DOI:
10.1177/0954411917749617

Title: A practical clinical kinematic model for the upper limbs

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Abstract

A novel clinically practical upper limb model is introduced that has been developed through clinical use in children and adults with neurological conditions to guide surgery to the elbow and wrist. This model has a minimal marker set, minimal virtual markers, and no functional joint centres to minimise the demands on the patient and duration of data collection. The model calculates forearm supination independently from the humerus segment, eliminating any errors introduced by poor modelling of the shoulder joint centre. Supination is calculated by defining the forearm segment twice, from the distal and proximal ends. Firstly, using the ulna and radial wrist markers as a segment defining line and secondly by using the medial and lateral elbow markers as a segment defining line. This is comparable to the clinical measurement of supination utilising a goniometer and enables a reduced marker set, with only the elbow, wrist, and hand markers to be applied when only the wrist and forearm angles are of interest. A sensitivity analysis of the calculated elbow flexion-extension angles to the position of the glenohumeral joint centre is performed on one healthy female subject, aged 20, during elbow flexion and a forward reaching task. A comparison of the supination angles calculated utilising the novel technique compared to the rotation between the humeral and forearm segments is also given. All angles are compared to a published kinematic model that follows the recommendations of the International Society of Biomechanics.

Keywords: Modelling/Simulation [Biomechanics], Biomechanical Testing/ Analysis, Biomedical Instrumentation, Gait Analysis, Joint Biomechanics, Motion Analysis Systems.

Introduction

There is an increasing interest in performing routine clinical upper limb movement analysis (ULMA) to assist surgical treatment planning in individuals with cerebral palsy (CP). Surgical intervention in CP is predominantly performed distally in the upper limb, with the most common interventions performed at the forearm, wrist, and hand[4,5]. Surgical intervention to the shoulder in CP is typically only performed on severely affected individuals to correct adduction and internal rotation contractures of the shoulder that cause difficulty with underarm hygiene and wearing clothes[5]. Therefore, the main focus of a clinical ULMA in this group is the wrist and forearm. The difficulties with employing existing kinematic models is that they are complex and time consuming, primarily due to the complexity of modelling the shoulder joint[1] and scapula motion tracking[2,3]. Therefore, there is a need for a simple kinematic model that has minimal skin contacting retro-reflective markers and virtual markers to facilitate rapid data collection whilst enabling the acquisition of accurate joint angle data for the distal upper limbs. This will maximise the clinical feasibility of performing ULMA in children and individuals with cognitive or behavioural limitations.

In this paper we describe a novel kinematic model, the Evelina Upper Limb (EUL) model that enables the calculation of wrist and forearm joint angles independent of shoulder joint centre location, together with a simple model of the shoulder for below head-height movements of the upper limb to enable elbow flexion/extension angles to be assessed. Forearm supination and elbow flexion are compared with a model[3] that is compliant with the recommendations of the International Society of Biomechanics (ISB)[6] and has been previously utilised in children with CP[7]. A sensitivity analysis of elbow flexion on shoulder joint centre location in the EUL model is also performed.

Model:

The EUL model consists of 16 retro-reflective markers, three marker clusters, and three anatomical landmarks tracked as virtual markers relative to the chest marker cluster. These markers are utilised to define seven segments, the thorax, upper arms, forearms, and hands. The marker locations are given in Table 1 and Figure 1.

Marker Name	Marker Type	Location
CLAV	Marker	Superior aspect of the sternum at the centre between the clavicals.
C7	Virtual	Seventh cervical spine vertebra
RBAK	Marker	Centre of the right scapula. This marker is an asymmetry marker and can be placed onto the subject's clothing.
STRN	Virtual	Inferior end of the sternum
T10	Virtual	Tenth thoracic spine vertebra
Chest cluster (CHEA, CHEB, CHEC, CHED)	Cluster	On the chest, inferior to the CLAV marker
SHO	Marker	Superior aspect of the acromion
Upper arm cluster (UPA, UPB, UPC, UPD)	Cluster	Lateral aspect up the upper arm
ELM	Marker	Medial aspect of the elbow.
ELL	Marker	Lateral aspect of the elbow
WRR	Marker	Radial aspect of the wrist
WRU	Marker	Ulnar aspect of the wrist
MCPR	Marker	Superior surface of the ring finger metacarpal-phalangeal joint
MCPI	Marker	Superior surface of the index finger metacarpal-phalangeal joint

Table 1: Marker names, types, and locations. Note: The ELM and ELL markers form a line through the elbow corresponding to the flexion/extension axis of the elbow joint. WRR and WRU should form a line through the wrist corresponding to the flexion/extension axis of the wrist joint. When the elbow is flexed 90 degrees with the forearm in neutral supination (thumb up), looking along the long axis of the forearm, the line between WRU and WRR should be perpendicular to the line between ELM and ELL except in individuals with a deformity altering the axis of flexion/extension of the elbow.

Segment		
Thorax	Origin	The mid-point between the spinous processes T10 and the sternal notch (STRN) markers.
	Y	The line connecting mid-point of C7-CLAV and T10-STRN.
	Z	The line connecting the LSHO and RSHO.
	X	The common line perpendicular to Y and Z, pointing anteriorly.
Upper Arm	Origin	The elbow joint centre (EJC) is the mid-point between the medial and lateral elbow markers (ELM and ELL).
	Shoulder joint	The shoulder (gleno-humeral) joint centre location (SJC) is positioned 17% of shoulder girdle width inferior to the shoulder marker[8].
	Y	The line connecting EJC and SJC.
	Z	The line connecting ELM and ELL.
	X	The common line perpendicular to Y and Z, pointing anteriorly.
Forearm	Origin	The wrist joint centre (WJC) is the mid-point between the ulnar and radial wrist markers (WRU and WRR).
	Y	The line connecting WJC and EJC.
	Z	The line connecting WRR and WRU.
	X	The common line perpendicular to Y and Z, pointing anteriorly
ForarmAlt1	Origin	The WJC.
	Y	The line connecting WRR and WRU.
	Z	The line connecting WJC and EJC.
	X	The common line perpendicular to Y and Z, pointing anteriorly.
ForarmAlt2	Origin	The EJC.
	Y	The line connecting ELL and ELM.
	Z	The line connecting WJC and EJC.
	X	The common line perpendicular to Y and Z, pointing anteriorly.
Hand	Origin	Hand origin is a point offset anteriorly, perpendicular to the plane formed by WJC, MCPI, and MCPR markers, to the midpoint of the hand markers on the index and ring finger metacarpal-phalangeal joints (MCPI and MCPR), where the hand offset is determined by: $\text{Hand offset} = \frac{\text{hand thickness} + \text{marker diameter}}{2}$
	Y	The line connecting the hand origin and WJC.
	Z	The line connecting MCPI and MCPJ.
	X	The common line perpendicular to Y and Z, pointing anteriorly.

Table 2: Segment definitions for the EUL model

Segment definitions:
Segment coordinate systems were used to determine the joint angles. A right-handed co-ordinate system (XYZ) was constructed with the principal axis (Y) aligned with the principal segment axis, and the secondary axis (Z) pointing left to right in the coronal plane, perpendicular to the sagittal plane. The segments are connected by a three-degrees-of-freedom joint with a fixed centre of rotation at the shoulder (glenohumeral joint), elbow, and wrist.

A series of Euler rotations, sequenced XZY (flexion/extension, abduction/adduction, axial rotation) were used to express joint angles of the distal segment with respect to the proximal segment. The thorax angles are relative to the global reference frame. Supination/pronation is defined as the relative angle between two independent forearm segments, the first (forearmAlt1) defined using the ulnar and radial wrist markers and the second (forearmAlt2) defined using the medial and lateral elbow markers. The rotation between these segments, calculated using Euler rotations, sequenced XZY, are used to determine the angles between these two forearm segments. This defines the supination angle. This is comparable to the measurement of supination in clinic using a goniometer. The model was developed using Vicon BodyBuilder V3.6.1 (Vicon Motion Systems, Ltd., Oxford, England). Full segment definitions are given in Table 2.

Method

Kinematic data was collected using a 9-camera Vicon Nexus motion capture system (Vicon Motion Systems, Ltd., Oxford, England) from one healthy female volunteer aged 20 years. The subject sat on an adjustable chair with her ankles, knees and hips at 90°. The subject performed three tasks:

1. Elbow flexion and extension with the forearm in a neutral position.
2. Forearm supination and pronation with the elbow held flexed at 90º
3. Forward reach to touch a target located midline at chest height, at arm length anterior to the chest.

The data was collected whilst the volunteer wore two markers sets, the EUL model and an ISB compliant cluster-based model (COM Model)[3], enabling direct comparison of the joint angles calculated using the two models. The COM model was processed using the model specific ULEMA[3] software in Matlab (V2014a). The EUL model was labelled and processed in Vicon Nexus (V2.5).

To investigate the sensitivity of the calculated elbow flexion/extension angle to SJC position, the SJC was shifted by half of the shoulder offset[8] (8.5% of shoulder girdle width, 34.5 mm for this subject) in 6 perpendicular directions forming a sphere of radius equal to 8.5% of shoulder girdle width as shown in figure 3(C). This was chosen to represent extreme error in SHO marker placement, and in calculation of the SJC relative to the acromion. Elbow flexion was calculated for each SJC position during the elbow flexion task and the forward reach task. Forearm supination in the EUL model is calculated as the relative rotation between the two forearm segment definitions (as explained above). This is compared to the traditional method for measuring supination, the axial rotation between the humerous and forearm segments (the elbow rotation angle) for both the COM and EUL models. The average root mean square error (RMSE) was computed for each trial between the joint angles from the EUL and COM models. The impact of moving the SJC on the kinematics of the EUL model was evaluated by computing the average RMSE for each trial between the artificially altered model for each SJC offset and the original EUL model.

Results

A comparison of the EUL forearm supination, the EUL elbow rotation, and the COM model during an active supination task are given in figure 2(A). A low 2.3º RMSE was observed between the EUL forearm supination and the EUL elbow rotation angle. A 5.8º RMSE was observed between the COM and EUL model during the same task (see Table 3). Elbow flexion calculated using the EUL and COM model during isolated elbow flexion and the forward reach task are shown in figures 2(B) and 2(C). The RMSE between the EUL and COM model during the isolated elbow flexion task was 12.8º, and 4.8º during the forward reach task (Table 3).

The sensitivity of elbow flexion on SJC location during isolated elbow flexion and a forward reach task are shown in figures 3(A) and 3(B). The largest RMSE compared to the original shoulder location in the EUL model was observed between the anterior and posterior offsets, with an RMSE of 7.5º and 7.4º respectively (Table 3). During the forward reach task, elbow flexion was more sensitive to the SJC in the superior-inferior direction, with an RMSE of 5.4º and 5.8º.

Task	Model	SJC Shift direction	RMSE (º)
Elbow flexion	COM	N/A	12.8
	SJC 1	Superior	1.1
	SJC 2	Inferior	1.5
	SJC 3	Medial	2.5
	SJC 4	Lateral	2.7
	SJC 5	Anterior	7.5
	SJC 6	Posterior	7.4
Forward reach	COM	N/A	4.8
	M1	Superior	5.4
	M2	Inferior	5.8
	M3	Medial	2.5
	M4	Lateral	2.3
	M5	Anterior	3.9
	M6	Posterior	3.2
Supination	EUL elbow rotation	N/A	2.3
	COM	N/A	5.8

Table 3: RMSE for the COM model relative to the EUL model in each task together with the RMSE for the joint angles calculated using the EUL model with the SJC shifted by half the shoulder offset in 6 perpendicular directions.

Discussion

Good agreement was observed between the novel method of measuring forearm supination proposed in the EUL model compared to the rotation of the forearm segment relative to the upper arm segment (EUL elbow rotation) with an RMSE of 2.3º. A larger RMSE was observed between the EUL and COM model of 5.8º. This is likely to be due to the different elbow markers utilised by the two models (COM- virtual; EUL – physical), and the difference in the methods used to calculate supination. The EUL model uses two forearm segments (forearmAlt1 and forearmAlt2), with supination defined as the rotation between these segments. Alt1 is defined from the distal end, (first defining line between the two wrist markers), and Alt2 from the proximal end (first defining line between the elbow markers). This method was chosen to enable supination to be calculated independent of the SJC and to be analogous to the clinical definition of forearm supination instead of modelling supination as rotation of the elbow joint, which is not anatomically possible. Despite these differences, the EUL model performed well compared to the reference COM model.

Elbow flexion-extension was found to be sensitive to SJC location, with an RMSE of 1.1º to 7.5º during isolated elbow flexion. However, the SJC offsets applied are much larger than the anticipated repeatability in SHO marker placement, and therefore the repeatability of elbow flexion angle between assessments may be less than the maximum RMSE of 7.5º.

An RMSE of 12.8º was observed between the EUL and COM models during the isolated elbow flexion task, with the largest difference observed at full elbow extension. During the forward reach task a lower RMSE of 4.8º was observed. The difference between the models may be due to a difference in the location of the virtual medial and lateral elbow markers between the models, which will be most pronounced near full extension; however further investigation of this is required.

The EUL model performed well compared to a more complex published model that is compatible with the recommendations of the ISB, but had a shorter data collection time, with the EUL model requiring only 3 virtual markers to be defined for a bilateral assessment compared to 18 plus a shoulder functional joint centre calibration trial in the COM model for a unilateral assessment. The EUL model has potential as a clinically feasible upper limb model and future investigation of the repeatability of the model and validation in a clinical population is required.

Acknowledgements

This research was supported by the National Institute for Health Research (NIHR) Biomedical Research Centre at Guy's and St Thomas' NHS Foundation Trust and King's College London. The views expressed are those of the author(s) and not necessarily those of the NHS, the NIHR or the Department of Health.

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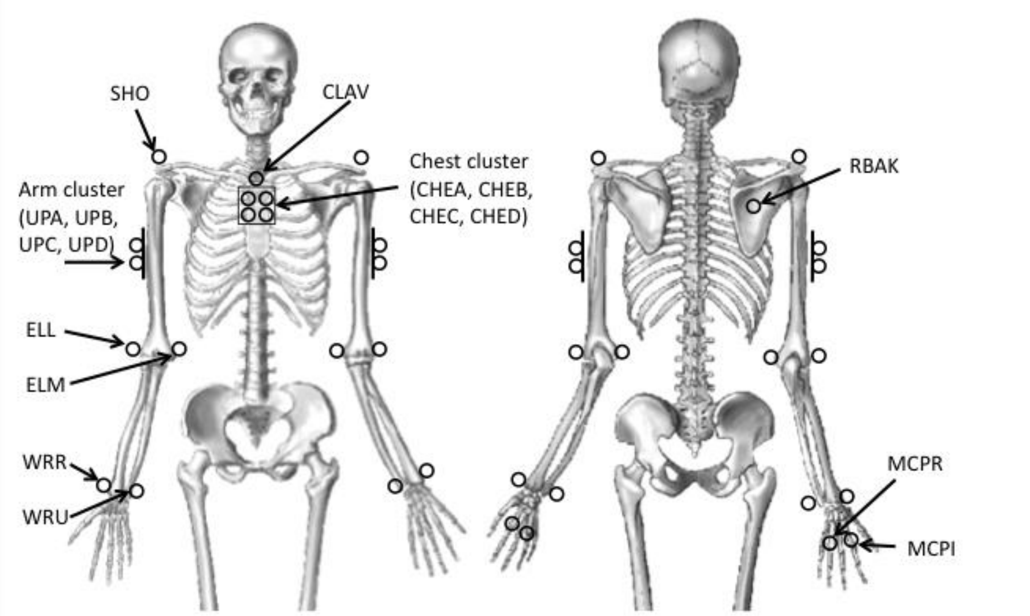
Figure captions:

Figure 1: Schematic showing retro-reflective marker placement in the EUL model.

Figure 2: (A) Forearm supination and pronation during selective full range supination and pronation. EUL model (solid line) - the rotation between the two forearm segment definitions, forearmAlt1 and forearmAlt2; Euler elbow rotation for EUL model (long dashed line); COM model (short dashed line). B) Elbow flexion/extension during isolated elbow flexion for the EUL model (solid line) and the COM model (dashed line). (B) Elbow flexion/extension during a forward reach task for the EUL model (solid line) and the COM model (dashed line).

Figure 3: (A) Elbow flexion/extension during isolated elbow flexion for the EUL model and each SJC location. (B) Elbow flexion/extension during a forward reach task for the EUL model and each SJC location. (C) Schematic diagram of the shoulder showing the estimated SJC location (X) and the shifted position of the SJC for each shoulder offset used in A and B.



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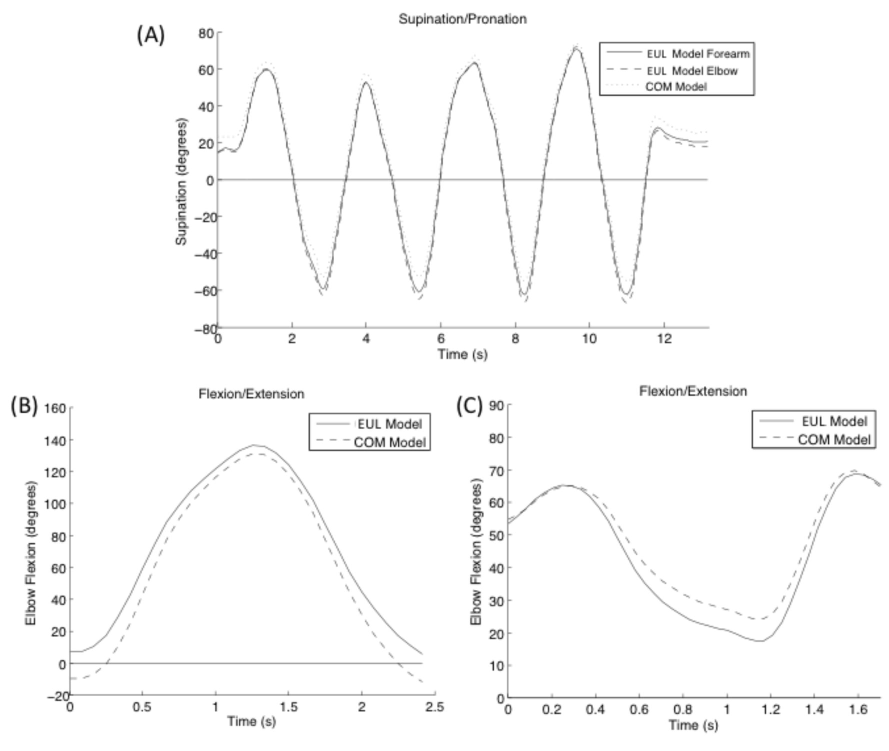

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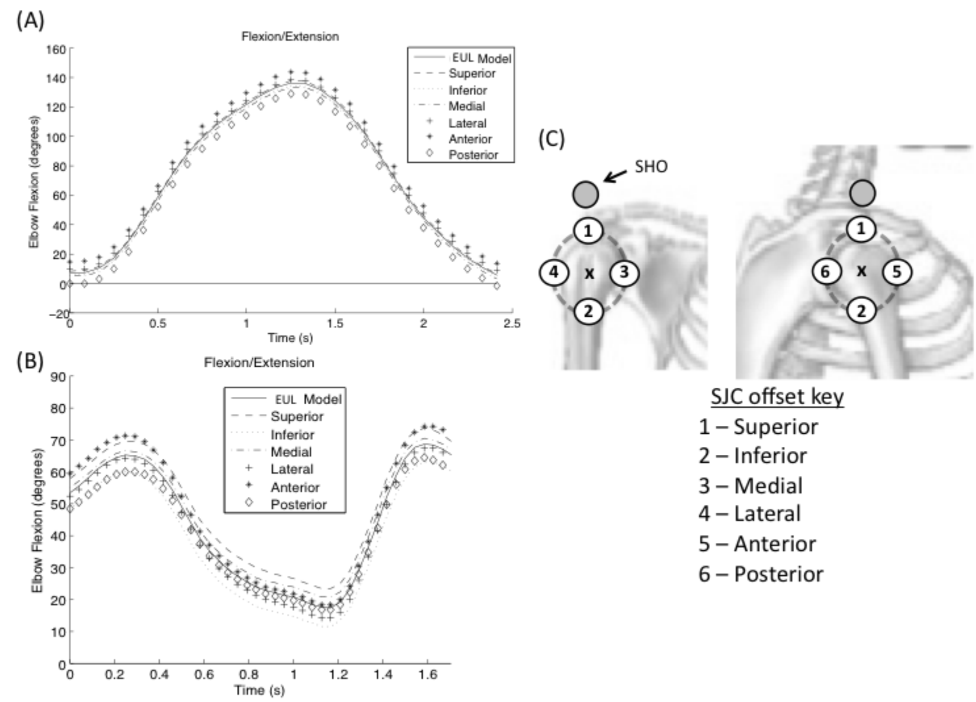

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