SHOULDER DATABASE

Version 1.1

1. Introduction

For research into subject-specific musculoskeletal modelling of the shoulder, functional and image data were collected on five healthy subjects. The data have been used for two publications (Bolsterlee et al., 2014). We would like to encourage others to use this dataset by making some of these data publicly available. This document describes the measurement protocol, data processing procedures and the format in which the data can be downloaded. For any further questions regarding the data, please contact Bart Bolsterlee (b.bolsterlee@neura.edu.au).

2. Types of measurements

Data were collected of five healthy, young adults. Some general information of the subjects (age, weight, height, etc.) is presented in Table 1 (definitions for the dimensions are given in Table 2). None of the subjects had any prior shoulder complaints or was specifically trained. Table 1 also contains muscle volumes that were derived by manually outlining muscle boundaries on MRI scans of the subjects.

2.1 Motion capture

An Optotrak system (Northern Digital, Inc., Waterloo, Ontario, Canada) with four units was used to collect marker positions of six clusters of (skin-fixed) markers on thorax, scapula, humerus, forearm and hand of the subject and to a scapula-locator (Figure 1). The marker locations were measured at 100 *Hz*. Prior to the dynamic measurements, the bony landmarks as recommended by the ISB (Wu et al., 2005) were palpated with a motion capture stylus to obtain the location of these landmarks with respect to the segment cluster. This allowed for reconstructing the location of these anatomical landmarks based on the location of the marker clusters. A list of landmarks and definitions is presented in Table 3. In addition to palpable landmarks, the location of the glenohumeral (GH) joint centre was determined using the instantaneous helical axis method (Nikooyan et al., 2011).

Matlab MAT-files containing the following kinematic data can be downloaded which contain the following information:

1. The location of bony landmarks, as reconstructed from the segment cluster locations and static palpation trials (Table 3). To follow ISB guidelines proposed by Wu and Cavanagh (1995) , the data were transformed such that the y-coordinate is pointing upwards.
2. Bone orientation angles according to the ISB convention (Wu et al., 2005). These angles were calculated by first creating local coordinate systems based on the landmark locations and then decomposing the rotation matrices into the Euler-sequence proposed by the ISB for the specified bone (Table 4).

2.2 Electromyography

EMG data were collected of the following muscles using surfing electrodes (Ambu N-00-S ECG) and a 16-channel Porti system (TMS International, Enschede, The Netherlands, sampling frequency of 1000 Hz). Electrode placement was performed according to SENIAM recommendations (http://www.seniam.org).

- M. Trapezius ascendens
- M. Trapezius transversalis
- M. Trapezius descendens
- M. Deltoideus anterior
- M. Deltoideus medialis
- M. Deltoideus posterior
- M. Pectoralis major, clavicular part
- M. Pectoralis major, sternal part
- M. Biceps caput breve
- M. Triceps medial part
- M. Brachioradialis
- M. Infraspinatus
- M. Latissimus dorsi
- M. Triceps caput longum

2.3 External forces

Each subject was instructed to exert maximum force in six different directions on a handle that was gripped by the right hand, while standing with the elbow 90° flexed (Figure 2). Forces and moments exerted on the handle were measured in three perpendicular directions (sample frequency 1000Hz)

a) b)

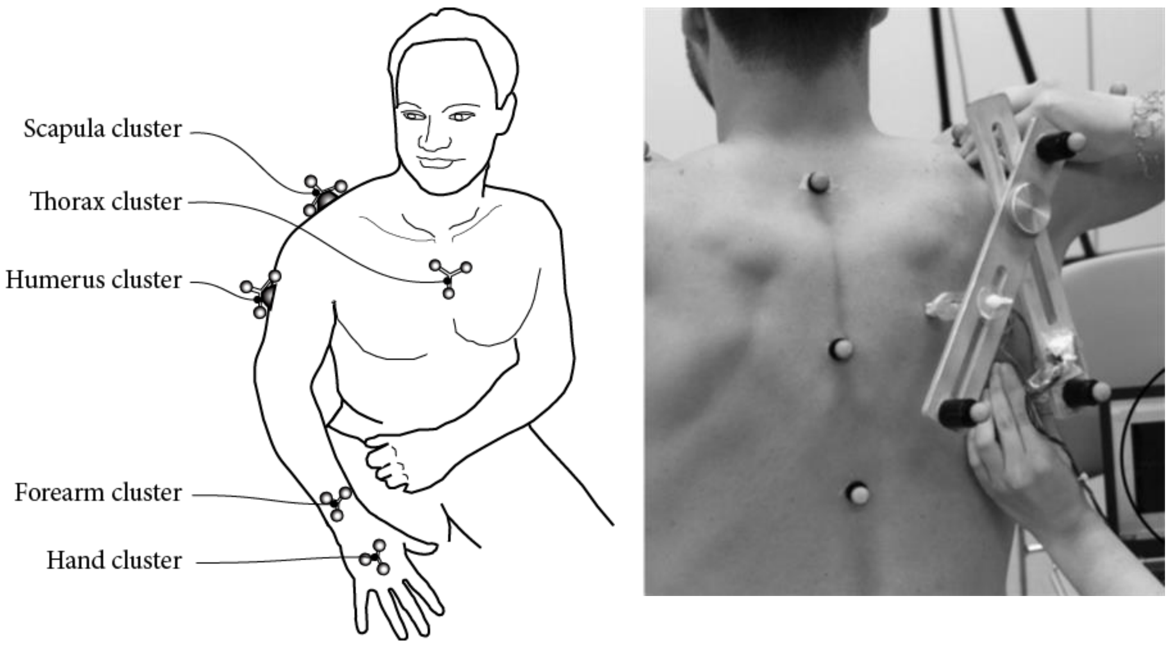

Figure 1 a) Placement of clusters of Optotrak markers. b) The scapula locator. The scapula locator is a triangular framework with three screws on each end, which are placed on three bony landmarks of the scapula (picture from Karduna et al. (2001), but a similar device was used for our measurements).

with a six-DOF force transducer (SRMC3A, Advance Mechanical Technology Inc., USA) that was connected to the handle. Before the measurements, the force transducer was calibrated (conversion of voltage output to forces/moments) and all data are presented as forces and moments.

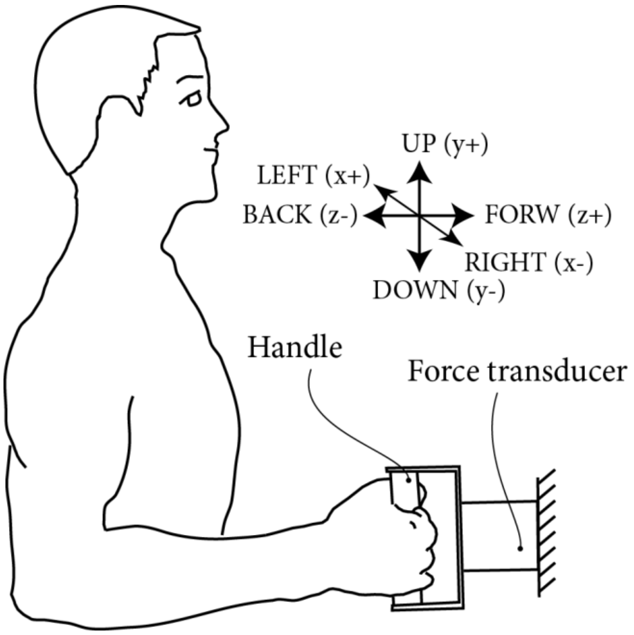

Figure 2 Schematic representation of the experimental setup for the force tasks.

3. Measurement tasks

Measurements were done while the subjects performed the following tasks (see also Table 5):

1. **Range of motion tasks** such as shoulder abduction and anteflexion where the subject is instructed how to perform the movement (see also Table 6)
    - Shoulder anteflexion (FLEX)
    - Shoulder abduction (ABD)
    - Shoulder scaption (SCAP)
    - Endo/exorotation (ENDO)
    - Elbow flexion (ELBOW)
    - Forearm pro/supination (PROSUP)
    - The movements was sometimes performed at two speeds: SLOW and FAST. The exact speed of the movement can be derived from the data.
2. **Activities of daily living** where the subject is free to choose how to perform these movements. The subject was asked to make the movement he/she would make if he/she were to:
    - comb his/her hair (COMB)
    - eat a cup of soup (EAT)
    - lift a box (2.5kg) on a shelf at maximum reaching height (LIFT)
    - wipe his/her bottom (perineal care - PERI)
    - wash his/her opposite axilla (WASH)
3. **Force tasks** that assess the maximum force generation in six different directions on a handle that is gripped by the right hand. Each subject was instructed to exert maximum force in six different directions on a handle that was gripped by the right hand, while standing with the elbow 90° flexed (Figure 2). Contact between thorax and elbow was avoided. Subjects were instructed to gradually build up force (within a few seconds) and then maintain their maximum for approximately three seconds. The order of force exertion was: upwards (UP), downwards (DOWN), forwards (FORW), backwards (BACK), to the left (LEFT) and to the right (RIGHT). Ten seconds rest was given between subsequent directions. After three minutes rest this procedure was repeated. No feedback on force magnitude or direction was given. Forces and moments exerted on the handle were measured in three perpendicular directions
4. **Maximal voluntary contractions** where the subject was instructed to contract their muscles maximally during the tasks suggested by Boettcher et al. (2008). In addition to these tests, a maximal elbow flexion and extension test with the elbow in 90° flexion are performed for inducing maximal activation in the major muscles crossing the elbow joint. EMG recordings during the MVC trials can be used for scaling EMG levels to provide an inter-subject standardised reference level. See Table 6 for an overview of the tasks.

The measurements that were done per task

Task	Motion capture	EMG	Force transducer
MVC	No	Yes	No
Force	No*	Yes	Yes
RoM	Yes	Yes	No
ADL	Yes	Yes	No

* The force tasks were executed isometrically, and the (very small) movements during the tasks were not recorded, because the force measurement setup was outside the field of view of the Optotrak cameras. We do however have kinematic data of the subjects in a similar position as the force tasks were performed in, but without executing force or holding a handle.

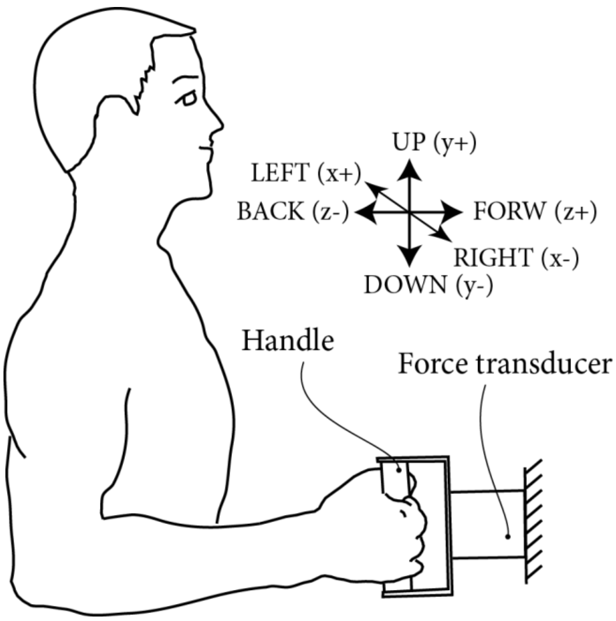

Figure 2 Experimental setup for the force tasks.

4. Data format

4.1 Kinematics

The kinematic data are stored in the folder ‘Kinematics’. There are two subfolder, one containing the data for the range of motion tasks (RoM) and one for the activities of daily living (ADL). These folders contain MAT-files for all tasks and subjects, named as follows:

S#_*taskname*.mat

with # the subject number and ‘taskname’ the name of the task. For example, the file S3_ABDFAST1.mat contains the data from a fast abduction movement of subject 3.

By opening the MAT-file in Matlab (for example using the *load(filename)* command), the following variables are loaded into the workspace:

- **Landmarks**: a *3 × (# of landmarks) × (# of frames)* matrix containing the x, y and z-coordinate (1st dimension) of all landmarks (2nd dimension) for each motion capture frame.
- **Landmarks_Names**: List of landmark names (see Table 3) which correspond to the 2nd dimension of the ‘Landmarks’-matrix
- **SegmRot**: 17 × *(# of frames)* matrix containing the bone rotations described in Table 4 for each motion capture frame.
- **SegmRot_Names**: List of rotation names (Table 4) corresponding to the columns in matrix ‘SegmRot’
- **Events**: a *n × 2* matrix in which the element numbers represent the motion capture frames where the subjects were in the start positions (1st columns) and end positions (2nd column) as described in Table 5. These frame numbers can be used to cut out the relevant portions of the data. A datafile can contain more than one execution of the same movement; each row in ‘Events’ corresponds to one movement.

The kinematics data can be viewed using the Matlab-based ‘DataViewer’.

4.2 EMG

The EMG data are stored in the folder ‘EMG’ and are put in subfolder ‘RoM’for the range of motion tasks, ‘ADL’ for the activities of daily living, ‘Force’for the maximum force tasks and ‘MVC’for the maximum voluntary contractions. The files are named the same as the corresponding kinematics data, except for that ‘_emg’ is added to the filename. By opening one of the MAT-files in Matlab (for example using the *load(filename)* command), the following variables are loaded into the workspace:

- **EMG_raw**: *(# of samples) × 17*-matrix with the raw, unfiltered EMG data. Column 1-14 represent the EMG signals, 15-16 are unused and column 17 contains the synchronisation pulse. The EMG data acquisition was always started prior to starting the motion capture measurements. At the time-frame in the EMG-data that the motion capture was started, the synchronisation signal switches from a values of 256 to 257, and returns to 256 when the Optotrak was switched off. See also *example.m* for how to use this signal to cut out the relevant portion of data.

- **EMG_Names**: List of muscle names of which the EMG signal was recorded. The numbering corresponds to the columns in the matrix ‘EMG_raw’.
- **samplefreq**: the sample frequency of the EMG signal in Hz (usually 1000 Hz)

The subfolder ‘MVC’ contains all the data for the maximum voluntary contraction tasks. See Table 6 for a description of the tasks and abbreviations.

In the folder ‘EMG’ there are five excel-files named ‘WrongSignals_S#.xls’ (with # the subject number). These files contain the sample numbers of the part of the signal that is deemed unrealistic after visual inspection and should be excluded when calculating maximum EMG values. For example, in S1_WrongSignals.xls you’ll see that samples 56400 until 56850 from the EMG signal stored in file ‘S1_Force2.mat’ should be excluded. A 0 means that the whole signal for that muscle and task is unreliable. The EMG for the RoM and ADL tasks have not been inspected yet.

4.3 External forces

The data for the maximum force tasks are stored in the folder ‘ExtForce’. By opening a MAT-file, a *(# of samples)* × *6*-matrix is loaded into the Matlab workspace. The first three columns contain the forces in *N* in x, y and z-direction on the handle (x+ = force to the left, y+ = upwards force , z+ = forwards force, see also Figure 2), the last three columns the moments around the x-, y- and z-axis in *Nm*. The sample frequency was 1000 Hz. For each subjects, two data-files are available corresponding to the first and second trial (each series of maximum forces was performed twice).

4.4 Matlab-scripts

Some useful Matlab-scripts and an example file on how to load, view and manipulate the data are attached to the dataset in the subfolder ‘matlab_scripts’.

5. Versions and changes

Version	Description of changes wrt previous version
1.0	First version containing all force, EMG and kinematic data.
1.1	1) The starting rotation of the thorax was not correctly set to 0° axial rotation in some of the trials. This has been corrected. 2) Some data was stored twice with slightly different filenames. The duplicates are removed now.

References

Boettcher, C.E., Ginn, K.A., Cathers, I., 2008. Standard maximum isometric voluntary contraction tests for normalizing shoulder muscle EMG. Journal of Orthopaedic Research 26, 1591-1597.

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Karduna, A.R., McClure, P.W., Michener, L.A., Sennett, B., 2001. Dynamic Measurements of Three-Dimensional Scapular Kinematics: A Validation Study. Journal of Biomechanical Engineering 123, 184-190.

Nikooyan, A.A., van der Helm, F.C.T., Westerhoff, P., Graichen, F., Bergmann, G., Veeger, H.E.J., 2011. Comparison of two methods for <italic>in vivo</italic> estimation of the glenohumeral joint rotation center (GH-JRC) of the patients with shoulder hemiarthroplasty. PLoS ONE 6, e18488.

Wu, G., Cavanagh, P.R., 1995. ISB recommendations for standardization in the reporting of kinematic data. Journal of Biomechanics 28, 1257-1261.

Wu, G., van der Helm, F.C.T., Veeger, H.E.J., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., Buchholz, B., 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion--Part II: shoulder, elbow, wrist and hand. Journal of Biomechanics 38, 981-992.

Tables

Table 1 Anthropometric measurements: values

	S1	**S2**	**S3**	**S4**	**S5**
Gender	Male	Female	Female	Male	Male
Age (yr)	29	29	27	33	28
BL (cm)	186	168	171	180	176.5
BW (kg)	109	60	79	68.5	81
HEADC (cm)	58	55	97	55	57.5
HEADL (cm)	18	16	16	15	16
CHSTC (cm)	108	83	100	94	101
WASTC (cm)	111	77	92	76	85
ACRDL (cm)	-	33	95	37	37.5
AXARC (cm)	41	31	36	38.5	41
BICPC (cm)	33	27	32	31.5	31
ELBOC (cm)	32.5	26	28	31.5	31
RDSTL (cm)	-	26	6.5	30	27
WRSTC (cm)	18	16	15.5	16	18
FARMC (cm)	29	24	25.5	29	30
STMCL (cm)	-	8.4	11	11	10
HANDC (cm)	21.5	18	19	21	22
HANDB (cm)	5.7	6.5	9	10	10
Muscle volumes in cm^3					
Biceps	193.8	86.2	128.1	209.5	259.2
Brachialis	138.0	87.8	102.0	206.3	127.5
Coracobrachialis	44.3	29.4	36.8	53.3	68.0
Deltoideus	470.2	229.6	301.0	479.1	514.5
Infraspinatus	149.6	78.8	94.7	198.2	182.7
Pectoralis major	322.7	187.2	224.0	470.8	379.2
Pectoralis minor	61.9	27.3	38.7	48.4	81.9
Rhomboideus	102.6	45.9	52.1	91.7	104.6
Subscapularis	211.9	102.5	143.1	226.9	240.5
Supraspinatus	61.4	41.7	37.0	65.1	65.8
Teres major	148.3	79.8	81.9	215.4	158.3
Teres minor	39.7	22.7	24.0	41.5	34.6

Trapezius	239.4	113.8	180.5	249.5	275.8
Triceps	453.3	238.2	311.7	580.3	569.5
Total muscle volume	2637.0	1370.8	1755.6	3136.0	3062.1

Table 2 Anthropometric measurements: description

Abbrevation*	**Name**	**Description**
BH	Body height	
BW	Body weight	
HEADC	Head circumference	With the tape passing above the brow ridges and parallel to the Frankfort plane (relative), measure the maximum circumference of the head.
HEADL	Head length	Using spreading calipers, measure the maximum horizontal breadth of the head.
CHSTC	Chest circumference	With a tape passing over the nipples and perpendicular to the long axis of the trunk, measure the circumference of the chest.
WASTC	Waist circumference	With a tape passing over the umbilicus and perpendicular to the long axis of the trunk, measure the circumference of the waist.
ACRDL	Acromion-radiale length	Acromion-Radiale Length: With a beam caliper, measure the distance along the long axis of the upper arm between the acromion and radiale landmarks.
AXARC	Arm circumference, axillary	With a tape perpendicular to the long axis of the upper arm and passing just below the lowest point of the axilla, measure the circumference of the upper arm.
BICPC	Biceps circumference	With a tape perpendicular to the long axis of the upper arm, measure the circumference of the upper arm at the level of the maximum anterior prominence of the biceps brachii.
sELBOC	Elbow circumference	The elbows of the cadaver were flexed to about 125°. With a tape passing over the olecranon process of the ulna and into the crease of the elbow, measure the circumference of the elbow.
RDSTL	Radiale-stylion length	With a beam caliper parallel to the long axis of the forearm, measure the distance between radiale and the stylion landmark.
WRSTC	Wrist circumference	With a tape perpendicular to the long axis of the forearm, measure the minimum circumference of the wrist proximal to the radial and ulnar styloid processes.
FARMC	Forearm circumference	With a tape perpendicular to the long axis of the forearm, measure the maximum circumference of the forearm.
STMCL	Stylion-metacarpale III length	With a sliding caliper parallel to the forearm-hand axis, measure the distance between the stylion and metacarpale III landmarks.
HANDC	Hand circumference	With a tape passing around the metacarpalphalangeal joints, measure the circumference of the hand.
HANDB	Hand breadth	With a sliding caliper, measure the breadth of the hand across the distal ends of metacarpus II and V.

Table 3 Bony landmark description

Name	**Full name**	**Description**	**Segment**
IJ	Incisura Jugularis	Deepest point of Incisura Jugularis (suprasternal notch)	Thorax
PX	Processus Xiphoideus	Most caudal point on the sternum	Thorax
C7	7th cervical vertebra	Processus Spinosus (spinous process) of the 7th cervical vertebra	Thorax
T8	8th thoracal vertebra	Processus Spinosus (spinal process) of the 8th thoracic vertebra	Thorax
SC	Sternoclavicular joint	Most ventral point on the sternoclavicular joint	Clavicle
ACv	Acromioclavicular joint	Most ventral point on the acromioclavicular joint (shared with the scapula)	Scapula
AA	Angulus Acromialis	Most laterodorsal point of the scapula	Scapula
TS	Trigonum Spinae	The midpoint of the triangular surface on the medial border of the scapula in line with the scapular spine	Scapula
AI	Angulus Inferior	Most caudal point of the scapula	Scapula
PC	Processus Coracoideus	Most ventral point of processus coracoideus	Scapula
ACd	Acromioclavicular joint	Most dorsal point on the acromioclavicular joint (shared with the scapula)	Scapula
BL	Full name	Description	Segment
EM	Epicondylus Medialis	Most caudal point on lateral epicondyle	Humerus
EL	Epicondylus Lateralis	Most caudal point on medial epicondyle	Humerus
RS	Styloideus Radialis	Most caudal–lateral point on the radial styloid	Forearm
US	Styloideus Ulnaris	Most caudal–medial point on the ulnar styloid	Forearm
MCP2	Epicondylus Medialis (EM)	Most proximal lateral point on the MCP-II joint	Hand
MCP5	Epicondylus Lateralis (EL)	Most proximal lateral point on the MCP-V joint	Hand
SCREWAA	Scapulalocator screw AA	Tip of the screw on the scapulalocator coinciding with AA	Scapula
SCREWTS	Scapulalocator screw TS	Tip of the screw on the scapulalocator coinciding with TS	Scapula
SCREWAI	Scapulalocator screw AI	Tip of the screw on the scapulalocator coinciding with AI	Scapula

Table 4 Segment rotation descriptions

Name in excel	Description
ThorZ	Thoracic flexion (negative) or extension (positive) wrt global coordinate system
ThorX	Thoracic lateral flexion rotation of the thorax to the right (positive) or left (negative) wrt global coordinate system
ThorY	Thoracic axial rotation to the left (positive) or to the right (negative) wrt global coordinate system
ClavY	Clavicular retraction (negative) or protraction (positive) wrt thorax
ClavX	Clavicular elevation (negative) or depression (positive) wrt thorax
ClavZ	Clavicular axial rotation of the clavicle wrt thorax. Rotation of the top backwards is positive, forwards is negative.
ScapY	Scapular retraction (negative) or protraction (positive) wrt the thorax coordinate system, measured with the acromion cluster
ScapX	Scapular anterior (negative) or posterior (positive) tilt wrt the thorax, measured with the acromion cluster
ScapZ	Scapular lateral (negative) or medial (positive) rotation wrt the thorax, measured with the acromion cluster
HumY1	Humeral plane of elevation wrt thorax. 0° is abduction, 90° is forward flexion.
HumX	Humeral elevation (negative) wrt thorax.
HumY2	Humeral axial rotation, endo- or internal rotation (positive) and exo- or external rotation (negative).
EL	Elbow flexion (positive) and hyperextension (negative).
PS	Axial rotation of the forearm wrt humerus: pronation (positive) and supination (negative).
ScapLocY	Scapular retraction (negative) or protraction (positive) wrt the thorax coordinate system, measured with the scapula locator
ScapLocX	Scapular anterior (negative) or posterior (positive) tilt wrt the thorax, measured with the scapula locator
ScapLocZ	Scapular lateral (negative) or medial (positive) rotation wrt the thorax, measured with the scapula locator

Table 5 Task and event number descriptions.

Movement	**Description**	**Event column 1***	**Event column 2***
ABD	Abduct the arm in the frontal plane until maximal humeral elevation is reached. Hand should be kept facing medially. Then return to starting position.	starting position with arm hanging vertical down just before initiating abduction	return at starting position after abducting the arm
FLEX	Anteflex the arm in the sagittal plane until maximal humeral elevation is reached. Then return to starting position.	starting position with arm hanging vertical down just before initiating anteflexion	return at starting position after flexing the arm
SCAP	Flex the arm in the scapular plane (approximately 45° with frontal plane) until maximal humeral elevation is reached. Then return to starting position.	starting position with arm hanging vertical down just before initiating scaption	return at starting position after scaption of the arm
ENDO	Exorotate the shoulder while holding the upper arm still until maximal exorotation is reached. Then return to starting position.	starting position with humerus at ±60° abduction and endorotated	return at starting position after exorotation the arm
PROSUP	Pronate forearm as far as possible until hand faces downward. Then return to starting position.	Starting position with elbow flexed and forearm pro/supinated	Return at starting position after forearm pro/supination
ELBOW	Flex the elbow until maximum flexion is reached. Then extend to starting position.	Elbow at full extension	Return at full extension.
LIFT	Lifting a box placed on the ground on a virtual shelf above shoulder height.	starting position with arm hanging vertically down before picking up box	frame at which box is put on (virtual) shelf
PERI	Move the arm to the backside and move as if wiping your bottom.	Starting position with arm hanging down	Return at starting position after (virtually) wiping your backside
WASH	Move the arm across the body and move as if to wash the opposite axilla.	Starting position with arm hanging down	After making a (virtual) washing movement of the opposite axilla
EAT	Move the arm as if eating something with a spoon.	Starting position with arm hanging down	After making a couple eating movement (spoon to mouth)
COMB	Move the arm as if combing your hair.	Starting position with arm hanging down	After making a (virtual) hair combing movement

* Optotrak frame number at which the described position is reached

Table 6 Maximum voluntary contraction positions and tasks suggested by Boettcher et al. (2008). Two extra tasks were added (ELBFLEX and ELBEXT) to induce maximum activity in muscle crossing the elbow.

Task name	Description	Picture
Empty can (EC)	The ‘‘empty can’’ test position with the shoulder abducted to 90° in the plane of the scapula, internal humeral rotation, and elbow extended. The arm is abducted as resistance is applied at the wrist.	
Internal rotation 90° (INTROT)	The “internal rotation 90°” test position with the shoulder abducted to 90° in the plane of the scapula, neutral humeral rotation, and elbow flexed 908. The arm is internally rotated as resistance is applied at the wrist.	
Flexion 125° (FLEX)	The ‘‘flexion 1258’’ test position with the shoulder flexed to 125° as resistance is applied above the elbow and at the inferior angle of the scapula, attempting to de-rotate the scapula with the subject sitting in an erect posture with no back support.	
Palm press (PALM)	The ‘‘palm press’’ test position with the shoulders flexed to 90° bilaterally, the heel of the hands together, elbows flexed 20°, and then the arms horizontally adducted.	

Extension (EXT)	Subject seated with the arm at 30° abduction, elbow fully extended and thumb toward the body; arm extended as resistance applied over the distal forearm.	
Elbow flexion (ELBFLEX)	With the elbow in 90° flexion and upper arm vertically down, press the distal forearm downwards while holding the elbow in position with the other hand.	
Elbow extension (ELBEXT)	With the elbow in 90° flexion and upper arm vertically down, press the distal forearm upwards while holding the elbow in position with the other hand.	