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Short communication

Correspondence between scapular anatomical coordinate systems and the 3D axis of motion: A new perspective on an old challenge

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ABSTRACT

Several scapular anatomical coordinate systems have been reported in the literature to describe shoulder kinematics. Unfortunately, the use of different conventions hinders comparison across studies. Further, inconsistencies between a coordinate system and the scapula's 3D axis of motion means that scapular motion will be incorrectly attributed to axes about which it did not rotate. The objectives of this study were to: 1) determine the extent to which the axes of four common scapular coordinate system conventions correspond to the 3D axis of scapular motion (i.e., instantaneous helical axis, IHA), and 2) report the prevalence of scapulothoracic gimbal lock for each convention. Shoulder kinematics were tracked during scapular plane abduction in 45 participants using biplane videoradiography. Scapulothoracic kinematics were described using the original convention proposed by van der Helm, the convention recommended by the International Society of Biomechanics (ISB), a glenoid-based coordinate system, and a glenoid-oriented coordinate system. The 3D angle was calculated between the IHA and each axis of the four conventions (IHA-axis angular deviations). A repeated measures ANOVA was used to compare IHA-axis angular deviations between conventions. The glenoid-oriented and ISB conventions resulted in the smallest and largest IHA-axis angular deviations, respectively (21.7°±3.6° vs. 30.5°±5.2°, $p < 0.01$). Gimbal lock was approached in 17.8% of participants when using the original convention, 2.2% when using the ISB convention, and 0% when using the glenoid-based or -oriented conventions. These findings suggest the glenoid-oriented coordinate system may be worthy of further consideration when investigating shoulder kinematics during scapular plane abduction.

1. Introduction

Anatomical coordinate systems are fundamental tools in biomechanics that allow joint kinematics to be described in a clinically-relevant manner. However, kinematic descriptions depend on how coordinate systems were defined precluding direct comparison across studies that use different conventions. This challenge is especially prevalent when investigating shoulder kinematics where no less than nine different coordinate system conventions have been used for the scapula (Amadi et al., 2008; Calderone et al., 2014; Hebert et al., 2000; Kedgley and Dunning, 2010; Kolz et al., 2020; Ohl et al., 2015; Pearl et al., 1992; van der Helm, 1997; Wu et al., 2005).

Historically, the most commonly used scapular coordinate systems are those proposed by van der Helm (van der Helm, 1997) and the International Society of Biomechanics (ISB) (Wu et al., 2005). Originally, van der Helm proposed that the scapular axes should be constructed using the root of the scapular spine, posterior acromioclavicular joint, and inferior angle (van der Helm, 1997). Less than a decade later, however, the ISB replaced the posterior acromioclavicular landmark with the posterolateral acromion to help prevent gimbal lock (Wu et al., 2005). However, the resulting axes no longer represent the scapula's anatomical plane, which is important for clinical interpretation (Ludewig et al., 2010) and possibly the rationale for its continued use by many researchers (e.g., Lawrence et al., 2014; Ludewig et al., 2009; McClure et al., 2006).

More recently, a glenoid-based coordinate system has been used to describe glenohumeral translations and arthrokinematics (Peltz et al., 2015) since the glenoid provides a more meaningful reference than the full scapula for these measures. Widespread use of a glenoid-based coordinate system is hindered, however, due to the glenoid's inaccessibility to palpation, which is necessary for surface-based motion capture techniques using sensors or markers. Finally, a glenoid-oriented

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coordinate system has also been proposed in which the medial–lateral axis is oriented to the glenoid center instead of the acromion, offering a potential compromise between the original van der Helm and ISB conventions.

Although several researchers have compared kinematics described using different scapular coordinate systems (Calderone et al., 2014; Kolz et al., 2020; Ludewig et al., 2010), it remains unclear which convention corresponds mostly closely with the true 3D axis of scapular motion, which can be described using an instantaneous helical axis (IHA). This gap in our knowledge is especially problematic given the frequent use of Euler angles, which describe a joint's kinematics as an ordered sequence of rotations typically about the distal segment's axes, and inconsistencies between these axes and the 3D motion axis will result in mathematical artifact confounding clinical descriptions. Helical angles have been suggested as an alternative; however, they lack physical interpretation (Woltring, 1991). Consequently, Euler angles remain the primary method for describing kinematics despite their many limitations and uncertain correspondence with the true 3D motion axis. Therefore, the objectives of this study were to: 1) determine the extent to which the axes of four common scapular coordinate system conventions correspond to the true 3D axis of scapular motion (IHA), and 2) report the prevalence of scapulothoracic gimbal lock for each convention.

2. Methods

2.1. Participants

This analysis includes data from 45 asymptomatic participants collected as part of an ongoing investigation (55 ± 4 years, 64% female). The study was approved by Henry Ford Health's Institutional Review Board. Written informed consent was obtained prior to data collection.

2.2. Data collection and processing

Shoulder kinematics were assessed during scapular plane abduction (SAB) using a high-speed biplane videoradiography system as previously described (Lawrence et al., 2021). A CT scan was also acquired, and the humerus, scapula, and third rib were segmented using Mimics software (Materialise NV, Leuven, Belgium). Anatomical landmarks were calculated or digitized on the CT-derived 3D bone volumes (Table 1). Anatomical coordinate systems were reconstructed for each frame of the motion trial using filtered landmark trajectories (4th order Butterworth, 5 Hz low-pass cutoff). Specifically, the humeral and torso coordinate systems were created based on ISB recommendations (Wu et al., 2005) and four anatomical coordinate systems were defined on the scapula (Table 1, Fig. 1).

Next, the 3D axis of scapulothoracic motion was calculated using the IHA (Veeger, 2006; Woltring et al., 1994). The correspondence between the IHA and each scapular coordinate system convention was calculated for each frame of the motion trial as the 3D angle between the IHA and each coordinate axis (i.e., IHA-axis deviation). If the IHA and a coordinate system axis were pointed in opposite directions, the direction of the IHA was reversed so that the smallest supplementary angle was calculated between the axes.

Once IHA-axis deviations were calculated across all frames within a participant's motion trial, they were summarized into a single RMS estimation of the IHA-axis angular deviation for each coordinate axis within a participant. Given the IHA-axis angular deviations were calculated as a single 3D angle, the principal direction of the IHA needed to be identified to determine which IHA-axis angular deviation to interpret when identifying the convention that best coincides with the true 3D axis of motion. To do this, a single centroid IHA was calculated across the IHAs during the motion trial (Lawrence et al., 2020; Woltring, 1990) and the coordinate axis with the smallest IHA-axis angular deviation was interpreted. In 99.4% of participants and coordinate system conventions (Fig. 1), the principal direction of the scapulothoracic centroid IHA was most consistent with the scapular anterior/posterior axis. Therefore, the anterior/posterior IHA-axis angular deviation served as the primary indicator of correspondence between the coordinate system and the 3D axis of scapular motion.

Finally, scapulothoracic and glenohumeral kinematics were quantified and compared statistically between the 4 scapular coordinate system conventions. More details and the results of this secondary analysis are available in the **Supplementary Materials**.

Table 1
Definition of scapular anatomical coordinate systems. *Details about the construction of the glenoid-based coordinate system are available in the Supplementary Materials. Abbreviations: centerGlenoid = center of the glenoid, IA = inferior angle, PLA = posterolateral acromion, postAC = posterior acromioclavicular joint, RS = root of scapular spine.

Coordinate System	Axis Definition
Original (van der Helm, 1997)	
Z axis ($\vec{Z}$)	(postAC − RS) / |postAC −RS|
Intermediate axis ($\vec{I}$)	(IA − RS) / |IA −RS|
X axis ($\vec{X}$)	$(\vec{Z}\times\vec{I})/\lvert\vec{Z}\times\vec{I}\rvert$
Y axis ($\vec{Y}$)	$(\vec{Z}\times\vec{X})/\lvert\vec{Z}\times\vec{X}\rvert$
Origin	postAC
ISB (Wu et al., 2005)	
Z axis ($\vec{Z}$)	(PLA − RS) / |PLA −RS|
Intermediate axis ($\vec{I}$)	(IA − RS) / |IA −RS|
X axis ($\vec{X}$)	$(\vec{Z}\times\vec{I})/\lvert\vec{Z}\times\vec{I}\rvert$
Y axis ($\vec{Y}$)	$(\vec{Z}\times\vec{X})/\lvert\vec{Z}\times\vec{X}\rvert$
Origin	PLA
Glenoid-based*	
X axis ($\vec{X}$)	Anterior/posterior-directed principal axis fit to the glenoid rim points
Y axis ($\vec{Y}$)	Superior/inferior-directed principal axis fit to the glenoid rim points
Z axis ($\vec{Z}$)	Medial/lateral-directed principal axis fit to the glenoid rim points
Origin	centerGlenoid
Glenoid-oriented (Kolz et al., 2020)	
Z axis ($\vec{Z}$)	(centerGlenoid − RS) / |centerGlenoid −RS|
Intermediate axis ($\vec{I}$)	(IA − RS) / |IA −RS|
X axis ($\vec{X}$)	$(\vec{Z}\times\vec{I})/\lvert\vec{Z}\times\vec{I}\rvert$
Y axis ($\vec{Y}$)	$(\vec{Z}\times\vec{X})/\lvert\vec{Z}\times\vec{X}\rvert$
Origin	centerGlenoid

2.3. Statistical analysis

A one-factor repeated measures ANOVA was used to compare the IHA-axis angular deviation between coordinate system conventions. The prevalence of scapulothoracic gimbal lock was calculated by determining the proportion of participants that approached the singular position for each convention. Upward rotation served as the warning for gimbal lock because the phenomenon occurs when the second ordered rotation (i.e., upward rotation for Y-X'-Z'') approaches 90° (±20°) (Woltring, 1991). Statistical analysis was performed in SAS 9.4 (SAS Institute Inc., Cary, NC, USA).

3. Results

The glenoid-oriented coordinate system had the smallest IHA-axis angular deviation with a mean (±SD) deviation of 21.7°±3.6° followed by the original (23.9°±4.3°), glenoid-based (25.6°±4.8°), and ISB (30.5°±5.2°) conventions (Fig. 2). Pairwise comparisons between each

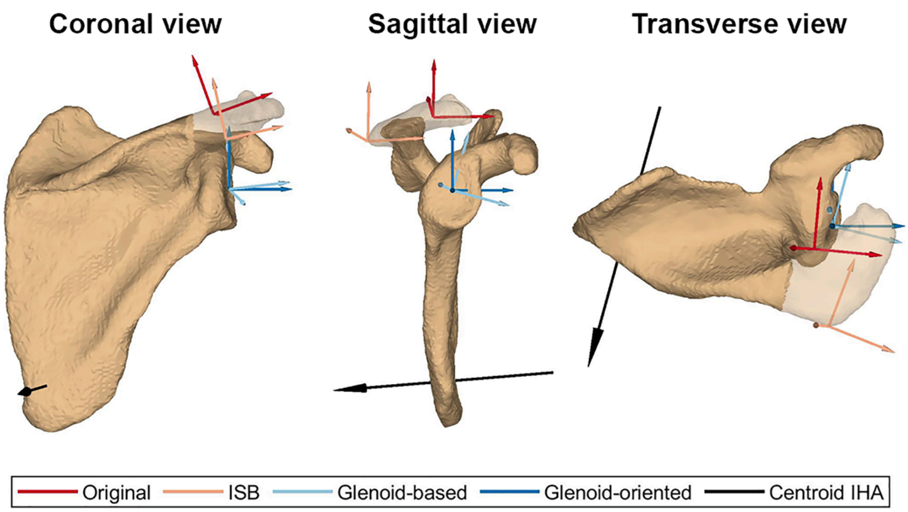

Fig. 1. Comparison of the four scapular coordinate system conventions and the centroid scapulothoracic instantaneous helical axis (IHA) during scapular plane abduction in a representative participant having the approximate median RMS angular deviation between the centroid IHA and the anterior/posterior axis across each scapular anatomical coordinate convention. Note that the glenoid-based coordinate system reflects glenoid morphology and ignores overall scapular shape, while the glenoid-oriented coordinate system reflects scapular morphology as the medial/lateral axis is oriented (i.e., directed) from the root of the scapular spine towards the glenoid center.

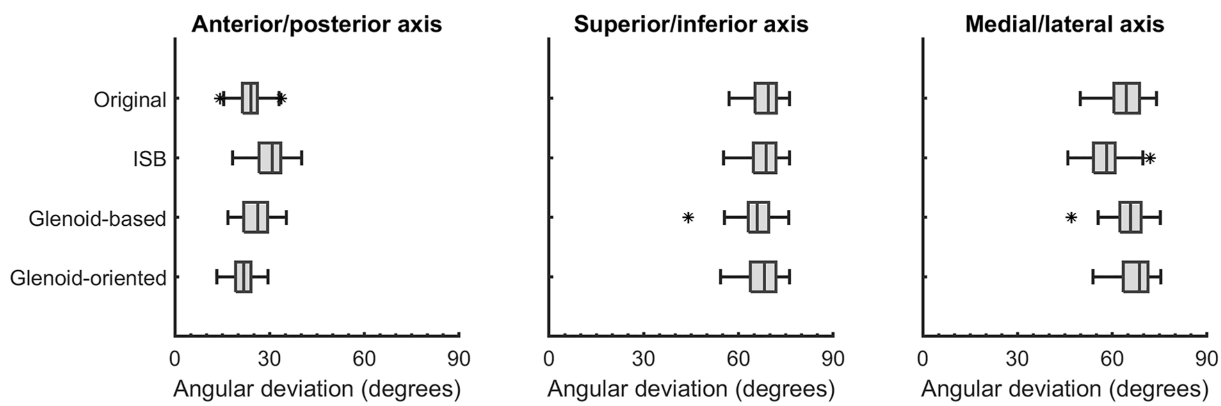

Fig. 2. Boxplots describing the angular deviation (RMS error) between the instantaneous helical axis and each axis of the scapular coordinate systems (i.e., IHA-axis angular deviations). During scapular plane abduction, the principal direction of the scapulothoracic centroid IHA was most consistent with the scapular anterior/posterior axis in nearly all participants across all coordinate system conventions. Therefore, the IHA-axis angular deviation for the anterior/posterior axis served as the primary indicator of correspondence between the coordinate system and the 3D axis of scapular motion. The boundaries of the box represent the 25th and 75th quartiles and the solid line within the box represents the median. The whiskers represent the upper and lower adjacent values (i.e., the most extreme data points not considered outliers). An outlier is indicated by an asterisk (*).

convention were statistically significant ($p < 0.03$).

On average, participants achieved a maximum humerothoracic elevation angle of 152.9°±7.9°. The mean scapulothoracic upward rotation magnitude at the maximum elevation angle was 65.4°±5.4°, 55.1°±6.4°, 54.1°±5.6°, and 46.4°±5.4° according to the original, ISB, glenoid-based, and glenoid-oriented conventions, respectively. Gimbal lock was approached in 8 participants (17.8%) using the original convention, 1 participant (2.2%) using the ISB convention, and 0 participants using the glenoid-based or glenoid-oriented conventions.

4. Discussion

The primary objective of this study was to compare four scapular coordinate system conventions in their correspondence with the 3D axis of scapular motion (i.e., IHA) during SAB. The glenoid-oriented convention had the smallest IHA-axis angular deviation (21.7°±3.6°) suggesting it represents 3D scapular motion most accurately during SAB (Figs. 1 and 2). The glenoid-oriented convention also avoided gimbal lock in a cohort with unrestricted functional range of motion. Taken together, these findings suggest the glenoid-oriented convention may deserve further consideration when investigating shoulder kinematics during SAB if researchers aim to accurately represent physiological motion using Euler angles.

Understanding the correspondence between a coordinate system and the 3D axis of motion is important because kinematics are typically described using Euler angles, which artificially parse joint kinematics into an ordered sequence of rotations about coordinate axes (Woltring, 1991). In the case of scapulothoracic kinematics, this is typically done about the scapular axes. Consequently, kinematic descriptions are mathematically constrained to occur about the scapular axes and rotation will be mathematically attributed to axes about which the scapula did not actually rotate, potentially disagreeing with clinical assessment. This consideration is why the ISB-recommended rotation sequence for scapulothoracic kinematics (Y-X'-Z'') first adjusts for scapulothoracic internal rotation before describing upward rotation and posterior tilt (Wu et al., 2005).

The high between-subject variability in acromial morphology likely influenced the IHA-axis angular deviations for the original and ISB conventions. Specifically, previous research suggests that the acromion is a primary source of variation in scapular shape between individuals (Lee et al., 2020) with high between-subject variability in landmark locations (Kolz et al., 2020). Both considerations likely impact the between-subject variability in coordinate systems and kinematic descriptions using Euler decompositions. Additionally, glenoid pathology (e.g., osteoarthritis) may influence the definition of the glenoid-based and glenoid-oriented coordinate systems (Walch et al., 2013). Even so, it is possible that the glenoid center landmark may be less sensitive to pathological changes in morphology as it is calculated as the centroid of hundreds of points along the glenoid rim (**Supplementary Materials**) instead of as a single landmark.

Protecting against gimbal lock is another important consideration when establishing coordinate system conventions. Gimbal lock occurs when the magnitude of the second rotation causes the first and third rotation axes to become nearly collinear and therefore mathematically indistinguishable (Woltring, 1991). For the ISB-recommended Y-X'-Z'' sequence for scapulothoracic kinematics (Wu et al., 2005), gimbal lock will occur when upward/downward rotation approaches 90°. Although this magnitude of upward rotation may not be often observed, even positions nearing gimbal lock (±20°) will be affected by high kinematic variability (van der Helm, 1997; Woltring, 1991). Fig. 3 illustrates an example from the current study in which the participant's upward rotation exceeded 70° based on the original convention. In this case, values for internal rotation and posterior tilt become increasingly questionable for the original convention yet remain plausible (i.e., no dramatic deviations in data trajectory) for the ISB, glenoid-oriented, and glenoid-based conventions. Overall, gimbal lock was approached in 17.8% of participants when using the original convention and 2.2% when using the ISB convention, suggesting that protecting against gimbal lock remains important during SAB.

Although the ISB convention resulted in fewer instances of gimbal lock than the original convention, this finding may only be relevant when shoulder kinematics are tracked using modern videoradiography techniques where the range of motion that can be investigated is less constrained. When scapular kinematics are tracked using surface-based sensors, however, kinematic interpretation is generally limited to < 120° humerothoracic elevation as tracking errors increase substantially at higher angles (Karduna et al., 2001). In the current study, no participant approached gimbal lock below 120° humerothoracic elevation, suggesting that the use of the original convention may remain appropriate below 120°, especially considering its relatively close correspondence with the 3D axis of motion (Fig. 2).

Ultimately, the selection of the most appropriate coordinate system convention may be study-specific depending on the motions investigated and the anatomy available to define the scapular coordinate system. When detailed anatomical information is available from 3D bone models, it may be prudent to select a less common convention (e.g., glenoid-based or glenoid-oriented) to improve data relevance even if doing so makes it difficult to compare with previous studies without converting between conventions (Kolz et al., 2020). Additionally, it may be possible to estimate a landmark near the glenoid center that is otherwise impalpable. For example, Pearl et al. estimated a landmark near the superior glenoid by calculating the midpoint between the coracoid process and the posterolateral acromion (Pearl et al., 1992). Although this alternative convention was not investigated in the current study, previous research suggests it may represent a potential compromise between the original and glenoid-oriented coordinate systems by preventing gimbal lock while also representing the scapula's anatomical plane (Ludewig et al., 2010).

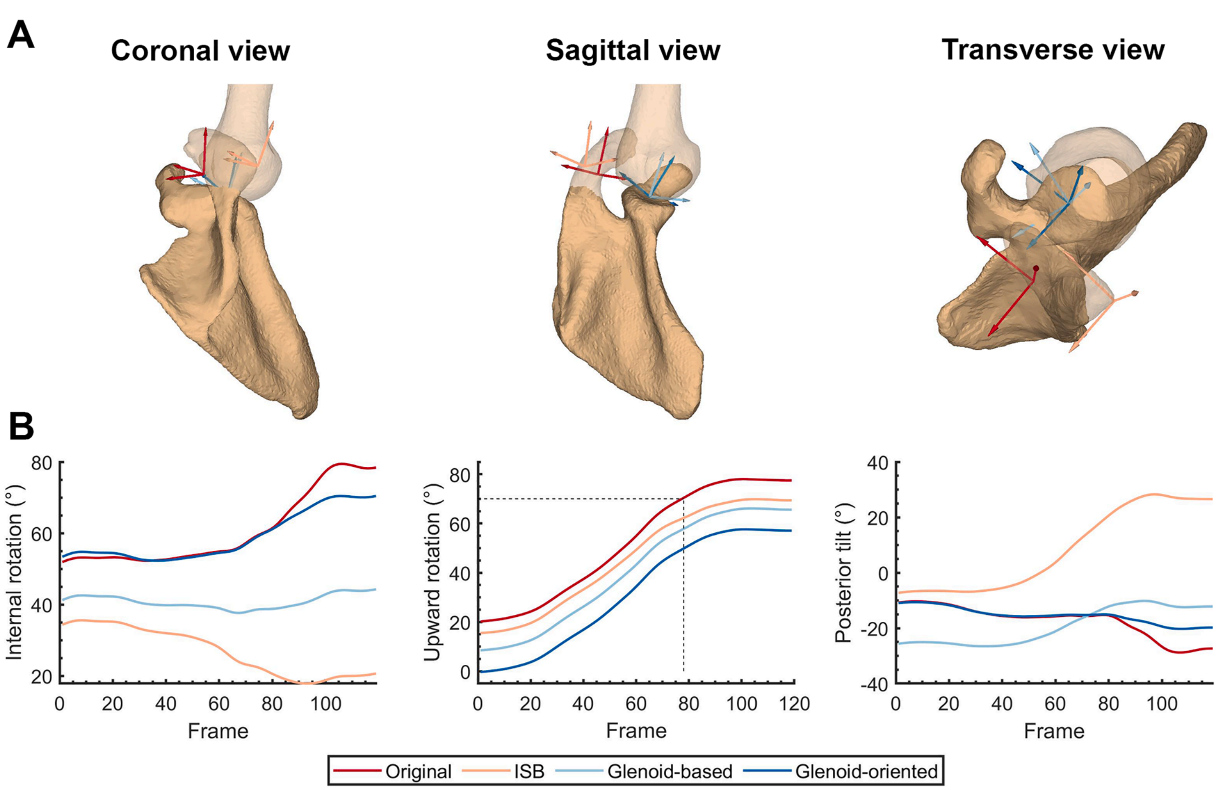

Fig. 3. Example of a participant who approached gimbal lock during the scapular plane abduction motion trial. A) Visualization of the scapula and humerus relative to the thorax coordinate system (image axes) at the final frame of the motion trial (171° humerothoracic elevation). B) Scapulothoracic internal rotation, upward rotation, and posterior tilt across the motion trial (calculated using a Y-X'-Z'' rotation sequence). Data for scapulothoracic upward rotation were transformed into positive values to facilitate interpretation. The dashed line in the upward rotation subplot represents the frame at which the participant first began to approach gimbal lock for the original coordinate system convention (i.e., upward rotation ≥ 70°). Note in the coronal and sagittal views that the scapular medial/lateral axis for the original convention is nearly aligned with the image vertical (i.e., the thorax superior/inferior axis). Likewise, in the transverse view, the scapular medial/lateral axis for the original convention is nearly pointing directly out of the page. Therefore, rotation about the scapular medial/lateral axis is nearly indistinguishable from that of the first rotation axis (scapular superior/inferior axis), which was initially aligned with the thorax superior/inferior axis (i.e., image vertical in the coronal and sagittal views) prior to the first rotation. These are classic characteristics of gimbal lock. Interestingly, the integrity of the calculated Euler angles for the original convention is called to question without an obvious singularity in the raw data. Note also that the descriptions of internal rotation and posterior tilt using the original convention change abruptly after frame #78, when the participant first began to approach gimbal lock.

This study has limitations to consider. Only four conventions were investigated based on the frequency used in the literature and hypothesized correspondence to the 3D motion axis. Furthermore, SAB was investigated based on its popularity in the shoulder literature. Care must be taken when applying the results of this study to other shoulder motions.

In conclusion, the glenoid-oriented coordinate system corresponded most closely to the 3D scapular axis of motion for SAB while avoiding gimbal lock. The glenoid-oriented coordinate system may be worthy of further consideration when investigating shoulder kinematics during SAB.

CRediT authorship contribution statement

Rebekah L. Lawrence: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Visualization, Writing – original draft. **Kevin Roseni:** Investigation, Writing – review & editing. **Michael J. Bey:** Writing – review & editing, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2022.111385.

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