Journal of Biomechanics 104 (2020) 109733

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Expressing angles relative to reference postures: A mathematical comparison of four approaches

Jeff M. Barrett, Daniel Viggiani, Jonathan Park, Jack P. Callaghan *

Department of Kinesiology, University of Waterloo, Canada

ARTICLE INFO

Article history:
Accepted 27 February 2020

ABSTRACT

Three-dimensional joint angles are most often quantified using Euler Angles. These measures are often easier to interpret if they are reported relative to a reference posture. However, since Euler Angles are not vectors, directly subtracting their values is difficult to justify mathematically. We compared four methods for subtracting a reference posture: the Subtraction Method (SM), directly subtracting the Euler Angles; two variants on the Relative Segment Method (RSM), one aligned to global (gRSM) and one aligned to the distal segment (dRSM), which considers the relative rotation of each segment to the reference posture; and the Relative Joint Method (RJM), which considers the relative rotation of the joint coordinate systems compared to that of the reference posture. One exemplar male subject (height: 175 cm; body mass: 90 kg; age: 27) performed three trials where they extended, laterally bent to the right, and extended while returning to a neutral posture between these movements. Two reference postures were compared: a standing neutral posture, and 90 degrees of flexion.

All four methods showed strong agreement when the reference posture was a neutral one (lowest $R^2 = 0.971$). However, when the reference posture was 90 degrees of flexion, both the RJM and gRSM swapped their lateral bend and axial twist measures. Additionally, when the reference posture was oriented 90 degrees from the global coordinate system, the gRSM swapped flexion and lateral bending. Therefore, the RJM, dRSM, and even the SM, are more robust than the gRSM. Either the RJM or dRSM are recommended as it is a compromise between mathematical validity and interpretability, however, the RJM seems to provide more readily interpretable angular velocities. The SM is only a viable approach under very strict conditions and should be avoided.

1. Introduction

Three-dimensional joint angles are typically quantified using a unique Euler or Cardan sequence corresponding to the relative rotation matrix between the local coordinate systems of adjacent segments—referred to here as Euler Angles. While it may be beneficial to report Euler Angles in absolute terms, considering the angles as deviations from a neutral or reference posture can be easier to interpret. This practice is commonly done by simply subtracting the Euler Angles describing a reference trial from those describing the task of interest (Bourdon et al., 2017; Cotter et al., 2014; Feipel et al., 2006, 1999; Hemming et al., 2017; Mazzone et al., 2016; Michaud et al., 2014; Riddell et al., 2016). This simple subtraction is difficult to justify mathematically since Euler Angles are not vectors (Robertson et al., 2013). Robertson et al. (2013), acknowledged this limitation of Euler Angles and presented an alternate technique to direct subtraction for joint angle normalization. That method calculates Euler Angles based on how each segment has deviated from its neutral posture. However, Robertson et al. (2013) noted that if a trial is oriented orthogonal to the reference posture, it is prone to gimbal lock. This result is problematic as joint angles should be independent of the orientation of the global coordinate system. To correct for this, Hagemeister et al. (2011) suggested a more general method for subtracting out a reference posture that is immune to the dependence on the global coordinate system.

Therefore, the purpose of this investigation was to compare four methods used to remove a reference posture and quantify the lumbar joint angles in a variety of movements. The first is the direct subtraction of the reference posture's Euler Angles from that of the trial posture. The second was the method proposed in Robertson et al. (2013), and the corrected version by Hagemeister et al. (2011). Finally, we introduce a fourth method based on the relative change of the joint coordinate systems rather than those of the segments. While we focus on the lumbar spine, the methods evaluated in this manuscript would readily generalize to other joints.

* Corresponding author.

https://doi.org/10.1016/j.jbiomech.2020.109733
0021-9290/

2. Methods

2.1. Euler angles and rotation matrices

For this investigation—in keeping with International Society of Biomechanics (ISB) standards for reporting angles of the lumbar spine—the first angle (ϕ) is about the *z*-axis and represents flexion-extension, the second angle (θ) is about the *y*-axis and represents axial twist, and the last angle (ψ) is about the *x*-axis and represents lateral bending (Wu et al., 2002). Thus, the rotation matrix, $\boldsymbol{R}$, considered here is represented as the following:

$$\boldsymbol{R} = \boldsymbol{R_z}(\phi)\boldsymbol{R_y}(\theta)\boldsymbol{R_x}(\psi) = \begin{bmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & -\sin\psi \\ 0 & \sin\psi & \cos\psi \end{bmatrix}$$
$$= \begin{bmatrix} \cos\phi\cos\theta & -\sin\phi\cos\psi + \sin\psi\sin\theta\cos\phi & \sin\phi\sin\psi + \sin\theta\cos\phi\cos\psi \\ \sin\phi\sin\theta & \sin\phi\sin\psi\sin\theta + \cos\phi\cos\psi & \sin\phi\sin\theta\cos\psi - \sin\psi\cos\phi \\ -\sin\theta & \sin\psi\cos\theta & \cos\psi\cos\theta \end{bmatrix}$$

The corresponding Euler angles may be computed from this rotation matrix. We call this function, $f(\boldsymbol{R})$, and it is given by:

$$\begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = f(\boldsymbol{R}) = \begin{bmatrix} \arctan 2(R_{21}, R_{11}) \\ -\arcsin(R_{31}) \\ \arctan 2(R_{32}, R_{33}) \end{bmatrix} \quad (1)$$

Where arctan2 is the inverse tan function taking in two arguments. Each Euler-Sequence has its own decomposition function, stemming from the non-commutativity of rotations.

2.2. Angular velocity

The time-derivative of the Euler Angles are not the components of the angular velocity vector, $\vec{\omega}$. Most often, the components of $\vec{\omega}$ are related to the time-derivatives of the Euler Angles—$\dot{\phi}, \dot{\theta}$ and $\dot{\psi}$—through the expression (Goldstein et al., 1950):

$$\begin{bmatrix} \omega_z \\ \omega_y \\ \omega_x \end{bmatrix} = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\phi & \sin\phi\cos\theta \\ 0 & -\sin\phi & \cos\phi\cos\theta \end{bmatrix}\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \quad (2)$$

It is a matter of convention that we have chosen to write $\vec{\omega} = (\omega_z, \omega_y, \omega_x)$, respecting the ISB standard for the spine to use a ZYX Euler Sequence. In dealing with rotation matrices, it is convenient to define the cross-product matrix as follows:

$$\left[\vec{v}\times\right] = \begin{bmatrix} 0 & -v_3 & v_2 \\ v_3 & 0 & -v_1 \\ -v_2 & v_1 & 0 \end{bmatrix} \quad (3)$$

where $\vec{v} \in \mathbb{R}^3$ is the angular velocity vector. When the coordinate system is changed via rotation by the rotation matrix $\boldsymbol{R}$, $\left[\vec{v}\times\right]$ obeys the property:

$$\boldsymbol{R}^T\left[\vec{v}\times\right]\boldsymbol{R} = \left[\left(\boldsymbol{R}^T\vec{v}\right)\times\right] \quad (4)$$

2.3. Joint angle calculations

We compared four ways of calculating relative joint angles for the lumbar spine: direct subtraction (Subtraction Method; SM), the Relative Segment Methods of Robertson et al. (2013) (gRSM) and Hagemeister et al. (2011) (dRSM), and the Relative Joint Method (RJM). First, define the pelvis local coordinate system (LCS) direction cosine matrix (DCM) during the trial as $\boldsymbol{V}$, and the reference LCS as $\boldsymbol{V}_0$. Likewise, the trunk's LCS is $\boldsymbol{U}$ and $\boldsymbol{U}_0$ for the trial and reference posture, respectively. The columns of these matrices are the bases, $\hat{i}, \hat{j}$ and $\hat{k}$, expressed in the global coordinate system. The relative rotation matrix ($\boldsymbol{W}$ for the trial, and $\boldsymbol{W}_0$ for the reference posture) between the two systems is expressed as:

$$\boldsymbol{W} = \boldsymbol{V}^T\boldsymbol{U}, \boldsymbol{W}_0 = \boldsymbol{V}_0^T\boldsymbol{U}_0 \quad (5)$$

where the superscript T denotes the matrix transpose. The 'raw' spine angle can be calculated directly from $\boldsymbol{W}$ using Eq. (1), however, we consider measuring the angular deviation from a reference posture. The first method we consider is the Subtraction Method (SM), written mathematically:

$$(\Delta\phi_{SM}, \Delta\theta_{SM}, \Delta\psi_{SM}) := f(\boldsymbol{W}) - f(\boldsymbol{W}_0) \quad (6)$$

Here, the joint angles are the difference between the calculated raw Euler Angles on a given frame, and those of the reference posture. A particularly nice property of this equation is that the angular velocity calculated from these joint angles will be in the pelvis coordinate system; however, as noted by Robertson et al. (2013), it fails to respect that Euler Angles are not vectors. To account for this, Robertson et al. (2013) suggested using the RSM that quantifies joint angles by:

$$(\Delta\phi_{gRSM}, \Delta\theta_{gRSM}, \Delta\psi_{gRSM}) := f\left(\left(\boldsymbol{V}\boldsymbol{V}_0^T\right)^T\left(\boldsymbol{U}\boldsymbol{U}_0^T\right)\right) \quad (7)$$

Like before, this comes with the desired property that a neutral posture is mapped to zero joint angle, and it respects the notion that Euler Angles are not vectors. However, it has one subtle flaw from a mathematical point-of-view: the joint angles calculated by this method will depend on the orientation of the global coordinate system. To avoid this error, Hagemeister et al. (2011) proposed first aligning the reference posture segments to either the proximal, distal, or a tertiary segment, a process we refer to as pre-alignment. Let the pre-alignment coordinate system be represented by the direction cosine matrix $\boldsymbol{C}$, then Hagemeister et al. (2011) generally posited the following method:

$$(\Delta\phi_{RSM}, \Delta\theta_{RSM}, \Delta\psi_{RSM}) := f\left(\boldsymbol{C}^T\left(\boldsymbol{V}\boldsymbol{V}_0^T\right)^T\left(\boldsymbol{U}\boldsymbol{U}_0^T\right)\boldsymbol{C}\right) \quad (8)$$

As written this method suffers from one subtle flaw mathematically: the angular velocity calculated from this method may be difficult to interpret. To demonstrate this, we consider calculating the angular velocity of the argument in Eq. (8). The angular velocities of orthogonal matrices are related to their time rates of change by:

$$\dot{\boldsymbol{U}} = \left[\vec{\mu}\times\right]\boldsymbol{U}, \dot{\boldsymbol{V}} = \left[\vec{v}\times\right]\boldsymbol{V}, \dot{\boldsymbol{W}} = \left[\vec{\omega}\times\right]\boldsymbol{W} \quad (9)$$

where $\vec{\mu}$, $\vec{v}$, and $\vec{\omega}$ are the angular velocities of $\boldsymbol{U}$, $\boldsymbol{V}$, and $\boldsymbol{W}$ in the global coordinate system, respectively. The RSM considers the angular velocity of $\boldsymbol{W}'$:

$$\boldsymbol{W}' = \boldsymbol{C}^T\boldsymbol{V}_0\boldsymbol{W}\boldsymbol{W}_0^T\boldsymbol{V}_0^T\boldsymbol{C} \tag{10}$$

Taking the time derivative of this expression, and rearranging using Eq. (8) reveals that:

$$\dot{\boldsymbol{W}}' = \left[\left(\left(\boldsymbol{V}_0^T\boldsymbol{C}\right)^T\boldsymbol{V}^T\left(\vec{\mu} - \vec{\nu}\right)\right)\times\right]\boldsymbol{W}' \tag{11}$$

Implying that the angular velocity of $\boldsymbol{W}'$ is the difference between the trunk and pelvis angular velocities in global ($\vec{\mu} - \vec{\nu}$), projected in the rotated pelvis system, then re-expressed in the pelvis' reference coordinate system projected into the system $\boldsymbol{C}$. The last transformation is difficult to justify mathematically, as the coordinate system transformations are no longer kept consistent. Therefore, it is difficult to interpret what coordinate system the angular velocity is truly being calculated in. To correct for this limitation, we propose the following method, which we call the Relative Joint Method (RJM), based explicitly on the joint coordinate systems rather than the segments:

$$\left(\Delta\phi_{RJM}, \Delta\theta_{RJM}, \Delta\psi_{RJM}\right) := f\left(\boldsymbol{W}\boldsymbol{W}_0^T\right) \tag{12}$$

Like the previous two measures, this method also has the property that neutral postures are mapped to zero angular displacement. Additionally, it does not subtract Euler Angles as if they were vectors. Post-multiplying the current frame's joint rotation matrix by that of the reference posture also has the property of maintaining interpretable angular velocities. To demonstrate this—like before—we calculate the angular velocity of the argument in Eq. (12), and rearrange using Eq. (4).

$$\begin{aligned}\dot{\boldsymbol{W}} &= \left[\vec{\omega}\times\right]\boldsymbol{W} = \dot{\boldsymbol{V}}^T\boldsymbol{U} + \boldsymbol{V}^T\dot{\boldsymbol{U}} = -\boldsymbol{V}^T\left[\vec{\nu}\times\right]\boldsymbol{U} + \boldsymbol{V}^T\left[\vec{\mu}\times\right]\boldsymbol{U} \\ &= -\boldsymbol{V}^T\left[\vec{\nu}\times\right]\boldsymbol{V}\boldsymbol{V}^T\boldsymbol{U} + \boldsymbol{V}^T\left[\vec{\mu}\times\right]\boldsymbol{V}\boldsymbol{V}^T\boldsymbol{U} \\ &= \boldsymbol{V}^T\left(\left[\vec{\mu}\times\right] - \left[\vec{\nu}\times\right]\right)\boldsymbol{V}\left(\boldsymbol{V}^T\boldsymbol{U}\right) = \left[\boldsymbol{V}^T\left(\vec{\mu} - \vec{\nu}\right)\times\right]\boldsymbol{W}\end{aligned} \tag{13}$$

This implies that the angular velocity of $\boldsymbol{W}$ is the difference between the global angular velocities of the trunk and pelvis ($\vec{\mu} - \vec{\nu}$), projected into the pelvis' coordinate system. Both SM and RJM explicitly use $\boldsymbol{W}$ to calculate angles rather than explicitly using the segment orientations. We note that there is a deep connection between the RSM proposed by Hagemeister et al. (2011) and the RJM utilized in this investigation. In using the proximal reference segment as the pre-alignment system, or choosing $\boldsymbol{C} = \boldsymbol{V}_0$, one recovers the same matrix $\boldsymbol{W}\boldsymbol{W}_0^T$ upon which the relative joint method operates. The other choice for $\boldsymbol{C}$ that Hagemeister et al. (2011) advocate for using is the distal segment's reference posture, $\boldsymbol{C} = \boldsymbol{U}_0$. Therefore, we tested the methods of Robertson et al. (2013) RSM ($\boldsymbol{C} = \boldsymbol{I}$, which we call gRSM as the global coordinate system is used for pre-alignment), against the RSM using the distal ($\boldsymbol{C} = \boldsymbol{U}_0$, which we call dRSM as the distal segment is used for pre-alignment), and the RJM, which is the RSM aligning to the proximal segment ($\boldsymbol{C} = \boldsymbol{V}_0$).

2.4. Experimental methods

One exemplar male subject (height: 175 cm; body mass: 90 kg; age 27) was instrumented with active optoelectronic marker clusters over the L1 spinous process and pelvis (NDI Canada, Waterloo Ontario). Kinematic data were continuously sampled at 100 Hz. Virtual markers on each segment were digitized to construct local coordinate systems consistent with ISB standards (Fig. 1) (Wu et al., 2002). The Euler Angles between the L1 and pelvis local coordinate systems were used to quantify the participant's lumbar joint angle. The subject performed three trials where they began from a neutral posture, extended, lateral bent to the right, and flexed, while returning to a neutral posture between movements. This motion provided a range of values for the quantification of Euler Angles relative to reference trials using SM, gRSM, dRSM, and RJM. Reference trials were five-second static postures and included neutral standing and 90 degrees of trunk flexion.

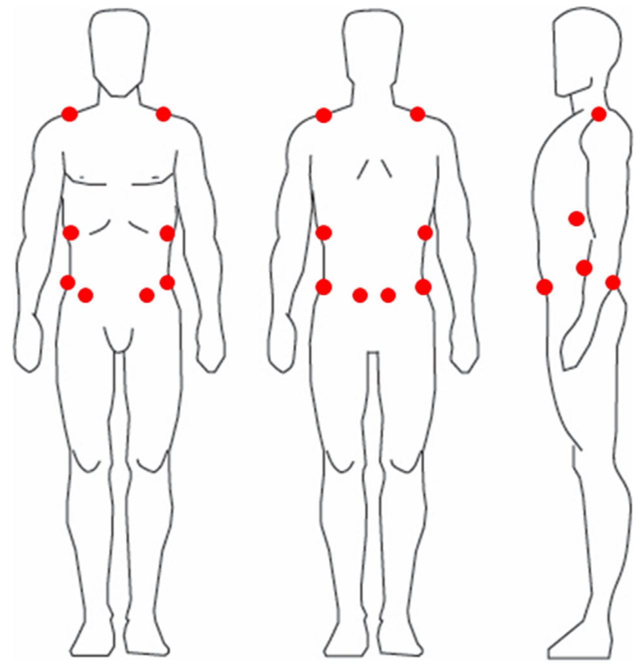

Fig. 1. Marker set-up for the experiment. The trunk coordinate system was defined using the rib and acromion process markers, whereas the ASIS and PSIS were used to define the pelvis segment system.

3. Results

Despite each method's varying attention to mathematical rigour, when the reference posture was a neutral one, all four provided similar results (Fig. 2). The agreement between methods is further demonstrated in that the smallest R^2 among the angles measured was 0.971. However, when the reference posture was 90 degrees of flexion, the RJM and gRSM methods exhibited changes in the lateral bending and axial twist angles (Fig. 3). On the other hand, the dRSM and the SM both maintained the interpretation of lateral bending.

4. Discussion

The current study found that calculating a relative joint angle using the RJM, SM, gRSM or dRSM, have varying levels of mathematical validity and interpretability. All four methods yield similar results for a predominantly planar motion (Fig. 2). We advise against the Robertson et al. (2013) gRSM, as the angular velocities calculated from it are in an ambiguous coordinate system, which limits both its physical and clinical significance. Additionally, the orientation of the reference trial with respect to the global coordinate system—a measure that should not affect joint angle measures—affects the angles calculated from it. To demonstrate this, we artificially rotated the reference trial by 90 degrees about the global *y*-axis and recalculated the relative joint angles for the same trial as in Figs. 2 and 3. It becomes clear under these conditions that the original RSM confuses flexion with lateral bending (Fig. 4). This error could manifest itself if a participant was performing a task as innocuous as walking around in a circle.

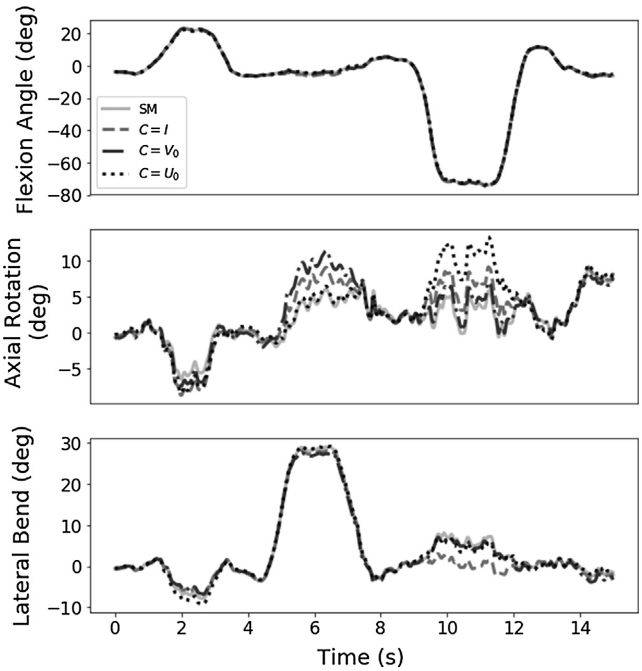

Fig. 2. Comparison of angles calculated from each method in an example trial where the participant sequentially extended, laterally bent to the right, and then flexed forward while returning to a neutral posture between these movements. This compares a subtraction method (SM), where the Euler Angles are purely subtracted; and three variants of the Relative Segment Method. In this method, coordinate systems are first aligned to a reference system C. In the originally proposed method by Robertson et al. (2013), these systems are aligned to the global coordinate system ($\boldsymbol{C} = \boldsymbol{I}$). Conversely, they could either be aligned to the proximal ($\boldsymbol{C} = \boldsymbol{U}_0$) or distal ($\boldsymbol{C} = \boldsymbol{V}_0$) segments in the reference posture.

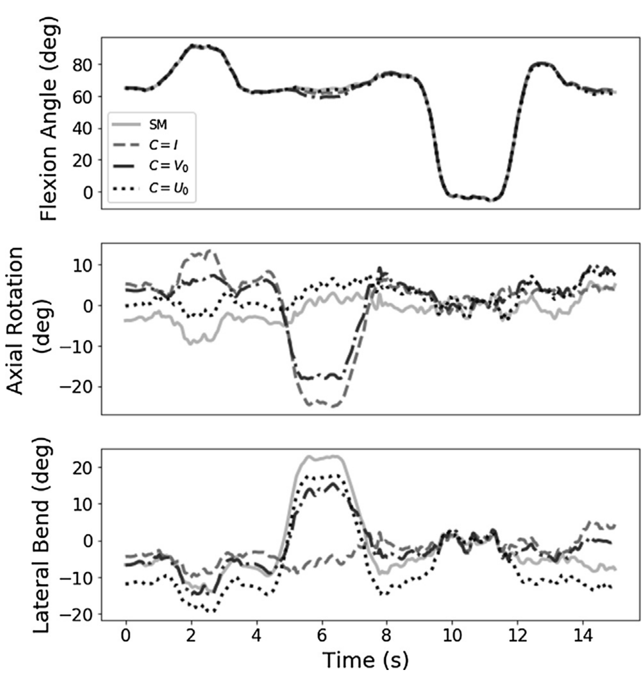

Fig. 3. Relative angles according to their respective methods for the same trial as in Fig. 2, when the reference posture consisted of approximately 90 degrees of flexion. In this case, zero degrees of flexion would correspond to a fully flexed posture. In this case, because all the movements are purely planar, the subtraction method is unchanged. Using either the global coordinate system ($\boldsymbol{C} = \boldsymbol{I}$) or proximal segment ($\boldsymbol{C} = \boldsymbol{V}_0$) to pre-align the systems results in a confluence of axial rotation and lateral bending. Conversely, aligning to the distal segment's reference ($\boldsymbol{C} = \boldsymbol{U}_0$) system did not demonstrate this conflation.

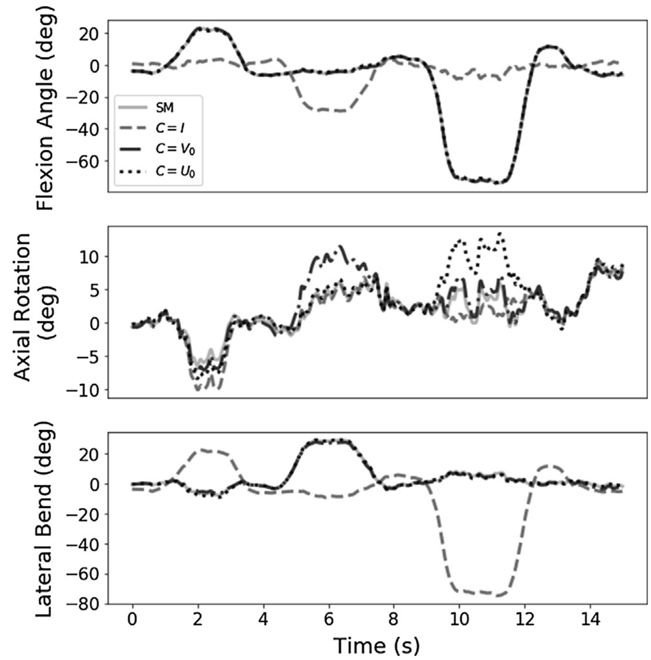

Fig. 4. Demonstration of the dependence of the global coordinate system on the original RSM where ($\boldsymbol{C} = \boldsymbol{I}$). Simply rotating the global coordinate system by 90 degrees about the y-axis is enough to permute lateral bending and flexion for the original RSM. Conversely, the SM, RSM and RJM remain independent of the choice of global coordinate system.

The RJM and SM agreed when a neutral reference posture was selected but disagreed dramatically when the reference posture was 90 degrees of flexion. A first-order Taylor approximation of Eq. (1) revealed that the two methods are roughly related to each other by the linear transformation:

$$\begin{bmatrix} \Delta\phi_{RJM} \\ \Delta\theta_{RJM} \\ \Delta\psi_{RJM} \end{bmatrix} \approx \begin{bmatrix} 1 & 0 & -\sin\theta_0 \\ 0 & \cos\phi_0 & \sin\phi_0\cos\theta_0 \\ 0 & -\sin\phi_0 & \cos\phi_0\cos\theta_0 \end{bmatrix} \begin{bmatrix} \Delta\phi_{SM} \\ \Delta\theta_{SM} \\ \Delta\psi_{SM} \end{bmatrix} \tag{13}$$

where $(\phi_0, \theta_0, \psi_0)$ are the raw joint angles in the reference posture. This expression is similar to the relationship between derivatives of Euler Angles and angular velocities (Eq. (2)) because each Euler Angle axis is dependent on context (*i.e.* the axis the second Euler Angle quantifies rotation about depends entirely on the axis and magnitude of the first angle). For example, when the first angle was 90 degrees of flexion, then the second angle rotated about what previously was a 'lateral bending' axis, despite representing what would arguably be an axial rotation angle. Both the RJM and angular velocity calculation attempt to keep the axes of rotation consistent so that algebraic manipulations can be done on them as if they are vectors. The mathematical rigour comes at some cost, however, as the clinical interpretation becomes unclear (Fig. 3 versus Fig. 2). In Fig. 3, the participant is intuitively extended and laterally bent relative to the reference posture, an interpretation that is conflated with axial rotation and lateral bend with the RJM. For engineering applications where mathematical rigour is desirable the RJM should be employed. For clinical applications, the SM affords a simpler interpretation. Practically, if reference postures are taken from an anatomically neutral posture, as was the case here, then there is little difference between the two methods. This is consistent with the results of Michaud et al. (2014), who found that under certain conditions it was justifiable to subtract Euler Angles. As they noted in that investigation, for planar motions, the SM is justified. However, in general, it should be avoided, as it does propagate error into the angles calculated.

The generalized dRSM and the RJM are, mathematically, the same method for different choices of reference segment. The RJM used here expresses angular differences with respect to the pelvis, or proximal segment. Conversely the dRSM uses the thorax, or distal segment. Practically, for the lumbar spine, there does not seem to be much difference between these two methods (Fig. 2). However, angular velocities calculated from the RJM are intuitive to interpret, as they are simply the difference in angular velocity directly expressed in the instantaneous pelvis coordinate system.

5. Conclusions

The RJM is mathematically valid, provides consistent angular velocity measures, and is recommended as a standardized approach for expressing Euler angles relative to a reference posture. If the RSM is used, the reference segment must be clearly stated, as the choice of $\boldsymbol{C}$ has a dramatic influence on the resulting angular velocity vector. In clinical applications, the SM provides the simplest clinical calculations but suffers from considerable mathematical drawbacks. Overall, when using neutral spine postures for reference, there is little difference between RJM and dRSM. Therefore, it is recommended that RJM or dRSM be used. The original RSM using the global coordinate system ($\boldsymbol{C} = \boldsymbol{I}$) should be avoided as it is more difficult to justify mathematically, is sensitive to the orientation of the reference trial, and possesses all of the potential challenges to clinical interpretations inherent in the RJM.

Conflict of Interest Statement

None to declare.

References

Bourdon, E., Mavor, M., Hay, D.C., 2017. Assessment of three-dimensional trunk kinematics and muscle activation during cycling with independent cranks. J. Sport. Sci. Med. 16, 536–542.

Cotter, B.D., Nairn, B.C., Drake, J.D.M., 2014. Should a standing or seated reference posture be used when normalizing seated spine kinematics?. J. Biomech. 47, 2371–2377. https://doi.org/10.1016/j.jbiomech.2014.04.023.

Feipel, V., Rondelet, B., Le Pallec, J.P., Rooze, M., 1999. Normal global motion of the cervical spine: an electrogoniometric study. Clin. Biomech. 14, 462–470. https://doi.org/10.1016/S0268-0033(98)90098-5.

Feipel, V., Salvia, P., Klein, H., Rooze, M., 2006. Head repositioning accuracy in patients with whiplash-associated disorders 31, 51–58.

Goldstein, H., Poole, C., Safko, J., 1950. Classical Mechanics. Addison-Wesely, Flushing, New York, NY, USA.

Hagemeister, N., Senk, M., Dumas, R., Cheze, L., 2011. Effect of axis alignment on in vivo shoulder kinematics. Comput. Methods Biomech. Biomed. Engin. 14, 755–761. https://doi.org/10.1080/10255842.2010.493887.

Hemming, R., Sheeran, L., van Deursen, R., Sparkes, V., 2017. Non-specific chronic low back pain: differences in spinal kinematics in subgroups during functional tasks. Eur. Spine J. 27, 1–8. https://doi.org/10.1007/s00586-017-5217-1.

Mazzone, B., Wood, R., Gombatto, S.P., 2016. Spine kinematics during prone extension in people with and without low back pain and among classification-specific low back pain subgroups. J. Orthop. Sports Phys. Ther. 46, 571–579. https://doi.org/10.2519/jospt.2016.6159.

Michaud, B., Jackson, M.I., Prince, F., Begon, M.S., Michaud, B., Jackson, M.I., Prince, F., Begon, M.S., Michaud, B., Jackson, M.I., 2014. Can one angle be simply subtracted from another to determine range of motion in three- dimensional motion analysis ? Comput. Methods Biomech. Biomed. Engin. https://doi.org/10.1080/10255842.2012.696104.

Riddell, M.F., Gallagher, K.M., McKinnon, C.D., Callaghan, J.P., 2016. Influence of input device, work surface angle, and task on spine kinematics. Work 55, 773–782. https://doi.org/10.3233/WOR-162452.

Robertson, G., Caldwell, G., Hamill, J., Kamen, G., Whittlesey, S., 2013. Research methods in biomechanics, 2E. Human Kinetics.

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., Whittle, M., D'Lima, D.D., Cristofolini, L., Witte, H., Schmid, O., Stokes, I., 2002. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. J. Biomech. 35, 543–548. https://doi.org/10.1016/S0021-9290(01)00222-6.