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Short communication

Rotation sequence and marker tracking method affects the humerothoracic kinematics of manual wheelchair propulsion

Anna C. Severin *, Jørgen Danielsen

Department of Neuromedicine and Movement Science, Center for Elite Sports Research, Norwegian University of Science and Technology, Trondheim, Norway

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ABSTRACT

The literature on shoulder (humerothoracic) kinematics in manual wheelchair propulsion is growing. Inconsistencies in the reporting of which rotation sequence is used to compute three-dimensional (3D) angles complicates the interpretation and comparison between studies. The purpose of this study was to compare the effects of three often used and recommended rotation sequences (ZXY, XZY, and YXY) and two tracking methods (anatomical and cluster only) on the humerothoracic kinematics of manual wheelchair propulsion. Fourteen able-bodied participants performed manual wheelchair propulsion on a treadmill, while a motion capture system recorded the movements at 120 Hz. Humeral and thoracic segment coordinate systems were constructed according to ISB recommendations. Humerothoracic angles were calculated using each of the three rotation sequences. The ZXY and XZY sequences yielded similar angles in terms of both shape and amplitude, but, perhaps unsurprisingly, these differed substantially from the YXY sequence. Anatomical tracking showed neither gimbal locks nor phase angle discontinuities for any rotation sequence, while cluster tracking yielded phase angle discontinuities for the ZXY and YXY rotation sequences. The two tracking methods yielded similar joint angles for all sequences except for internal/external rotation, and the cluster-only method had larger variability than the anatomical method. These results highlight the importance of reporting which rotation sequence and tracking method are used when calculating humerothoracic angles in order to allow for straightforward interpretation of results and comparison across studies.

1. Introduction

Kinematic analyses of manual wheelchair propulsion (MWC) often focus on the upper extremities and shoulder (Briley et al., 2020; Gorce and Louis, 2012; Hybois et al., 2019). However, the complexity of the shoulder girdle makes three-dimensional (3D) modelling challenging (Anglin and Wyss, 2000; Creveaux et al., 2018). Thus, a common simplification is to analyse the humerus in relation to the thorax (humerothoracic motion) (e.g., Anglin and Wyss, 2000; Briley et al., 2020; Creveaux et al., 2018; Gorce and Louis, 2012; Koontz et al., 2002). Since the choice of anatomical landmarks, local coordinate systems (LCS), and rotation sequences used in the analysis can affect the data (Boser et al., 2018; Senk and Cheze, 2006), the ISB has recommended standardising such analyses (Wu et al., 2005). While studies on MWC often refer to the ISB recommendations in the methodological sections (Briley et al., 2020; Collinger et al., 2008; Gorce and Louis, 2012; Hybois et al., 2019; Madansingh et al., 2020), there are inconsistencies in the amount of reported information. These methodological inconsistencies complicate comparison across studies and limits the interpretation and application of findings.

It is important to report the choice of rotation sequence since different sequences may yield different angles (Bonnefoy-Mazure et al., 2010; Creveaux et al., 2018; Senk and Cheze, 2006). For most joints, the ISB recommend the Z_t-X_f'-Y_h'' (ZXY) sequence (referring to rotations about the lateral, anteroposterior, and vertical axes respectively), but for describing humerothoracic motion, the Y_t-X_f'-Y_h'' (YXY) sequence is recommended (Wu et al., 2005). The ZXY sequence is suggested to be inappropriate when describing humerothoracic motion since different end point positions may occur depending on the order and magnitudes of the movement (Anglin and Wyss, 2000). Conversely, researchers have highlighted that the YXY sequence is vulnerable to singularities, such as gimbal locks (GL) or phase angle discontinuities (PAD), when used for shoulder kinematics (Bonnefoy-Mazure et al., 2010; Senk and Cheze, 2006). PAD occurrences can be corrected mathematically during post

* Corresponding author at: Department of Neuromedicine and Movement Science, Center for Elite Sports Research, Norwegian University of Science and Technology, 7489 Trondheim, Norway.
E-mail address: cecilia.severin@ntnu.no (A.C. Severin).

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processing, but GL cannot, so it is generally advised to select a rotation sequence that avoids singularities (Creveaux et al., 2018). Studies have compared how different rotation sequences affect certain movements and agree that the 'best' sequence (often defined as one avoiding singularities and yielding reasonable angle magnitudes) is task specific (Bonnefoy-Mazure et al., 2010; Creveaux et al., 2018; Senk and Cheze, 2006). Both the ZXY and YXY sequences have been used in studies on MWC (Briley et al., 2020; Collinger et al., 2008; Gorce and Louis, 2012; Madansingh et al., 2020), while the use of X_t-Z_f'-Y_h'' (XZY) in the MWC literature is limited. However, XZY has been recommended for tasks with large movements in the frontal plane (Kontaxis et al., 2009), such as tennis serve (Bonnefoy-Mazure et al., 2010), so it may be appropriate also for MWC analyses. However, how different rotation sequences affect humerothoracic angles during MWC has not been directly compared.

Apart from the chosen rotation sequence, joint angle amplitudes depend on many other factors such as, estimations of joint centre of rotations (Crabolu et al., 2017; Stagni et al., 2000) or motion capture tracking method of the segments (e.g., Boser et al., 2018; Della Croce et al., 2005). For a perspective on the magnitude of differences that rotation sequences may induce, we additionally compared how two commonly used methods of tracking segment motion affect humerothoracic angles. The two tracking methods chosen were 'anatomical model' [AM, similar to the anatomical model in Boser et al. (2018)] and 'cluster model' [CLUS, following the method of Winter (2009)]. This additional comparison of tracking method may allow for a more relative judgement of possible effects of rotation sequence.

The main aim of this study was to examine the effects of three different rotation sequences (ZXY, XZY, and YXY), and the secondary aim was to compare two tracking methods (AM and CLUS) for analysing humerothoracic joint angles during MWC.

2. Methods

2.1. Participants

Five females (33 ± 11 yrs., 69 ± 10 kg, 1.69 ± 0.05 m) and nine males (32 ± 11 yrs., 83 ± 10 kg, 1.85 ± 0.06 m) voluntarily participated in the study. All were right-handed, free of upper-extremity injuries at the time of testing and had no experience of MWC. Written informed consent was obtained in accordance approval from the Norwegian Centre for Research Data (216680).

2.2. Experimental protocol

A standard wheelchair (Küschall K-Series Attract, Invacare, Oslo, Norway) was mounted on a 5 × 3 m motorised treadmill (Forcelink Technology, Culemborg, The Netherlands) via a custom-built rail system with a transverse bar mounted across the belt that secured the wheelchair. Thus, only forward and backward movements on the treadmill were possible. Participants warmed up and got familiarized with MWC for 5–10 min at a self-selected speed (0.7 ± 0.1 m·s^{-1}). They then performed four minutes of MWC at 1.11 m·s^{-1}, at an incline of 4.4°.

2.3. Kinematics

All participants wore tight-fitting pants and a sleeveless top during data collection. Participants were fitted with 7 retroreflective markers (14 mm) according to the ISB recommendations (Wu et al., 2005): C7, T8, Incisura Jugularis and Processus Xiphiodeus, as well as the right Angulus Acromialis, Lateral Epicondyle, Medial Epicondyle. A non-collinear marker cluster with three markers was attached to the lateral surface of the middle upper arm. A static trial was obtained with participants in the anatomical position prior to data collection. Additional markers were placed on the hub of the right wheel and on the styloid process of the right radius.

Kinematic data were collected using an eight-camera motion capture system (Qualisys AB, Gothenburg, Sweden) at 120 Hz and imported to Matlab R2021a (MathWorks, Nantick, MA, USA). All marker position data were lowpass filtered at 6 Hz (4th order Butterworth). The 'start of push' event was defined as the minimum speed of the wheel marker, while the 'end of push' event was defined as the lowest point of the lateral wrist marker after the 'start of push' event. From visual inspection, these definitions appeared to represent the timing of events reasonably well compared to using hand rim forces (Briley et al., 2020; Hybois et al., 2019). One cycle was defined as the time between two 'start of push'.

2.4. Data analysis

The inertial and the LCS were defined according to the ISB recommendations (Wu et al., 2005) with detailed descriptions in the Supplementary material S1 (S1). The GH joint centre was estimated based on the Angulus Acromialis marker in accordance with Veeger (2000). AM involved tracking anatomical markers (Wu et al., 2005), while CLUS involved tracking and defining a cluster coordinate system (LCSc) which was related to the humerus LCS through a rotation matrix established from the static trial data (Winter, 2009). To reduce soft-tissue artefact (Söderkvist and Wedin, 1993), segmental optimisation was applied for both tracking methods following similar procedures as Duprey et al. (2010), with the humerothoracic joint (humerus in relation to the thorax) considered to have 6 degrees of freedom. Fixed segment lengths were obtained individually from static trial data. In the optimization, anatomical markers were used as input in AM while cluster markers were used in CLUS.

3D angles were identified from the resulting rotation matrices for each rotation sequence (S1). All angles were checked for singularities, counting all cycles affected by GL and/or PAD, with all PADs subsequently corrected. The joint angles were time normalized to 100% of a cycle, and the maximum and minimum angle and range of motion were extracted for comparison.

3. Results

The data were both automatically and visually inspected to identify GL or PADs. No instances of GL were seen in any of the rotation sequences or tracking methods. The AN method resulted in no PADs, while the CLUS yielded PADs for the 1st and 3rd rotations (Fig. 1, Table 1). PADs were evident for all participants and occurred at no consistent or specific instance throughout the cycle.

Fig. 2 shows that ZXY and XZY yielded similar angles about the anatomical Z- and X-axes (mediolateral and anteroposterior, respectively), and that the differences about the Y-axis were relatively small. As may be expected, the YXY sequence yielded considerably different angles regarding both pattern and amplitude. Furthermore, when comparing the tracking methods, differences were relatively small and consistent for all sequences except for 'internal/external rotation'. Table 2 shows the range of motion obtained for each sequence and tracking method.

4. Discussion

This study suggests that both rotation sequence and tracking method affects angle amplitudes and occurrences of singularities in the study of humerothoracic motion during MWC. While the effect of tracking method was smaller than the effect of rotation sequence, the overall effects are clearly large enough to highlight the importance of detailing both for proper interpretation and comparison across studies. Still, based on our data, a special emphasis is placed on the necessity of clear reporting of rotation sequence and associated terminology.

The ZXY and XZY sequences yielded similar angle patterns for the humerothoracic joint during MWC, however, these were considerably

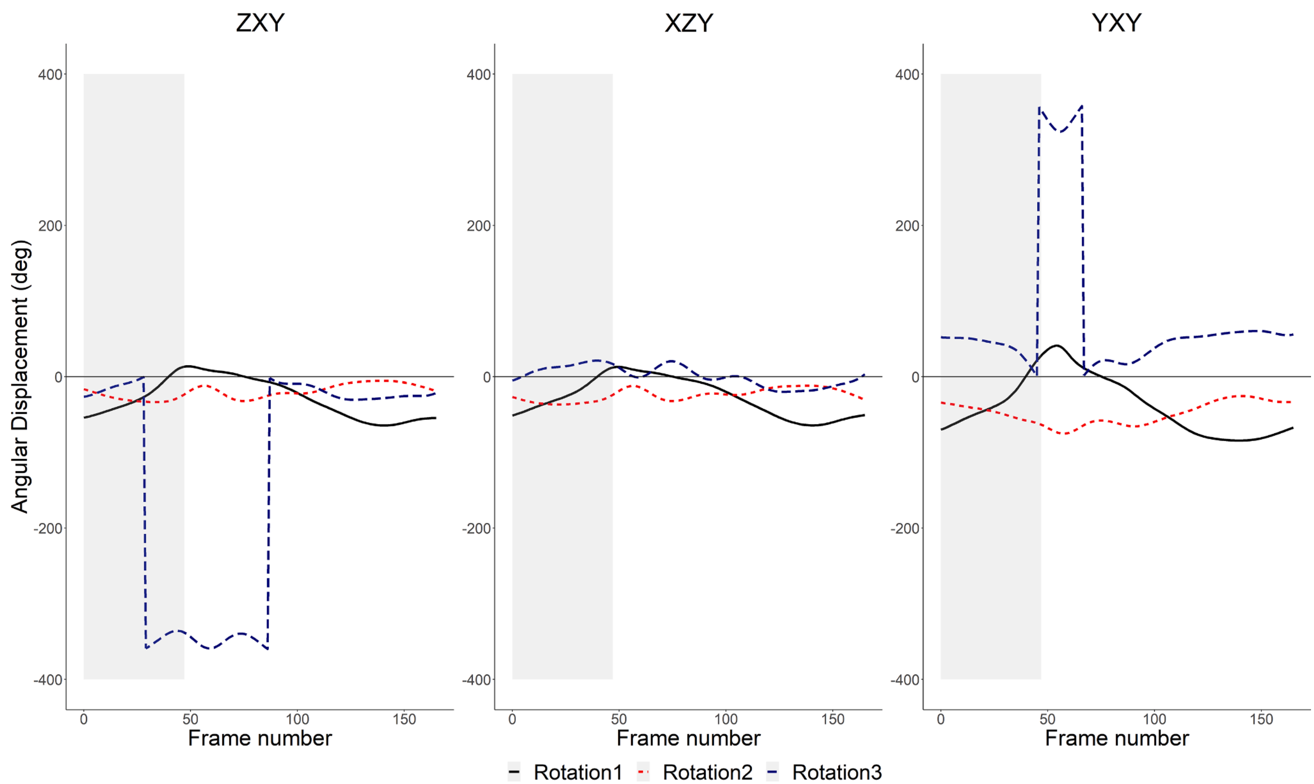

Fig. 1. Time trace over one cycle of manual wheelchair propulsion for one representative participant using the CLUS tracking method. Rotations 1, 2 and 3 represents the three rotations in the order indicated for each sequence. The occurrences of PAD are seen for the ZXY and YXY sequences. The shaded area represents the push phase.

Table 1
Occurrences of phase angle discontinuities for the two tracking methods in each rotation sequence in MWC. Data is presented as mean ± SD of occurrences per cycle. Rotations 1, 2, and 3 refers to the three rotations in the order indicated by the sequence.

Tracking method	Rotation sequence	Rotation 1	Rotation 2	Rotation 3
AN	ZXY	–	–	–
	XZY	–	–	–
	YXY	–	–	–
CLUS	ZXY	–	–	1.5 ± 0.4
	XZY	–	–	–
	YXY	–	–	1.8 ± 0.8

different from the YXY (Fig. 2). While the XZY sequence has not been reported in previous studies on MWC, angle patterns similar to ours have been reported for both the ZXY and YXY sequences (Briley et al., 2020; Collinger et al., 2008; Madansingh et al., 2020). However, this is, to the best of our knowledge, the first time they are directly compared, and the considerable differences between them are highlighted. When using the YXY sequence for describing humerothoracic motion, it has been recommended to describe the movements as 'plane of elevation', 'elevation', and 'internal/external rotation', rather than the conventional 'flexion/extension' terminology, since these may be "easier to visualise" (Anglin and Wyss, 2000; Wu et al., 2005). However, there is confusion about which terminology best describes the YXY rotations. While Collinger et al. (2008) use the YXY sequence, they highlight that "for simplicity", they use the traditional clinical terminology (e.g., flexion/extension) to describe the rotations. Further, Briley et al. (2020) state that they used the ISB recommendations, which suggests YXY, but also present their results using the traditional terms. Upon visual inspection, their angle patterns resemble the ZXY or XZY sequences more than the YXY presented here, suggesting a mismatch between their described methods, and presented results. These instances highlight the challenge for researchers dealing with shoulder kinematics, and the present study adds to the literature showing that the ISB recommendations (e.g., plane of elevation) and the traditional clinical definitions are not comparable (Creveaux et al., 2018; Senk and Cheze, 2006). Thus, researchers are advised not to mix these terms and instead clearly define the sequence used and adhere to the terminology specific to that sequence.

Both tracking methods tested here yielded quite similar (differences in) joint excursions regardless of rotation sequence (Fig. 2), which is consistent with previous research on upper body kinematics (Boser et al., 2018). While offsets existed between the tracking methods, especially for internal/external rotation, the choice of rotation sequence yielded larger differences in range of motion (Table 1). It is to be acknowledged that CLUS yielded larger standard deviations than AN and encountered singularities in two of the sequences. Fortunately, all instances were PADs which were subsequently corrected.

A limitation of this study was that the participants were able-bodied individuals propelling at only one speed. It is possible that other populations (e.g., experienced wheelchair racers or regular MWC users) propelling at different speeds may yield different results, such as differences in range of motion (e.g., Slowik et al., 2015). However, this study included a broad range of individuals in terms of height and age, which yielded quite large variability in both range of motion and movement patterns (e.g., Kwarciak et al., 2009). Since we found no relationship between specific movement patterns and occurrences of PADs, the results are expected to be quite generic. Nonetheless, our results reiterate the importance of detailing what rotation sequence and tracking method were used for the sake of interpretation, clarity, and comparisons between studies (e.g., Creveaux et al., 2018).

In conclusion, this study showed that for analysing humerothoracic motion during MWC, the ISB recommended YXY sequence yielded angle amplitudes and patterns that differed considerably compared to those computed using the ZXY and XZY sequences, the difference between which were rather small. Both tracking methods yielded comparable

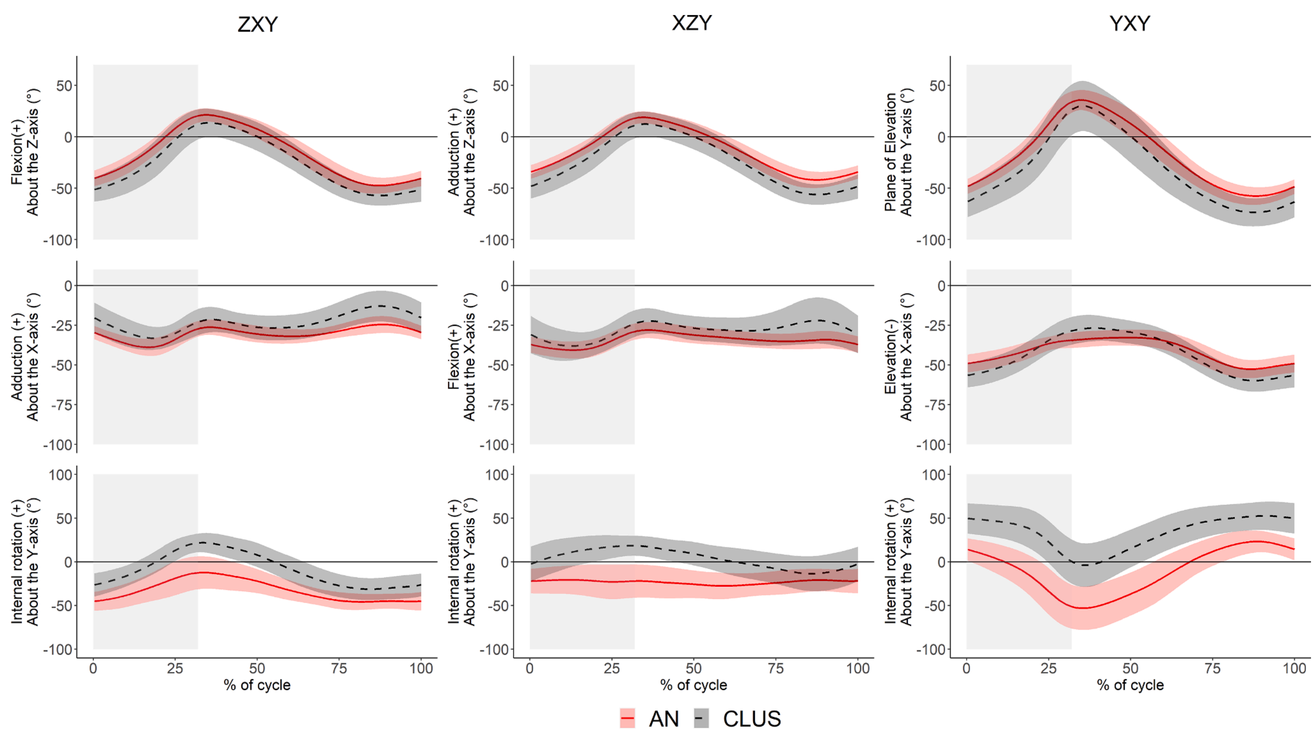

Fig. 2. Time traces for the humerothoracic angular displacement in 3D obtained with the three different rotation sequences using two tracking methods. Note that the order of the middle column (XZY) has been rearranged for easy comparison with the other sequences (so the top row represents flexion/plane of elevation). Shaded areas indicate the push phase. AN: anatomical tracking method, CLUS: cluster tracking method.

Table 2
Range of motion values for angular displacement (°) of the humerothoracic motion during MWC propulsion obtained using the two tracking methods for each rotation sequence. Presented as mean ± SD.

Tracking method	Rotation sequence	Flexion/Plane of elevation	Adduction/ Elevation	Internal rotation
AN	ZXY	70.6 ± 7.5	16.4 ± 6.0	36.8 ± 14.9
	XZY	62.5 ± 7.1	13.9 ± 4.6	17.7 ± 5.9
	YXY	95.8 ± 11.6	22.1 ± 6.9	78.9 ± 18.8
CLUS	ZXY	72.8 ± 7.9	23.8 ± 5.9	55.9 ± 10.4
	XZY	70.3 ± 7.9	22.5 ± 6.0	34.9 ± 11.2
	YXY	106.2 ± 19.9	35.5 ± 10.3	60.2 ± 15.7

Note: the ZXY and XZY sequences are described using the terms 'Flexion/ Extension', 'Adduction/Abduction' and 'Internal/External rotation', while the YXY sequence is described using 'Plane of elevation', 'Elevation' and 'Internal rotation' (Anglin and Wyss, 2000; Wu et al., 2005).

angles around the first two rotations, while differences existed about the third rotation (internal/external rotation). Further, CLUS resulted in (correctable) PADs for the ZXY and YXY sequences (but not the XZY sequence). Thus, this study shows that the choice of rotation sequence as well as tracking method affects the kinematics of the humerothoracic joint during MWC, highlighting the importance of reporting adequate details regarding rotations sequence and tracking method.

CRediT authorship contribution statement

Anna C. Severin: Conceptualization, Methodology, Investigation, Formal analysis, Resources, Data curation, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Jørgen Danielsen:** Conceptualization, Methodology, Investigation, Formal analysis, Resources, Data curation, Project administration, Visualization, Writing – original draft, Writing – review & editing.

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 material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2022.111212.

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