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Complete 3D kinematics of upper extremity functional tasks

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Abstract

Upper extremity (UX) movement analysis by means of 3D kinematics has the potential to become an important clinical evaluation method. However, no standardized protocol for clinical application has yet been developed, that includes the whole upper limb. Standardization problems include the lack of a single representative function, the wide range of motion of joints and the complexity of the anatomical structures. A useful protocol would focus on the functional status of the arm and particularly the orientation of the hand. The aim of this work was to develop a standardized measurement method for unconstrained movement analysis of the UX that includes hand orientation, for a set of functional tasks for the UX and obtain normative values. Ten healthy subjects performed four representative activities of daily living (ADL). In addition, six standard active range of motion (ROM) tasks were executed. Joint angles of the wrist, elbow, shoulder and scapula were analyzed throughout each ADL task and minimum/maximum angles were determined from the ROM tasks. Characteristic trajectories were found for the ADL tasks, standard deviations were generally small and ROM results were consistent with the literature. The results of this study could form the normative basis for the development of a 'UX analysis report' equivalent to the 'gait analysis report' and would allow for future comparisons with pediatric and/or pathologic movement patterns.

Keywords: 3D kinematics; Upper extremity; Hand orientation; ADL; Range of motion

1. Introduction

The development of clinical gait analysis is established in the treatment of clinical conditions affecting the lower extremities [1]. Likewise, analysis of upper extremity (UX) functions by means of 3D kinematics can potentially become an important tool in clinical decision making and outcome measure in patients with UX disorders.

Quantifying upper extremity dysfunction, as seen in orthopedic and neurological disorders, is technically complex because of the multi-joint structure. Interpretation is hindered by the variability of possible movements. Nevertheless, quantitative measurement of UX function in 3D is necessary to compare aberrant intersegmental coordination to normal task execution. This includes primary deviations as a consequence of the disease, i.e. loss of muscle control and/or power, and secondary consequences, i.e. compensatory movements [2]. Three-dimensional analysis would also be a first step in evaluating treatment effects.

Compared to gait analysis, motion analysis of the UX carries several disadvantages. First, there is no single most relevant functional activity for the UX. Several activities of daily living (ADL) have been suggested in the literature [3,4]. Recently it was attempted to implement functional tasks in clinical studies [5–8]. The variety of possible functional tasks complicates standardization procedures. Second, UX functional activities show a larger variation of execution in the normal population (as opposed to the

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stereotyped gait pattern) related to less stringent task accomplishment and the higher number of degrees of freedom in the UX. Third, the UX and especially the shoulder joint, has a very large working range, compared to the lower extremity. This causes measurement problems, including soft tissue artifacts. Finally, there are challenges in communicating the results of 3D movement analysis in a way that would be both biomechanically sound and informative to the clinician in order to support decision making.

The kinematics of the UX have been studied before [9]. Until recently, however, no systematic 3D quantitative function analysis procedure has been developed for the whole UX. Previous studies considered either shoulder/elbow motion [4,10,11] or elbow/hand motion (grasping) [12,13]. Hand positioning and orientation is a major determinant in the accomplishment of functional tasks, while the arm may be considered a positioning instrument for the hand. For example, if shoulder range of motion (ROM) is increased following a reconstructive procedure, functional gain will be absent when the hand is not able to use this extended ROM. Several methods have been suggested for movement analysis of the complete UX, i.e. hand, forearm, humerus and trunk motion [5–8,14]. Scapular movement, however, was neglected in these studies. Scapular movement is an essential component of arm elevation. It comprises a large compensation component in pathologies such as frozen shoulder [15], impingement [16], or glenohumeral joint replacement [10]. Non-invasive tracking of scapula motion by means of a scapula locator (a sensor mounted on a tripod, placed manually over the scapular bony landmarks) was the only efficient method for clinical measurement [4,10]. However, these measurements require a static position. Recently, the studies of Karduna et al. [17] and Meskers et al. [18] showed that tracking scapular motion by attaching a sensor on the acromion is valid for humerus elevation up to approximately 120°. This technique offers the possibility to perform dynamic measurements of scapula kinematics. A clinically useful method would require unconstrained measurement to minimize load and pain for patients and to allow for natural (including compensatory) movements. This applies especially to (young) children. The above studies [5–8,14] use different marker configurations, different definitions of segment and joint coordinate systems and rotation orders, and different sets of functional tasks. These differences complicate the comparison between studies and highlights the need for standardization. Recently, the International Society of Biomechanics (ISB) published recommendations on joint coordinate systems and rotation orders for the UX [19] which would lead to more comparable studies.

The purpose of this study was firstly to define a measurement method for the 3D kinematic analysis based on (a) a marker model that is clinically feasible; (b) follows the ISB standards for anatomical calibration of the marker model and (c) describes the complete UX anatomical chain: thorax–scapula–upper arm–lower arm–hand. Secondly, the aim was to describe the possible stereotype execution of a common set of functional tasks (norm values) as well as the normal variation in the adult population.

2. Materials and methods

2.1. Subjects

Ten healthy subjects, six male and four female (mean age 28.5 ± 5.7) with no upper extremity complaints voluntarily participated in the study. All subjects except one had a dominant right arm. All subjects signed an informed consent after being informed on the aims and procedures of the experiments.

2.2. Instrumentation

Movements of the UX were measured using stereophotogrammatic recording of active LED-markers using an Optotrak (Northern Digital Inc., Waterloo, Canada) system with three cameras. The accuracy of the system was 0.1 mm and all data were sampled at 50 Hz. Three marker clusters of three markers each were fixed on the thorax, acromion and hand using double-sided adhesive tape. A cuff with a cluster of three markers was strapped to the lateral upper arm just below the insertion of the deltoid. Another cuff with six equally distributed markers was used for tracking the forearm and was strapped just proximal to the ulnar and radial styloids (Fig. 1). The thorax cluster was attached to the sternum, the acromion cluster was attached on the flat part of the acromion and the hand cluster was placed on the dorsal surface of the hand. Before the study, we compared shoulder motion derived from the acromion marker with those measured with a scapula locator and found these to be similar (up to 120° elevation) with other validation studies [17,18]. To link the marker cluster positions to local anatomical coordinate systems, 19 bony landmarks (Table 1) were digitized using a standard pointer device. The proximal landmark of the humerus, the glenohumeral rotation center, was estimated by calculating the pivot point of instantaneous helical axes from abduction, anterior flexion and rotation of the humerus with respect to the thorax [20,21]. From the combination of local coordinate

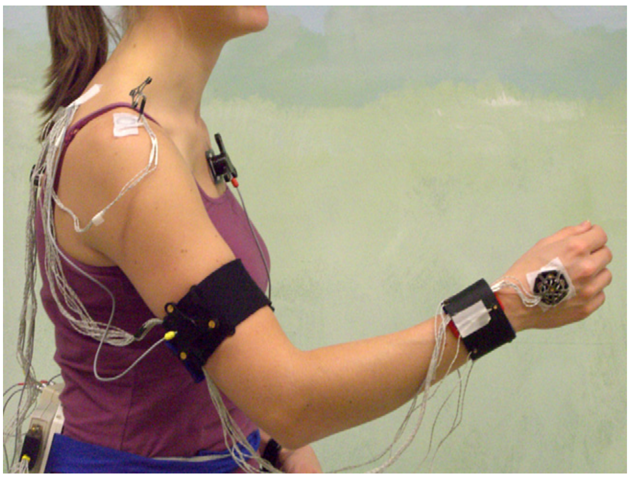

Fig. 1. Illustration of placement of the marker clusters.

Table 1
List of bony landmarks that were used to construct local anatomical coordinate systems

Bony landmarks	Description
Thorax	
C7: processus spinosus 7th cervical vertebra	Most dorsal point
T8: processus spinosus 8th thoracic vertebra	Most dorsal point
PX: processus xiphoideus	Most caudal point on the sternum
IJ: incisura jugularis	Deepest point of IJ (suprasternal notch)
Clavicula	
AC: acromioclavicular joint	Most dorsal point
SC: sternoclavicular joint	Most ventral point
Scapula	
AI: angulus inferior	Most caudal point of the scapula
AA: angulus acromialis	Most laterodorsal point of the scapula
PC: processus coracoideus	Most ventral point of the scapula
TS: trigonum spinae scapulae	Midpoint of the triangular surface on the medial border of the scapula in line with the scapular spine
Humerus	
GH: glenohumeral rotation center	Estimated by helical axis method [20,21]
EL: lateral epicondyle	Most caudal point on the EL
EM: medial epicondyle	Most caudal point on the EM
Forearm	
US: ulnar styloid	Most caudal and medial point on the US
RS: radial styloid	Most caudal and lateral point on the RS
Hand	
MC3: processus styloideus os metacarpal 3	Most dorsal point on dorsal side of the hand
MCP2: metacarpophalangeal 2	Distal head of MCP2
MCP3: metacarpophalangeal 3	Distal head of MCP3
MCP5: metacarpophalangeal 5	Distal head of MCP5

systems constructed from these anatomical landmarks and the marker cluster motions, global and relative orientations of segment coordinate systems and subsequently the approximated joint rotations were calculated. Local coordinate systems and segment rotations were defined according to the ISB standardization proposal for the upper extremity [19]. Following these recommendations, the second option for the definition of the humerus bone-embedded frame, based on the anatomical landmarks of the humerus and the forearm, was used. In this definition, the position of the landmarks is based on the upper arm cluster of markers through a specific static calibration trial. Therefore, during each given dynamic trial the pose of the humerus frame is entirely linked to the upper arm cluster and thus affected by similar soft tissue artifact to that of the cluster. This can result in an underestimation of the humerus axial rotation of about 35% [22]. The ISB definition of the humerus frame can, however, be slightly modified by taking the forearm orientation into account during each frame of the dynamic trial [12]. The ulnar and radial styloids are then continuously used for the measurement of humeral internal/external rotation and the humeral bone-embedded frame is totally independent of the rotation of the upper arm cluster around the long axis of the humerus.

2.3. Measurement procedure

All right upper extremities were measured and all tasks were performed three times. The subjects started with four tasks which represent a range of functional activities. The tasks were selected after extensive consultation with the clinical staff and based on earlier studies [4,5,9,23]. The tasks are similar to the tasks performed in the Mallet score which is commonly used for evaluation of shoulder function in patients with Obstetric Brachial Plexus Lesion [24]. In order to encourage consistent performance, subjects were asked to copy the movements of the instructor standing in front of them. The following tasks were completed:

1. *Hand to the contra lateral shoulder*. Subjects started with the arm in the anatomical position with their hand hanging beside their body in a relaxed and neutral position. The end point was reached when the hand touched the contra lateral shoulder. This task represents all activities near the contra lateral shoulder such as washing axilla or zip up a jacket.
2. *Hand to mouth/drinking*. In the starting position the hand was situated on the knee and a cup filled with water was held in the hand. The subjects were instructed to move the cup to their mouth and take a sip, after which the end position was reached. This task also represents activities such as eating and reaching the face.
3. *Combing hair*. Both the start and end positions were the anatomical position as described in task 1. Subjects were instructed to move their hand to the fore head, continue to move the hand over their head towards the neck (as if they were combing their hair) and then move the hand back to the anatomical (end) position. This task represents activities such as reaching the (back of the) head and washing hair.
4. *Hand to back pocket*. This task started with the hand in the anatomical position as in task 1. The end position was reached when the hand was placed on the back pocket. This task also represents reaching the back and perineal care.

In addition, six standard range of motion tasks were performed. These tasks were added to develop a complete ‘UX analysis report’ and it allows for future comparison in patients between their isolated active ROM and the actual amount of ROM used in the functional tasks. The subjects were instructed to actively reach their maximum joint angle during the tasks.

The following ROM tasks were completed:

1. wrist palmar flexion/dorsal flexion
2. forearm pronation/supination
3. elbow flexion/extension
4. internal/external rotation with 90° humerus abduction
5. anterior flexion/extension
6. abduction/adduction.

For wrist palmar/dorsal flexion and forearm pronation/supination, the subjects started with 90° of elbow flexion and the forearm maximally pronated. For the remaining tasks subjects started in the anatomical position.

2.4. Definitions of segment orientation and rotation

In this study the motions of the hand, forearm, humerus, scapula and thorax were taken into account. Segment angles were defined based on the ISB standardization proposal of the International Shoulder Group [19]. The rotation order for the hand was 'flexion/extension'–'radial/ulnar deviation'–'pronation/supination'. The rotation order for the forearm was 'flexion/extension'–'ab/adduction (carrying angle)'–'pronation/supination'.

Humerus rotations are presented as thoracohumeral motion which would be clinically meaningful. The difference between thoracohumeral and scapular motion represents glenohumeral motion. Thoracohumeral motion was described according to the globe system [25,26]: 'plane of elevation'–'elevation'–'internal/external rotation'. For the scapula the order was 'pro/retraction'–'lateral/medial rotation'–'anterior/posterior tilt'. According to the ISB definitions, scapular lateral rotation and humeral elevation would have negative values. However, we reported these angles as positive which is clinically meaningful. Motions of the thorax relative to the global coordinate system were 'flexion/extension'–'lateral flexion'–'axial rotation'.

2.5. Data analysis

All tasks were performed three times in succession and the second one was used for further analysis to make sure that the task was completed from starting to end point. Time of each movement was normalized (0–100%) to facilitate comparison. This also allows for future comparison with patient data. BodyMech (www.bodymech.nl), a Matlab based open source package for 3D kinematic analysis was adapted and used. The following clinically relevant angles were chosen to be presented here (the complete dataset is provided as online material): wrist palmar (+) and dorsal flexion (−), pronation (+), elbow flexion (+), humeral internal (+) and external rotation (−), humeral elevation (+) and scapula lateral rotation (+). From the ROM tasks only the maximum and minimum angles were used.

3. Results

3.1. Activities of daily living

The trajectories of the ADL tasks are presented in Figs. 2–5 by means of the average segment angles ± S.D. during the movement from the start to the endpoint of the task.

1. *Hand to contra lateral shoulder* (Fig. 2, Figure 7 provided online). The increase in elbow flexion and humerus elevation during this task was to be expected. S.D.s were reasonably constant during the task, except for the humerus rotation at the beginning of the task. Humerus internal rotation was observed towards the task endpoint. Pronation decreased when the hand was moving towards the shoulder and wrist flexion did not change significantly.
2. *Hand to mouth/drinking* (Fig. 3, Figure 8 provided online). The end points of this task were similar to the previous one. Wrist flexion and extension were more pronounced during taking a sip from the cup. Initial elbow flexion was increased due to the starting position with the hand on the lap.
3. *Combing hair* (Fig. 4, Figure 9 provided online). Large S.D.s appeared in wrist flexion and pronation starting halfway during the task; this occured approximately when the hand was on the head. Instructions were given for the first part of the trajectory, i.e. move the hand to the

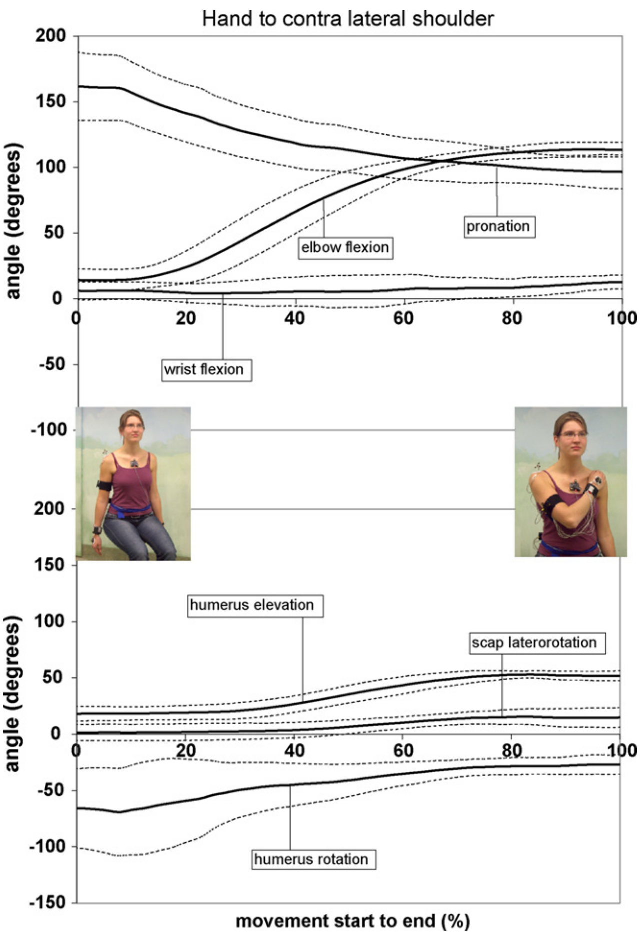

Fig. 2. Average segment angles (solid lines) ± S.D. (dashed lines) during the functional task 'hand to contra lateral shoulder'.

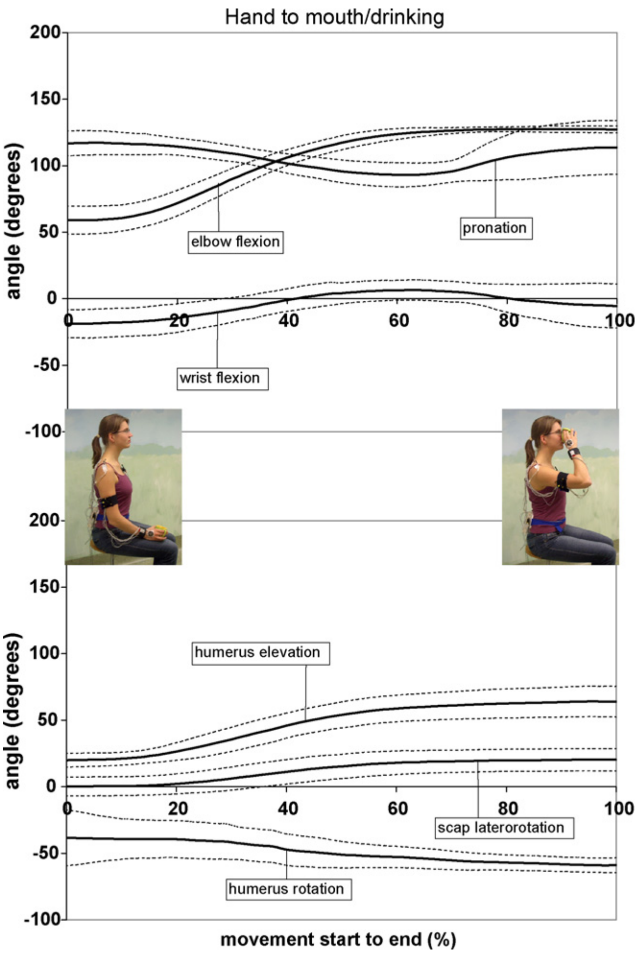

Fig. 3. Average segment angles (solid lines) ± S.D. (dashed lines) during the functional task ‘hand to mouth/drinking’.

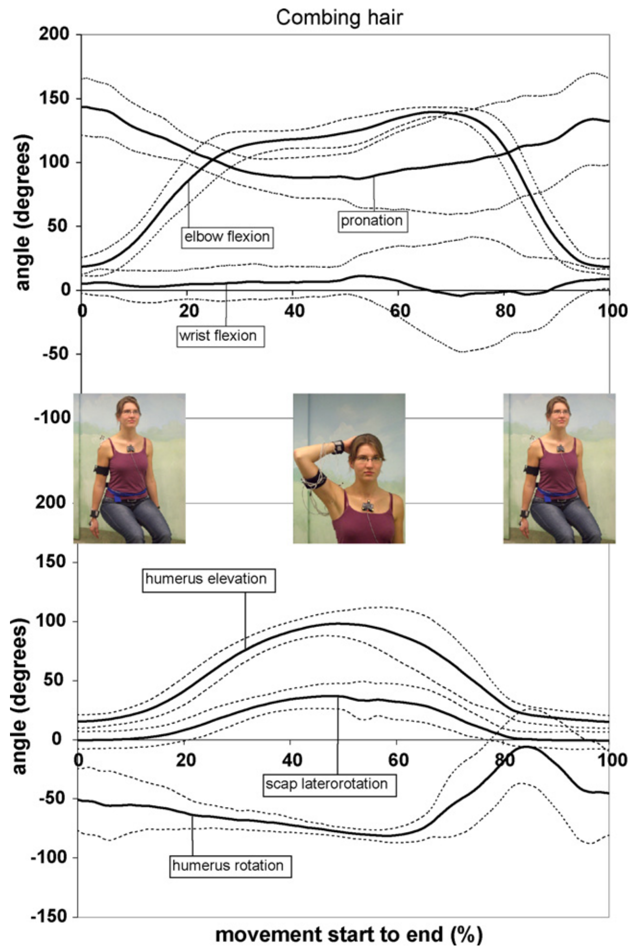

Fig. 4. Average segment angles (solid lines) ± S.D. (dashed lines) during the functional task ‘combing hair’.

top of the head. It is likely that subjects used different strategies when moving the arm from the head back to the anatomical position. When the elbow was stretched near the end of the task, the humerus rotation showed a peak.

4. *Hand to back pocket* (Fig. 5, Figure 10 provided online). Large humerus internal rotation was shown in completing this task. A large decrease in pronation was also present.

3.2. Range of motion

The mean results of the ROM are given in Fig. 6. Peak wrist palmar flexion was $66 \pm 8^\circ$ and dorsal flexion was $-64 \pm 6^\circ$. Forearm pronation reached $161 \pm 16^\circ$, keeping in mind that the anatomical position is close to the alignment of the anatomical coordinate systems and therefore that is defined as a pronation of 0°. Maximum elbow flexion was $143 \pm 5^\circ$. Humeral internal rotation reached $60 \pm 9^\circ$ and peak external rotation was $-89 \pm 13^\circ$.

Maximum humeral elevation during anterior flexion ($138 \pm 9^\circ$) and abduction ($133 \pm 9^\circ$) were very close. Maximum scapula lateral rotation during anterior flexion also appeared to be close to values observed during abduction ($51 \pm 12^\circ$ versus $55 \pm 14^\circ$).

4. Discussion

The developed measurement procedure was technically feasible for healthy adults. ROMs of shoulder, elbow and wrist were comparable with earlier results [4,10,27,28]. The joint angles during the functional tasks show that the subjects use similar trajectories to reach the end goal of the task, i.e. the norm values of the task can be determined. Some variation, however, was detected.

4.1. Hand to contra lateral shoulder

The variation of humerus rotation is much larger at the beginning of the task, this phenomenon is also seen in combing hair and moving the hand to the back pocket. In these starting positions, the ‘‘gimbal lock’’ effect occurs. In the chosen Euler decomposition order, gimbal lock occurs when humerus elevation is 0° or 180°. Near these positions, the interaction between ‘‘plane of elevation’’ (first rotation) and ‘‘axial rotation’’ (third rotation), sometimes leads to apparently extreme results. Another possible source of variation in humerus rotation may be due to the use of the forearm orientation to construct the humerus anatomical

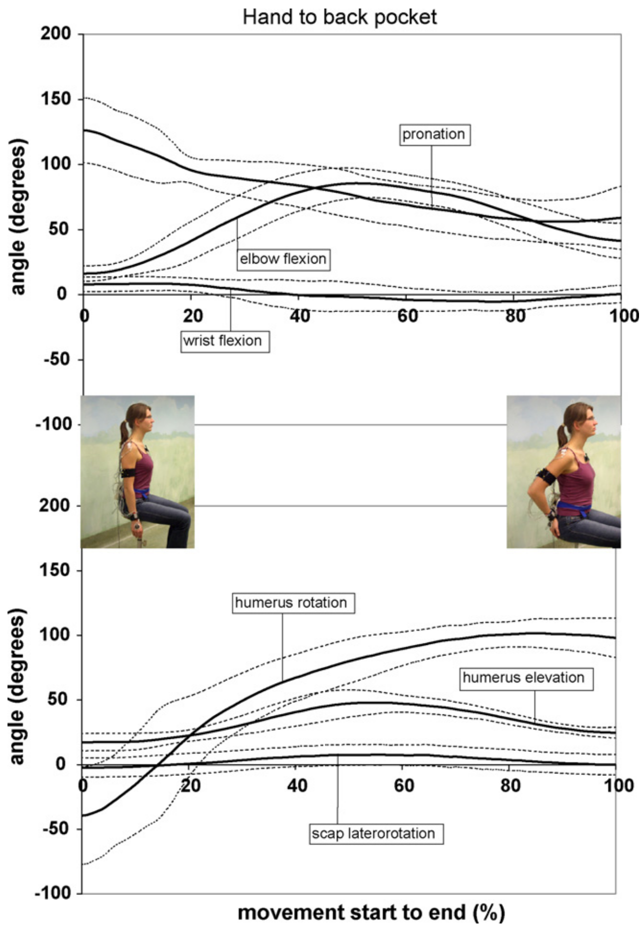

Fig. 5. Average segment angles (solid lines) ± S.D. (dashed lines) during the functional task ‘hand to back pocket’.

coordinate system, in order to compensate for soft tissue artifacts. The starting position of these tasks is the anatomical position when the elbow is almost fully extended; the lack of any significant elbow flexion makes it difficult to reconstruct the forearm orientation with respect to the humerus, as the longitudinal axes of the humerus and forearm are nearly aligned. There is no consensus in the literature about the minimum amount of elbow flexion needed for correct calculation of the humerus internal/external rotation: this varies from 15° [12] to 40° [22]. Another drawback of using the forearm orientation for construction of the humerus anatomical coordinate system is the kinematic coupling with the elbow. The real axes of elbow flexion/extension and forearm pronation/supination are not generally aligned with the landmark based local coordinate systems. A pure elbow flexion/extension or pure pronation/supination movement may generate apparent variations in humeral axial rotations that are not related to real axial rotations [22]. The ISB recommendation modified according to Schmidt et al. [12] used in our analysis makes the measures of humeral internal/external rotations essentially ‘artifact free’. However, further improvements are necessary. Cutti et al. [29] recently published a new technique that compensates for the kinematic coupling with the elbow which reduces soft tissue artifact that affects axial rotation of the upper arm. This technique appears to work best when compensating for apparent variations in humeral axial rotation during flexion/extension trials. They reported that improvements are still needed to obtain good results for the pure pronation/supination trials. Determining the elbow flexion-extension and pronation/supination axes by means of helical axes may also reduce soft tissue artifacts in humeral rotation [30].

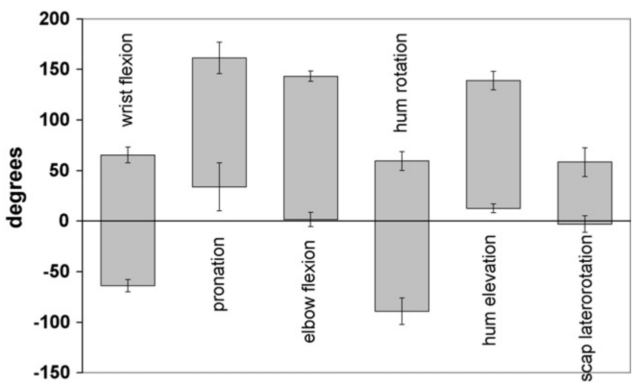

Fig. 6. Average values of ROM tasks ± S.D.

4.2. Hand to mouth/drinking

The variation in pronation and wrist flexion increases near the end of the task, possibly due to differences in drinking technique. Drinking from the cup was achieved by using either more pronation or more wrist dorsal flexion.

4.3. Combing hair

There were large S.D.s seen in wrist flexion and pronation after approximately 50% of the movement time. It is likely that, despite instructions, the subjects used different strategies when moving the arm from the head back to the anatomical position. The peak in humerus rotation near the end of the task may be explained by the arm movement when the hand moves from the back of the head via the front of the trunk back to the starting position. At maximum humeral elevation, the mean elbow flexion was 122° and the mean pronation 89°. This is in agreement with results of Magermans et al. [4], who found an average of 136° elbow flexion and 100° pronation in the same task. Morrey et al. [27] reported for a ‘combing hair position’ (hand on occiput) a mean elbow flexion of 144° and a pronation of 88°.

4.4. Hand to back pocket

This task required a sufficient amount of humeral internal rotation while the other tasks required only external rotation. This is a clinically relevant issue: focusing treatment on restoring external rotation which is a requirement for most ADL, may be at the expense of internal rotation which would have serious implications for the patients' personal care and therefore their independency. The pronation at the start of this task is smaller than at 'hand to contralateral shoulder' and 'combing hair', despite similar start positions. This may be task related, since this task requires a supinating movement, while the other two tasks require a pronating movement. While moving the hand from the back pocket towards the starting position, subjects showed an 'anticipatory supination'.

The ADL results also show that an elbow flexion of at least 85° or more is used for all functional tasks. Furthermore, wrist palmar and dorsal flexions are relatively small which suggests that a 'neutral' wrist position would be most favorable for functional tasks. The humerus reaches nearly 100° of elevation in the hair combing task, but during the other tasks it stays below 70°. Using a cluster of markers on the acromion to represent the movements of the scapula is, therefore, justified, as this method is valid until approximately 120° of elevation [17]. Pronation/supination showed variation during both the functional and the ROM tasks. Improvements for the determination of the pronation/supination axis will be considered in future work. A possible solution to this problem is to use the helical axis method for determining the real pronation/supination axis of the forearm. The zero degree angle for the pronation/supination ROM task may be better defined by using a different starting position for the pronation/supination task, e.g. upper arm hanging beside thorax, 90° elbow flexion and the forearm in a neutral position (thumbs pointing upwards). This position is also more likely to be manageable for patients.

Day-to-day variability and trial-to-trial variability were not considered in this study. Since all subjects were young and healthy, the day-to-day variability was assumed to be a minor issue. The trial-to-trial variability was not calculated because the emphasis of this study was placed on the technical challenge to measure and report movement trajectories of the UX during functional tasks, not only the point of task achievement. However, for future clinical applications, both day-to-day and trial-to-trial variability needs to be considered.

In this study, all subjects were young and had no shoulder complaints, therefore it was assumed their passive ROM would not be much different from their active ROM. Patient active and passive ROM may, however, be different. This is also important to consider in future work.

As mentioned in the introduction, the fact that previous studies did not use ISB standards makes comparison of results difficult. The recently published study by Petuskey et al. [8] acknowledged the need for common definitions and standardized terminology. The basic principle of both studies is comparable: to create a standardized protocol for quantitative UX motion analysis. Moreover, Petuskey et al. [8] provided a normative pediatric database of 3D kinematic values during selected ADLs. Their selection of simulated ADLs was somewhat different to ours or other studies [5–7,28]. This emphasizes the need for standardized functional tasks. Because of the similarity between the tasks 'hand to contra lateral shoulder' and 'hand to mouth/drinking' in the present study, we consider to replace the task 'hand to contra lateral shoulder' with the task 'high reach' [5,8] in future work.

Presentation of data for clinical use is challenging, especially with respect to the shoulder joint. The globographic definition 'plane of elevation', 'elevation angle', 'rotation angle' is not in accordance with clinical definitions. Clinicians measure shoulder motion in one of the three orthogonal planes (sagittal, frontal or transversal) or around the longitudinal axis (rotation). However, this method is limited in unambiguously describing shoulder positions outside of these planes, as is the case for almost all daily functional movements of the arm. These different perceptions may create confusion in communicating results of 3D motion analysis. A few studies showed that 3D shoulder movements during functional tasks could be presented in a globe system which is easily interpretable for clinicians [25,26,31], though this method can not be easily extended to the elbow and wrist. Klopcar et al. [32] measured the position of the wrist in a 3D space with passive arm movements and implemented this in a kinematic model which calculates the arm reachable workspace. Although, this resulted in a graphically powerful description tool, it would not be appropriate for our aims since the position of the hand was not taken into account and the procedure could not be easily extended with this additional constraint. In order to avoid misinterpretation, graphical presentations and animations should be part of reporting results of 3D motion analysis, especially when these results are communicated to clinicians. In the present study, results of segment angles during the functional tasks were presented in graphs from starting to endpoint of the tasks. This allows for intersegmental comparison during the execution of the complete task, not only at the endpoint of the task. Together with the standardized method, using the ISB guidelines, future studies on children and/or patients with UX pathology may use this standardized protocol to compare and evaluate their kinematic data. In conclusion, this method defines a basis for a clinical 'UX analysis report'.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2007.03.002.

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