Arthroplasty Today 30 (2024) 101508

Contents lists available at ScienceDirect

Arthroplasty Today

journal homepage: http://www.arthroplastytoday.org/

Original Research

Patient-Specific Acetabular Safe Zones in Total Hip Arthroplasty: External Validation of a Quantitative Approach to Preoperatively Templating Spinopelvic Parameters

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A R T I C L E I N F O

Article history:
Received 23 March 2024
Received in revised form
24 June 2024
Accepted 11 August 2024
Available online xxx

Keywords:
Total hip arthroplasty
Revision
Spinopelvic
Instability
Safe-zones

A B S T R A C T

Background: Spinopelvic mechanics are critical in total hip arthroplasty; however, there is no established consensus for adjusting acetabular component positioning based on spinopelvic parameters. This study aimed to (1) validate a recently developed Patient-Specific acetabular safe-zone calculator that factors in spinopelvic parameters and (2) compare differences with hip-spine classification targets.
Methods: A total of 3750 patients underwent primary total hip arthroplasty across 3 academic referral centers, with 33 (0.88%) requiring revision for instability. Spinopelvic parameters were measured before initial total hip arthroplasty, and acetabular component position was measured following the index and revision procedures. Most operations employed either computer navigation or robotic assistance (94%). Surgical approaches included both anterior and posterior techniques. Utilizing our recently developed patient-specific safe-zone calculator, theoretical intraoperative positions were calculated and compared to true component positions before and after revision.
Results: Among 33 patients who underwent revision, none dislocated at an average follow-up of 5.1 years. In the external validation cohort, the average absolute differences between the patient-specific safe-zone and the median hip-spine classification recommendation were 3.8° ± 2.1° inclination and 5.0° ± 3.2° version. For the pooled cohort, the absolute differences between the patient-specific safe-zone targets and the prerevision component positions were 7.9° ± 5.1° inclination and 11.4° ± 6.9° version. After revision, the mean absolute differences decreased to 3.6° ± 3.1° inclination and 5.8° ± 3.5° version ($P < .001$).
Conclusions: A patient-specific approach improved acetabular component positioning accuracy within 6° of version and 4° of inclination of stable, revised hips. Patient-specific safe zones provide quantitative targets for nuanced spinopelvic preoperative planning that may mitigate risk of instability and may indicate use of assisted technologies.

Introduction

Hip stability following total hip arthroplasty (THA) is influenced by various factors, including the intricate interplay between spinopelvic kinematics and prosthetic components used during surgery [1-32]. The evolving understanding of this relationship has emphasized the importance of preoperative spinopelvic assessment, particularly given the rising incidence of concurrent lumbar spinal pathologies that complicate surgical planning [33-35]. To address this, the hip-spine classification was recently introduced to streamline the decision-making process regarding acetabular component positioning. This initial effort helped to reduce the incidence of postoperative dislocations by synthesizing an individual's spinopelvic parameters into component positioning recommendations [36].

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https://doi.org/10.1016/j.artd.2024.101508

While the hip-spine classification has simplified the approach to acetabular positioning by creating “component safe-zones,” the existing criteria are primarily qualitative and rely on threshold-based classifications [36]. However, spinopelvic mechanics do not conform to a qualitative model. Instead, they are a complex interplay that are better described using advanced mathematical approaches such as vector calculus and linear algebra [37,38]. Moreover, acetabular component positioning during activities of daily living is highly dependent on patient anatomy and spine flexibility [23]. These realizations have led to the development of a more sophisticated tool that can better recapitulate acetabular positioning in an individualized manner [39]. Incorporating parameters of spinopelvic function allows for the calculation of patient-specific safe zones, providing more precise targets for component positioning.

The recent introduction of the patient-specific safe zone calculator offers a tailored approach to component positioning. The calculator uses a rotation matrix to adjust the vector that represents acetabular component position, providing anteversion and inclination angles that reflect the patient’s individual anatomy and spinal flexibility. These angles are then used to define a safe zone, which are further refined by accounting for changes in pelvic tilt or sacral slope measured from sitting and standing lateral radiographs (Fig. 1) [7]. Ramkumar et al [39] showed that use of this patient-specific calculator closely approximated revised and newly stable hips with a tolerance of 5° version and 3° inclination.

While the predictive accuracy of this new approach is promising, its application requires further study across a variety of patients, surgeons, and institutions. The dual purposes of this study were to externally validate the patient-specific acetabular safe zone calculator, applying it to a novel cohort of patients with unstable THAs requiring revision, and to conduct a comparative analysis with the hip-spine classification’s safe zone recommendations. This study also seeks to compare the outcomes of the patient-specific safe zone calculator against the conventional hip-spine classification targets, with the goal of demonstrating the practical utility of incorporating patient-specific biomechanical data into preoperative planning for THA. In summary, this research aims to bridge the gap between a qualitative, consensus-based approach and a quantitative, individualized method to improve THA planning and outcomes.

Material and methods

Demographics and spinopelvic consideration

From January 1, 2014, to May 31, 2022, 2457 primary THAs (group 1) were performed across 3 institutions by 5 arthroplasty-trained surgeons using anterior (29%) and posterior based (71%) approaches. The mean patient age was 63 years, and 59% were female. A total percent of 90.8% of operations used computer navigation (Intellijoint, Waterloo, Ontario, Canada — 11%; OrthAlign

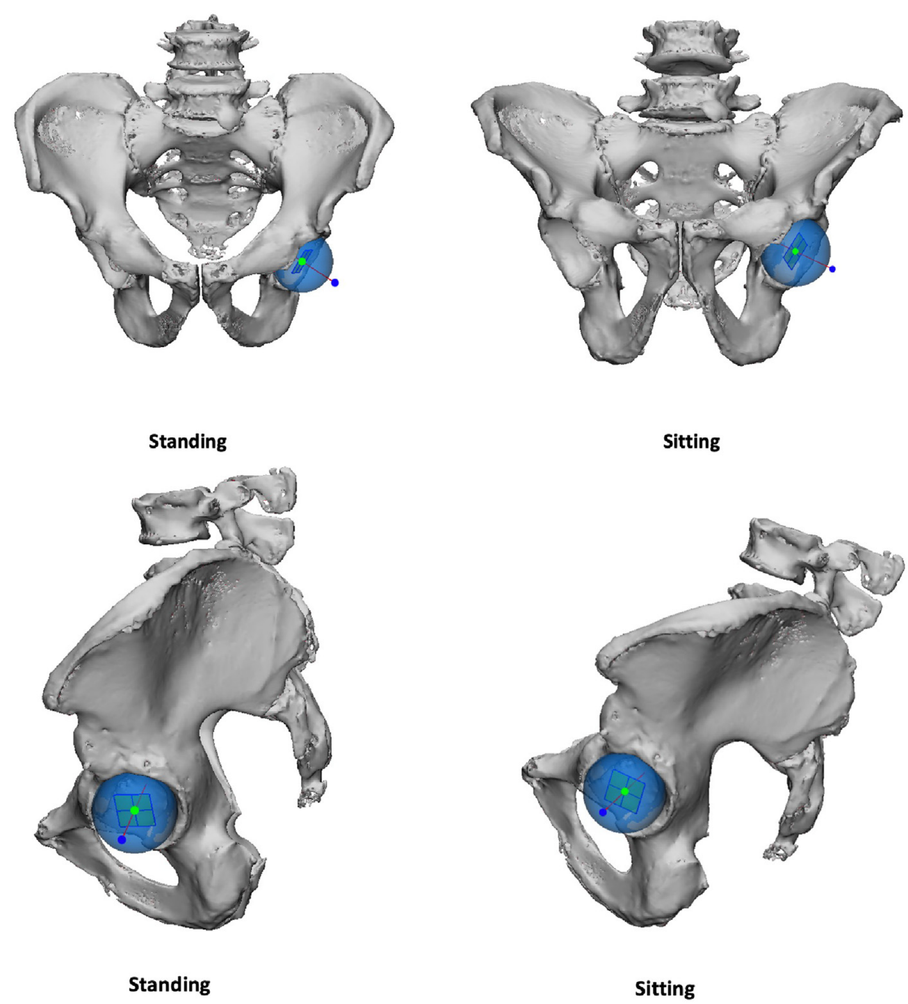

Figure 1. Coronal and sagittal renderings of the projected unit vector changes for both standing and sitting positions.

Hip, Aliso Viejo, California, USA – 25%; and Achieve CAS Smith & Nephew, London, United Kingdom – 8%) or robotic-assisted surgery (Stryker Mako, Mahwah, NJ with 3.0 software – 56%). From January 1, 2018, to October 31, 2022, 1293 primary THAs (group 2) were performed from one institution by 2 arthroplasty-trained surgeons using posterior based approaches with computer navigation (Intellijoint, Waterloo, Ontario, Canada). All patients in this cohort had preoperative sitting and standing lateral pelvic radiographs. Surgeons chose surgical approach both during primary and revision procedures based on their personal preference. Postoperative component position was measured using computed tomography scan and pelvis radiographs were taken while standing. The mean patient age was 64 years, with 53% females. These groupings were based on institutional cohorts to adequately power the objective of external validation for this study. Dual mobility components were utilized for patients who exhibited hip-spine classifications 2B and/or spinal fusion with at least 3-level fusion for both cohorts at the time of revision THA. All other classifications received 36-mm heads at the time of revision. Cases of instability requiring acetabular component revision were recorded, and prerevision and postrevision component positions were compared. All data were collected retrospectively.

The hip-spine classification was determined by the presence of spinal deformity and stiffness to characterize hip-spine pathology during preoperative workup. Each patient was classified in triplicate by 3 independent raters as 1A, 1B, 2A, or 2B (Table 1) [36]. Anterior pelvic plane, standing pelvic tilt/sacral slope, and sitting pelvic tilt/sacral slope were measured prior to index THA. Acetabular anteversion and inclination were measured following index and revision procedures by 2 surgeons and a radiologist. Spinopelvic parameters were presumed to remain constant between index and revision operations, assuming spine pathology did not significantly change during this period. The average time interval between the index and revision operations was 5.1 years [2,3,16].

Surgeon-selected standing acetabular target was retrospectively transformed into a patient-specific intraoperative acetabular target position accounting for spinopelvic mechanics as described previously [39]. Safe-zone target range was established by the change in sacral slope from sitting and standing lateral radiographs. For instances without an established target, hip-spine classification intraoperative targets were used for standardization, and this was used for all assistive technology devices. The position difference between the patient-specific target and acetabular component pre- and post-revision was analyzed using paired-samples t-tests. Additionally, the range of inclination and anteversion (median and extremes) defined by the hip-spine classification targets were compared to the patient-specific zones using paired-samples t-tests. Patients who underwent isolated acetabular component revision for instability were reported for the overall cohort (n = 33), internal validation (group 1) cohort (n = 22), and external validation (group 2) cohort (n = 11). Statistical analyses were performed using R, version 4.2.1 (Vienna, R Core Team) with a significance level of 0.05.

Results

Cohort demographics and spinopelvic description

Thirty-three dislocations across 3 institutions underwent an acetabular component revision for instability. The most common indications for index THA included osteoarthritis (84%), developmental dysplasia of the hip (12%), and avascular necrosis (4%). At the index procedure, all were posterior approach with capsular repair, all head sizes were 36 mm, and no index procedures underwent dual mobility at the primary operation. All revisions utilized the prior posterior-based approach. The mean follow-up for dislocation was 5.1 ± 1.3 years with 100% follow-up for these cohorts. Of the 22 patients who underwent revision in the internal validation cohort (group 1), 14 (64%) were women. Navigation or robotic assistance was used in 19 of 22 revisions (86%). All dislocations were posterior. Of the 11 patients who underwent revision in the external validation cohort (group 2), 6 (54%) were women. Navigation or robotic assistance was used in 11 of 11 revisions (100%). All dislocations were posterior. The two 2B hips received dual mobility at revision surgery. The dislocation patients were classified as follows: 1A (n = 13), 1B (n = 15), 2A (n = 3), 2B (n = 2). Descriptive statistics for the 2 cohorts are depicted in Table 1.

Pooled cohort analysis

In the pooled analysis, the difference between patient-specific safe zone target and the actual unstable, prerevision acetabular component position was 11.4° ± 6.9° version and 7.9° ± 5.1° inclination (Table 2). In comparison, the difference between the patient-specific safe zone target and the actual stable, postrevision acetabular component position was 5.8° ± 3.5° version ($P < .001$) and 3.6° ± 3.1° inclination ($P < .001$). When comparing acetabular component positions between the patient-specific safe zone and the recommended hip-spine classification target for the median and the most extreme but “acceptable” positions, respectively, the mean differences were 2.7° ± 2.1° inclination/5.4° ± 3.5° version and 3.8° ± 2.8° inclination/7.8° ± 3.3° version (Table 3). To understand the clinical threshold between stable and unstable hips across all classifications, the difference between stable,

Table 1
Prerevision and postrevision acetabular component position and predicted patient-specific safe zone stratified by hip-spine classification.

Hip-spine classification	Prerevision position	Postrevision position	Predicted patient-specific safe zone
	Inclination/Anteversion	Inclination/Anteversion	Inclination/Anteversion
Group 1 (n = 22)			
1A (n = 6)	40.8° ± 9.9°/18.5° ± 12.0°	42.2° ± 2.2°/29.0° ± 4.4°	45.2° ± 3.4°/24.5° ± 5.6°
1B (n = 11)	37.6° ± 4.0°/14.1° ± 8.6°	43.4° ± 2.3°/30.7° ± 2.9°	44.0° ± 2.0°/22.2° ± 4.4°
2A (n = 3)	60.3° ± 6.7°/39.3° ± 3.1°	48.0° ± 10.4°/31.3° ± 1.5°	42.0° ± 0.2°/16.5° ± 0.9°
2B (n = 2)	53.5° ± 2.1°/19.0° ± 24.0°	39.5° ± 0.7°/27.0° ± 2.8°	37.2° ± 0.5°/15.6° ± 2.3°
Group 2 (n = 11)			
1A (n = 7)	44.0° ± 4.0° /35.1° ± 5.1°	47.0° ± 5.4°/31.4° ± 5.0°	47.2° ± 1.6°/28.9° ± 2.6°
1B (n = 4)	54.3° ± 8.9° /27.0° ± 4.8°	43.4° ± 4.7°/32.0° ± 6.3°	47.2° ± 1.6°/29.0° ± 2.6°
Pooled (n = 33)			
1A (n = 13)	44.1° ± 7.8°/28.5° ± 15.1°	46.1° ± 5.8°/32.0° ± 5.9°	46.3° ± 2.7°/26.9° ± 4.8°
1B (n = 15)	42.2° ± 10.2°/16.2° ± 10.8°	43.4° ± 4.6°/30.0° ± 7.3°	44.9° ± 2.3°/24.0° ± 5.0°
2A (n = 3)	54.8° ± 2.4°/35.3° ± 1.3°	36.7° ± 9.9°/23.2° ± 1.9°	42.0° ± 0.2°/16.5° ± 0.9°
2B (n = 2)	44.6° ± 9.1°/11.7° ± 25.8°	36.5° ± 0.4°/17.5° ± 5.0°	37.2° ± 0.5°/15.6° ± 2.3°

Table 2
Differences between patient-specific component target and prerevision and post-revision component position.

Measurement	Difference relative to patient-specific safe zone		
	Prerevision	Postrevision	*P* value
Group 1 (n = 22)			
Inclination	9.1° ± 4.3°	3.2° ± 3.0°	<.001
Anteversion	13.3° ± 6.8°	5.3° ± 2.7°	<.001
Group 2 (n = 11)			
Inclination	5.5° ± 5.9°	4.2° ± 3.3°	.52
Anteversion	7.7° ± 5.7°	6.9° ± 4.7°	.71
Pooled (n = 33)			
Inclination	7.9° ± 5.1°	3.6° ± 3.1°	<.001
Anteversion	11.4° ± 6.9°	5.8° ± 3.5°	<.001

postrevision components to unstable, prerevision components across all 33 patients was 6.9° version and 0.80° inclination.

Internal validation (group 1) analysis

For the 22 dislocations in the first cohort, the difference in prerevision acetabular component positions and the patient-specific safe zone was 13.3° ± 6.7° version and 9.1° ± 4.2° inclination (Table 2). The difference between the patient-specific safe zone target and the actual, stable postrevision component was 5.3° ± 2.7° version ($P < .001$) and 3.2° ± 3.0° inclination ($P < .001$). When comparing acetabular component positions between the patient-specific safe zone and the recommended hip-spine classification target for the median and the most extreme but "acceptable" positions, respectively, the mean differences were 2.2° ± 1.9° inclination/5.6° ± 3.7° version and 3.0° ± 2.3° inclination/7.9° ± 3.5° version (Table 3).

External validation (group 2) analysis

For the 11 dislocations in the second cohort, the difference in prerevision acetabular component positions and the patient-specific safe zone was 7.7° ± 5.7° version and 5.5° ± 5.9° inclination (Table 2). In comparison, the difference between patient-specific safe zone target and the actual stable, postrevision acetabular component position was 6.9° ± 4.7° version ($P = .71$) and 4.2° ± 3.3° inclination ($P = .52$). When comparing acetabular component positions between the patient-specific safe zone and the recommended hip-spine classification target for the median and the most extreme but "acceptable" positions, respectively, the mean differences were 3.8° ± 2.1° inclination/5.0° ± 3.2° version and 5.4° ± 3.1° inclination/7.5° ± 3.2° version (Table 3).

Table 3
Differences between patient-specific target and median and extreme hip-spine component targets.

Measurement	Differences between patient-specific target and hip-spine targets	
	Median	Acceptable extreme
Group 1 (n = 22)		
Inclination	2.2° ± 1.9°	3.0° ± 2.8°
Anteversion	5.6° ± 3.7°	7.9° ± 3.5°
Group 2 (n = 11)		
Inclination	3.8° ± 2.1°	5.4° ± 3.1°
Anteversion	5.0° ± 3.2°	7.5° ± 3.2°
Pooled (n = 33)		
Inclination	2.7° ± 2.1°	3.8° ± 2.8°
Anteversion	5.4° ± 3.5°	7.8° ± 3.4°

Discussion

Consideration of spinopelvic biomechanics is a crucial step during preoperative planning for THA revision. The concept of a prescriptive and quantitative patient-specific acetabular safe zone that builds upon ideas presented in the formative hip-spine classification was recently introduced and internally validated [38]. This study aimed to externally validate the Patient-Specific acetabular target calculator. Moreover, there were no statistically or clinically significant differences between the internal and external validation cohorts, demonstrating the generalizability of Patient-Specific safe zones. We demonstrate that patient-specific safe zone targets approximate clinical stability within 6° (5.8° ± 3.5°) of version and 4° (3.6° ± 3.1°) of inclination in 33 stable postrevision hips. To contextualize this finding, the average difference between stable and unstable THA components was 6.9° version and 0.80° inclination, underscoring the sensitivity of component positioning in preventing dislocations. Murphy et al. demonstrated the sensitivity of version in component positioning, and a patient-specific safe zone that approximates version within 6° represents a preferred, patient-specific approach to minimizing instability risk [40]. Leveraging the significance of patient-specific targets, acetabular component positions were compared between the Patient-Specific Safe Zone and the median and extreme "acceptable" targets recommended by the hip-spine classification. Version differences of 5.4° ± 3.5° and 7.8° ± 3.3° version were found for the median and extreme but acceptable positions, suggesting that positioning within the acceptable ranges of the hip-spine classification targets may still precipitate instability with a 6.9° version threshold.

The second group of 1 patients with dislocations following THA served as an external validation cohort. The difference in prerevision acetabular component positions and the patient-specific safe zone was 7.7° ± 5.7° version and 5.5° ± 5.9° inclination. The difference between patient-specific safe zone target and the stable, postrevision acetabular component position demonstrated minimally improved differences but narrower tolerances as evidenced by slight decreases with 6.9° ± 4.7° version ($P = .71$) and 4.2° ± 3.3° inclination ($P = .52$). However, when comparing the patient-specific safe zone and the recommended hip-spine classification targets for the median and the most extreme but "acceptable" positions, respectively, the mean differences were 3.8° ± 2.1° inclination/5.0° ± 3.2° version and 5.4° ± 3.1° inclination/7.5° ± 3.2° version. While the externally validated cohort targets were not statistically dissimilar between the stable component position and the patient-specific safe zone target, the patient-specific target represents an improvement over the hip-spine classification recommendations that may allow for version differences up to 7.5°, exceeding the threshold of 6.9° observed in this cohort.

The hip-spine classification system categorizes patients undergoing THA based on spinopelvic pathologies [36]. By analyzing dislocations patterns in 18 patients requiring a revision procedure, the complexities of spinopelvic pathologies were distilled down to flexibility and alignment. Until now, acetabular component target positions were decided qualitatively and by expert consensus. This classification system allows surgeons to stratify patients by dislocation risk and modify surgical planning to improve outcomes. With only the anterior pelvic plane and change in sacral slope from sitting to standing, patients can be assessed preoperatively for dislocation risk. Following a patient cohort undergoing THA, Innmann et al. [41] found that abnormal preoperative spinopelvic characteristics can normalize 1 year postoperatively following THA. This finding underscores the dynamic nature of spinopelvic biomechanics and demonstrates the value of a Patient-Specific Safe Zone in planning THA. By accounting for evolving postoperative spinopelvic characteristics, this Patient-Specific acetabular target may enhance stability and minimize dislocation risk. Further, titrating version and inclination within single digit degrees may be an indication to use assistive technologies. This study does not take into account non-acetabular sided considerations such as limb length, femoral version, and offset that would certainly affect stability. Future studies should investigate these parameters, as well as the efficacy of patient-specific safe zones on spinopelvic normalization following THA.

Differences in recommended component positioning between the hip-spine classification and the patient-specific target should also be considered. Compared to the internal validation cohort, the external validation cohort patient-specific target differed more in median and acceptable-extreme inclinations. The external cohort anteversion predicted by hip-spine classification was closer to post-revision component positioning than the internal cohort. In all cases, anteversion predicted by hip-spine classification differed by at least 7° compared to the patient-specific target for acceptable extreme positions (Table 3). This discrepancy in component positioning is salient considering the average difference in version between unstable and stable hips was only 6.9°. By minimizing this discrepancy, adoption of patient-specific safe zones may improve patient satisfaction following THA for patients who experience subclinical functional restrictions. While dislocation was the primary endpoint of this study, we believe that patient-specific acetabular component position may improve functional experiences following THA and may lend to higher satisfaction during physical activities. This individualized approach aligns with the growing body of literature that indicates personalized approaches can significantly improve patient satisfaction [42-45]. Notably, all 33 dislocations occurred after posterior-based approaches. However, these data are not powerful enough to identify surgical approach as an independent risk factor for dislocation. Interestingly, none of the surgeons in this study changed from a posterior to anterior approach based on personal experience with instability. Further research should aim to directly assess the impact of surgical approach, as well as acetabular patient-specific safe zones on patient satisfaction after THA.

While this study is a step toward validating the acetabular patient-specific safe zone, it has limitations. Since dislocation following THA is a rare event, the sample size is small relative to the overall number of THA procedures. The risk of prosthetic hip dislocation is a small number and requires a longer study with a larger volume of patients to evaluate. As a result, estimates of acetabular components are subject to higher variance, and true effects may be obfuscated. A greater emphasis of study around THA stability should focus on soft-tissue mechanics from anterior based and posterior based approaches. Second, the validation cohort did not have any patients classified as 2A or 2B, limiting the generalizability for those spinopelvic conditions. External validation efforts will continue as we receive additional radiographic imaging of spinopelvic parameters for hips revised for instability. Third, cases of dislocation were identified retrospectively which can introduce unmeasured confounding variables. Future investigations assessing the acetabular patient-specific safe zone efficacy should be carried out prospectively. Finally, this study did not capture surgeon-specific differences in posterior approaches for the 33 dislocations in our cohort. Future studies should further operationalize surgical techniques to identify procedural specifics that precipitate instability.

Conclusions

A patient-specific approach improved acetabular component positioning accuracy within 6° of version and 4° of inclination of stable, revised hips. Patient-specific safe zones provide quantitative targets for nuanced spinopelvic preoperative planning that may mitigate risk of instability and may indicate use of assisted technologies.

Conflicts of interest

Antonia Chen reports being a board member/committee appointments for Musculoskeletal infection society; being a part of Medical/Orthopaedic publications editorial/governing board for Arthroplasty Today, Journal of Bone and Joint infection, JBJS, CORR, Journal of Arthroplasty, Arthroplasty; being a paid consultant for Stryker Corporation, Innovation Technologies, Medical Device Business Services, Avanos Medical, ConvaTec, Ethicon, Orthalign, Smith+Nephew, Pfizer, Pacira Therapeutics, innovation Technologies,Alexion Pharmaceuticals, MicroPort, Oethopedics; and reports receiving royalties from Stryker Corporation.

Jeffrey K Lange reports receiving other financial or material support from Orthalign, Conformis, Smith+Nephew, Stryker; being a paid consultant for Aesculap Implant Systems, LLC.

Jonathan Vigdorchik reports being a part of Medical/Orthopaedic publications editorial/governing board for BJJ, Journal of hip surgery; reports receiving other financial or material support from OMNIlife science, Inc, Zimmer Biomet Holdings, Inc.; being a paid consultant for Stryker Corporation, Medical Device Business Services, Inc., MEDACTA USA, INC., Intellijoint Surgical Inc.; and reports receiving royalties from DePuy Synthes Products, Inc.

Richard Iorio reports being a board member/committee appointments for American Association of Hip and Knee Surgeons; being a part of Medical/Orthopaedic publications editorial/governing board for The Journal of Arthroplasty; reports receiving other financial or material support from Aesculap Implant Systems, Llc, Stryker Corporation, Chugai Pharmaceutical Co., Ltd.; being a paid consultant for Aesculap Implant Systems, Llc.

Ran Schwarzkopf reports being a part of Medical/Orthopaedic publications editorial/governing board for Arthroplasty Today, Knee Surgery & Related Research, Journal of Hip Surgery, The Journal of Arthroplasty; receiving research support, royalties, and a part of speakers bureau from Smith+Nephew, Inc.; being a paid consultant for Smith+Nephew, Inc, Zimmer Biomet Holdings, Intellijoint Surgical.

For full disclosure statements refer to https://doi.org/10.1016/j.artd.2024.101508.

CRediT authorship contribution statement

Michael Pang: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jonathan M. Vigdorchik:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Data curation. **Ran Schwarzkopf:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Data curation. **Antonia F. Chen:** Writing – review & editing, Project administration, Methodology, Investigation. **Richard Iorio:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Data curation. **Jeffrey K. Lange:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Prem N. Ramkumar:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Investigation, Formal analysis, Data curation, Conceptualization.

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