Comparison of modelling and tracking methods for analysing elbow and forearm kinematics

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Abstract

This study aimed to find an optimal measurement protocol of elbow and forearm kinematics using different modelling and tracking methods. Kinematic data of elbow flexion/extension and forearm pronation/supination was acquired using optical motion capture from 12 healthy male volunteers. Segment coordinate systems for humerus, forearm, radius, ulna, and hand were defined. Different tracking methods, using anatomical markers or rigid or point maker clusters, were used to compute the three-dimensional rotations. Marker placement errors were assessed to evaluate the rigid body assumption. Multiple comparisons demonstrated statistical differences between tracking methods: compared to using only anatomical markers, tracking using clusters reduced the estimated range of pronation/supination by 14.9%–43.2%, while it estimated increased flexion/extension by 5.3%–9.1%. The study suggests using only anatomical markers exerts the optimal estimation of elbow and forearm kinematics. Modelling using the coordinate systems of the humerus and forearm and of the humerus and ulna, respectively, demonstrated good consistency with literature and are correspondingly regarded as the most appropriate approach for measuring pronation/supination and flexion/extension. The results are valuable in establishing a measurement protocol for analysing elbow and forearm kinematics, avoiding confusions and misinterpretations in communicating results from different methodologies.

Keywords

Forearm kinematics, elbow, biomechanical modelling, motion tracking, range of motion, flexion/extension, pronation/supination

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Introduction

The elbow-forearm complex is composed of four different joints: the humeroulnar and humeroradial joints at the elbow and the proximal and distal radioulnar joints within the forearm. Studies on the kinematics of the elbow and forearm can provide quantitative evaluation and data for clinical use and orthosis or prosthesis design.¹ Meanwhile, the non-invasive and non-irradiating optical motion capture technique offers an efficient approach to estimate joint kinematics using marker-based musculoskeletal models.² However, in most studies that used a marker-based elbow model, the forearm was treated as a rigid segment,^{3,4} and the elbow was commonly defined as a joint of two independent degrees of freedom: elbow flexion-extension (F/E) and pronation/supination (P/S), ignoring the fact that relative motion exists between ulna and radius. Particularly for forearm P/S, previous studies mainly

used a goniometer directly on the subject to measure the overall rotation of a stick which is held in the hand during P/S.⁵ This kind of simplification may fail to estimate motion characteristics aside from the primary motion, while other motions like the radioulnar motion during P/S are also crucial for the biomechanical analysis of the forearm.⁶

The International Society of Biomechanics (ISB) proposed a well-established ISB joint coordinate

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Table 1. Markers and the abbreviations used in this study.

Classification	Marker name	Locations
Anatomical markers	RAC	Right acromion centre
	LAC	Left acromion centre
	EL	Most caudal point on lateral epicondyle
	EM	Most caudal point on medial epicondyle
	RS	Most caudal–lateral point on radial styloid
	US	Most caudal–medial point on ulnar styloid
	LH	Distal head of the second meta carpal
	MH	Distal head of the fifth metacarpal
Rigid marker cluster	FA(4 markers)	Near the distal end of the anterior forearm ^a
	UA(3 markers)	Laterally on the humerus
Point marker cluster	F1	Near the radial styloid, on radius
	F2	Middle of ulnar crest
	F3	Middle of radius
	OLE	Tip of olecranon
Derivative markers	GH	Glenohumeral rotation centre, estimated by regression ¹⁴
	M	Midpoint of EL and EM
	M-WC	Midpoint of RS and US
	M-HC	Midpoint of LH and MH

All the marker locations are on the right upper extremity of the participants unless otherwise specified.

^aThe rigid marker cluster was attached to the wrist as near as possible but keep a safe distance to avoid marker artefact.

system (CS) recommendation,⁷ in which elbow-related CSs included two different CSs for the humerus, a CS for the ‘rigid’ forearm (i.e. assuming the ulna and the radius are rigidly connected), a CS for the ulna, and a CS for the radius. Some researchers mainly investigated the effect of the two recommendations of the humerus on describing elbow kinematics, and no difference was found.^{1,8} Still, no agreement has been reached on the most appropriate modelling approach of the forearm for estimating elbow and forearm kinematics.

Furthermore, the tracking method, that is, the use of reflective markers apart from anatomical bony markers, is commonly used in motion capture techniques to determine the position and orientation of a segment while minimizing the soft tissue artefact. Rigid marker cluster (RMC)^{9,10} and point marker cluster (PMC)¹¹ are two widely used tracking methods. RMC refers to a rigid cluster comprising of normally three to four asymmetrically markers positioned on a ‘solid’ surface, while PMC refers to a cluster of separate markers directly distributed on the skin surface of a segment. Both cluster methods are independent from anatomical bony markers. However, the tracking method is task-dependent and it affects the reliability of the computed joint kinematics,¹² and both RMC and PMC are mainly validated for the lower limb, while few studies evaluated the suitability of these tracking methods for the upper extremities. Tanaka et al.¹³ suggested using PMC tracking was less accurate than using only anatomical bony markers when estimating humeral rotations. However, it remains unclear if RMC and PMC are appropriate for tracking forearm kinematics.

Therefore, this study aims to (1) compare the effects of different modelling methods on the estimation of elbow and forearm kinematics using marker-based measurement and (2) investigate which kind of tracking

method is most applicable for measuring forearm kinematics.

Methods

Experiment

Twelve healthy, right-handed male adults participated in the experiment. The mean (standard deviation (SD)) age, height, and weight were 25.10 years (2.37 years), 176.17 cm (4.84 cm), and 68.17 kg (7.49 kg), respectively. This study was approved by the institutional review board of Shanghai Jiao Tong University. All participants signed a written consent before the start of the experiment.

A 7-camera optoelectronic motion capture system (Qualisys Inc., Sweden) was used to track the participants’ movement at a rate of 100 Hz. Positions of the markers are listed in Table 1 and depicted in Figure 1. Participants were instructed to perform two standard motions: elbow F/E and forearm P/S. Each motion was captured at least five times and each trial was performed at a self-selected steady speed within 8–10 s. Elbow F/E: At the beginning, the humerus hung beside the trunk, and the elbow was extended to its limit with the palm of the hand facing forward. The participants first flexed the forearm towards the stationary humerus and then extended back to the starting point in the sagittal plane. Forearm P/S: The neutral position of the forearm in P/S was defined as the elbow flexed 90° in the sagittal plane, the humerus hanging beside the trunk and the palm in the sagittal plane of the trunk with the thumb pointing upwards. The participants first pronated and then supinated the forearm to their limits, while maintaining the elbow flexed in 90° and the hand stationary to the forearm.

Figure 1. The segment coordinate system and the corresponding tracking marker method (please note the geometry of the bone, and the size and position of the marker are only for visualization). Abbreviations of markers are explained in Table 1.

Modelling and data processing

Kinematic models were created in Visual3D (C-Motion Inc., USA). Five segment CSs (see Table 2 and Figure 1) were defined based on the ISB recommendation,⁷ including CSs for humerus (ISB 1 and ISB 2), forearm, ulna, and radius. The humerus CS was defined by the humerus bony landmarks only (ISB 1) or based on bony landmarks of both humerus and forearm (ISB 2). In addition, to allow comparison of studies that measured the forearm P/S rotation using a goniometer to track the longitudinal rotation axis of the hand (referred to as Hand rotation), a CS of the hand was added. Five joints were established based on the different segment CSs, including humerus 1 to forearm (U1-f), humerus 2 to forearm (U2-f), humerus 1 to ulna (U1-ulna), humerus 2 to ulna (U2-ulna), and radius to ulna (Radius-ulna), and they were referred to as the modelling method in this study. The U1-f and U2-f referred to the elbow joint in the common usage ('rigid' forearm relative to the humerus). The U1-ulna and U2-ulna joint referred to the humeroulnar joint, and the Radius-ulna referred to the radioulnar joint. In summary, four modelling methods were used for estimating P/S, that is, U1-f, U2-f, Radius-ulna, and Hand rotation. For elbow F/E also four modelling methods were used, that is, U1-f, U2-f, U1-ulna, and U2-ulna.

The raw marker trajectories were filtered at 6 Hz using a fourth-order, low-pass Butterworth filter. Four tracking methods (see Table 2 and Figure 1) were used to reconstruct the motion of the segments in the forearm, (1) using only anatomical markers (AM), (2) using the rigid marker cluster and anatomical markers (RMC + AM), (3) using only the rigid marker clusters (RMC), and (4) using the point marker cluster and anatomical markers (PMC + AM). The PMC used for tracking a specific segment referred to the scattered markers on the corresponding segment, depicted as pink markers in Figure 1. Due to the lack of space for scattered markers on the radius and ulna, the PMC tracking was combined with the AM. As the RMC did not easily fit on the ulna, the ulna was not tracked using the RMC and RMC + AM methods. For the reference segment, the humerus was only tracked by RMC as this is the commonly used tracking method for the upper arm in previous studies, and the hand was only tracked by AM due to limited space on the back of the hand.

Analysis

The variability of the inter-marker distance of a marker placement was analysed to examine the rigid body assumptions,¹⁵ that is, to see if the distance between two markers over time remains the same. The marker-pair distance was computed from the marker trajectories used in tracking the moving segments over the F/E or P/S motion cycles. For instance, the AM method used four markers to track the 'rigid' forearm in F/E, thus there would be six inter-marker pairs. The SD of the marker-pair distance was calculated between the mean distance of each marker-pair and its instantaneous distance in each time frame. The marker placement error (MPE) also depends on the relative distance between the markers,¹⁶ thus this SD was further divided by the mean marker-pair distance and normalized as the percentage of the mean marker-pair distance (relative SD). The SD and the relative SD were averaged over all the marker-pairs in the tracking group and were regarded as the corresponding absolute and relative MPE.

To assess the effects of different modelling and tracking methods, range of motion (ROM) of the primary axis was computed as a quantitative indicator.¹ Statistical analysis was performed using SAS 9.4 (SAS Institute Inc., USA). A post hoc Student-Newman-Keuls (SNK) test was used for multiple comparisons of the ROM computed by different tracking and modelling groups. In addition, paired t-tests were used to compare specific pairs of interest. The coefficient of multiple correlation (CMC) was used to evaluate the repeatability and similarity of the joint angle waveforms.¹⁷ The F/E and P/S angles were computed for each combination of modelling and tracking method.

Table 2. Definitions of the segment coordinate system.

Segment	Definition		Tracking method
Humerus 1 (ISB 1)	Origin	GH	RMC
	Z-axis	From M to GH (proximal positive)	
	Y-axis	Cross-product of Z-axis and vector $\mathbf{v}$ from EM to EL (anterior positive)	
	X-axis	Cross-product of Z-axis and Y-axis (lateral positive)	
Humerus 2 (ISB 2)	Origin	GH	RMC
	Z-axis	From M to GH (proximal positive)	
	X-axis	Cross-product of Z-axis and vector $\mathbf{v}$ from US to M (lateral positive), the axis is taken with the elbow flexes at 90 degree in the sagittal plane and the forearm fully pronated.	
	Y-axis	Cross-product of Z-axis and Y-axis (anterior positive)	
Forearm ('Rigid')	Origin	US	AM
	Z-axis	From US to M (proximal positive)	RMC + AM
	Y-axis	Cross-product of Z-axis and vector $\mathbf{v}$ from US to RS (anterior positive)	RMC
	X-axis	Cross-product of Z-axis and Y-axis (lateral positive)	PMC + AM
Radius	Origin	RS	AM
	Z-axis	From RS to EL (proximal positive)	RMC + AM
	Y-axis	Cross-product of Z-axis and vector $\mathbf{v}$ from US to RS (anterior positive)	RMC
	X-axis	Cross-product of Z-axis and Y-axis (lateral positive)	PMC + AM
Ulna	Origin	US	AM
	Z-axis	From US to M (proximal positive)	PMC + AM
	Y-axis	Cross-product of Z-axis and vector $\mathbf{v}$ from EM to EL (anterior positive)	
	X-axis	Cross-product of Z-axis and Y-axis (lateral positive)	
Hand	Origin	M-WC	AM
	Z-axis	From M-HC to M-WC (proximal positive)	
	Y-axis	Cross-product of Z-axis and vector $\mathbf{v}$ from MH to LH (anterior positive)	
	X-axis	Cross-product of Z-axis and Y-axis (lateral positive)	

ISB: International Society of Biomechanics; GH: glenohumeral; RMC: rigid marker cluster; US: ulnar styloid; AM: anatomical markers; RS: radial styloid; PMC: point marker clusters.

Tracking method: AM, RMC, and PMC.

CMCs were calculated separately for each participant's repeated motions (within-session repeatability) and for the mean joint angle curves from all participants (within-group similarity). Before calculating CMCs, the offset in joint angles was adjusted to make sure each curve started from the same zero baseline.

Although the 'true' value estimated from the optical motion capture system cannot be assessed, numerous studies have published a large dataset of estimated elbow ROM using various modelling and measurement approaches, including medical imaging, goniometer, optical motion tracking, and inertial measurement units (IMUs)^{1,5,18–29} (a selection of this literature is listed in Supplementary Table 1). We selected the reported P/S ROM varying from 152.8° to 185.9° (see Figure 2(a)) from 10 studies,^{1,5,20–28} as a reference range (only excluding extreme estimations below 120°,^{1,29} as anatomy showed clearly a value near 180° can be

reached^{6,20,30}) and results out of this range were regarded as unacceptable. The reported F/E varied within a relative small range from 125° to 150° (see Figure 2(b)). We selected results from a previous study¹⁹ as the reference, '136.5° (9°)' (20 subjects, male, age 18–50 years), since radiography is often used as a gold standard and the characteristics of their subjects were similar to ours.

Results

The ROM computed for the overall 25 combinations of the modelling and tracking methods, and the statistical differences between the groups, as well as the corresponding MPEs, are presented in Tables 3 and 4 for forearm P/S and elbow F/E, respectively. Figure 2 shows the typical angular displacements of the primary

Figure 2. Angular displacements of the primary axis during tasks of forearm pronation/supination (a, first pronation then supination) and elbow flexion/extension (b, first flexion then extension) for one representative subject. Each line is generated using different modelling/tracking methods (abbreviations are explained in section ‘Modelling and data processing’), and the offset of joint angle of each line is adjusted to enable a zero baseline. Shaded areas represent the corresponding reference ranges of the previous reported mean maximal joint range of motion (details are explained in section ‘Analysis’). Due to the similarities of the angle profiles between modelling methods using ‘U1-’ and ‘U2-’ (two ISB methods for constructing humerus coordinate), only results from using ‘U1-’ are shown in this figure for conciseness.

Table 3. Ranges of motion (ROM) of forearm pronation/supination, and marker placement error (MPE) of the moving segment.

Tracking method		U1-f	U2-f	Radius-ulna	Hand rotation	p**
AM	ROM (°)	170.9 (8.7)	171.4 (8.7)	129.6 (9.9)	174.5 (8.7)	0.001
	Absolute MPE (mm)	2.9 (0.5)		2.8 (0.5)	1.6 (0.5)	
	Relative MPE (%)	1.9 (0.5)		2.1 (0.5)	2.0 (0.6)	
RMC + AM	ROM (°)	145.5 (21.8)	146.4 (22.2)	77.9 (9.7)	–	0.018
	Absolute MPE (mm)	3.5 (0.4)		3.0 (0.3)		
	Relative MPE (%)	3.2 (0.4)		3.4 (0.4)		
RMC	ROM (°)	137.5 (37.8)	137.5 (37.8)	73.7 (23.0)	–	0.001
	Absolute MPE (mm)	1.5 (0.3)		1.5 (0.3)		
	Relative MPE (%)	3.8 (0.8)		3.8 (0.8)		
PMC + AM	ROM (°)	129.2 (37.2)	130.0 (38.3)	78.5 (30.4)	–	0.011
	Absolute MPE (mm)	2.9 (0.4)		2.9 (0.5)		
	Relative MPE (%)	2.4 (0.4)		2.3 (0.4)		
p*		0.0089	0.0094	0.001	–	

AM: anatomical markers; ROM: range of motion; MPE: marker placement error; RMC: rigid marker cluster; PMC: point marker cluster.

1. Hand rotation refers to the rotation of the longitudinal axis of hand.

2. The statistical differences (p) within a modelling group (*) or a tracking group (**) is calculated using SNK multiple comparison tests, with $p < 0.05$ indicating significant statistical differences.

3. Tracking method: AM (anatomical markers), RMC (rigid marker clusters), and PMC (point marker clusters).

axis during tasks of forearm pronation/supination and elbow flexion/extension for one representative subject.

The absolute MPEs of the RMC were the smallest for both P/S (1.5 (0.3)mm) and F/E (2.8 (1.5)mm), where other MPEs varied between 2.8 (0.5) and 5.1 (0.6)mm. For the relative MPE, however, the RMC resulted in the highest relative error (3.8% for P/S and 6.7% for F/E), while the AM showed the smallest relative error (1.9% for P/S and 2.6% for F/E).

Forearm P/S

As shown in Table 3, the AM tracking method was different from the other three tracking methods irrespective of the modelling method (all $p < 0.01$). Tracking

with the AM always resulted in the largest ROM (around 171° (8.7°)), while tracking with clusters decreased the ROM by 19.6%–43.2% when using only RMC, by 14.9%–39.9% when using RMC + AM, and by 24.4%–39.4% when using PMC + AM. Only the AM computed a ROM that fell within the acceptable range (152.8°–185.9°) based on the literature database (Supplementary Table 1). In addition, tracking with AM showed the smallest SDs among all the tracking methods, demonstrating the lowest variability of the measured angles.

Only the AM tracking was taken into consideration when comparing the modelling methods. Of the four modelling methods, the ROM computed using Radius-ulna was different from the other methods (SNK, p

Table 4. Ranges of motion (ROM) of elbow flexion-extension, and marker placement error (MPE) of the moving segment.

Tracking method		U1-f	U2-f	U1-ulna	U2-ulna	p**
AM	ROM (°)	155.0 (10.6)	155.7 (10.1)	138.1 (13.7)	138.1 (13.7)	0.0005
	Absolute MPE (mm)	3.5 (0.9)		4.3 (0.8)		–
	Relative MPE (%)	2.6 (5.3)		3.8 (0.8)		–
RMC + AM	ROM (°)	169.2 (9.0)	169.9 (9.6)	–	–	–
	Absolute MPE (mm)	3.2 (0.9)				
	Relative MPE (%)	3.3 (1.1)				
RMC	ROM (°)	168.6 (12.6)	169.3 (13.2)	–	–	–
	Absolute MPE (mm)	2.8 (1.5)				
	Relative MPE (%)	6.7 (3.5)				
PMC + AM	ROM (°)	165.2 (13.1)	164.0 (13.9)	135.4 (21.5)	135.7 (21.6)	0.0001
	Absolute MPE (mm)	4.3 (0.5)		5.1 (0.6)		–
	Relative MPE (%)	3.9 (0.5)		5.2 (0.8)		–
p*		0.0715	0.0549	–	–	–

AM: anatomical markers; ROM: range of motion; MPE: marker placement error; RMC: rigid marker cluster; PMC: point marker cluster.

1. The statistical differences (p) within a modelling group (*) or a tracking group (**) is calculated using SNK multiple comparison tests, with $p < 0.05$ indicating significant statistical differences.

2. Tracking method: AM, RMC, and PMC.

< 0.001). The average ROM of the three other methods were all above 170° , which was well within the acceptable range, while Radius-ulna showed the smallest ROM. Furthermore, no statistical difference was found between pairs for U1-f, U2-f, and Hand rotation.

Elbow F/E

As shown in Table 4, for the different tracking methods, no statistical difference between the tracking groups was found, irrespective of the modelling method. However, paired t-tests showed statistical differences between AM and RMC + AM using U1-f ($p = 0.0072$) and U2-f modelling ($p = 0.0068$), and between AM and RMC using U1-f ($p = 0.0097$) and U2-f modelling ($p = 0.0081$). Compared to using only AM, the increase in F/E ROM when using clusters was 5.3%–9.1%.

For the four modelling methods, no differences were found between ISB U1 and U2 pairs (i.e. U1-f vs U2-f and U1-ulna vs U2-ulna). However, there was a difference between using a 'rigid' forearm and using the ulna to calculate the elbow F/E, where the former one estimated more F/E than the latter one (SNK, $p < 0.001$, for both AM and PMC + AM tracking). The U-ulna models (the U1-ulna and U2-ulna models) estimated a smaller ROM by 11.0%–18.0% compared to the U-f models (the U1-f and U2-f models) irrespective of the tracking methods. Only the U-ulna models showed no statistical difference from the reference literature data of the medical imaging¹⁹ ($p = 0.71$, mean value 138.1° (13.7°) vs (136.5° (9°))).

For each subject, the within-session CMC values of the repeated trials were all above 0.95, which indicated excellent within-session repeatability. For elbow F/E, the CMC values of all the subjects in each combination condition of different modelling and tracking methods were above 0.90, suggesting a high level within-group

similarity. However, for P/S, the CMC values of different tracking methods were around 0.75–0.78 for each modelling method, while it varied between 0.44 and 0.93 for the different modelling methods in each tracking method. The variation and low values of CMC for P/S suggested poor similarity among the groups.

Discussion

Tracking methods

In the analysis of the absolute MPE, the RMC showed the least-perturbed marker-pair distance among all the tracking conditions. As the markers were already fixed to a 'solid' shape, it can be inferred that the absolute MPE of RMC was mainly from the systematic or instrumental error. The main error source of the other tracking conditions included not only the systematic error but also the skin artefact, which is usually much larger.¹² All the other absolute MPEs in the study, however, had the same order of magnitude and SD as that of the RMC, and they were well within the reported range of mean systematic error (from 0.1 to 5.3 mm)³¹ and below the reported error introduced by soft tissue artefact (up to 55.3 mm).¹² As such, all tracking methods were considered to be consistent with the rigid body assumption.¹⁵ For the relative MPE, although a lower value did not guarantee a more rigid connection to the bone, a review¹² indicated that the larger the minimum distance between the rotating marker, the more accurate the results. In this study, the ROM estimated from the AM had the smallest SD in most tracking methods, indicating a lower variability than others. This might be the result of the decreased measurement errors which might indicate that using only AM enabled the tracked kinematics to be less sensitive to the MPE.

In addition to the MPE, the tracking methods also affected the estimated range of P/S and F/E motion, especially for the P/S. For P/S, tracking with marker

clusters resulted in a severe underestimation of the joint angles (from 73.7° to 146.4°) compared to using only AM (around 170°), falling outside the referred literature database. Irrespective of using RMC or PMC, markers attached to non-bony locations failed to represent the full relative motion between the ulna and radius due to the large amount of skin movement of the forearm. In particular, due to the skin movement, the forearm RMC was also sensitive to the distance from the wrist to the cluster when tracking P/S. Schmidt et al.²⁸ suggested that the RMC should be fixed close enough to the wrist to record most of the P/S (although they still found rotations were 17%–43% smaller than the true value). Their conclusion was consistent with our findings (tracking using RMC reduced the estimated range of motion by 19.6%–43.2% compared to using only AM) and helped explain the great variation of P/S ROM reported in previous studies using motion capture.^{1,26–28} When using only RMC, Andel et al.²⁶ found a larger P/S range (161°) than in this study (137.5°). However, Andel et al. used an active optical system, allowing to strap a cluster close enough to the ulnar and radial styloid, while we had to keep the cluster at a larger distance (around 3 cm) from the AMs around the wrist, to avoid artefacts from the passive optical system.

For elbow F/E, although no statistical differences were found in the entire tracking group, differences between pairs existed. Considering the U-f models, adding clusters slightly increased the F/E range of motion compared to using only AM, while the later one is closer to the reference of medical imaging study.¹⁹ This can also be explained by the high sensitivity of the clusters at the forearm to soft tissue artefacts. In addition, RMC and PMC showed comparable tracking effects, as no statistical difference was found between these methods. Therefore, tracking methods here affected the F/E less than the P/S, and using only AM to track F/E is also recommended.

Modelling methods

First, the two ISB definitions of humerus resulted in similar estimations of both elbow F/E and P/S ROM, which was in agreement with previous research.¹ Frayssé and Thewlis¹ suggested that ISB2 might improve inter-experimenter repeatability and ISB recommended using the ISB2 as the preferred selection when the forearm is available. However, based on the similar SD and CMC values in our results, there is no indication that ISB2 is less sensitive than ISB1 within this experimental protocol.

Second, the modelling approach of the forearm was crucial in the calculation of elbow kinematics. Although the X-axis rotations of U-f and U-ulna were both regarded as the approximation of F/E in the ISB recommendation,⁷ we found differences between the two models in this study. Only U-ulna models showed comparable results with the reference literature data of

the medical imaging ($p = 0.71$, mean value 138.1° (13.7°) vs 136.5° (9°)). This makes sense as the medical imaging studies only treated the ulna as the moving segment to study humeroulnar F/E instead of the whole forearm. Meanwhile, as the goniometer test remains as a common way for elbow F/E measurement, we also compared the F/E with a representative goniometer study,²² as it included a large sample of similar subject characteristics to ours. Comparing to the goniometer reference, 145.4° (9.4°) (114 subjects, male, age 20–44), we also found that only U-ulna models estimate comparable results without statistical difference ($p = 0.11$, mean value 138.1° (13.7°) vs 145.4° (9.4°)), though the relative difference with goniometer measurements was a bit higher than that to radiographic measurements. Results from the U1-f and U2-f models were consistent with neither medical imaging nor goniometer measurements. Therefore, the good agreement of the U-ulna model with literature^{18,19} could be expected, indicating the unsuitability of the ‘rigid’ forearm assumption of the U-f model in estimating elbow F/E.

The U-f model demonstrated a better estimation of P/S than the Radius-ulna model. However, Tersi et al.²⁰ indicated in their one-sample fluoroscopic analysis that the ‘rigid’ forearm model was less accurate than a model including both ulna and radius in their estimation of radioulnar joint kinematics. In this study, the reduced ROM when using the Radius-ulna model might be related to the skin artefact as well as the simplification of the segment coordinate systems, as the P/S axis was assumed to intersect the F/E axis⁷ although this is not physiological condition.

In this study, the calculated hand rotation during P/S was regarded as a simulation to the goniometer measurements, and it was found to be well consistent with the results from both U-f/AM modelling and the reference range of literature database.^{5,21–23} Caution should be taken here, although the Hand rotation model might be easy to be implemented to approximate the elbow P/S (as no markers were needed for humerus and forearm), its use is limited, as the wrist movement had to be controlled.

Limitations and future directions

The results of this study should be interpreted and extended within the limitations of the experimental protocol. One major limitation mainly concerned the comparison standard used in this study. Instead of directly measuring the motion using medical imaging or bone pins, we compared our results through literature review. However, although the ‘true’ value cannot be assessed, the inter-group differences and interrelationships between different methods, which is the focus of this study, can still give indications into the measurement protocol. In addition, the comparisons with literature, especially studies using radiography, showed good consistency; therefore, we are confident in the

aforementioned conclusions. Another limitation is the absence of independent PMC tracking in this study. We found it is difficult to guarantee at least three separate markers were well attached to the bone of interest and well tracked, as a rigid marker cluster already took a lot of space on the forearm, especially for P/S. This problem also affects the independent RMC tracking for the ulna.

In addition, recently IMUs show promise for tracking human motion. Some researchers³² proposed that combining an optical motion capture system with IMUs might overcome the high dependence on reflective markers for optical system as well as the drawbacks of sensor bias and drift for IMUs. Another study³³ indicated that the biomechanical model definitions influence the IMUs tracking effects (based on the transformation matrix between IMU and optical system) more than the technological error. Therefore, this study and results could be extended to investigate if the same optimal estimation of elbow and forearm kinematics can be generated for such a sensor fusion approach.

Conclusion

In general, this study showed that cluster tracking methods including both RMC and PMC are not appropriate for measuring elbow and forearm kinematics, especially for forearm P/S motion. We suggest the AM is the optimal method for forearm tracking. We consider the ISB U-f model as an appropriate generic model for analysing forearm P/S kinematics, while the U-ulna model is the most appropriate for measuring the humeroulnar joint or F/E kinematics. Knowing the effects of different modelling and tracking methods can help us understand the difference in previous research, avoiding misinterpretations in communicating results of different methodologies and therefore give researchers clear insights into the measurement protocol that can be used for analysing elbow and forearm kinematics.

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Supplemental material

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