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Original Research

The Hip-spine Assessment of a Novel Surgical Planning Software Provides Acetabular Component Targets That Are Reliable and in Agreement With Current Clinical Recommendations

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ABSTRACT

Background: Spinopelvic immobility has been reported to increase dislocation risk following total hip arthroplasty. Surgically placing acetabular components in a functional orientation has been shown to mitigate risk. The aim of this study was to evaluate the validity and reliability of novel surgical planning software to generate clinically recommended cup targets.

Methods: Hip-spine assessments were performed retrospectively on 40 patients. Five reviewers, including 3 arthroplasty-trained surgical fellows and 2 clinical research scientists performed the assessments. Hip-spine assessments consisted of measuring anterior pelvic plane tilt, sacral slope, pelvic incidence, and lumbar lordosis on standing anteroposterior pelvis and lateral standing and seated hip-spine images. Generated cup targets and a control group (40°/20° relative to the anterior pelvic plane) were compared to clinically recommended cup targets. Agreement was defined as a cup position within the recommended range or within 3° of a specific target (eg, 40° inclination) when no range was provided. Intraclass correlation coefficients were used to assess interrater and intrarater reliability, and McNemar's chi-square test was used to measure success relative to the control group.

Results: The intraclass correlation coefficient was 0.88 for delta sacral slope and 0.92 for pelvic incidence-lumbar lordosis mismatch. For patients with spinopelvic risk factors, the generated targets matched the clinical recommendations in 81% of patients compared to only 16% in the control group.

Conclusions: Excellent interrater and intrarater reliability was achieved using the novel surgical planning software. The resultant target values agreed with clinical recommendations to a greater extent than the control group.

Introduction

Total hip arthroplasty (THA) is a consistently successful surgery with high satisfaction rates; however, there continues to be a proportion of patients who require revision due to instability and dislocation. Revision surgeries are more time-consuming [1], costly [2], induce greater strain on both the surgeon [3] and the patient [4], and result in longer hospital stays [1,2]. A retrospective study examining the cause of revisions found that half could have been potentially avoided, with the largest proportion the result of sub-optimal acetabular component positioning [5]. Although the longevity of hip replacements has improved over time with better design and composition of components [6], instability and dislocation have remained a leading cause for revision surgery [7].

A reduction in spinopelvic mobility has been attributed to an increased dislocation rate [8,9]. This is particularly true for patients with spinal pathologies [10,11]. One study found the incidence of dislocation in patients with severe sagittal deformity to be 8% [11]. Another study compared the dislocation rates in individuals with spinal fusions and found that patients with fused spines were 2-3

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times more likely to dislocate than patients without a fusion [12]. A healthy posterior chain allows for the necessary sagittal pelvic movement to accommodate functional positions without impingement or edge loading. The pelvis will rotate posteriorly by ~20° when moving from a standing to a seated posture to increase the native anteversion and allow for impingement-free femoral flexion [13]. The reverse occurs in standing as the pelvis tilts anteriorly to allow extension free of posterior impingement. In pathological situations where the stiffness of the spine prevents sagittal pelvic movement, patients have a postoperative risk for instability, impingement, and resultant dislocation. To surgically compensate for the lack of pelvic movement due to spinal stiffness, a patient-specific functional cup orientation can be utilized to optimize the impingement-free range of motion.

Planning for a functional cup position requires radiographic sagittal plane imaging to be obtained in seated and standing positions to determine the patient's pelvic mobility and alignment. The mobility and alignment in functional positions indicate the direction of the patient's risk and therefore help determine how to best orient the cup to compensate for this risk, generally by increasing or decreasing anteversion. This methodology has been accepted in arthroplasty literature; however, there has been limited adoption into practice. Most existing planning options that incorporate spinopelvic mobility require computed tomography or magnetic resonance imaging, are implant or device-specific, are performed elsewhere by engineers, or are limited to measuring angles on a single image at a time. A novel surgical planning software [14] has recently been released as an easy-to-use, implant-agnostic, surgeon-controlled templating and planning solution that only requires x-rays to incorporate the hip-spine relationship to plan patient-specific cup targets for hip arthroplasty. The novel surgical planning software requires the user to measure pelvic obliquity, anterior plane pelvic tilt (APPt), and sacral slope on standing and sitting lateral images to provide a suggested cup target. The novel software provides measurements to the same accuracy and precision as TraumaCad [14], but there is still a need to examine the clinical validity of the patient-specific functional cup targets. Different research groups have proposed various methods of performing hip-spine analyses [15-17], but the most frequently used is the change in sacral slope value from standing to relaxed sitting (delta sacral slope [dSS]) and the difference between pelvic incidence and lumbar lordosis (PI-LL mismatch). Using these inputs, patients can be categorized via their spinopelvic mobility and alignment and then assigned a target acetabular component position value based on their category (see Table 1). Categorizing patients in this manner has been regarded as the current clinical recommendation when considering the hip-spine relationship [18] due to the low dislocation rate (0.8%) observed in a large multicenter study with a 5-year follow-up [8].

The purpose of this study was to investigate the clinical validity and reliability of the acetabular component targets provided using the hip-spine assessment of a novel surgical planning software. Clinical validity was assessed based on the agreement with validated targets within the clinical literature. The performance of the novel software would also be compared to that of a control group with the target 40°/20° relative to the anterior pelvic plane (APP). It was hypothesized that the targets from the novel surgical planning software would outperform the control group in the frequency of agreement with the current clinical recommendations [8,18].

Material and methods

Forty patients who underwent primary THA at a single institution from October 2019 to October 2021 were retrospectively reviewed to obtain their preoperative imaging. Patients were selected by the primary investigator to include a wide range of spinopelvic mobility and alignment parameters and to ensure that each of the reviewers was blinded. The average age of the patients were 62 years ± 13, and 65% were female (Table 2). Preoperative imaging consisted of standing anteroposterior (AP) and lateral views and a seated lateral image using stereoradiographic images (EOS Imaging, Paris, France). All images were deidentified and cropped to show the necessary landmarks, including all lumbar vertebrae to the proximal third of the femur on both lateral images and the superior border of the iliac crests to below the lesser trochanter of the femur on the standing AP view. These images were then randomized and imported into the surgical planning software, Intellijoint VIEW (v4.1 Intellijoint Surgical, Kitchener, ON), to undergo hip-spine assessments.

Five reviewers performed assessments on the individually randomized image sets. Three of the reviewers were board-certified arthroplasty fellows, and 2 of the reviewers were research scientists. For the intrarater reliability analysis, one of the research scientists performed the review 3 separate times on the images, which were randomized for each review. A hip-spine assessment was executed within the planning software to obtain operative cup targets (inclination and anteversion). To perform the assessment, the following parameters were measured: pelvic obliquity (interischial line or teardrop line on the AP image), sacral slope in standing and sitting lateral images (angle between the sacral endplate and the horizontal), and the APPt (angle between the vertical and a line that connects the pubis and a point bisecting the

Table 1
Clinical classifications and cup target recommendations based on the 2021 Otto Au Franc Award Winner [8], "A simple hip-spine classification for total hip arthroplasty".

Classification	Alignment (PI-LL mismatch)	Mobility (dSS)	Target recommendations
1A – normal alignment, normal mobility	<10°	>10°	Inclination: 40°-45° Anteversion: 20°-25°
1B – normal alignment, stiff spine	<10°	≤10°	Inclination: 45° Anteversion: 25°-30°
2A – flatback deformity, normal mobility	≥10°	>10°	*Anterior Pelvic Tilt* Inclination: 40°-45° Anteversion: 20°-25° *Posterior Pelvic Tilt*[a] Inclination: 40° Anteversion: 20°-25°
2B – flatback deformity, stiff spine	≥10°	≤10°	Inclination: 40° Anteversion: 25° Unless posterior pelvic tilt magnitude ≥13°, then target should be less than native anatomy (or inclination: 45°, anteversion 25°-35° relative to the functional pelvic plane)

[a] If magnitude ≥13°, then target should be less than native anatomy.

Table 2
Patient demographics and characteristics.

Patient characteristics	
Age ±SD (range)	62 ± 13 (13-80)
Sex	26 F (65%), 14 M (35%)
BMI ±SD (range)	29.1 ± 6.2 (16.5-44.2)
Race	White or Caucasian – 32 (80%)
	Black or African American – 5 (12.5%)
	Asian – 1 (2.5%)
	Other – 4 (10%)
Operative side	Left – 15 (37.5%)
	Right – 25 (62.5%)

anterior superior iliac spines). The previous measurements are the only requirements for the software to provide a cup target, but PI (angle between the line connecting the center of the femoral head(s) to the middle of the sacral endplate and a line perpendicular to the sacral slope) and LL (angle formed between the superior endplates of L1 and S1) were also measured to categorize patients and obtain the clinically recommended targets. The surgical planning software provides a patient-specific cup position that has inclination and anteversion values that are expressed in both the radiographic functional coronal plane and the APP, but only the functional values [19] were used within the analyses. The 'functional values' refer to the inclination and anteversion values of the projected cup relative to the standing radiographs (cup angles are calculated assuming that the vertical axis of the image corresponds to the patient's coronal plane while standing). The APP values express the same cup orientation but are relative to the patient's pelvic tilt (when APPt = 0, functional = APP) [20]. While the planning software provides a range of target values, the auto-balance cup feature was used to produce a single inclination and anteversion target for each patient to use for the analysis. The control group allowed for a within-patient comparison that used the same anatomical measurements (APPt, PI, LL, and dSS), but had a consistent cup placement of 40° of inclination and 20° of anteversion relative to the APP (instead of software's suggested target). The corresponding functional values were then recorded and utilized so that every comparison was made in the same reference plane as the current clinical recommendations. The 40°/20° value was selected to simulate a common surgical target delivered relative to the patient's anatomy. Figure 1 depicts an example of a hip-spine assessment of one patient with the software's cup target in the top row of images and the control group's plan in the bottom row of images. Despite having the same input measurements, the cup targets are notably different.

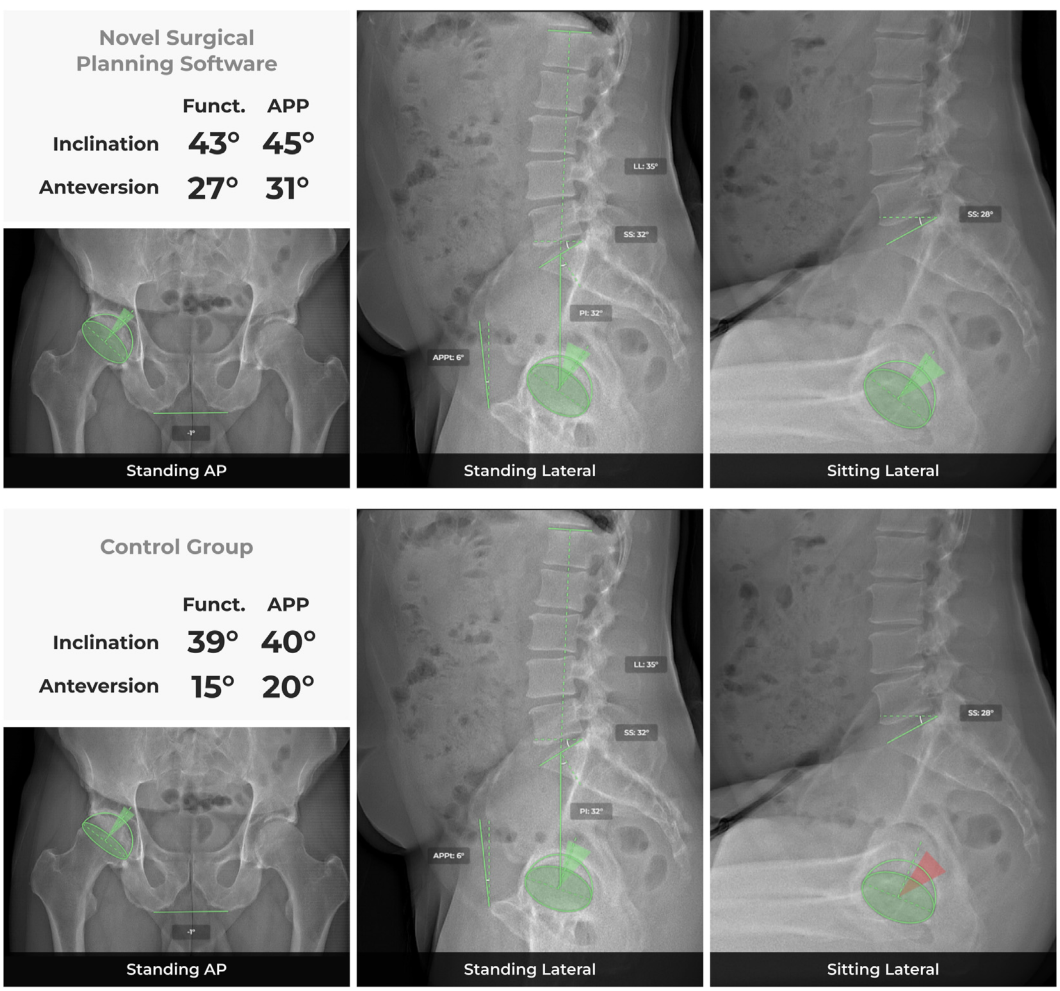

Figure 1. Methodological figure depicting the hip-spine assessment that was performed within the novel surgical planning software. The same patient is depicted twice with the above panels demonstrating the planning software's predicted cup target and the bottom panels showcasing the control group's cup position (the functional values of a cup placed at 40°/20° in the APP). PI-LL was measured at −3° and dSS at 4°, which would classify this patient in the 1B category. Agreement for 1B patients was defined as 45° ± 3° for inclination and 25°-30° for anteversion in the functional standing coronal plane.

The dSS and PI-LL mismatch values were used to classify patients into 4 categories (1A, 1B, 2A, 2B) based on the 2021 Otto Aufranc Award paper [8]. The purpose of these categories was to establish clinically valid cup target recommendations for each patient. Agreement was then defined as a cup orientation (from the planning software or control group) that fell within the clinical target range (eg, 40°-45° of inclination) or within ±3° of a singular target when no range was provided (eg, 45° of inclination). To agree with the classifications, both the inclination and anteversion targets needed to match the clinical recommendations. Classifications and targets from the reference study are listed in Table 1.

McNemar's chi-square test [21] was used to compare the frequency of agreement between the surgical planning software's targets and the control group for all cases and within each classification. Intraclass correlation coefficients (ICC) were used to measure interrater and intrarater reliability. The outcome variables dSS and PI-LL were chosen for the ICC analysis since these were the inputs used to establish the spinopelvic mobility classifications. All statistical tests were performed in Excel 365 (Microsoft; Redmond, Washington), and a P-value <.05 was used to establish significance. This study was approved by the institutional review board (#2021-2076-AM1) and complied with the Declaration of Helsinki.

Results

Hip-spine assessments were performed on 40 patients by 5 reviewers using the surgical planning software resulting in a cumulative total of n = 200. In 90% of the cases, at least 4 of the 5 reviewers had the same classification. In summary, 100 cases were classified as 1A (normal mobility, normal alignment), 34 as 1B (stiff spine, normal alignment), 47 as 2A (normal mobility, spinal deformity), and 19 as 2B (stiff spine, spinal deformity). Both the interrater and intrarater reliability were excellent [22]. The interrater reliability ICC for dSS was 0.88 (95% confidence interval [CI] 0.83-0.93) and 0.92 (95% CI 0.78-0.96) for PI-LL mismatch. Intrarater reliability ICC was 0.97 (95% CI 0.96-0.99) for both dSS and PI-LL mismatches.

The surgical planning software provided significantly more targets in agreement with the clinical recommendations than the control group ($\chi2 = 47.16$, $P < .05$; Table 3). For patients with any spinopelvic risk factor (stiff spine, PI-LL mismatch, or both), the software targets agreed with clinical recommendations 81% of the time, while the control group only matched 16% ($\chi2 = 42.05$, $P <$ .05; Fig. 2). In patients with stiff spines, and therefore the highest dislocation risk [8,23], the software agreed with the clinical recommendations 89% of the time in 1B patients and 100% in 2B, in contrast to the control group, which agreed 0% for 1B and 5% for 2B. Within each spinopelvic classification, the software outperformed the control group at the frequency of agreement with the clinical recommendations (see Fig. 2; 1A$\chi2 = 6.82$, 1B$\chi2 = 11.65$, 2A$\chi2 =$ 14.23, and 2B$\chi2 = 18.00$, all $P < .05$).

There were 12 instances where targets were not provided by the surgical planning software. This occurred when there was significant anterior pelvic tilt (>7°) in combination with a stiff spine (patients should be assessed in clinic to rule out a resolvable flexion contracture) or when hypermobility exceeded 50°. There were no missing targets in the control group (40°/20° relative to the APP); however, the targets from each of these cases did not agree with the clinical recommendations of the reference study. These cases were still included in the McNemar's chi-square analysis for full transparency in the agreement results.

Discussion

The relationship between spinopelvic pathologies and increased dislocation risk in THA has established a need for an accessible way that any surgeon could plan for patient-specific functional cup targets. The purpose of this study was to evaluate the validity and reliability of a surgeon-controlled surgical planning software to provide clinically relevant cup targets. To achieve this, the cup positions generated from the hip-spine assessment of the software as well as a control condition (40°/20° with respect to APP) were compared to the targets from the largest published cohort with a long-term follow-up period and a low dislocation rate. The results from the software were reproducible, as shown by excellent interrater and intrarater reliability. The congruency of the results between the arthroplasty fellows and research scientists demonstrates the accessibility and ease-of-use between users of different backgrounds. The surgical planning software also provided significantly more targets in agreement with the clinical recommendations than the control condition.

In patients with stiff spines (classifications 1B and 2B), the surgical planning software provided targets that agreed with the clinical recommendations a combined 93% of the time compared to the control condition, which only fell within the clinical range in 2% of cases. These are the patients who are at the highest risk for dislocation [8,9]. The lack of agreement in the control group highlights the risks of using the same cup target for all patients and orienting the cup only relative to the patient's anatomy without considering their pelvic orientation in different functional positions. It is critical to perform hip-spine assessments in all patients, rather than only those who have observable spinal hardware or a patient history, because of the frequency of spinal stiffness within the THA population. In a study of 6340 primary THA patients, it was found that 81% of those who were classified as having a stiff spine did not have an instrumented fusion [24]. In the same study, 33% of the patients who had a fused spine had normal spinal mobility [24]. Another study performed hip-spine assessments in patients undergoing revision surgery and found that 77% of inappropriately positioned cups would not have been identified if only a supine anteroposterior image was used [25]. This discrepancy is well explained by Pierrepont and colleagues, who showed the variations in pelvic tilt from supine to standing and seated [26].

Most of the cases that fell outside of the agreement criteria came from the groups with normal mobility or hypermobility (classifications 1A and 2A). To agree with the recommendations for these

Table 3
Frequency of agreement with clinical recommendations contingency table for all cases.

McNemar's chi-square $X^2 = 47.16$ ($P < .05$)	Control group		Total
	Agreed with clinical recommendations	No agreement with clinical recommendations	
Novel surgical planning software			
Agreed with clinical recommendations	32	93	125
No agreement with clinical recommendations	20	55	75
Total	52	148	200

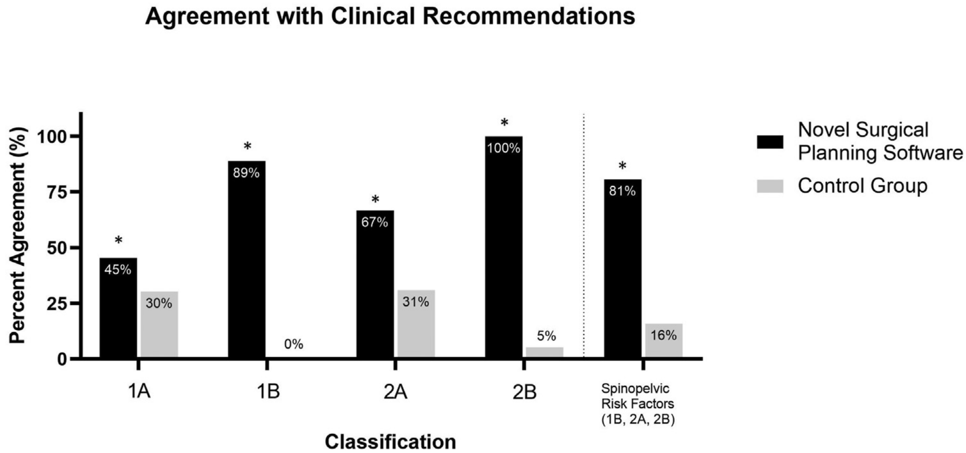

Figure 2. The percent agreement to clinical recommendations of provided cup targets from the novel surgical planning software and the control group as stratified by spinopelvic classification and grouped by all patients with spinopelvic risk factors. The novel surgical planning software significantly outperformed the control group within each classification, as denoted by *($P < .05$).

groups, the anteversion angle had to fall between 20 and 25°, and in the cases that did not, the software's suggested anteversion angles were lower. The surgical planning software anticipates the presence of a flexion contracture and intentionally suggests a lower anteversion angle in cases with a mobile spine and substantial anterior pelvic tilt (>7°). One study showed an average of 8° of posterior pelvic tilt resolution 1 year after THA in a cohort of 30 patients with a preoperative APPt of 14.3° ± 4.0° [27]. Every degree of pelvic tilt changes the natural version of the pelvis by 0.7° [20], and inadvertently not accounting for this postoperative change could result in a cup target that has an additional 5° of anteversion. Spinopelvic hypermobility, which occurs in many of the same patients, is postulated to occur to compensate for stiffness at the hip. Once the stiffness at the hip resolves postoperatively, so does the spinopelvic hypermobility; 95% of patients returned to normal mobility 1 year after THA [28]. Patients with spinopelvic hypermobility have been shown to have a low dislocation rate [28], even though they are the subset of patients whose cup placement has been shown to be the least accurate [29].

There were limitations to this study. First, the sample size was 40 participants. While this is a relatively small sample size, it did encapsulate a wide variety of spinopelvic mobility and alignment values representative of the range found within the THA population. Second, there are challenges associated with performing the hip-spine assessment with any software, as it is dependent on the quality of the patient images and ability to visualize landmarks. Field of view can be of concern as it can be difficult to acquire a lateral x-ray that includes both the superior endplate of the L1 vertebrae and the proximal third of the femur for tall patients. While the surgical planning software does not require visualization of L1 to determine a cup position, it was necessary for this study so that comparisons to the clinical recommendations based on PI-LL mismatch could be made.

The cup target position should be planned with the final pelvic orientation in mind and not only the preoperative alignment. Since postoperative lateral imaging is very uncommon, it is challenging to predict the acute and long-term postoperative changes. Flexion contractures have been shown to resolve within a year of surgery [27] and hypermobility is often a compensatory response of the spine to accommodate a stiff hip and thus also typically resolves post-THA [28]. These postoperative spinopelvic changes are considered in the suggested cup targets; however, without more long-term data, it is not possible to predict the exact magnitude of these presumed changes.

Conclusions

The novel surgical planning software yielded consistent results with excellent interrater and intrarater reliability. The resultant target values were clinically meaningful and agreed with current clinical recommendations, with differences in anteversion targets a product of the compensation for flexion contractures and hypermobility. The current findings suggest that the planning software can both save time in performing a hip-spine assessment (does not require PI or LL measurements) and provide targets to patients regardless of height using x-rays since the suggested cup positions were clinically relevant based only on APPt and dSS. The software simplifies the complexity of the hip-spine relationship, making it accessible to all surgeons with minimal time added before surgery. The surgical planning software is surgeon-controlled, easy-to-use, only requires x-rays, and can provide patient-specific acetabular component targets that may reduce the risk of dislocation and instability in patients with stiff spines.

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Conflicts of interest

E. McIntosh and J. Muir were employees of Intellijoint Surgical. J. Vigdorchik is a paid consultant for Intellijoint Surgical. J. Muir and J. Vigdorchik have stock or stock options in Intellijoint Surgical.

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Author contributions

Elizabeth Davis contributed to formal analysis, investigation, writing – review and editing. Jeffrey M. Muir contributed to formal analysis, investigation, methodology, validation, writing – review and editing. Nana O. Sarpong contributed to formal analysis, investigation, writing – review and editing. John R. Steele contributed to formal analysis, investigation, writing – review and editing. Emily I. McIntosh contributed to conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, resources, validation, visualization, writing – original draft, writing – review and editing. Jonathan M. Vigdorchik contributed to conceptualization, data curation, supervision, writing − review and editing. Haley G. Canoles contributed to data curation, project administration, writing − review and editing.

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