Three-dimensional kinematics of upper limb anatomical movements in asymptomatic adults: Dominant vs. non-dominant

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A B S T R A C T

The effect of dominance on upper limb (UL) kinematics has only been studied on scapular movements. Moreover, when an anatomical UL movement is performed in a specific plane, secondary movements in the remaining planes involuntarily occur. These secondary movements have not been previously evaluated. The aim of this study was to compare the kinematics of primary and secondary angles of dominant and non-dominant UL during anatomical movements in asymptomatic adults.

25 asymptomatic adults performed 6 anatomical movements bilaterally: shoulder flexion-extension, abduction-adduction, horizontal abduction-adduction, internal-external rotation, elbow flexion-extension and wrist pronation-supination. Kinematics of the dominant and non-dominant UL were compared by their ranges of motion (ROM) and their angular waveforms (Coefficient of Multiple Correlations, CMC).

The comparison between dominant and non-dominant UL kinematics showed different strategies of movement, most notably during elbow flexion-extension (CMC = 0.29): the dominant UL exhibited more pronation at maximal elbow flexion. Significant secondary angles were found on most of the UL anatomical movements; e.g. a secondary ROM of shoulder (humero-thoracic) external-internal rotation (69° ± 16°) was found when the subject intended to perform maximal shoulder abduction-adduction (119° ± 21°).

Bias of dominance should be considered when comparing pathological limb to the controlateral one. Normative values of primary and secondary angles during anatomical movements could be used as a reference for future studies on UL of subjects with neurological or orthopedic pathologies.

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1. Introduction

The Upper Limbs (UL) can be affected by trauma, inflammatory diseases or degeneration among other etiologies. These pathologies can alter the normal function of muscles, tendons or joints and in consequence change the normal three-dimensional (3D) movement patterns of the different joints of the UL (Millett, Giphart, Wilson, Kagnes, & Greenspoon, 2016; Shinohara et al., 2014). Thus, knowledge of the normal motion of the upper extremities in 3D is essential in the assessment of UL affections and in treatment evaluation.

There is no single movement which is of particular importance to the study of the upper limbs. Ranges of Motion of the UL would be best evaluated by anatomical movements of the UL joints, such as flexion-extension, abduction-adduction and internal-external rotation which are primarily performed in one plane. Since each of the UL joints have more than one degree of freedom during each of the movements, involuntary movements could occur in the two remaining planes and are usually referred to as secondary movements. It would be clinically relevant to investigate which secondary movements (the second and third angles of the Euler or Cardan sequences) are performed during the execution of the full ROM in the primary plane.

Furthermore, in most of the clinical studies, the kinematics of a pathological limb is compared to those of the controlateral limb (Roren et al., 2012). Thus, it is essential to quantify the kinematic differences between normal dominant and non-dominant UL. The effect of dominance has only been studied on scapular kinematics (Lee, Yang, Kim, & Choy, 2013; Matsuki et al., 2011; Schwartz et al., 2014). These differences have still not been explored in the other joints of the UL.

The aim of this study is to compare the kinematics of both the primary and secondary planes of anatomical movements between the dominant and non-dominant UL in an asymptomatic adult population.

2. Methods

2.1. Population

Twenty five healthy adults (13 females, 12 males) with a mean age of 28.7 ± 7 (mean ± 1SD), from the institution where the motion capture laboratory is installed, had voluntarily participated in this study. Twenty one subjects identified themselves as right-handed and four as left-handed. All Participants had no history of musculoskeletal or neurological impairments. Written informed consent was obtained from all participants. The Institutional Review Board of the Hotel-Dieu de France Hospital/University of Saint-Joseph approved the study design.

2.2. Experimental protocol

The participants were seated at a height-adjustable chair with lower back support, hips and knees flexed at 90° and both feet flat on the ground. The subjects were instructed to keep their backs in their physiological postures. No physical restraints were used in order to avoid affecting the normal movement of the upper limbs. Each task was explained and tested before the acquisition. The participants were asked to perform anatomical movements of the UL. All movements were tested bilaterally and repeated 3 times by each UL. Twelve randomly selected participants (3 females, 9 males) were evaluated on two occasions, by the same operator, with at least one week interval in order to assess measurement repeatability.

Participants were asked to minimize trunk movement as much as possible and to reach the maximum range of motion possible. The anatomical movements consisted of:

1. Shoulder flexion-extension: the participants started with their arm positioned vertically beside their trunk, in a relaxed position with their palm in the neutral position (palm in the parasagittal plane). Then, they were asked to perform complete flexion followed by complete extension of the shoulder and to return to the starting position (movement mainly in the sagittal plane).
2. Shoulder abduction-adduction: from the same starting position, the participants had to move their UL laterally (movement mainly in the frontal plane).
3. Shoulder horizontal abduction-adduction: the UL is held at 90° of abduction as a starting position. A horizontal adduction (moving the UL, elbow extended, to the opposite shoulder) followed by a horizontal abduction is performed; from the starting position backward while keeping a 90° angle with the trunk (movement mainly in the horizontal plane).
4. Shoulder internal-external rotation: from 90° of abduction of the shoulder and 90° of flexion of the elbow (pointed forward) we asked the participants to perform an internal rotation of the shoulder (moving the palm of the hand downward and backward) followed by the external rotation (moving the palm of the hand upward with the palm facing forward): the humerus is rotated around the lateral axis passing by the 2 shoulders.
5. Elbow flexion-extension: same starting position as in task 1. We asked the participants to perform complete flexion of the elbow followed by complete extension.
6. Hand pronation-supination: the arm positioned vertically beside the trunk with 90° of flexion of the elbow and with the thumb pointing upward. The participants were asked to move their palm downward (pronation) and upward (supination).

The anatomical movements were illustrated in Fig. 1.

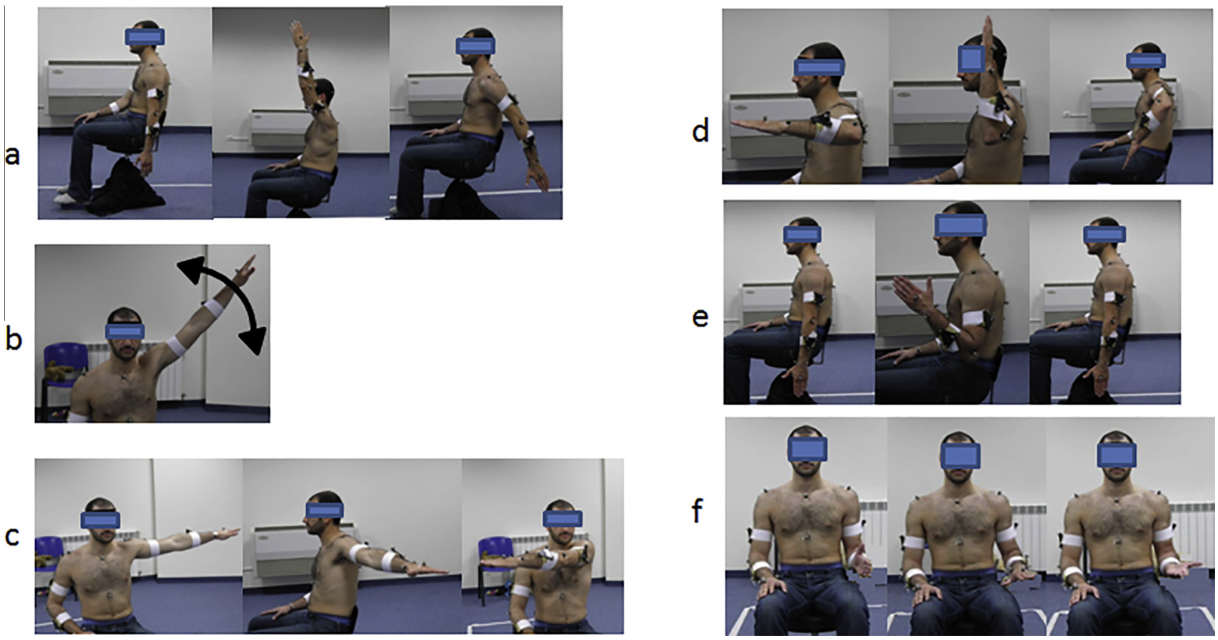

Fig. 1. Illustrations of the anatomical movements performed by the subjects: (a) shoulder flexion-extension, (b) shoulder abduction-adduction, (c) shoulder horizontal abduction-adduction, (d) shoulder internal-external rotation, (e) elbow flexion-extension and (f) wrist pronation-supination.

2.3. Biomechanical protocol

The kinematic model and marker placement (on the trunk, arms, forearms and hands) were based on ISB recommendations (Wu et al., 2005). Additionally, clusters of 3 markers were placed and well attached on the arm and the forearm bilaterally. Motion capture was performed with 7 infrared Vicon MX3 cameras (Vicon Motion Analysis system, Oxford Metrics, UK), sampled at 200 Hz.

The glenohumeral (GH) joint center was estimated by the sphere-fitting method, using the following movements: flexion-extension, abduction-adduction, horizontal abduction-adduction, rotation and circumduction of the shoulder (Lempereur, Kostur, Leboucher, Brochard, & Remy-Neris, 2013; Lempereur et al., 2010; Stokdijk, Nagels, & Rozing, 2000). The anatomical coordinate systems of the different segments were based on ISB guidelines (Wu et al., 2005).

The angles of the following joints of the UL were calculated: humero-thoracic, scapulo-thoracic, elbow (forearm relatively to the arm) and wrist (hand relatively to the forearm). In the rest of this paper, when referring to humero-thoracic angles, the term "shoulder" is used instead. Since the Euler sequence YXY, proposed by the ISB recommendations, resulted in gimbal lock in different angles of different movements, the Cardan ZXY sequence was used for the flexion/extension movement of the shoulder and the Cardan XZY sequence was used for shoulder abduction, horizontal abduction/adduction and internal/external rotation (Bonnefoy-Mazure et al., 2010; Lempereur, Brochard, Mao, & Remy-Neris, 2012; Senk & Cheze, 2006).

2.4. Data processing

Raw data was processed using the pipeline in Workstation® (Vicon Motion Systems, Oxford, UK): fill gap routine (at 20 frames) and the Woltring filter with a scale of 10. The markers were labeled in the static acquisition and the autolabel function was used during dynamic acquisitions. The movement cycles were defined visually using video acquisitions, frame by frame, from the starting position, for each movement or task, to the next starting position. The collected data were exported and processed in MATLAB® (Mathworks®, Natick, MA, USA). A mean curve was calculated for each joint angle, in each movement from all the trials. The angles were time-normalized over the movement cycle. Angular waveforms (mean ± SD) were elaborated for each angle and for both dominant and non-dominant UL. The ranges of motion (ROM) of each movement, in each joint, were then calculated.

2.5. Statistical analysis

Statistical analysis was performed using MATLAB®. The kinematics obtained from the two repeatability sessions were compared for the 12 subjects who completed the exam twice. The ICC (Interclass Correlation Coefficient), (2, k) model, served for the inter-session repeatability of the ROM: ICC > 0.80 indicates very high reliability, 0.60–0.79 moderately high reliability, 0.40–0.59 moderate reliability and <0.40 low reliability (Weir, 2005). The inter-session standard error of measurement (SEM) was also calculated for each parameter. When the data was found to follow a normal distribution, the paired *t*-test was used to compare between the dominant and non-dominant UL ROM, otherwise the Wilcoxon test was applied. The threshold of significance was set at $p < 0.05$. The Coefficient of Multiple Correlations (CMC) was calculated for each angle of interest, in all movements, in order to compare the differences in angular waveforms between the dominant and non-dominant UL. CMC-values >0.9 were considered excellent, 0.80–0.89 good, 0.60–0.79 moderate or <0.60 poor (Kadaba et al., 1989).

3. Results

Inter-session repeatability was evaluated on ranges of motion and displayed in Table 1. For the dominant UL, three angles displayed low ICC when the ROM from the 2 sessions were compared: shoulder internal-external rotation and scapular retraction-protraction angles during the movement of shoulder horizontal abduction-adduction as well as shoulder

Table 1
Repeatability of kinematic measurements, on ROM, for upper limb anatomical movements performed by asymptomatic adults, for both dominant and non-dominant limbs. Low ICC values were shaded in grey.

Repeatability :		Dominant upper limb			Non Dominant upper limb		
Movements	Angles of Interest	ROM			ROM		
		ICC		SEM	ICC		SEM
Shoulder Flexion-Extension	Sh Flex-Ext	0.45	mod	9	0.58	mod	6
	Sh Abd-Add	0.57	mod	3	0.37	low	1
	Sh Int-Ext Rot	0.52	mod	7	0.78	m high	7
	Sc Retra-Prot	0.75	m high	3	0.67	m high	2
	Sc Lat-Med Rot	0.46	mod	3	0.02	low	1
	Sc Ant-Post Tilt	0.52	mod	1	0.48	mod	1
Shoulder Abduction Adduction	Sh Abd-Add	0.70	m high	6	0.86	v high	3
	Sh Int-Ext Rot	0.77	m high	8	0.78	m high	6
	Sh Flex-Ext	0.44	mod	4	0.11	low	2
	Sc Retra-Prot	0.86	v high	2	0.73	m high	2
	Sc Lat-Med Rot	0.60	mod	3	0.87	v high	1
	Sc Ant-Post Tilt	0.40	mod	1	0.65	m high	1
Shoulder Horizontal Abduction- Adduction	Sh Hor Abd-Add	0.79	m high	4	0.65	m high	5
	Sh Int-Ext Rot	0.28	low	3	0.20	low	3
	Sh Abd-Add	0.80	m high	3	0.05	low	3
	Sc Retra-Prot	0.10	low	0	0.10	low	0
	Sc Lat-Med Rot	0.57	mod	2	0.50	mod	1
	Sc Ant-Post Tilt	0.86	v high	1	0.34	low	1
Shoulder Internal - External Rotation	Sh Int-Ext Rot	0.81	v high	6	0.62	m high	10
	Sh Abd-Add	0.40	mod	3	0.54	mod	5
	Sh Flex-Ext	0.28	low	2	0.02	low	1
	Sc Retra-Prot	0.40	mod	1	0.60	mod	2
	Sc Lat-Med Rot	0.43	mod	1	0.50	mod	1
	Sc Ant-Post Tilt	0.40	mod	1	0.59	mod	1
Elbow Flexion-extension	Elb Flex-Ext	0.42	mod	7	0.50	mod	13
	Elb Prono-Sup	0.84	v high	7	0.51	mod	7
	Elb Abd-Add	0.63	m high	5	0.79	m high	4
Wrist Pronation-Supination	Wr Prono-Sup	0.70	m high	5	0.68	m high	8
	Wr Uln-Rad Dev	0.63	m high	6	0.69	m high	4
	Wr Flex-Ext	0.41	mod	5	0.86	v high	4
	Elb Prono-Sup	0.98	v high	1	0.98	v high	2

ROM: Range of Motion; ICC: Intraclass Correlation Coefficient; SEM: Standard Errors of Measurement; Sh: shoulder, Sc: scapula; Elb: elbow; Wr: wrist; Flex-Ext: flexion-extension; Abd-Add: abduction-adduction; Int-Ext: internal-external; Rot: rotation; Retra-Prot: retraction-protraction; Lat-Med: lateral-medial; Ant-Post: anterior-posterior; Hor: Horizontal; Prono-Sup: pronation-supination; Uln-Rad: ulnar-radial; m: moderately; v: very; mod: moderate.

flexion-extension angle during the movement of shoulder internal-external rotation. However, for the non-dominant UL, five angles showed poor repeatability, in addition to the same three angles which showed poor repeatability for the dominant UL.

The variations of the angles, during the movement cycle, in each joint of interest and for each movement, are displayed in Fig. 2 along with their corridors of normality (mean ± 1 SD). The comparison between the ROM of dominant and non-dominant UL kinematics over the whole movement cycle was exposed in Table 2. Four angles, from different movements, showed statistically significant differences ($p < 0.05$) between the dominant and non-dominant ROM: the scapular retraction-protraction and lateral medial rotation during shoulder flexion-extension movement, as well as the scapular lateral-medial rotation during both shoulder abduction-adduction and shoulder internal-external movements.

Moreover, when the Coefficient of Multiple Correlations (CMC) was applied to compare angular waveforms between the dominant and non-dominant UL, five angles showed poor CMC similarity: the shoulder abduction-adduction angle during

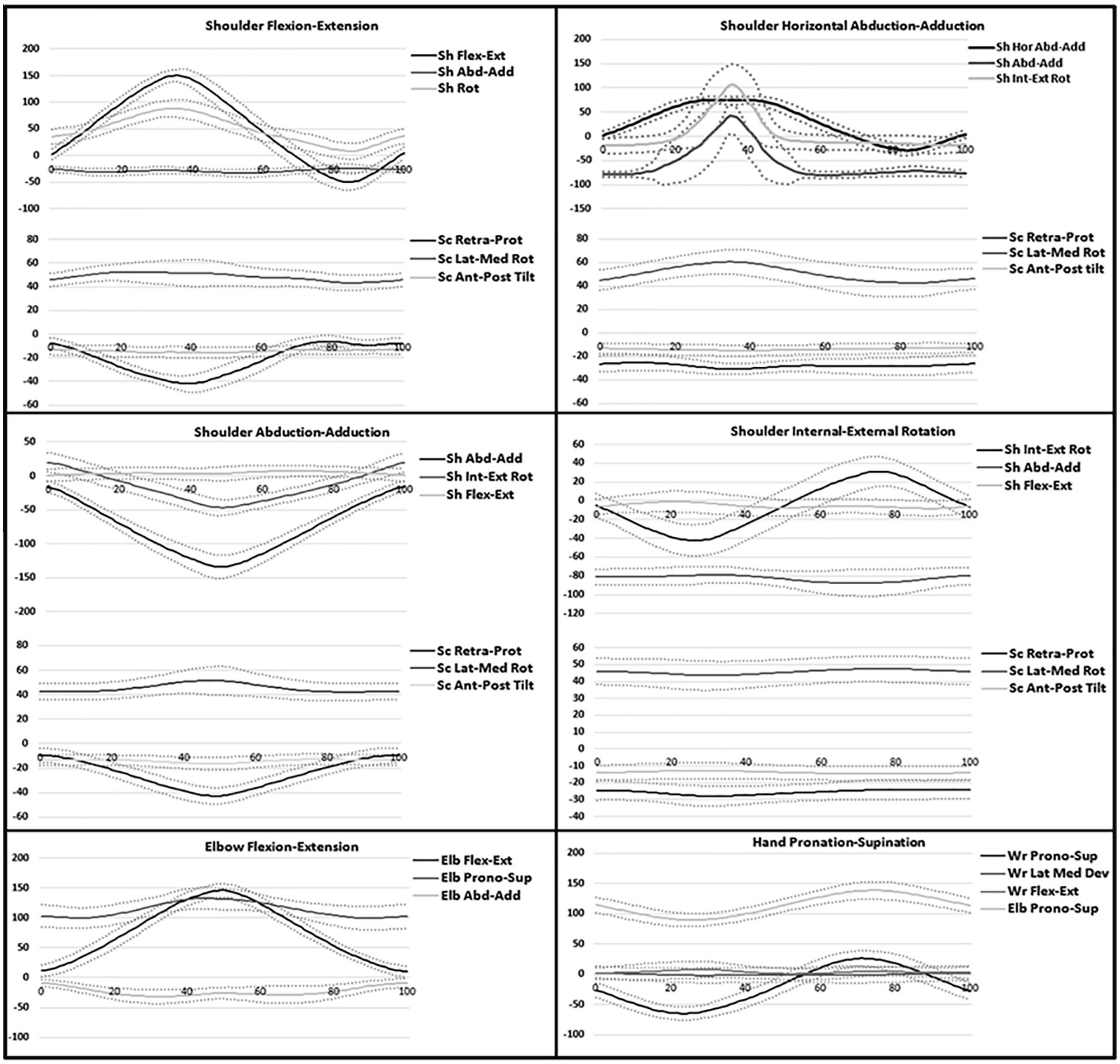

Fig. 2. Angular waveforms (°) describing anatomical movements normalized to the movement cycle. For all joints: Flexion (+), Extension (−), Adduction (+), Abduction (−), Internal rotation (+), External rotation (−). Shoulder: Horizontal adduction (+), Horizontal abduction (−). Scapula: Protraction (+), Retraction (−), Medial rotation (+), Lateral rotation (−), Posterior tilt (+), Anterior tilt (−). Elbow and Wrist: Pronation (+), Supination (−). Wrist: Medial deviation (+), Radial deviation (−). The means (continuous lines) and ±1 standard deviation (dotted lines) were displayed during the normalized movement cycle (horizontal axis: from 0 to 100%).

Table 2
Comparison between dominant and non dominant upper limb kinematics, on ROM (mean ± SD), in asymptomatic adults, during anatomical movements. Significant p-values were shaded in grey. The angles in italic are not to be interpreted.

Comparison between Dominant and Non Dominant upper limbs Ranges of Motion (in °)				
Movements	Angles of Interest	Mean ROM of Dominant UL	Mean ROM of Non Dominant UL	*p-value*
Shoulder Flexion-Extension	Shoulder Flexion-Extension	209 ± 18	205 ± 25	0,3
	Shoulder Abduction-Adduction	16 ± 6	16 ± 5	0,69
	Shoulder External-Internal Rotation	87 ± 14	82 ± 17	0,11
	Scapula Retraction-Protraction	39 ± 8	35 ± 6	0,01*
	Scapula Lateral-Medial Rotation	14 ± 6	11 ± 4	0,03*
	Scapula Anterior-Posterior Tilt	6 ± 3	6 ± 4	0,33
Shoulder Abduction-Adduction	Shoulder Abduction-Adduction	119 ± 21	114 ± 16	0,13
	Shoulder External-Internal Rotation	69 ± 16	68 ± 17	0,21
	Shoulder Flexion-Extension	17 ± 7	18 ± 8	0,39
	Scapula Retraction-Protraction	35 ± 7	33 ± 5	0,09
	Scapula Lateral-Medial Rotation	12 ± 5	9 ± 4	0,01*
	Scapula Anterior-Posterior Tilt	5 ± 2	4 ± 2	0,12
Shoulder Horizontal Abduction-Adduction	Shoulder Horiz Abduction-Adduction	113 ± 12	114 ± 17	0,31
	Shoulder External-Internal Rotation	*142 ± 38*	*153 ± 26*	-
	Shoulder Abduction-Adduction	*133 ± 35*	*128 ± 20*	-
	Scapula Retraction-Protraction	9 ± 3	9 ± 3	0,42
	Scapula Lateral-Medial Rotation	22 ± 7	20 ± 5	0,18
	Scapula Anterior-Posterior Tilt	5 ± 2	5 ± 2	0,66
Shoulder Internal - External Rotation	Shoulder External-Internal Rotation	77 ± 14	75 ± 17	0,8
	Shoulder Abduction-Adduction	23 ± 8	21 ± 8	0,34
	Shoulder Flexion-Extension	13 ± 5	17 ± 8	0,07
	Scapula Retraction-Protraction	7 ± 5	7 ± 4	0,14
	Scapula Lateral-Medial Rotation	6 ± 3	8 ± 3	0,03*
	Scapula Anterior-Posterior Tilt	3 ± 2	3 ± 2	0,84
Elbow Flexion-Extension	Elbow Flexion-Extension	138 ± 16	114 ± 17	0,08
	Elbow Pronation-Supination	40 ± 12	33 ± 8	0,44
	Elbow Abduction-Adduction	27 ± 11	30 ± 13	0,69
Wrist Pronation-Supination	Wrist Pronation-Supination	96 ± 13	99 ± 14	0,78
	Wrist Ulnar-Radial Deviation	23 ± 12	20 ± 9	0,09
	Wrist Flexion-Extension	22 ± 9	21 ± 8	0,16
	Elbow Pronation-Supination	52 ± 9	53 ± 9	0,58

UL: Upper Limbs; ROM: Range of Motion.
*Statistically significant at $\alpha = 0.05$.

shoulder flexion-extension movement (CMC = 0.50), the scapular anterior-posterior tilt during shoulder horizontal abduction-adduction movement (CMC = 0.53), the shoulder flexion-extension angle during shoulder internal-external rotation movement (CMC = 0.49), the elbow pronation-supination angle during elbow flexion-extension movement (CMC = 0.29) and the wrist flexion-extension angle during wrist pronation-supination movement (CMC = 0.4). The angular waveforms that best represented the differences between the dominant and non-dominant UL kinematics are displayed in Fig. 3.

Significant secondary ROM were found in most of the anatomical movements (Table 2).

For instance, a secondary ROM of shoulder external-internal rotation (69° ± 16°) was found when the subject intended to perform maximal shoulder abduction-adduction (119° ± 21°). A secondary ROM of shoulder external-internal rotation (87° ± 14°) was found when the subject intended to perform maximal shoulder flexion-extension (209° ± 18°).

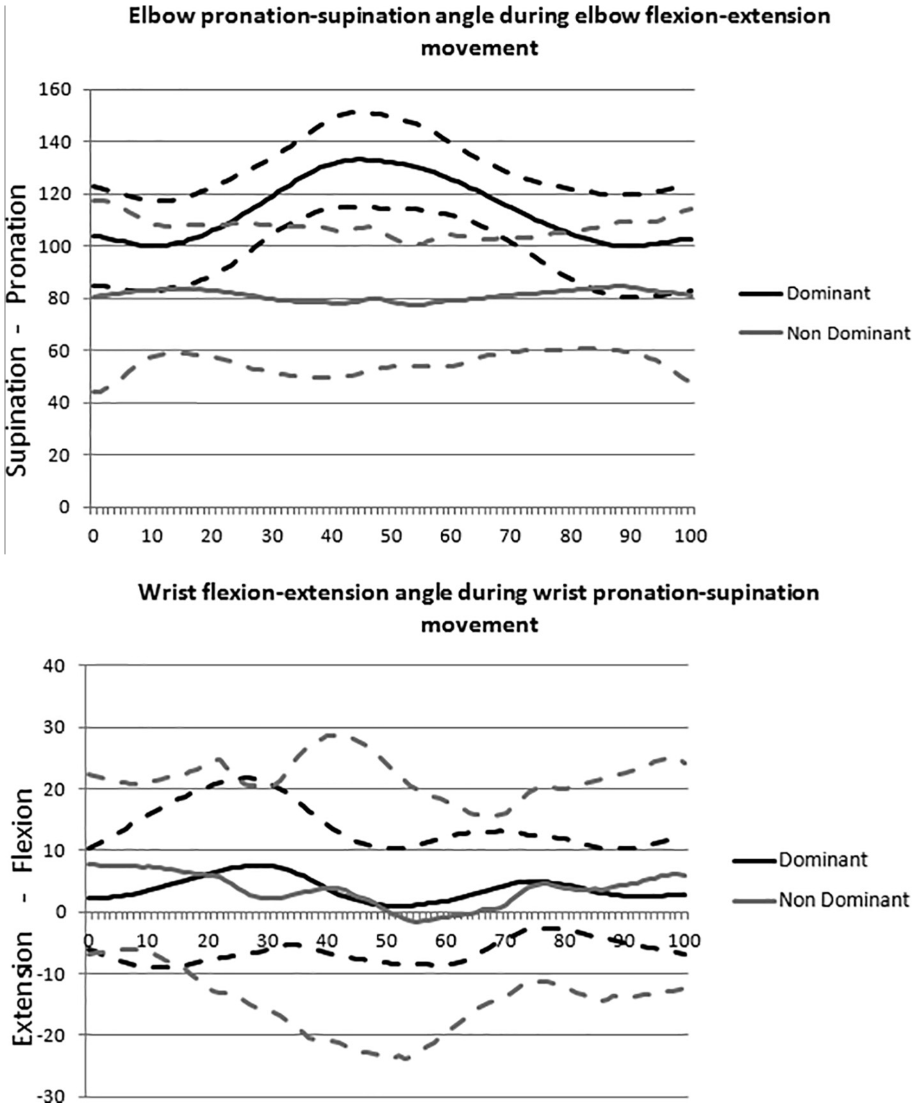

Fig. 3. Dominant v/s non-dominant: most significantly different angular waveforms. Elbow pronation-supination angle during elbow flexion-extension movement and wrist flexion-extension angle during wrist pronation-supination movement. The means (continuous lines) and ±1 standard deviation (dotted lines) were displayed during the normalized movement cycle (horizontal axis: from 0 to 100%).

4. Discussion

This study reports normative values of ROM of anatomical movements for both the dominant and non-dominant upper limbs. Comparison between dominant and non-dominant upper limbs (UL) was assessed for primary and secondary kinematic angles in each joint. Different movement patterns of elbow and wrist pronation-supination were detected between the dominant and non-dominant UL.

In general, moderate to very high repeatability was found on most of the angles. However, some poor repeatability values were found. These results can be due to either inaccurate between-session marker placement, soft tissue artefacts (especially in the case of the scapula) or limited marker visibility in certain movements. Moreover, there were more angles with poor repeatability when the movements were performed in the non-dominant UL, compared to when these same movements were performed by the dominant UL. This was noticed for all movements and likely reflects less dexterity in the non-dominant UL. There were few studies of repeatability assessment on anatomical movements to which we could compare our results; most of the studies reporting repeatability had done so on activities of daily living (Butler et al., 2010; Jaspers et al., 2011). Previous studies that had evaluated the repeatability on anatomical movements had only aimed to assess the reliability of scapular kinematics (Lee et al., 2013; Ludewig et al., 2009). In Ludewig's study, the inter-session repeatability of shoulder motion was assessed using invasive markers. While this eliminated the bias of soft tissue artefacts, it did not allow the subjects to reach maximal ROM. In Lee's study, a novel technique for marker placement based on ultrasonography was used, but the repeatability of only scapular motion was reported and the difference in repeatability between the dominant and non-dominant UL was not addressed. In our study, we reported the SEM (Table 1) for all ROM performed in all movements, in the three planes, for both dominant and non-dominant UL. The value of the SEM for each ROM could be used in future studies as a threshold in order to distinguish significant differences between ROM from non-significant ones (which could be due to measurement errors), especially when comparing the kinematics of subjects before and after treatment or to normative databases.

In general, the movements were similar when performed by either limb; the CMC varied from moderate to excellent for most of the angular waveforms, except in 5 instances where the CMC was poor. It should be noted that the poor CMC of the shoulder abduction-adduction angle during the movement of shoulder flexion-extension, scapular anterior-posterior tilt angle during the movement of shoulder horizontal abduction-adduction and shoulder flexion-extension angle during the movement of shoulder internal-external rotation are not to be interpreted since the CMC values are close to the threshold of moderate similarity (moderate CMC > 0.6), and since these angles had limited amplitudes during the movement.

The most important result of the differences between the dominant and non-dominant UL kinematics was the poor CMC (0.29) on the elbow pronation-supination angular waveform of the elbow flexion-extension movement, which is probably due to differing strategies of movement between the dominant and non-dominant UL: the dominant limb showed more pronation at the end of elbow flexion (middle of the movement cycle), while the non-dominant limb stayed in the neutral position throughout the whole movement cycle (Fig. 3).

Furthermore, the CMC of waveform differences between the dominant and non-dominant sides for the wrist flexion-extension angle during wrist pronation-supination movement was poor (0.4). This was probably due to a different global movement strategy. However, it should be noted that in both the dominant and non-dominant angular waveforms, the ROM of wrist flexion-extension was limited (Fig. 3).

All the significant differences found on the ROM comparisons between the dominant and non-dominant UL kinematics were related to scapular motion. While these results should be taken with caution because of the uncertainty of the biomechanical model used in this study to assess scapular kinematics (based on surface markers) and because of the small ROM performed by the scapula, other studies have reported similar findings. In Lee's study, when marker placement was based on ultrasound imaging, significant differences between dominant and non-dominant shoulders were only reported in the scapular anterior-posterior tilt angle during the shoulder abduction movement (Lee et al., 2013). These differences were even more important in Schwartz's study (Schwartz et al., 2014), in which 6 active infrared markers were placed on the scapula; the authors reported significant differences between dominant and non-dominant scapular motion in almost all planes during shoulder abduction and sagittal flexion movements. Matsuki et al. showed that different upward rotation angles were executed by the scapula between the dominant and non dominant UL during humeral abduction in the scapular plane (Matsuki et al., 2011). These findings could be related to different movement strategies of the scapula between the two UL.

In our study, all the other joints showed no significant differences in ROM, in any of the angles, between the dominant and non-dominant UL. Therefore, the extent of movement does not differ between the two limbs. To our knowledge, this is the first study that has compared the dominant and non-dominant UL kinematics of several anatomical movements in asymptomatic adults for the shoulder, the elbow and the wrist joints.

Moreover, the secondary angles of the UL joints, performed during anatomical movements, were reported along with the primary ones. Interestingly, relatively large secondary angles were registered during the execution of the anatomical movements. For example, during the movement of shoulder flexion-extension, a large ROM of internal-external rotation of the shoulder occurred (Table 2). This is probably due to the extent of hyper-flexion and hyper-extension of the shoulder, which might be associated with internal and external rotation of the shoulder, respectively (Fig. 2). During the movement of shoulder abduction-adduction, we found a ROM of 69° of internal-external rotation as a secondary angle. This is in accordance with clinical knowledge, which indicates that maximal abduction cannot be obtained without external rotation of the shoulder, in order to clear the greater tubercle from the acromion (Hurov, 2009; Peat, 1986). The results of shoulder angles during horizontal abduction-adduction should be taken with caution. The angle to be interpreted is shoulder horizontal abduction-adduction (with a ROM of 113° ± 12), which is the primary angle of this movement. The two remaining angles (shoulder internal-external rotation and shoulder abduction-adduction) could not be interpreted due to amplitude incoherence which could be a major disadvantage when using 3 consecutive rotations around mobile axes X,Z',Y'' (Phadke, Braman, LaPrade, & Ludewig, 2011; Senk & Cheze, 2006). During the movement of shoulder internal-external rotation, the main secondary angle was abduction-adduction with a relatively small ROM (23°). This was due to the unstable arm position, in 90° of abduction, during the execution of this movement. The elbow flexion-extension movement showed a secondary angle of pronation-supination (ROM = 40°) as the subjects tried to increase elbow flexion by pronating their forearms. Furthermore, when performing wrist pronation-supination, 52° of the total ROM was performed at the level of the elbow.

One of the limitations of this study was the scapular model used, which was based on surface markers located directly on palpable anatomical landmarks. This incurs measurement errors which are related to soft tissue artefacts during scapular motion. These artefacts could be reduced by using acromion marker clusters (van Andel, van Hutten, Eversdijk, Veeger, & Harlaar, 2009). Furthermore, transcortical pins could have also been used in order to track the motion of the scapula in a high degree of precision (Ludewig et al., 2009). The reported values in the current paper could be used as a reference for upper limb motion analysis exams performed in a usual clinical setting where surface markers are more commonly used.

Another limitation is the omission of shoulder movements (i.e. flexion-extension and abduction-adduction) in the scapular plane, 30 to 40° anteriorly to the coronal plane, since these movements are also used in the clinical examination of the shoulder joint. While it has been previously shown that the CMC is strongly related to number of subjects and test procedures (Roislien, Skare, Opheim, & Rennie, 2012), it was used in this study because of its simplicity of interpretation and popularity. The ROM was also compared in order to better evaluate the dominance-related differences.

5. Conclusions

In conclusion, this study described both primary and secondary kinematic angles of the dominant and non-dominant UL during anatomical movements. The ROM values reported in this study will serve as a reference during subsequent clinical evaluation of the kinematics of the UL in patients with neurological or orthopedic impairments.

The comparison between the dominant and non-dominant limbs showed almost identical results except for differing degrees of elbow pronation during the elbow flexion-extension movement and an apparent different strategy during the wrist pronation-supination movement, reflected by a difference in the pattern of the wrist flexion-extension angular waveform. Therefore, the comparison of a pathological limb to the controlateral healthy limb would not always be valid because of the bias of dominance in some of the joints during specific movements. Future studies should explore differences between dominant and non-dominant UL kinematics during activities of daily living.

Conflict of interest

None.

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