anteroposterior (0.12°) and around the mediolateral axis (0.09°), which are comparable to those in the present study (smaller than 0.1°). It is worth remarking that the prosthesis investigated by ten Brinke et al[4] was stemless and can therefore be expected to undergo possibly larger motions than the stemmed prostheses of the present study. Moreover, the three components of rotation of the present study were one order of magnitude smaller than the yield angle found by Ryan et al[25]: this can be expected as the implants tested in this study were expected to be stable, while they tested the implant to failure. Altogether, this comparison confirms that the results from the present study are in agreement with different studies in the literature, thus confirming the reliability of the experimental protocol.

The pull-out force of the long-stem and short-stem implants differed by less than 8% (this difference was not statistically significant). These results show that short uncemented stems can provide adequate primary mechanical stability. As the long-stem version of this stem is already clinically used, the present findings suggest that the short version can be reasonably expected to deliver similar outcomes in terms of implant stability.

The study has some limitations. Synthetic composite humeri were used for the mechanical testing. These synthetic models have been validated for providing comparable biomechanical properties to real human bones. In fact, synthetic bones have been often used in the evaluation of mechanical stability both of humeral implants[7,25] and of other implants, such as femoral stems.[6,12] Such models offer the great advantage of reducing interspecimen variability, thus allowing to better detect implant-related differences. The main disadvantage of such models is that they do not replicate the intersubject variability in terms of anatomy and tissue quality. Similarly, they do not allow testing different implant sizes. However, this study aimed to compare two different lengths of the same prosthesis under comparable conditions. Therefore, while the results on cadaveric humeri might not be the same in absolute terms, one can expect the differences and trends to be the same.

Another limitation relates to the fact that the proposed experiment can only simulate the early postoperative period, as it is not possible to simulate bone ingrowth and remodeling in an *ex vivo* experiment. This is indeed common to all *in vitro* studies where the mechanical stability of a prosthesis is measured.[6-8,19,25] However, this information is a valuable indicator of the primary stability, which is crucial for the short-term and long-term success of uncemented prostheses. In fact, implant micromotions in the early postoperative period can interfere with the process of osseointegration and affect the long-term stability.

The pull-out test does not represent a common failure scenario for humeral prosthetic stems. However, the pull-out test is used when a fast and reproducible test is needed and is often used to test other prosthetic devices (in some cases it is prescribed by the Food and Drug Administration[30]). Therefore, we included it in our study for completeness and to allow comparisons with other published studies.

Conclusions

The present study evaluated the primary stability of long-stem and short-stem shoulder arthroplasty prostheses. In particular, the possible risk that a short stem would undergo excessive micromotions within the host bone and therefore resulting in implant loosening was excluded. These tests confirmed that short stems are not susceptible to larger micromotions than long ones. Therefore, it seems that short stems can provide a safe, bone preserving, alternative in uncemented total shoulder replacement.

Acknowledgments

The authors wish to thank Francesco Vai, Matteo Vanzi and Roberto Budini for their technical support.

Disclaimers:

Funding: The University of Bologna was funded by Clover Orthopedics for this study. None of the authors received funds or any indirect benefits from Clover Orthopedics for the performance of this study.
Conflicts of interest: The authors, their immediate families, and any research foundation with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

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