In Silico Evaluation of the Primary Stability of Acetabular Revision Cups: Standard Versus Locking Screws

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Given the increasing complexity of revision total hip arthroplasty, ensuring optimal stability of acetabular revision cups (ARCs) is crucial, especially in cases of bone stock loss. In this study, the primary stability of ARCs was investigated by modeling various configurations of screw placements, including all standard, all locking, and mixed setups, under different load scenarios. Finite element (FE) models were implemented to evaluate the stress distribution and micromotions at the bone–prosthesis interface, simulating three primary load cases: "walking," "stairs-down," and "stand-up." The results indicated that the stairs-down load case generated the highest von Mises stresses and sliding distances, marking it as the most critical load scenario. Configurations using all standard screws showed higher peak stresses and reduced stable areas, compared to those utilizing locking screws. While the locking screws provided a stiffer connection, the mixed screw configuration offered a balanced performance by combining the compression benefits of standard screws with the rigid fixation of locking screws. Configurations with a single standard screw complemented by locking screws showed enhanced stability, suggesting this combination could be advantageous in clinical applications. This study underscores the importance of screw type and placement in ensuring the primary stability of ARCs. Locking screws are recommended for use when feasible. For ARCs allowing both screw types, a mixed configuration starting with a standard compression screw followed by locking screws appears optimal. Future research should further explore various combinations of screw geometries and lengths to refine these findings and enhance surgical outcomes in acetabular revisions. [DOI: 10.1115/1.4068226]

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Introduction

Total hip arthroplasty (THA) has undergone tremendous evolution and achieved outstanding clinical results during the last few decades [1]. With the ever-growing number of primary THA procedures, expanded indications for younger and more active patients have emerged, contributing to an increased revision rate [2].

While primary THA has been refined over the years, hip revision surgery remains a debated topic, particularly concerning the techniques and technologies to be implemented. Patients and surgeons must face more demanding challenges during revision arthroplasties due to their intrinsic complexity. Notably, deficiencies in the walls, rim, or columns may limit the available bony surface, which is essential for achieving excellent primary stability [3]. As regards the acetabular revision cup (ARC), even in cases of bone stock loss, primary stability is usually obtained with press-fit porous acetabular cups supplemented by screw fixation to minimize the micromotion [3]. Additional screws are routinely employed during revision procedures, but debate continues about their optimal placement, type, and number [4].

The introduction of ARCs supporting locking head screws (hereafter referred to as "locking screws") has provided an alternative to the traditional anchoring method using standard compression screws (hereafter referred to as "standard screws"). Research findings affirm that the inclusion of a threaded head results in a stronger linkage between the screw and the cup [5]. Furthermore, locking screws generate significantly lower stresses at the level of the ARC [6].

The ARCs available on the market predominantly allow the exclusive use of standard compression screws, while it is rare to find systems that permit the use of both compression screws and locking screws. In this regard, to the authors' knowledge, there are no studies in the literature evaluating the stability of ARCs using different types of screws simultaneously. Furthermore, clinical practice indicates that the insertion of an initial standard screw directed toward the wing of ilium, followed by additional locking screws, significantly increases the stability of the implant.

The few experimental studies on the stability assessment of the ARC have evaluated the impact of screw fixation with various press-fit methods [7,8]. Due to the complexity and high costs of these measurements, the stability of the ARC is often assessed using the finite element (FE) method.

Hsu et al. evaluated the impact of screw anchoring [9], quality of bone and coefficient of friction [4], through a FE model, and finally screw's eccentricity on the primary stability [10] through in vitro experiment. These studies primarily addressed the impact of different screw configurations on the stability of the cup under different load cases.

Finite element analysis, recently supported by multibody analysis, has also played a central role in investigating the impact of different surgical techniques [11–15] and in evaluating the loads acting on joints and bone [16–20]. By applying physiological loads to the structure, the influence of the prosthesis geometry on the surrounding bone tissue can be assessed. FE models allow for a detailed analysis of the prosthesis's behavior under specific load conditions, providing insights into the interaction between the prosthesis and the bone tissue [21–23]. Bergmann et al. [24,25] evaluated and recorded the loading systems during the performance of typical daily activities, such as walking at different walking gaits, ascending and descending stairs, standing up, and sitting down. The data analysis shows that each activity involves a different load system, varying in both intensity and directionality.

In the present study, a quantitative evaluation of the primary stability of an ARC was conducted, utilizing positions derived from clinical practice and considering configurations that include both standard compression screws and locking screws, also simultaneously employed. This evaluation was carried out using FE analysis to assess performance in terms of stable area and sliding distance under different loading scenarios and screw types.

Materials and Methods

Acetabular Revision Cup and Screws. Among the commercially available ARCs, the REDAPT system (Smith & Nephew PLC, London, UK) has been identified as the only one currently on the market capable of utilizing both types of screws, standard compression and locking (Fig. 1). This ARC features nine holes (12 for cups larger than 60 mm) with a "star" geometry, allowing fixation with both types of screw. The geometry of the cup was obtained through three-dimensional scanning using the EinScan Pro system (SHINING 3D, Hangzhou, China), and placed within the acetabulum of a right hemipelvis model (Pacific Research Laboratories, Inc., Vashon, WA). The locking screw features threading on both its body and head, whereas the standard screw has

Fig. 1 Photograph of the REDAPT system: (left) ARC involved in the study with holes capable of handling both standard and locking screws; (right) locking screw with threaded head and body (top); standard screw with spherical head and threaded body (bottom)

threading only on its body. This configuration gives the locking screw a much stiffer coupling with the cup [5], while the standard screw can exert a compressive effect of the cup on the acetabulum. The length of the standard screws varies from 15 to 70 mm, while locking screws are available in lengths from 15 to 50 mm.

Model Configurations. The cup was placed so that holes A, C, and D were within the safe zone defined by Wasielewski et al. [26], while hole B was near the boundary of declared region (Fig. 2). For each screw, all available bone tissue in the direction parallel to the axis of the hole into which the screw was inserted was utilized.

The configuration providing the minimum stability consists of screws in holes A, B, C, and D, as suggested by clinical practice in the absence of specific bone defects. This configuration was assessed in three different arrangements (Table 1): all locking screws (ABCD), all standard screws (ABCD), and standard screws in hole A with the others locking (ABCD). The same evaluations were conducted following the insertion of the screw in the hole E (Table 1), which has the effect to grant angular stability on the posterior column. Configurations with only standard screws aimed to simulate the performance of a traditional acetabular cup.

Finite Element Model. A FE model was implemented in ANSYS MECHANICAL R23 (Ansys, Inc., Canonsburg, PA) to assess the stability of the ARC. Standard and locking screws were modeled as cylinders with a diameter of 6.3 mm and a head height of 3.5 mm.

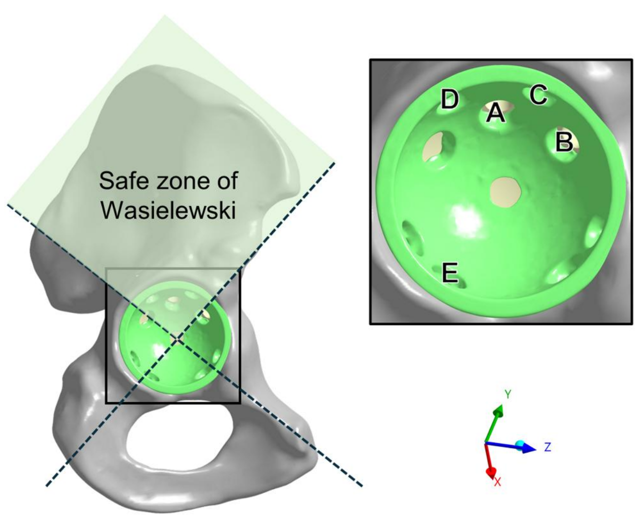

Fig. 2 (Left) Safe zone of Wasielewski and acetabular cup placement. (Right) Detailed view with the nomenclature for hole positioning, all within the safe zone.

Table 1 List of tested screw configurations, with the first three having four screws and the next three having five screws

Configuration	Screw A	Screw B	Screw C	Screw D	Screw E
ABCD	Standard	Locking	Locking	Locking	–
ABCD	Locking	Locking	Locking	Locking	–
ABCD	Standard	Standard	Standard	Standard	–
ABCDE	Standard	Locking	Locking	Locking	Locking
ABCDE	Locking	Locking	Locking	Locking	Locking
ABCDE	Standard	Standard	Standard	Standard	Standard

Underlined letters indicate standard screws.

The materials associated with the model components were assumed to be linear isotropic (Table 2).

Following a mesh convergence analysis (see Supplemental Fig. 1 available in the Supplemental Materials on the ASME Digital Collection), first-order tetrahedral elements were used for the pelvis (mesh size of 2 mm) and the ARC (mesh size of 0.5 mm), while the screws were modeled using first-order hexahedral elements with a 0.5 mm mesh size (Fig. 3). The acetabulum and the cup were set to have the same diameter (58 mm) [9]. The press-fit effect was not considered in order to solely investigate the stability induced by the fixation screw.

A "frictional" contact with a coefficient of 0.95 [27] was employed for the interaction between the cup and acetabulum, aiming to achieve tight and uniform penetration and gap. The screw thread was neglected to avoid additional computational costs [29], and instead, a "bonded" contact with multipoint constraint (MPC) formulation was employed [30]. To distinguish the behavior of the screws, a bonded MPC contact was used for the interaction between

Table 2 Material properties of the components involved in the study

Component	Material	Elastic modulus (MPa)	Poisson's ratio
ARC	Conceloc [27]	4300	0.3
Screws	Ti6Al4V [9]	110,000	0.3
Hemipelvis	Trabecular bone [28]	400	0.3
Hemipelvis	Cortical bone [28]	17,000	0.4

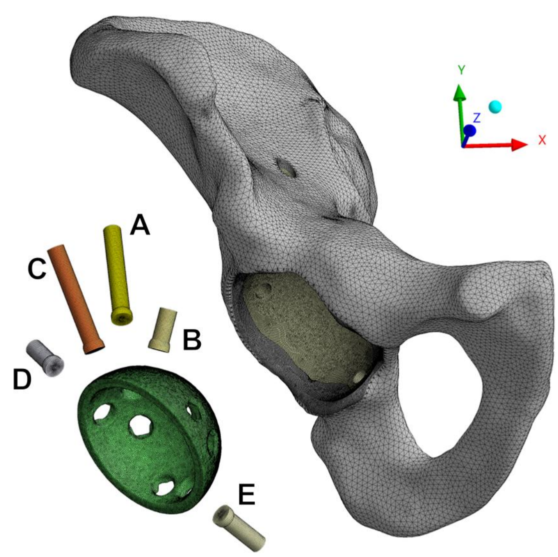

Fig. 3 Exploded view of the model. First-order tetrahedral elements were employed for the pelvis and the ARC, while first-order hexahedral elements were used to model the screws. While a coarse mesh was applied to the entire pelvis, a finer mesh was used in the area of contact with the ARC.

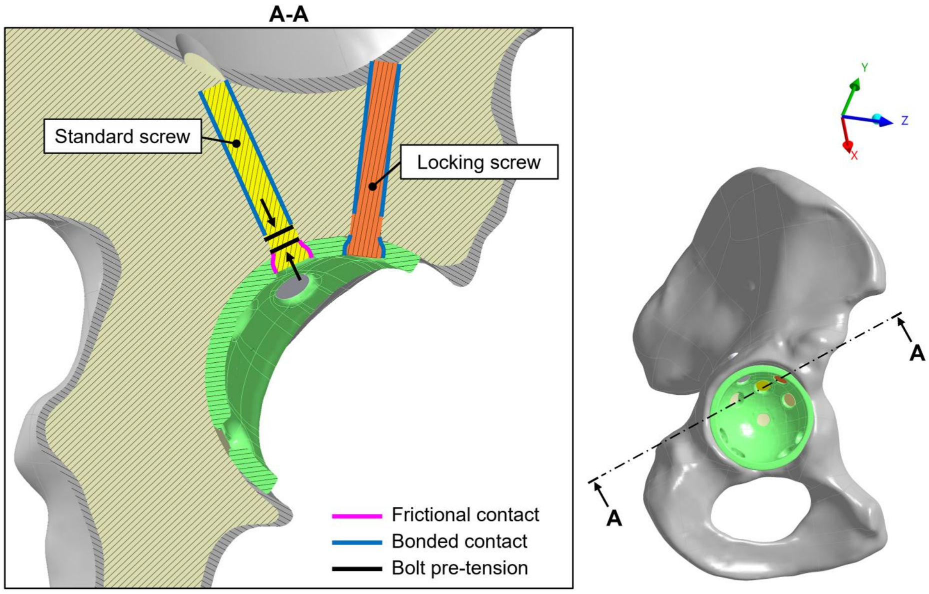

Fig. 4 Section view A–A of hemipelvis. Standard screw model: head-ARC contact is frictional and body-bone is a bonded contact; locking screw model: head-ARC and body-bone are bonded.

the locked screw head and the hole surface, while a frictional contact type with a coefficient set at 0.36 [31] was implemented for the standard screw head and hole (Fig. 4).

To model the shortening of the grip-length of standard screws, a preload was applied to a section of the cylinder located at the midpoint of the screw body [32]. The pretension load was set at a value of 350 N for screws with a length of 40 mm and proportionally adjusted for shorter screws. The pretension value was selected to ensure that the material limits within the model are not exceeded, while also guaranteeing the stability of the sliding distance (see Supplemental Figs. 2 and 3 available in the Supplemental Materials on the ASME Digital Collection). The locking screws were not pretensioned [33].

For configurations involving standard screws, the following steps were implemented. In the initial step, the first standard screw (A) was pretensioned with all its contacts activated. A bonded contact between the head and the ARC was activated for all the other screws (both locking and standard), while the contact between the screw shaft and the bone was deactivated. The terms "activate/deactivate" refer to the ANSYS function that allows enabling or disabling a contact for various time intervals. Once the pretensioning step was complete, the screw length was fixed to maintain the preload constant.

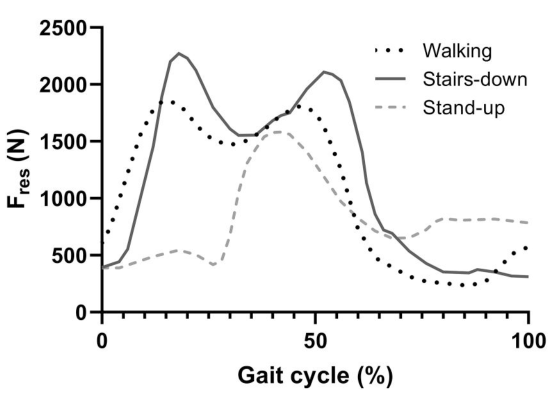

Fig. 5 Resultant forces (F_{res}) applied to the ARC from walking (dashed black curve), stairs-down (solid dark gray curve), and stand-up (dashed light gray curve) [26]

In the second step, if additional standard screws were present in the configuration, the head-cup contact was switched from bonded to frictional, the stem-bone contact was activated, and the pretensioning load was applied to the new screw. The process was repeated until all standard screws were preloaded. After all pretensioning steps were completed, the contacts between the screw shaft and bone for the remaining locking screws were activated.

All configurations with four screws (Table 1) were tested under three different load cases: walking, stairs-down, and stand-up [24], assuming a body weight of 75 kg, in order to evaluate the effect of the load case on the stability of the ARC and to identify the most critical one (Fig. 5). Configurations with five screws were tested only under the most critical load case to assess the influence of screw type. The loads were applied statically, with variable sampling to optimize the number of points in the characteristic portions of the curve. The load cases were applied through a remote point at the centroid of the ARC using the MPC formulation to distribute the load across its internal surface. The sacroiliac joint and pubic symphysis nodes were constrained in all directions.

The maximum equivalent stress (von Mises) averaged over the elements for the ARC, screws, trabecular bone, and cortical bone was assessed to determine the impact of the type of load case. The assessment of the primary stability of the component involved in the relative sliding between the ARC and the acetabulum's surface [34]. Sliding below 28 μm promotes osteogenesis, whereas sliding above 150 μm leads to the formation of fibrous tissue, which would compromise secondary stability of the prosthesis. Micromotions between 28 and 150 μm, however, exhibit a hybrid behavior that is generally accepted in surgical practice. Specifically, the evaluation included the peak of the stress distribution and the percentage of the cup's area with a relative motion of less than 28 μm.

Results

The maximum von Mises stresses for all components of the model across the three load cases are summarized in Fig. 6. Among the configurations, the stairs-down load case generated higher von Mises stresses for all model components, except for the cup in the configuration with all standard screws, where the values were similar. Walking ranked second in terms of stress levels, while stand-up induced the lowest stresses on the components.

For all components, the stresses developed remained below the yield strength of materials used. Regardless of the analyzed

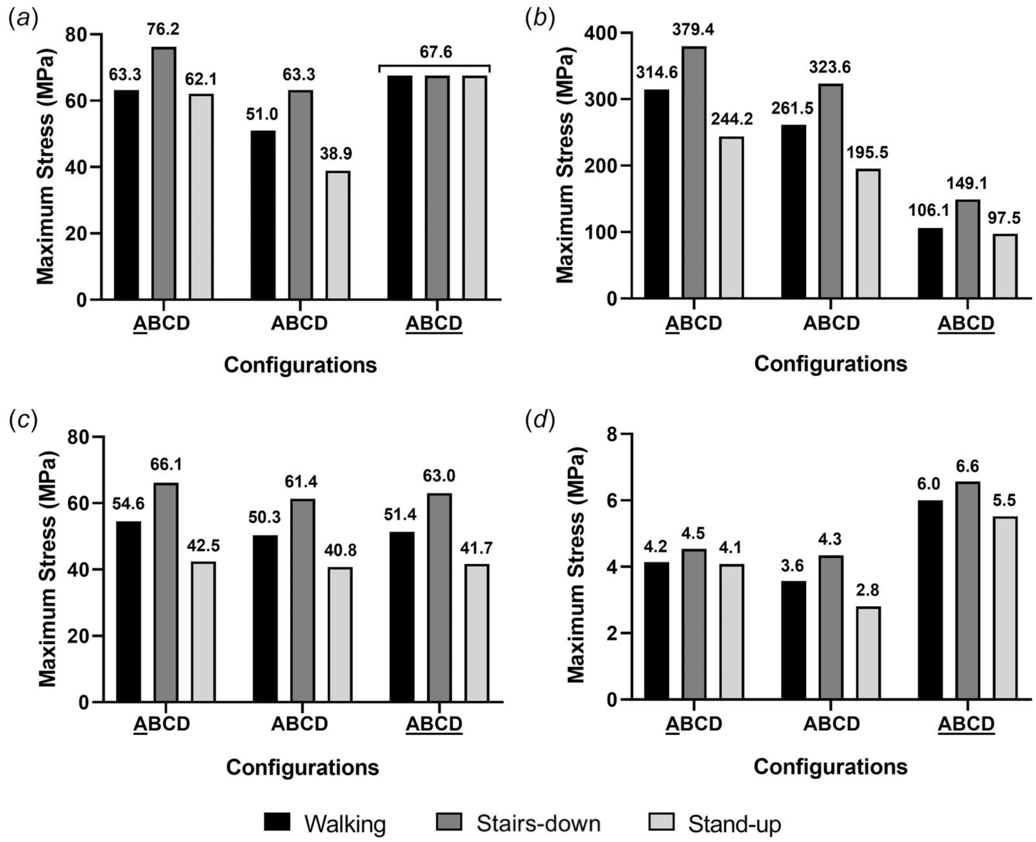

Fig. 6 Maximum equivalent stresses (von Mises) averaged over the elements for all components in the model: (*a*) ARC, (*b*) screws, (*c*) cortical bone, and (*d*) trabecular bone. Underlined letters indicate standard screws.

configurations, the stairs-down load case resulted in a greater sliding distance between the cup and the acetabulum, along with a smaller stable area, compared to the other load systems evaluated (Fig. 7). The sliding distance distributions were similar through the different load cases, and the region with a relative displacement greater than 28 μm was located close to the cup rim and the ischial region (Fig. 8).

When observing the configurations with four and five screws separately (Fig. 9), the cup fixed with mixed configurations (ABCD and ABCDE) and all locking screws configurations (ABCD and ABCDE) had a similar value of sliding distance. In the four-screw configuration, the mixed approach had a sliding distance of 54 μm, while the all-locking screws approach had a sliding distance of 54.7 μm. In the five-screw configuration, the mixed configuration had a sliding distance of 28.7 μm, compared to 30.3 μm for the all-locking screw configuration. However, the configurations with all standard screws (ABCD and ABCDE) exhibited a higher maximum sliding distance (76.6 μm and 48.3 μm, respectively) compared to configurations with the same number of screws. Conversely, the cup fixed with a single standard screw (ABCD and ABCDE) demonstrated a higher stable area than the other two alternatives in the four- and five-screw configurations. The cup fixed with all locking screws had a slightly lower stable area compared to the previous ones, while the configurations with all standard screws had the lowest stable area (84.18% and 91.92%).

Discussion

Acetabular cups exploiting only standard screws were considered the gold standard in orthopedic surgery during revision procedures. Historically, the ability to eccentrically redirect the screws toward better quality bone stock was fundamental. Moreover, the compression mechanism provides the surgeon with increased sensitivity while placing the screws, ensuring valuable stability feedback during surgery. On the other hand, the recent introduction of locking screws in hip surgery could significantly change clinical practice. For this reason, standard and locking screws were compared to identify the most stable configuration in terms of stable area and sliding distance under different loading scenarios.

In the first part of the work, three types of loads acting on the ARC were compared to identify the most critical one. For all components, the stairs-down load resulted in a von Mises stress distribution with higher peaks compared to walking and stand-up, regardless of the screw configuration examined. The only exception is found in the von Mises stresses of the ARC with all standard screws, where no differences were observed between the various load cases. The peak values of the von Mises stress obtained align with the values characterizing the individual load cases, as the stairs-down load has the highest resultant magnitude among the three load cases.

In configurations with one or more standard screw, von Mises stresses were localized around their hole of insertion, regardless of load system. This effect was due to the compression effect typical of spherical head screw. The stresses developed in all locking screws configurations, on the other hand, were caused by misalignment between screw and the hole axis. All standard configurations had similar peak of stresses, regardless of load system, because they were due from compression effect, while the cup fixed with locking screw had stresses dependent on the load applied.

The stairs-down load case remained one of the most critical scenarios also for assessing the stability of the acetabular cup [24]. This conclusion was drawn from consistent findings in the same configuration, where higher sliding distance values and a lower stable area indicated reduced implant stability. The relative sliding between the prosthetic surface and the acetabulum identified the stability of the prosthetic cup. In particular, the peak of the displacements and the stable area indicate, respectively, regions with poor integration with the implant and regions with greater

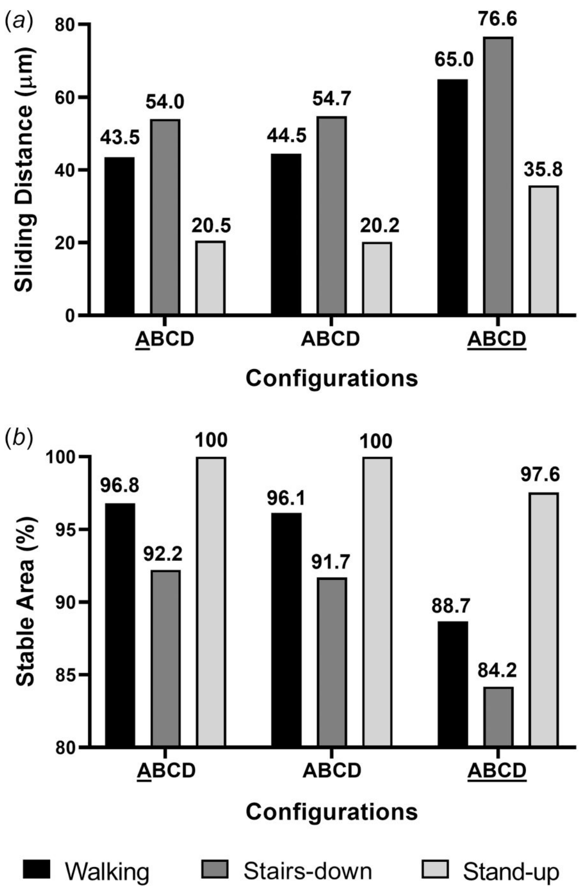

Fig. 7 (*a*) Sliding distance and (*b*) stable area for walking, stairs-down, and stand-up load cases. Underlined letters indicate standard screws.

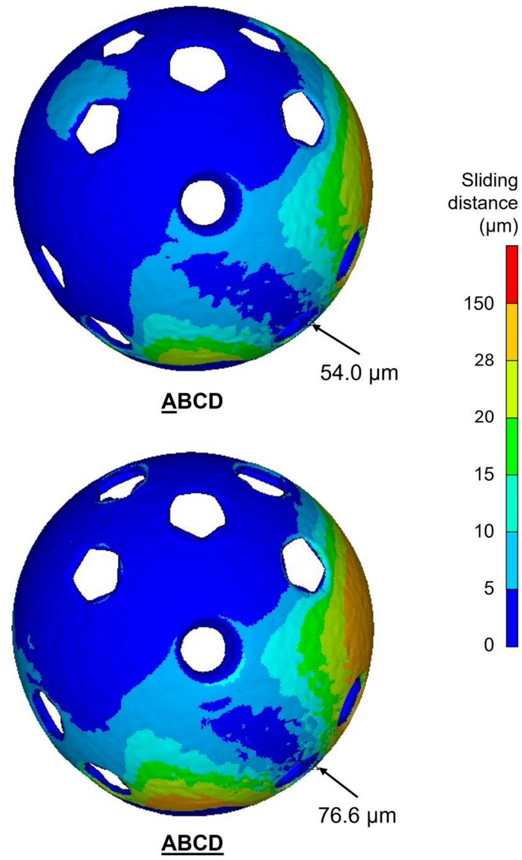

Fig. 8 Sliding distance of configurations with a single standard screw (top) and with all standard screws (bottom). In both cases, the maximum was located in proximity to the ischiatic region. Underlined letters indicate standard screws.

bone–prosthesis interface. The region with the maximum sliding distance is consistently located near the holes in the ischial direction, close to the edge of the acetabular cup, across all analyzed cases.

The position of screws was able to influence the relative displacement distribution. In general, the cup fixed with five screws had a better stability than four screw configurations. The insertion of multiple screws enabled the extension of what was termed the stable region, even under different load cases. It would be optimal for the screw insertion points to be as far apart as possible to increase the surface area of the stable area. Furthermore, it would be advantageous for the insertion points to be close to the edge of the acetabular cup to reduce peak values of the displacement field [4,5].

Regarding screw type, fixation with standard screws only was found to perform significantly worse than configurations with locking screws in terms of peak of sliding distance and stable area. The relative peak displacement increased by approximately 41%, while the stable area decreased by 7–8% when comparing all standard four-configuration setups to those with locking screws. This performance trend was similar for the five-screw configurations, although the parameter difference between configurations is less. The standard screw spherical heads allowed relative movement with holes, whereas the threaded head constrained the two bodies. This resulted in a significantly stiffer structure with locking screws [5], which positively influenced the stability of the acetabular cup. However, in configurations with only locking screws, the compression effect of standard screws was absent. The compression had positive aspects in terms of increasing the cup-acetabulum friction components by improving their stability and was able to promote osteogenesis processes. Nevertheless, all configurations evaluated had a relative displacement below the limit of fibrous tissue generation (150 μm).

Since the stability outcome may depend on bone quality, it was chosen to eliminate this variable and examine the effect of stability by inserting the acetabular cup into an ideal pelvic model. Considering an acetabulum with varying degrees of defects would introduce largely uncontrollable variables into the study (e.g., shape and location of the defect, previous cementation, and bone quality). This could be regarded as a future topic once a consensus on the optimal positioning of screws in an ideal context has been reached. Furthermore, although in recent years it has become possible to define local properties of trabecular bone in FE analyses [35], in clinical practice, it is currently not feasible to predict the adaptability of the bone tissue to the prosthesis. Therefore, in this study, trabecular bone was treated as homogeneous, and its behavior was assessed exclusively at the macroscale. Finally, the decision to utilize the geometry of a synthetic hemipelvis (Pacific Research Laboratories, Inc., Vashon, WA) for the construction of the FE model may prove advantageous in facilitating potential future experimental validations, which have not yet been carried out.

A limitation of the study may lie in the assumption of a fully adherent contact for the bone/screw interface, as the intention was to test an ideal scenario.

Moreover, future studies would be useful to evaluate different combinations of screws in terms of geometric configuration, type, and length. In particular, it would be helpful to determine the optimal position of the fifth screw that provides the best primary stability.

In conclusion, this study assessed the primary stability of the acetabular cup fixed with different screw types under various load cases. The load system significantly affects the peak of relative displacement between the cup and the acetabulum. The stairs-down load case was one of the most critical in terms of von Mises stresses, sliding distance, and stable area of the cup.

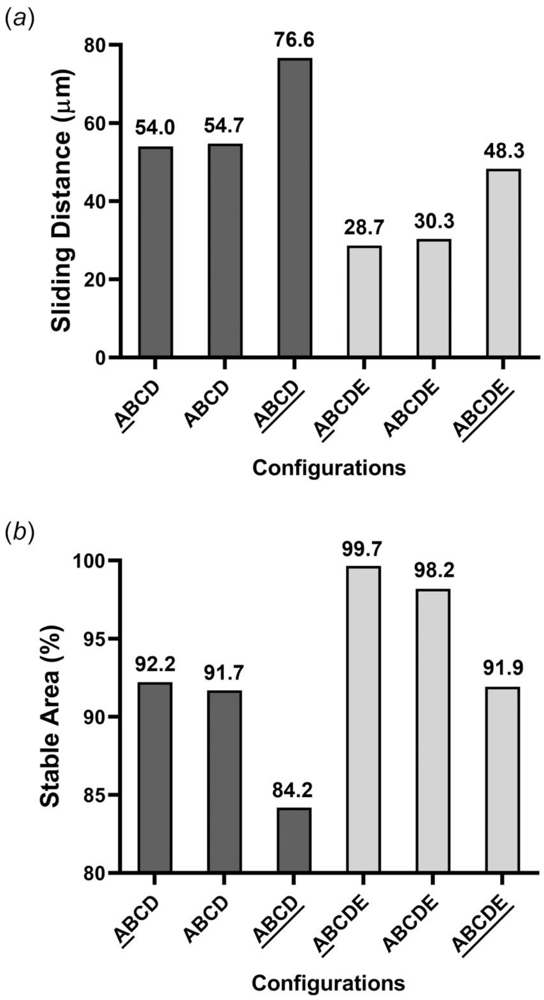

Fig. 9 (*a*) Sliding distance and (*b*) stable area (four-screw configurations in dark grey and five-screw configurations light grey) during 'stairs-down' load case. Underlined letters indicate standard screws.

In the absence of press-fit technique, primary stability relied entirely on the geometric configuration and length of the inserted screws. The locking screw increased the primary stability of the prosthesis due to a stiffer cup-screw structure and is recommended when only one type of screw can be used.

Instead, in cases where the ARC allows for a combination of standard and locking screws, it is recommended to insert an initial standard compression screw (hole A), followed by locking screws in the surrounding holes (B, C, and D). Furthermore, in cases featuring exclusively standard screws configurations, the inclusion of a fifth screw does not demonstrate any advantage, unlike configurations containing only locking screws and mixed configurations.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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