Gait & Posture 57 (2017) 278–294

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Review

Shoulder assessment according to the international classification of functioning by means of inertial sensor technologies: A systematic review

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ARTICLE INFO

Keywords:
Ambulatory
Shoulder
Movement
Inertial sensor
Scapula
Kinematic

ABSTRACT

This review investigates current protocols using Inertial Measurement Units (IMUs) in shoulder research, and outlines future paths regarding IMU use for shoulder research. Different databases were searched for relevant articles. Criteria for study selection were (1) research in healthy persons or persons with shoulder problems, (2) IMUs applied as assessment tool for the shoulder (in healthy subjects and shoulder patients) or upper limb (in shoulder patients), (3) peer-reviewed, full-text papers in English or Dutch. Studies with less than five participants and without ethical approval were excluded. Data extraction included (1) study design, (2) participant characteristics, (3) type/brand of IMU, (4) tasks included in the assessment protocol, and (5) outcomes. Risk of bias was assessed using the Downs and Black checklist. Scapulothoracic/glenohumeral and humerothoracic kinematics were reported in respectively 10 and 27 of the 37 included papers. Only one paper in healthy persons assessed, next to scapulothoracic/glenohumeral kinematics, other upper limb joints. IMUs' validity and reliability to capture shoulder function was limited. Considering applied protocols, 39% of the protocols was located on the International-Classification-of-Functioning (ICF) function level, while 38% and 23% were on the 'capacity' and 'actual performance'-sublevel, of the ICF-activity level. Most available IMU-research regarding the shoulder is clinically less relevant, given the widely reported humerothoracic kinematics which do not add to clinical-decision-making, and the absence of protocols assessing the complete upper limb chain. Apart from knowledge on methodological pitfalls and opportunities regarding the use of IMUs, this review provides future research paths.

1. Introduction

Shoulder dysfunctions are the third most common musculoskeletal complaint [1]. They hamper proper movement of the upper limb and negatively influence daily activity performance and daily life autonomy. Since they furthermore lead to work absenteeism, shoulder dysfunctions are responsible for an increasing burden on the socio-economical system [1]. To adequately diagnose shoulder complaints and to plan and follow-up treatment, accurate assessment tools are critical. Next to clinical shoulder assessments, other objective and quantitative measurements, assessing on the different levels of the International Classification of Functioning (ICF), are needed to provide insights in the etiology and progression of shoulder dysfunctions. Furthermore, these measurements should be easy-to-use and non-expensive.

Current clinical shoulder assessment consists of different tests and scales [2], e.g. the Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire [3], the Simple Shoulder Test (SST) [4], the Constant-Murley score [5], the American Shoulder and Elbow Surgeons Standardized Shoulder Assessment Form (ASES score) [6] and the Visual Analogue Scale (VAS) score for pain and stiffness. Apart from the easy-to-use aspect of clinical scales and tests and their opportunity to assess outcomes on all ICF levels, they have the disadvantage of suffering from subjectivity. In addition, they provide no or too little information about specific movement characteristics (i.e. movement velocity, movement fluidity, joint range of motion, the timing of joints involved) or on compensatory movements from other joints during movement. Since these parameters can influence the functional status of the shoulder girdle, e.g. shoulder pathologies might result from an aberrant or compensatory movement pattern [7], this is an important weakness of clinical scales. This is well illustrated by the work of Cutti et al. (2016), who introduced an adapted version of the Constant-Murley score [8]. This adapted version, taking scapulothoracic movement patterns into consideration, scored shoulder function in persons recovering from rotator cuff surgery significantly different than the original Constant-Murley Score.

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http://dx.doi.org/10.1016/j.gaitpost.2017.06.025
Received 2 January 2017; Received in revised form 12 May 2017; Accepted 23 June 2017

Dynamic movement analysis can thus overcome most of the shortcomings of clinical tests by providing additional information on movement characteristics. Currently, movement analysis of the shoulder is mostly done in laboratory settings using optoelectronic or electromagnetic registration systems [9]. Registered kinematic data thereby provide detailed and objective information on motor performance and movement quality. However, laboratory-based settings have the disadvantage to suffer from spatial constraints, which hampers the assessment during a functional movement protocol, resembling daily activity performances. Mobile measurement systems provide an alternative for lab-based methods as they have the potential to measure shoulder characteristics in real life environments without space constraints. They are furthermore much less expensive than laboratory systems. The last decade, inertial sensor devices are emergent in the mobile assessment of shoulder characteristics [10]. They consist of an accelerometer, a gyroscope and often a magnetometer, which enables them to register kinematic data (velocity, acceleration, orientation, gravitational forces). However, the value of kinematic movement analysis by means of inertial sensors in clinical decision-making or the evaluation of treatment efficacy is entirely dependent on the validity and reliability of the sensors' output, and on the clinical relevance of these outcomes.

It would be helpful and useful for researchers and practitioners starting in the field of inertial shoulder motion analysis to have an overview of existing knowledge on the psychometric properties and the use of inertial sensors for shoulder assessment. However, such an overview is currently lacking. Therefore, the authors want to provide a compendium regarding the current status of inertial motion analysis in shoulder research, i.e. proven psychometric properties of the different outcome parameters, applied measurement protocols and procedures, data analysis methods, etc. In this way, the opportunities for inertial sensors in clinical shoulder research can be emphasized. Secondly, the authors want to propose specific recommendations for further research paths regarding the use of inertial measurement units (IMUs) for shoulder assessment.

2. Methods

Protocol details were registered in the international prospective register of systematic reviews (PROSPERO, http://www.crd.york.ac.uk/prospero, registration number is: CRD42016035856). Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed [11].

2.1. Search strategy and study selection

Papers were selected from different databases: PubMed, Web of Science, CINAHL, Pedro, Embase, ACM and IEEE Xplore (until April 2017), using a combination of Medical Subject Headings (Mesh) and free text terms for inertial sensors (inertia*, inertial sensors) and the shoulder girdle (scapulohumeral, scapulothoracic, scapula, glenohumeral, shoulder). The search terms were customized to each database (Supplementary material 1). Furthermore, experts were consulted to ensure that no relevant papers for inclusion were missed.

Selection criteria which were defined in advance according to the study objectives, had to be fulfilled to be included in the review. Following inclusion criteria were defined: (1) application of inertial sensors as assessment tool, (2) the applied inertial sensor(s) consist(s) of at least an accelerometer and gyroscope, (3) participants are healthy persons or musculoskeletal shoulder patients, (4) written in English or Dutch language, (5) peer reviewed, original research journal article and (6) full-text available. Exclusion criteria were (1) use of inertial sensors only for rehabilitation/training purposes, (2) reviews, systematic reviews or *meta*-analyses, or commentaries, (3) articles with less than five participants, (4) studies without ethical approval and (5) cadaveric or animal studies.

Eligibility assessment was done by two assessors (LDB and TM) in a blinded manner by screening the title and abstract of all studies retrieved form the electronic database search. From all eligible studies based on title and abstract, and from those studies whose abstract did not provide enough information for eligibility, full texts were read to finally select the papers for inclusion. Reference lists of included papers were manually screened by both reviewers for additional eligible papers. In case of disagreement between the two assessors, a third assessor (AT) was contacted for consensus.

2.2. Risk of bias in individual studies

Risk of bias assessment of selected studies was done using the validated 27-items Downs and Black Checklist [12], which is recommended by the Cochrane collaboration for non-randomized studies. The checklist was modified to suit the observational study designs of the papers included in this review. Ten items were removed from the checklist as they related to intervention trials. Furthermore, one item was not applicable for studies with a cross-sectional design and five items only pertained to case-control studies. Per study, the total score was converted to a percentage. A score $\geq 65\%$ and $\geq 90\%$ was determined as the cut-off to be classified as having substantial and high quality, respectively [12].

Two raters (LDB and RvdS) independently scored the risk of bias of the included papers. Raters were not masked for authors and journal name but were blinded to each other's quality results. In case of disagreement between assessors, consensus was reached after discussion.

2.3. Data extraction

Data extraction was performed according to a standard form, including (1) characteristics of included studies (in terms of participant characteristics; ICF classification of the protocol; study design; applied assessment protocol, including type and placement of inertial sensors, calibration protocol and movement tasks; outcome parameters), and (2) study results. Data extraction was done by one assessor (LDB) and checked by a second one (RvdS), using the standardized forms.

2.4. Data synthesis and analysis

No *meta*-analysis could be performed due to study-heterogeneity (e.g. study population, outcome parameters, movement protocol, etc.). Therefore, a descriptive review of the included studies' results is provided. First, characteristics of the included studies are presented, followed by a synthesis of study results according to the validity and reliability of outcome parameters, and their ability to discriminate.

3. Results

3.1. Systematic search and risk of bias analysis

Our database search identified 617 articles. The selection process is visualized in a flow-diagram (Fig. 1). A total of 37 papers were included in this review. According to the Downs and Black checklist, six papers did not have substantial quality (score below 65%). Those papers were all cross-sectional one-group studies, from which four were situated on the ICF function level [13–16], and three on the ICF activity level [17–19]. These studies were all in healthy persons. Sixteen papers had substantial quality [20–35], and another 14 papers high quality [8,36–48]. The details of the risk of bias assessment can be found in Supplementary material 2.

3.2. Characteristics of included studies

For a sake of clarity and brevity, general characteristics are described in text. Detailed information on the extracted data per study is

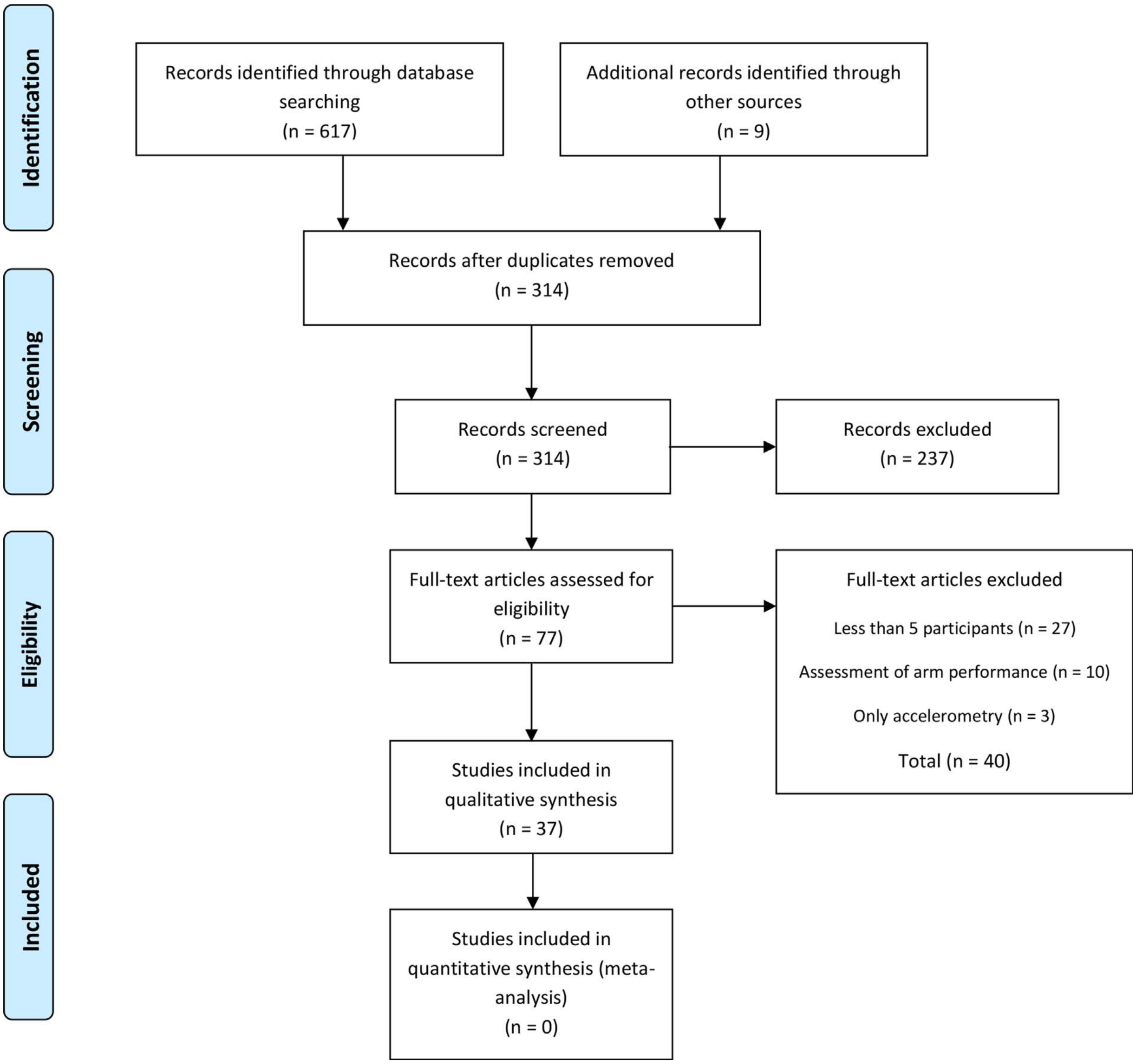

Fig. 1. Flowchart of search strategy.

described in Table 1 and Supplementary material 3.

3.3. Patient characteristics

Twenty-six studies reported results from *healthy persons*, while 11 papers (additionally) included persons with *shoulder disorders* (including scapular dyskinesia, rotator cuff pathology, subacromial impingement, glenohumeral osteoarthritis and adhesive capsulitis. Details on type of shoulder disorder per study can be found in Table 1). Sample sizes ranged between five and 111 participants for studies on healthy persons, and between 10 and 175 participants for studies on persons with shoulder disorders. The mean age of the healthy persons was 31 (± 8) years, while the mean age of the persons with shoulder disorders was 55 (± 5) years.

3.4. Classification according ICF-level

From the 26 studies in healthy persons, 13 studies could be situated on the ICF *body function level* [13–16,20–22,37,40,45–48]. From the other 13 papers, seven papers were situated on the 'capacity' sublevel [19,23–25,27,42,44] and six on the 'actual performance' sublevel of the ICF *activity level* [17,18,26,28,41,43](Fig. 2). In contrast, from the 11 studies assessing persons with shoulder disorders, only two were on *body function* level [38,49] while nine were on *activity level*, i.e. seven on the 'capacity sublevel' [8,29,31,33–36] and two on the 'actual performance' sublevel of the ICF [30,32] (Fig. 2).

Fig. 2. Classification of the included papers following the ICF [50,51].

3.5. Study designs

The main research question of 21 papers pertained to the *psychometric properties* of kinematic outcome parameters measured by inertial sensors (18 in healthy persons, from which nine were located on function level [13,14,16,22,37,40,46–48] and nine on activity level [17,19,23–25,27,41,42,44]; three in persons with shoulder disorders, from which one was located on function level [38] and two on activity level [33,36]). Four papers in healthy persons (one on function level [15], three on activity level [17,28,43]) had a purely *descriptive* character. Eleven papers, six in healthy persons (five on function level [20,21,47,48,52], one on activity level [26]) and eight in persons with shoulder disorders (one on function level [49], seven on activity level [8,29–32,34,35]) were mainly *comparative* studies, from which seven had a *longitudinal* character [8,29–32,34,35].

Table 1
Characteristics of included studies.

	Study design and main research objective	Participant characteristics	Number, type, brand of IMUs	Tasks included in the assessment protocol	Outcome parameters with regard to the shoulder
		Type; number n; age mean (SD); gender M (male)/F (female)			
A.Healthy population Studies located on the ICF Function level					
Bouvier et al, 2015	Cross-sectional Psychometric assessment Comparison between different calibration techniques	n = 10; 29 (3.4); M	4 wireless IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, humerus, forearm and hand MTw, Xsens, The Netherlands	Maximal wrist flexion-extension and ab-adduction Maximal elbow flexion-extension and pro-supination Maximal shoulder flexion and shoulder abduction in the scapular plane Wheel movements	Humerothoracic joint angles
Crabolu et al, 2017	Cross-sectional Psychometric assessment Comparison between different estimation techniques	n = 5; 36 (4); M/F	3 IMUs consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, scapula and humerus MTw2 Awinda, Xsens, The Netherlands Note: the sternal sensor is not used to calculate the glenohumeral joint center	Cross and star types of movement, performed at 2 velocities and 2 ranges of motions	Glenohumeral joint center
Cutti et al, 2014	Cross-sectional Descriptive study Comparison between age-groups and methods to provide reference data for scapulohumeral patterns	n = 111; 38 (14); M/F 3 age-groups: n = 46;18–30;M/F n = 35;31–50;M/F n = 30;51–70;M/F	3 IMUs consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, scapula and humerus MTx, Xsens, The Netherlands	Arm elevation in the sagittal and scapular plane	Monolateral prediction bands and intervals for the scapulohumeral movement patterns and the scapular resting position in 3 different age groups Differential (left-right differences) prediction bands and intervals
de Vries et al, 2010	Cross-sectional Psychometric assessment	n = 5; 27 (1.9); ?	4 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, humerus, forearm and hand MTx, Xsens, The Netherlands	Thorax: (1) flexion-extension, (2) lateral flexion, (3) axial rotation Humerus: (1) arm forward flexion with extended elbows, holding a bar at shoulder breadth, thumbs pointing lateral, (2) ab-adduction, (3) in-external rotation with the elbows supported at the olecranon, (4) elbow flexion (the movement of the forearm expressed in the humeral IMU) Forearm: (1) flexion-extension while holding a bar, thumbs pointing laterally to fix the forearm from pro-supination, elbows supported at the olecranon, (2) pro-supination, free in the air, hand kept straight in line with the forearm, (3) pro-supination, elbow and ulna supported Hand: (1) hand flat on the table for 5 s, (2) dorsal flexion with forearm supported, palm of the hand facing the table, (3) same position, performing radial-ulnar deviation, by sliding the palm of the hand over the surface	Segments' local coordinate system
El Gohary, 2012	Cross-sectional	n = 8; ?; ?	2 IMUs, consisting of a 3D accelerometer and 3D	Shoulder flexion-extension and ab-	Humerothoracic joint angles

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Table 1 *(continued)*

	Study design and main research objective	Participant characteristics	Number, type, brand of IMUs	Tasks included in the assessment protocol	Outcome parameters with regard to the shoulder
		Type; number n; age mean (SD); gender M (male)/F (female)			
	Psychometric assessment		gyroscope, placed on humerus and forearm	adduction Elbow flexion-extension Forearm pro-supination Touching nose with the index finger Reaching for the doorknob to open a door	
Lorussi et al, 2016	Cross-sectional Psychometric assessment	n = 5; ?; ?	2 IMUs consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, on the sternum and humerus, integrated in a shirt, which was additionally equipped with textile strain sensor MTw, Xsens, The Netherlands	Humeral elevation in the sagittal and frontal plane	Humerothoracic orientation by the IMUs and scapulothoracic translation by the textile strain sensor
Parel et al, 2014	Cross-sectional Psychometric assessment	n = 23;29 (8);M/F	3 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, scapula, humerus Xsens, The Netherlands	Humeral elevation in the sagittal and scapular plane	Scapulothoracic joint angles
Pellegrini et al, 2016	Comparison between pitchers who did and did not receive stretching	n = 11; ?;?	3 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, scapula, humerus Xsens, The Netherlands	Humeral elevation in the sagittal and scapular plane	Scapulothoracic joint angles
Picerno et al, 2015	Cross-sectional Psychometric assessment	n = 45; 27 (8)/ 22 (3);M/F	1 IMU, consisting of 3D accelerometer and 3D gyroscope, placed on the humerus FreeSense, Sensorize, Italy	Shoulder abduction holding a one kg dumbbell in the hand	Strength curve
Roldan-Jimenez and Cuesta-Vargas, 2015	Cross-sectional Observational research	n = 11; 24.7 (4.2); M/F	4 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, scapula, humerus and forearm InertiaCube3 ™Intersense Inc., USA	180° of shoulder flexion and abduction, with the elbow extended and the wrist in neutral position	Scapulothoracic and glenohumeral joint angles
Roldan-Jimenez and Cuesta-Vargas, 2016	Cross-sectional Comparison between young and older adults	Young adults: n = 11; 24.7 (4,2); M/F Older adults: n = 14: 55,7 (9,4); M/F	3 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, scapula and humerus InertiaCube3™Intersense Inc., USA	180° of shoulder flexion and abduction, with the elbow extended and the wrist in neutral position	Scapulothoracic and glenohumeral joint angles
Schiefer et al, 2015	Cross-sectional Psychometric assessment	n = 20; 37.4 (9.9); M/F	13 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the forehead, the back at the level of L5/S1 and Th4, both humeri, the forearms, the hands, upper legs and lower legs CUELA, IFA, Germany	Cervical spine: flexion-extension, lateral flexion, rotation Thoracic and lumbar spine: Sideway rotation, lateral bending Shoulder: In-external rotation Elbow: flexion-extension, pro-supination Wrist: flexion-extension, ab-adduction	Humerothoracic joint angles
van den Noort et al, 2014	Cross-sectional Psychometric assessment	n = 20; 36 (11); M/F	4 wireless IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, scapula, humerus and forearm MTw, Xsens, The Netherlands	Humeral elevation in the sagittal and frontal plane, with the elbow fully extended and with the thumb pointing up.	Scapulothoracic joint angles
Studies located on the ICF Activity level					
Coley, Jolles, Farron, Aminian, 2008	Cross-sectional Psychometric assessment	Lab-based study: n = 5; 26 (3.8); ? Daily life study:	3 IMUs, consisting of 3D accelerometer and 3D gyroscope, placed on the thorax and both humeri Analog Devices	Lab-based study: Shoulder flexion-extension and ab-adduction Daily life study:	IMU on thorax: body posture detection IMUs on humerus: Humerothoracic elevation angle during daily physical activity

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Table 1 *(continued)*

	Study design and main research objective	Participant characteristics	Number, type, brand of IMUs	Tasks included in the assessment protocol	Outcome parameters with regard to the shoulder
		Type; number n; age mean (SD); gender M (male)/F (female)			
		n= 31; 32 (8); M/F		Long-term (~8h) daily life recording	
Coley, Jolles, Farron, Pichonnaz, Bassin, Aminian, 2008	Cross-sectional Observational research	n=35; 32 (8); ?	3 IMUs, consisting of 3D accelerometer and 3D gyroscope, placed on the thorax and both humeri Analog Devices	Long-term (~8h) daily life recording	IMU on thorax: body posture detection IMUs on both humeri: Dominant shoulder estimation
Ertzgaard et al, 2015	Cross-sectional Psychometric assessment	n=10; 34.3 (13.1); M/F	5 IMUs, consisting of 3D accelerometer and 3D gyroscope, placed on the upper body, both humeri and both forearms Analog Devices, Adis 16350	Cone lifting and dropping: Moving 4 cones from one lower level on a table to a higher in a forward direction Throw: throwing and catching task that mainly involves elbow flexion Coordination task 1: hands move from start position to top of head, to the shoulder, clapping back of hands together, moved hands to the knee and then to toe Coordination task 2: The hands moved from the starting position to the ears, to the eyes and then to the mount.	Arm function during daily activity by capturing humerothoracic joint angles and joint angle velocity patterns
Fantozzi et al, 2015	Cross-sectional Psychometric assessment	n= 8; 26.1 (3.4); M	7 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, both humeri, both forearms and both hands Opal, APDM, Portland, OR USA	Simulated front-crawl and breaststroke swimming	Humerothoracic joint angles
Kim and Nussbaum, 2013	Cross-sectional Psychometric assessment	n=14; 22.9 (4.9); M/F	17 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the head, sternum, pelvis, both scapulae, both humeri, both forearms, both hands, both upper legs, both lower legs, both feet MVN, Xsens, The Netherlands Note: - scapular IMUs were not used in the analyses - subjects were standing on a force plates and load cells were attached at the lateral faces of the box as handles	Symmetric lifting/lowering, to/from ground height Symmetric lifting/lowering, to/from knuckle height Asymmetric lifting/lowering Carrying Pushing/pulling (symmetrically)	Humerothoracic joint angles, angular velocities, moments of selected body parts
Khurelbaatar et al, 2015	Cross-sectional Psychometric assessment	n=5; 27 (1); M	17 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the head, sternum, pelvis, both scapulae, both humeri, both forearms, both hands, both upper legs, both lower legs, both feet MVN, Xsens, The Netherlands Note: - scapular IMUs were not used in the analyses - in-shoe pressure sensors were used for force and moment measurements	Gait	Humerothoracic joint forces and moments
Kirking et al, 2016	Cross-sectional Descriptive, feasibility study	n=5; ?; ?	2 IMUs consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, on the sternum and humerus Opal, APDM, Portland, OR USA	4 h of measurement during working activities in their work environment and 4 h off-work	3D humerothoracic joint angles (flexion-extension, abduction-adduction, internal-external rotation)
Koda et al, 2009	Cross-sectional	n=5; 22.2 (1.3); M	2 IMUs, consisting of 3D accelerometer and 3D	Pitching movement in baseball	trajectories of shoulder (humerothoracic),

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Table 1 *(continued)*

	Study design and main research objective	Participant characteristics	Number, type, brand of IMUs	Tasks included in the assessment protocol	Outcome parameters with regard to the shoulder
		Type; number n; age mean (SD); gender M (male)/F (female)			
	Psychometric assessment		gyroscope, placed on the humerus and forearm Accelerometer: Analog Device, ADXL320 and ADXL193 Gyroscope: Murata, ENCO3M and Microstone, MG3-01Ab		elbow and wrist
Morrow et al, 2016	Cross-sectional	n = 6; 45 (7); M/F	6 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the head, sternum, and on both humeri and forearms	One task (the peg transfer tasks) from a set of basic skills necessary to perform minimal invasive laparoscopy	Joint angles: Shoulder elevation relative to the trunk (humerothoracic), elbow flexion, neck flexion/extension, trunk flexion/extension
	Psychometric assessment		Opal, APDM, Portland, OR USA		
Schall Jr et al, 2016	Cross-sectional	n = 36; 30.8 (10.1); F	3 IMUs, consisting of 3D accelerometer, 3D gyroscope placed on the posterior thorax and on both humeri	A full work shift from nurses (ranging between 8 and 12 h)	Postures and movement velocities of the upper arms (humerothoracic) and the trunk, and rest/recovery exposure
	Comparison between nurses classified according to activity level				
Schall Jr et al, 2015	Cross-sectional	Lab-based study: n = 6; 29 (9.5); M	3 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, pelvis and humerus	Lab-based study: milking cluster attachment task	Trunk angular displacements in flexion-extension and lateral flexion, and upper arm (humerothoracic) elevation, defined as forward flexion or abduction
	Psychometric assessment	Field-based study: n = 10; 24 (1.8), M	l2 M Motion Tracking, Series SXT, Nexgen Ergonomics, Canada	Field-based study: a full work shift diary parlour work	
Rawashdeh et al, 2016	Cross-sectional	N = 11; 25 (7); ?	1 IMU, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the humerus	Baseball throws, volleyball serves, and seven other rehabilitation exercises	Humerothoracic shoulder motion gestures in athletics
	Psychometric assessment		Gyroscope: InvenSense, San Jose, CA, USA; accelerometer: Analog Devices, Norwood, MA, USA; magnetometer: Honeywell, Morris Plains, NJ, USA		
Yu et al, 2017	Cross-sectional	N = 10; ?; ?	6 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on head, sternum, both humeri and pelvis	Surgical procedure, consisting of parallel procedures at the robotic console and at the patient's bed side	Joint angles: Humerothoracic shoulder elevation, neck flexion and torso flexion over time, summarized into mean postural angles, range of motion, % of time in demanding postures, % of time in static postures, and number of posture changes per minute
	Descriptive study		Opal, APDM, Portland, OR USA		
B.Persons with shoulder disorders					
Studies located on the ICF Function level					
Parel et al, 2012	Cross-sectional	Healthy n = 20; 28.3 (5.5); M/F	3 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, scapula, humerus	Humeral elevation in the sagittal and scapular plane	Scapulothoracic joint angles
	Psychometric assessment	Different shoulder pathologies n = 20; 43.9 (19.9); M/F	MTx, Xsens, The Netherlands		
van den Noort et al, 2015	Cross-sectional	Scapular dyskinesis according to the scapular dyskinesis test n = 10; 24–63; M/F	4 wireless IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, scapula, humerus and forearm	Humeral elevation in the sagittal and frontal plane, with the elbow fully extended and with the thumb pointing up.	Scapulothoracic joint angles
	Comparison between different calibration techniques		MTw, Xsens, The Netherlands		
Studies located on the ICF Activity level					
Coley et al, 2007	Cross-sectional	Healthy, n = 10; 25.1 (4.1); ?	2 IMU, consisting of 3 3D accelerometers and 3 3D	Validation study: shoulder in-external	Validation study: humerothoracic joint

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Table 1 *(continued)*

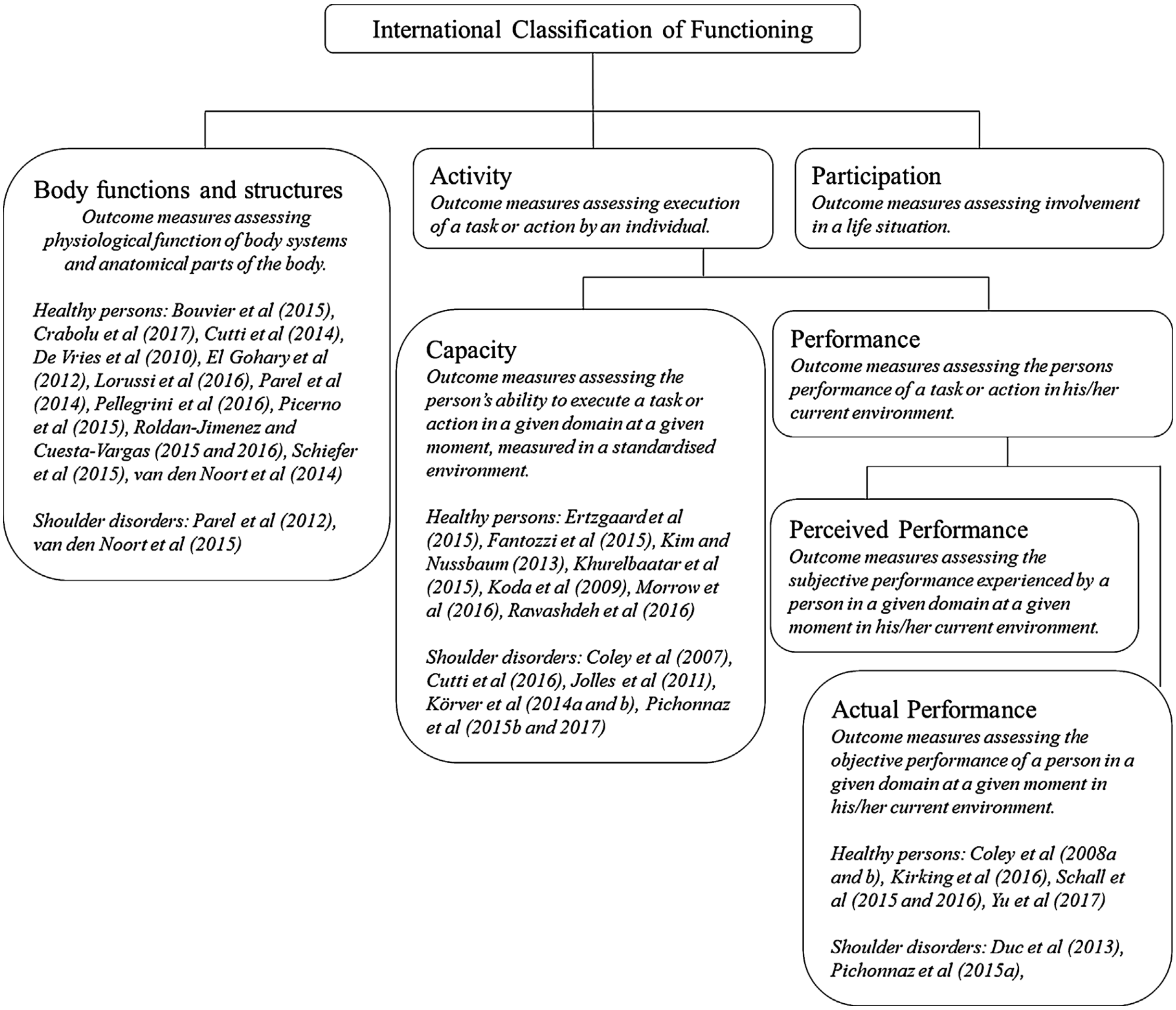
	Study design and main research objective	Participant characteristics	Number, type, brand of IMUs	Tasks included in the assessment protocol	Outcome parameters with regard to the shoulder
		Type; number n; age mean (SD); gender M (male)/F (female)			
			gyroscopes, placed on both humeri	rotation, flexion-extension and ab-adduction	angles
	Case-control		Analog Devices		
	Longitudinal	Unilateral shoulder pathology (rotator cuff disease, osteoarthritis), n = 10; 62.4 (10.4); M/F		Comparative study: Rest, hand to back, hand behind head, object ahead, 4 kg in abduction, 8 kg along the body, hand to the opposite shoulder, change a bulb, object on side	Comparative study: difference between healthy and painful shoulders:
	Psychometric assessment and comparison between healthy controls and patients before and at 3 and 6 months after surgery				- P-score (power): based on angular velocity and accelerations of the humerus - RAV-score (range of angular velocity): based on angular velocity of the humerus - M-score (moment): based on the sum of all moments of the humerus
Cutti et al, 2016	Cross-sectional	Arthroscopically treated for rotator-cuff tear, n = 32;53 (9); M/F	3 IMUs, consisting of 3D accelerometer, 3D gyroscope and 3D magnetometer, placed on the sternum, scapula, humerus	Arm elevation in the sagittal and scapular plane, as part of the assessment of the Scapula-Weighted Constant-Murley assessment	The scapula-weighted Constant-Murley Score: a modification of the Constant-Murley Score by adding 2 wted factors based on scapulothoracic joint angles
	Longitudinal		MTx, Xsens, The Netherlands		
Duc et al, 2013	Cross-sectional	Laboratory measurement:	3 IMUs, consisting of 3D accelerometer and 3D gyroscope, placed on the sternum and both humeri	Laboratory measurement:	Laboratory measurement:
	Case-control Longitudinal	Healthy n = 6; 28 (2.8); ?	Analog Devices	Displace bottles of 1.5l and pens up and down a shelf, and from left to right on a table, while standing	Detection of humeral movement relative to the trunk
		RC tear n = 5; 53 (5.3); ?			
	Psychometric assessment and comparison between healthy controls and patients before and at 3, 6 and 12 months after surgery	Daily routine monitoring: Healthy n = 41; 34 (9); ?		Daily routine monitoring: 7 h continuous monitoring during a weekday	Daily routine monitoring: Arm usage defined as - quantity of arm movement estimated by movement frequency and its symmetry index - quality of movement assessed by the Kolmogorov-Smirnov distance
		RC tear n = 21; 53 (9); ?			
Jolles et al, 2011	Case-control Longitudinal	Healthy, n = 31; 33.3 (8);M/F	2 IMU, consisting of 3 3D accelerometers and 3 3D gyroscopes, placed on both humeri Analog Devices	Hand to back, hand behind head, object ahead, abduction, hand to the opposite shoulder, change a bulb, object on side	difference between healthy and painful shoulders: - P-score (power): based on angular velocity and accelerations of the humerus - RAV-score (range of angular velocity): based on angular velocity of the humerus
	Psychometric assessment and comparison between healthy controls and patients before and at 3, 6 and 12 months after surgery	Glenohumeral OA n = 7,			
		RC tear n = 27; 57.5 (9.9); M/F			- M-score (moment): based on the sum of all moments of the humerus
Korver, Heyligers et al, 2014	Cross-sectional	Healthy, n = 113; 16–81; M/F	1 IMU, consisting of 3D accelerometer and 3D gyroscope, placed on the humerus Inertia-Link-2400-SK1, MicroStrain, USA	Two functional tasks while seated: - Hand to back, mimicking toilet hygiene	2 scores to calculate the asymmetry as the relative difference between both arm sides: - COMP-score: combination of the angular rate signal and acceleration signal of each independent axis
	Psychometric assessment	Shoulder pathology n = 62; 22–76; M/F		- Hand behind the head, mimicking combing hair	- AR score: based on angular rate only, average of the peak-to-peak difference in the

(continued on next page)

Table 1 *(continued)*

	Study design and main research objective	Participant characteristics	Number, type, brand of IMUs	Tasks included in the assessment protocol	Outcome parameters with regard to the shoulder
		Type; number n; age mean (SD); gender M (male)/F (female)			
					angular rate signal Higher scores indicate an increasing difference in shoulder function between both sides
Korver, Senden et al, 2014	Case-control Longitudinal	Healthy, n = 100; 47.6 (15.7); M/F	1 IMU, consisting of 3D accelerometer and 3D gyroscope, placed on the humerus	Two functional tasks while seated:	- AR score: based on angular rate only, average of the peak-to-peak difference in the angular rate signal
			Inertia-Link-2400-SK1, MicroStrain, USA	- Hand to back, mimicking toilet hygiene	- Asymmetry AR score: between both shoulders in the same subject
		Subacromial impingement, n = 15; 56.4 (11.8); M/F		- Hand behind the head, mimicking combing hair	- relative asymmetry AR score: : with regards to healthy reference database
	Psychometric assessment and comparison between healthy controls and patients before and 5 year after surgery				Higher asymmetry values indicate increasing asymmetry in shoulder function
Pichonnaz, Duc et al, 2015	Cross-sectional	Healthy, n = 41; 34.1 (8.8); M/F	3 IMUs, consisting of 3D accelerometer and 3D gyroscope, placed on the thorax and both humeri	7 h of regular daily activity performance	Dominant/non-dominant arm usage
	Case-control Longitudinal	Rotator cuff tear, n = 21; 53.3 (9); M/F	Analog Devices		
	Psychometric assessment and comparison between healthy controls and patients before and at 3, 6 and 12 months after surgery		Note: IMU on thorax was for body posture detection		
Pichonnaz, Lécureux et al, 2015	Cross-sectional	Healthy, n = 31; 33.2 (8.1); M/F	2 IMUs, consisting of 3D accelerometer and 3D gyroscope, placed on both humeri	hand to back, hand behind head, object ahead, 90° shoulder flexion, 90° shoulder abduction, hand to the opposite shoulder, change a bulb, shoulder external rotation with 90° elbow flexion	Power score, based on the 7 movement tasks, computed as the product of accelerations by angular velocities. The P score is the ratio of performance of the affected relative to the healthy side
	Longitudinal	RC tear, GH osteoarthritis, n = 35; 58 (9.9); M/F	Analog Devices		
	Psychometric assessment in healthy controls and patients before and at 3, 6 and 12 months after surgery				
Pichonnaz et al, 2017	Cross-sectional	Healthy, n = 20; 28.2 (6.2); M/F	2 IMUs, consisting of 3D accelerometer and 3D gyroscope, placed on both humeri	'Hand to back' and 'lift hand as to change a bulb'	B–B score (back-bulb score): a power-related parameter extracted from the recorded signals: the range of acceleration was multiplied by the range of angular velocity. This parameter is calculated for each axis and for each movement of the B–B score
	Psychometric assessment	RC pathology, adhesive capsulitis, fractures: n = 65; 58.5 (14.2); M/F	Analog Devices IMU system is reference system for concurrent validation of a smartphone for the measurement of the B–B score		

ICF: international classification of functioning; IMU: inertial measurement unit



Body functions and structures: Outcome measures assessing physiological function of body systems and anatomical parts of the body.

Healthy persons: Bouvier et al (2015), Crabolu et al (2017), Cutti et al (2014), De Vries et al (2010), El Gohary et al (2012), Lorussi et al (2016), Parel et al (2014), Pellegrini et al (2016), Picerno et al (2015), Roldan-Jimenez and Cuesta-Vargas (2015 and 2016), Schiefer et al (2015), van den Noort et al (2014)

Shoulder disorders: Parel et al (2012), van den Noort et al (2015)

Activity: Outcome measures assessing execution of a task or action by an individual.

Participation: Outcome measures assessing involvement in a life situation.

Capacity: Outcome measures assessing the person's ability to execute a task or action in a given domain at a given moment, measured in a standardised environment.

Healthy persons: Ertzgaard et al (2015), Fantozzi et al (2015), Kim and Nussbaum (2013), Khurelbaatar et al (2015), Koda et al (2009), Morrow et al (2016), Rawashdeh et al (2016)

Shoulder disorders: Coley et al (2007), Cutti et al (2016), Jolles et al (2011), Körver et al (2014a and b), Pichonnaz et al (2015b and 2017)

Performance: Outcome measures assessing the persons performance of a task or action in his/her current environment.

Perceived Performance: Outcome measures assessing the subjective performance experienced by a person in a given domain at a given moment in his/her current environment.

Actual Performance: Outcome measures assessing the objective performance of a person in a given domain at a given moment in his/her current environment.

Healthy persons: Coley et al (2008a and b), Kirking et al (2016), Schall et al (2015 and 2016), Yu et al (2017)

Shoulder disorders: Duc et al (2013), Pichonnaz et al (2015a),

Fig. 2. Situating of included papers in the International Classification of Functioning.

3.6. Applied assessment protocol

From the applied assessment protocols in the different studies, two protocols were more often used. The first one is proposed by Cutti et al. (2008) as part of the "INAIL Shoulder & Elbow Outpatient protocol" (ISEO) [10]. This protocol or an adapted version was applied by eight papers (22%) in this review [8,20,21,37,38,40,44,53]. Secondly, nine assessment protocols (24%) [17,18,29,31–36] on the classification or quantification of physical activity in terms of postures and tasks were based on the protocol of Coley et al. (2007) [29].

Detailed specifications about type and placement of inertial sensors, calibration protocols and movement tasks are given in Supplementary material 3.

3.7. Outcome parameters

From all included papers, 14 papers reported kinematic outcomes *exclusively* from the *humerothoracic joint* (six papers in healthy persons [17,18,22,26,27,43] and eight papers in persons with shoulder disorders[29–36]) and 10 exclusively from the *scapulothoracic or glenohumeral joint* (seven in healthy persons [14,20,21,37,40,45,47] and three in persons with shoulder disorders [8,38,49]. The other 13 papers in healthy persons reported, next to kinematic outcomes from the humerothoracic joint (n = 12) [13,16,19,23–25,28,41,42,44,46,48] and scapulothoracic or glenohumeral joint (n = 1) [15], kinematic outcomes of *other joints of the upper limb chain.*

3.8. Synthesis of study results

First, results regarding 'agreement', 'repeatability', 'reproducibility' and 'reliability' of reported IMU-outcomes (humerothoracic joint angles, scapulothoracic joint angles, other outcomes) are described, using following terminology [54]: 'repeatability' is defined as the agreement between measurements executed under identical conditions, 'reproducibility' refers to the agreement between measurements made under changing conditions (e.g. method comparison) and 'reliability' is related to the magnitude of the measurement error in observed measurements relative to the inherent variability between subjects. Finally, results from the comparative studies are reported.

3.9. Agreement and reliability results

3.9.1. Humerothoracic joint angles

The agreement (reproducibility defined as method comparison) between humerothoracic joint angles acquired via an IMU-based measurement and a lab-based reference system was only assessed in healthy persons, by means of different statistics. Bouvier et al. (2015) and Fantozzi et al. (2015) used the inter-protocol coefficient of multiple correlation (CMC_{ip}), as described by Ferrari et al. [55] and based on the work of Kadaba et al. (1989) [56], to assess humerothoracic waveform similarity [44,48], and found lower CMC_{ip} for humerothoracic abduction-adduction and internal-external rotation (0.53-0.86) than for flexion-extension (≥ 0.90) [48]. The root mean square error (RMSE) of humerothoracic joint angles was reported in five studies [13,41,42,44,48]. RMSE values were generally below 12° [13,41,42,44], with the exception of the results of Bouvier et al. (2015) who reported RMSE values up to 26° [48]. Limits of agreement (LoA) were analysed by two authors [42,57]. A systematic error of 0° [42] and of 0.46° [57] for humerothoracic flexion-extension, 1.30° for humerothoracic abduction-adduction [57] and −0.29° for humerothoracic internal-external rotation [57] was reported. Furthermore, Ertzgaard et al. (2015) described a proportional error of 2° for humerothoracic abduction-adduction and internal-external rotation, and of 0.01° for flexion-extension [57]. Morrow et al. (2016) described a general inverse proportional error, with an association of $r^2 = 0.55$ for the proportional error of the shoulder [42]. The relation between humerothoracic joint angles measured with IMUs and those from the reference system was further assessed using correlation coefficients (r). For humerothoracic joint angles, r was, as reported in three studies [13,29,44], higher than 0.91.

The agreement (repeatability) and reliability of IMU-based humerothoracic joint angles was exclusively investigated in healthy persons. The repeatability was assessed using the CMC$_2$, i.e. the inter-session agreement as defined by Kadaba et al. (1989) [48,56] and the m-index and r-index based on intrinsic and extrinsic error, as proposed by Schwartz et al. (2004) [48,58]. Results indicated lower CMC$_2$ for abduction-adduction and external-internal rotation (0.63-0.92) than for flexion-extension (≥0.96) [48]. The m-index (the mean of the extrinsic error) was between 5.8°-7.6° for flexion-extension, 4.9°-6.3° for abduction-adduction, and 6.1°−12° for internal-external rotation [48]. The r-index (the ratio of the mean extrinsic error over the mean intrinsic error) was between 1.2°-1.9° for flexion-extension, 1.4°-1.9° for abduction-adduction, and 1.4°-3.1° for internal-external rotation [48]. Reliability of the IMU-assessment of humerothoracic joint angles was assessed using Intraclass Correlations Coefficients. ICCs for humerothoracic abduction-adduction (within-session, ICC$_{(3,k)}$) [16], external-internal rotation (inter-observer, ICC type not specified) [18] and elevation angle (between-session, ICC$_{(2,k)}$) [22] were 0.96, 0.68-0.88, and 0.98 respectively.

3.9.2. *Scapulothoracic joint angles*

The agreement (reproducibility) between scapulothoracic joint angles acquired via an IMU-based measurement and via an optoelectronic-based assessment was assessed by Parel et al. (2014), in healthy persons, by means of RMSE and LoA analysis [37]. RMSE values were lower than 5° for medial-lateral rotation (until 120° of arm flexion and 100° of abduction), below 10° for protraction-retraction and below 11° for anterior-posterior tilt [37]. For medial-lateral rotation, the LoA bias had a small average value of 1.21 during arm flexion and 1.25 for arm abduction. The protraction-retraction LoA bias had a maximum value of 8.8° for flexion-extension and 5.8° for abduction. For anterior-posterior tilt, the LoA bias was negative. The coefficient of repeatability (CR) ranged for scapulothoracic protraction-retraction, medial-lateral rotation and anterior-posterior tilt between 1 and 10, 1–8 and 2–13, respectively [37]. For scapulothoracic medial-lateral rotation, this CR as calculated between the protocols ('CR between') was smaller than the CR as calculated within the IMU protocol or the opto-electronic-based protocol ('CR within'). For scapulothoracic protraction-retraction, the 'CR between' values were only smaller than the 'CR within' values for arm flexion below 70° and arm abduction below 100°. For tilt, the 'CR between' values were larger than the 'CR within' values across all motions [37].

The agreement (defined as 'repeatability' in case of measurements made by one instrument/one observers, and as 'reproducibility' in case of different observers) and reliability of the IMU assessment for scapulothoracic joint angles was assessed in healthy persons, with the exception of Parel et al. (2012), who included persons with shoulder disorders [38]. Intra-protocol repeatability was assessed by means of RMSE values, standard error of the measurement (SEMs) and LoA analysis [37]. Reported RMSE values were below 5° [37], SEMs ranged between 1.2°–3.9°, 1.8°–3.4° and 1.4°–2.8° for scapulothoracic protraction-retraction, medial-lateral rotation and anterior-posterior tilt, respectively, and LoA biases were within 1° for all scapulothoracic rotations. The CR increased with increased humerothoracic elevation, with average values across all scapulothoracic motions within 2° [37].

Intra- and inter-operator agreement ('repeatability' and 'reproducibility', respectively) of scapulothoracic joint angle assessment by means of IMUs was assessed by Parel et al. (2012) by means of the CMC$_2$, smallest detectable differences (SDDs) and SEMs [38]. Intra- and inter-observer CMC$_2$ values for scapulohumeral waveforms were between 0.85–0.96 and 0.87–0.95 for the sagittal and scapular plane respectively (with a SD of 0.04 to 0.11) [38]. Concurrent SDDs ranged between 4.48° and 8.68° for the inter-operator agreement and between 4.98° and 8.58° for the intra-operator agreement [38]. van den Noort et al. (2014) also reported intra- and inter-observer SDDs and SEMs [40]: intra- and inter-observer SEMs were for scapulothoracic medial-lateral rotation and anterior-posterior tilt lower than 5° (except for intra-observer posterior tilt at high humeral elevation angles). Intra-observer SEMs for protraction-retraction (range 4°−5°) were lower than inter-observer SEMs (range 5°–8°) across all humeral elevation angles [40]. For protraction-retraction, inter-observer SEMs were higher than intra-observer SEMs [40]. Inter- and intra-observer SDDs, as reported by van den Noort et al. (2014) ranged between 5° and 21° for inter-operator agreement and between 3° and 14° for the intra-operator agreement [40].

Finally, van den Noort (2014) assessed intra- and inter-observer reliability of scapulothoracic movement, using ICCs (type of ICC not specified)[40]. Both during arm flexion and arm abduction, intra- and inter-operator ICCs were comparable, especially for scapulothoracic protraction-retraction (ICC 0.65-0.85) and medial-lateral rotation (0.56-0.91). Lowest reliability was found for anterior-posterior tilting during arm flexion and abduction (ICC $<$ 0.40 at 0° and 30° of arm elevation) [40].

3.9.3. *Other outcomes*

Apart from joint angles, other outcomes based on kinematic output from IMUs were reported, such as glenohumeral joint center [47], arm posture detection [17], arm movement detection [27,30], joint force and moment [19], shoulder trajectory [25], arm use [32] and kinematic scores based on angular velocity and acceleration [31,34–36]. These outcomes and their agreement ('reproducibility') results are reported in Table 2. Additionally, in the study of Pichonnaz et al. (2017), the inertial sensor system was used as reference system for the validation of a kinematic score based on angular velocity and acceleration as measured by a smartphone [33].

Furthermore, mainly 'reliability' is assessed for the other outcomes. The within-session ICC(2,1) for "Angular velocity" was 0.97 in healthy persons [22]. ICCs(3,k) for "angular Exposure Variation Analysis (EVA)" and "angular velocity EVAs" ranged in healthy persons between 0.77 and 0.97 [57]. The "kinematic scores based on angular rate and accelerations" had ICCs(2,1) of 0.94 and 0.95 (inter-observer), and 0.90 and 0.91 (intra-observer) respectively in persons with shoulder disorders [36]. Only Picerno et al. (2015) reported the agreement of the "torque time curve" in healthy persons by means of the intra-protocol coefficient of multiple determination [56](CMD = 0.87) [22]. Crabolu et al. (2017) reported the error in the estimation of the glenohumeral joint center by means of a study specific error term, E$_{SD}$, ranging between 5.3–19 mm in healthy persons [47].

3.10. *Results of comparative studies*

Thirteen studies assessed differences between study protocols, study groups or between pre- and post-intervention status [8,17,20,21,26,29,30,32,34,35,39,45,48]. Results of these comparative studies can be found in Table 3.

Table 2
Agreement (reproducibility) of reported IMU-outcomes, other than joint angles.

Author, year of publication	Reported outcome parameter	Results of applied statistical tests considering the shoulder
Opto-electronic kinematic system as reference		
Coley et al., 2008	Arm posture detection	Overall sensitivity of 91% Overall specificity of 98%
Duc et al., 2013*a	Arm movement detection	Overall sensitivity of 96% Overall specificity of 98%
Khurelbaatar et al., 2015	Joint force Joint moments	RMSE: 6%, r: 0.8 RMSE: 24%, r: 0.5
Koda et al., 2010	Shoulder trajectory	RMSE: 0.1–0.15m, r: 0.73–0.96
Magnetic resonance imaging as reference		
Crabolu et al, 2047	Glenohumeral joint center estimation	Study-specific error term E: 11.2–38.5 mm
Clinical scores as reference		
Jolles et al., 2011 [a]	Kinematic scores based on angular velocity and accelerations, i.e. range of angular velocity score, moment score, power score	r: 0.61–0.80 (VAS pain, STT, DASH, ASES, Constant score)
Korver, Heyligers et al., 2014 [a]	Kinematic scores based on angular velocity and accelerations, i.e. COMP score (product of angular rate and acceleration) and angular rate score	COMP score: - sensitivity of 84% - specificity of 85% Angular rate score: - sensitivity of 98% - specificity of 81% r < 0.25 (DASH and SST)
Korver,Senden et al., 2014b [a]	Kinematic scores based on angular velocity and accelerations, i.e. asymmetry angular rate score between both shoulders of same subject, and relative asymmetry angular rate score with regards to a healthy reference database	r: 0.39 (DASH); r: 0.32 (SST)
Pichonnaz, Duc et al., 2015a [a]	Arm usage	No significant correlations between DASH, SST and relative Constant score across all stages
Pichonnaz, Lécureux et al., 2015b [a]	Kinematic scores based on angular velocity and accelerations, i.e. back-bulb score	r: 0.51–0.77 (DASH, SST, Constant score) Sensitivity of 97% Specificity of 94%
Visual observation as reference		
Rawashdeh et al., 2016	Detection and classification approach to count number of times certain motion gestures occur	Bland-Altman statistics: average difference between algorithm and observation for throwing: −0.45: for volleyball hits: −0.55

RMSE: Root mean square error; r: correlation coefficient; VAS: visual analogue scale; SST: simple shoulder test; DASH: disabilities of the arm, shoulder and hand questionnaire; ASES: American Shoulder and Elbow Surgeons shoulder score.

[a] indicates studies involving persons with shoulder disorders.

4. Discussion

Being able to objectively measure shoulder function and performance in an easy, unconstraint way during daily, functional activities, would improve the quality of evaluation in clinical research and practice. IMU-based measurements have the potential for such easy-to-perform and functional evaluations since IMU-systems are portable and do not suffer from complexity, space-constraints and expensiveness.

By placing an IMU on each body segment of interest, the relative motion between two consecutive segments can be calculated, and relevant and interpretable IMU-outcomes such as joint angles can be calculated. However, some considerations should be taken into account when using IMUs. Firstly, although the orientation of an IMU can be estimated by integration of the angular velocity measured by its tri-axial gyroscope, this process is prone to orientation drift problems [59]. In an attempt to resolve this, tri-axial accelerometers and magnetometers are included in IMUs to simultaneously estimate the sensor inclination with respect to the earth's vertical axis (based on gravitational acceleration) and the sensor's heading with respect to the magnetic north. Combining the three estimates (orientation by gyroscope, inclination by accelerometer and heading by magnetometer) is thus a prerequisite for a stable orientation measurement over time. Secondly, since IMUs suffer for ferromagnetic drift due to nearby metal objects [60,61], ferrous materials in the close neighborhood should be avoided. Lastly, an accurate sensor-to-segment calibration is essential to establish the relation between each IMU's technical coordinate system and the corresponding human segment on which it is attached (segment coordinate system) [46]. Given the above-mentioned caveats with regard to the use of IMUs, studies assessing the psychometric properties of IMUs in terms of reliable and stable measurements over time and in terms of validity, are essential. In this review, these properties are assessed in 27 of 37 papers.

Another challenge for the use of IMUs in clinical shoulder research and practice is the translation from a technical tool to a clinical valuable tool. Proper determination of clinically relevant outcome variables complying with the needs of therapists in ambulatory practice is essential. Relevant outcomes from both a therapist's and a patient's point of view (e.g. arm use) were identified in this review.

In this discussion, methodological study considerations are described, followed by an integrated interpretation of results based on the studies with substantial and high quality. Finally, recommendations for future research are given.

4.1. Methodological considerations

Despite most papers (81%) were of substantial or high quality based on the Downs and Black checklist, methodological issues should be considered.

With regard to the included participants, the age-difference between healthy persons and persons with shoulder complaints in the

Table 3
Results of comparative studies.

Author, year of publication	IMU- outcome		Results
Joint angles			
Bouvier et al., 2015	3D humerothoracic kinematics during lab-based assessments	Comparison of three classes of calibrations: segment axes equal to technical axes (TECH), segment axis generated during a static pose, segment axis generated during functional movements	- The TECH calibration appeared less precise than the other calibrations for humerothoracic internal-external rotation during arm elevation in the sagittal and scapular plane
Cutti et al, 2014	Monolateral and differential prediction bands and intervals for scapulohumeral movement patterns and resting orientation	- Comparison between non-parametric Bootstrap approach and two parametric Gaussian methods to provide reference data for scapulohumeral patterns - Comparison between age-groups	- A mean coverage for Bootstrap from 86% to 90%, compared to 67%–70% for parametric prediction bands and 87%–88% for parametric intervals - Bootstrap prediction bands showed a distinctive change in amplitude and mean pattern related to older age, with an increase toward scapula retraction, lateral rotation and posterior tilt
Pellegrini et al, 2016	3D scapulohumeral coordination patterns	- Comparison of throwing side and contralateral side of baseball pitchers to age-stratified reference bands - Comparison of the throwing side before and after a 4week stretching or control protocol	- Both the throwing shoulder and the contralateral shoulder are within the age-stratified reference bands - 4 out of 6 pitchers that received stretching showed clear signs of scapulohumeral alterations, all toward the reference band mean patterns, indicating an improvement of the scapulohumeral coordination of the throwing side after stretching
van den Noort et al., 2015 [a]	3D scapulothoracic kinematics during lab-based assessments	Comparison between single and double anatomical calibration (scapula locator) versus standard calibration (sensor alignment to spina scapulae)	- Single and double calibration resulted in the measurement of more anterior tilt for all elevation angles during anteflexion and abduction. - Single and double calibration showed 7° less protraction and double calibration resulted in the measurement of more lateral rotation at higher abduction angles as compared to standard calibration (no significant differences)
Roldan-Jimenez and Cuesta-Vargas, 2016	3D glenohumeral and scapulothoracic joint angles and accelerations during lab-based assessments	Comparison between younger and older healthy adults	- During abduction movement, less glenohumeral flexion-extension and ab-adduction angular mobility and acceleration was found in older versus younger adults. Linear acceleration was furthermore higher for glenohumeral in-external rotation in older versus younger adults. - During flexion movement, less glenohumeral abduction angular mobility and less flexion-extension acceleration was found in older versus younger adults. For glenohumeral in-external rotation, linear acceleration was furthermore higher in older versus younger adults. - During abduction and flexion movement, less scapulothoracic pro-retraction and acceleration was seen in older versus younger healthy adults - During flexion movement, more scapulothoracic medial-lateral angular mobility was seen in younger versus older adults
Other outcomes			
Coley et al., 2007 [a]	Kinematic scores based on humeral angular velocity and acceleration during lab-based assessments	Comparison between healthy controls and persons after surgery Comparison between pre- and postsurgical measurements in patients	- Significantly between the pre-surgical and post-surgical measurements at 3 and 6 months post-surgery in persons with shoulder pathology. - Significant differences between healthy persons and persons with shoulder pathology at each measurement (pre-surgical measurement and post-surgical measurements)
Coley, Jolles, Farron, Pichonnaz, Bassin, Aminian, 2008	Arm position in terms of duration and frequency during long-term daily life monitoring	Comparison between dominant and non-dominant arm side	- Arm position in terms of duration and frequency did not differ between dominant and non-dominant arm sides in healthy persons
Crabolu et al., 2017	Gleno-humeral joint center	Comparison between estimation methods and experimental conditions	- No differences in gleno-humeral joint center estimation between experimental conditions were found. - the highest accuracy and precision is found for a variant of the 'null acceleration point' algorithm proposed by Crabolu et al (2016)
Cutti et al, 2016 [a]	Scapula-weighted Constant Murley Score	- Comparison between Scapula-weighted Constant-Murley Score and the original Constant-Murley Score	- Both scores were significantly different, with differences between the estimated marginal means increasing from 6.5 to 10.25 points at 45 days and > 6 months after arthroscopically rotator cuff surgery respectively
		- Comparison of Scapula-weighted Constant-Murley Score between 4 different post-surgical time points	- At each time point (45 days, 70 days, 90 days, and after 6 months), the Scapula-weighted Constant-Murley Score was significantly different from each

(continued on next page)

Table 3 *(continued)*

Author, year of publication	IMU- outcome		Results
			other ($p < 0.000$). Differences between 45 days and the other time points were above the MCID. Effect sizes were > 0.80
Duc et al., 2013 [a]	Quantity and quality of arm use as measured during daily routine monitoring	Comparison between healthy controls and persons after surgery	- Quantity of arm use was different between patients and controls at three months post-surgery
		Comparison between pre- and postsurgical measurements in patients	- Quality of arm use was different between patients and controls at three and six months post-surgery - Quantity of arm use illustrated a change in arm dominance due to the shoulder disorder whereas movement quality appeared to be independent of dominance and occupation and showed a change in movement velocity
Jolles et al., 2011 [a]	Kinematic scores based on humeral angular velocity and acceleration during lab-based assessments	Comparison between healthy controls and persons after surgery	- Significantly between the pre-surgical and post-surgical measurements at 3, 6 and 12 months after surgery in persons with shoulder pathology
		Comparison between pre- and postsurgical measurements in patients	- Significant differences between healthy persons and persons with shoulder pathology at each measurement (pre-surgical measurement and post-surgical measurements)
Korver, senden et al., 2014 [a]	Asymmetry and relative asymmetry scores during lab-based assessments	Comparison between healthy controls and persons after surgery	- Patients had during a pre-surgical measurement significantly higher asymmetry and relative asymmetry scores than healthy subjects
		Comparison between pre- and postsurgical measurements in patients	- A significant decreased asymmetry and relative asymmetry score (improvement) was seen five years after treatment in patients
Pichonnaz, duc et al., 2015 [a]	Arm usage	Comparison between healthy controls and persons after surgery	- At 3 months post-surgery, shoulder patients had a significant arm underuse of 10.7% in comparison to healthy controls
		Comparison between pre- and postsurgical measurements in patients	- The patients only recovered to normal arm usage within 12 months, regardless of surgical side

[a] indicates studies involving persons with shoulder disorders.

comparison studies was remarkably high, i.e. on average 31 (± 8) versus 55 (± 5) years of age for healthy persons and persons with shoulder complaints, respectively. Younger controls were recruited to ascertain that no unrecognized shoulder pathology was apparent [30,35]. However, this age-difference makes result-interpretation not straightforward, as it is clearly indicated by Cutti et al. (2014) and Roldan-Jimenez and Cuesta-Vargas (2016) that shoulder kinematics are depending of age (Table 3) [20,45]. As such, it is not clear whether the reported study-results are either age-related or related to the shoulder disorder. Since the reported kinematic scores are furthermore calculated relative to the non-painful shoulder in shoulder patients (above 50 years of age) [29], it is clear that the healthy control population should also have been recruited from the same age category.

This review furthermore clearly indicates that no IMU-based kinematic research currently focusses towards the measurement of the shoulder as a part of the upper limb chain in shoulder patients. Since the shoulder consists of three separate joints (i.e. the sternoclavicular and acromioclavicular joint and the glenohumeral joint) and one pseudo-articulation (i.e. the scapulothoracic joint), which move by coordinated muscular actions in close cooperation with each other and with the elbow and trunk, this is a shortcoming for clinical decision-making and to plan therapy in case of shoulder disorders. Furthermore, this review demonstrated that 26 of the included papers (70%) only provided joint angels and derivative kinematic scores based on the movement of the humerus relative to the thorax (humerothoracic), thereby neglecting part of the degrees of freedom in the shoulder complex, i.e. the movement of the scapula relative to the thorax (scapulothoracic) and to the humerus (glenohumeral). Unfortunately, kinematic parameters derived from the non-specific humerothoracic movement are only of limited clinical value as they give no indication whether impaired or altered movement is situated either in the glenohumeral or the scapulothoracic joint, which is important information for adopting rehabilitation strategies toward the specifically impaired joint. Eleven papers (30%) did describe specific outcomes of the scapulothoracic or glenohumeral joint. Apart from two papers [14,15], all these papers were highly qualitative research, mainly on agreement/reliability of scapulothoracic joint angle assessment [37–40,47], scapulothoracic reference data [20], age-related differences in scapulothoracic joint kinematics by means of IMUs [20,45] and the development of a modified Constant-Murley Scale, including scapulothoracic kinematic information [8]. All above-mentioned research only applied a kinematic measurement protocol consisting of analytical movements (arm elevation in different movement planes). Since evidence suggest that analytical measurements do not resemble real life daily movements, this might seem like a shortcoming [62]. However, although standardized movements are not representative of daily living tasks, their proper execution is a foundation for proper daily living movements. Arm elevation is an easy to perform, non-invasive, but sensitive task that provides valuable information on scapular changes associated with shoulder pathology [7,63]. It is an easy way to have a benchmark to compare different subjects that can be used in clinical practice, in contrast to daily living tasks which are more difficult to standardize and do vary in importance among persons. Furthermore, in the management of altered glenohumeral and scapulothoracic motor control in persons at risk for developing shoulder pathology and/or pain, arm elevation is the first dynamic movement that will be trained [64].

The applied methodology, terminology, and statistics, and the reported results of several included agreement/reliability studies ask for discussion. IMU-based joint angles are often compared to joint angles of opto-electronical reference assessments. There are guidelines formulated by the International Society of Biomechanics for the analysis of three-dimensional movement of the upper limb [65]. The majority of validity studies included in this review however failed to adhere to these guidelines, making the reported validity results of limited value [14,19,24,25,41,48]. Another methodological inaccuracy in several studies is that only one sensor, located on the humerus, was applied to calculate kinematic scores based on humeral acceleration and angular rate [13,17,18,22,25,29,31,32,34,36]. In this, it is assumed that the thorax does not move during the measurement, which seems however unrealistic. With regard to terminology, the terms repeatability, agreement, reliability and reproducibility were often erroneously and inconsistently used [16,22,57]. Furthermore, inappropriate statistics were often applied to assess these constructs. Regarding reliability statistics, the value of the reported ICCs is limited as they were reported without measurement errors [16,18,22,36,57]. Since ICCs are influenced by the inter-subject variability, poor reliability can be hidden by great inter-subject variability. As such, ICCs should always be interpreted together with their measurement errors [66]. To assess overall waveform similarities, the intra- and inter-protocol coefficients of multiple correlation (CMC) were used [55,56]. In general, the CMC measures the overall similarity of waveforms. The original within- and between-day (intra- and inter-session, respectively) CMC (taking concurrent effects of differences in offset, correlation, and gain into account) [56], was reformulated by Ferrari et al. (2010) [55] to assess the inter-protocol similarity, i.e. to investigate the effect of different measurement systems on waveform similarity. As such, it is important to formulate which type of CMC was used in the analysis. This was properly done by Bouvier et al. (2015) [48], Fantozzi et al. (2015)[44], Picerno et al. (2015) [22] and Parel et al. (2012) [38]. These studies furthermore reported CMCs together with their measurement errors [22,38,41,48]. To end, data was in some studies interpreted based on a non-statistical analysis, i.e. it was purely done by means of on data-observation [15,18,29].

4.2. Integrated result interpretation

4.2.1. Scapulothoracic and glenohumeral joint angles

High quality research was performed on the repeatability, reproducibility and reliability of scapulothoracic joint angle assessment by means of IMUs by Parel et al. (2012, 2014) and van den Noort et al. (2014, 2015) [37,38,40,49]. In their papers, the ISEO protocol was applied [10] which was based on three inertial sensors located on the thorax, scapula and humerus, and categorized on the ICF function level. In this protocol, a standard calibration procedure (sensor-to-segment calibration) was applied. This means that the sensor is aligned perpendicular with the spina scapulae while standing in static upright posture. Results indicated high intra-protocol agreement (intra-observer 'repeatability') and reliability (as assessed with SEM [40], RMSE and LoA [37], and ICC [40]), high inter-observer agreement ('reproducibility') and reliability (as assessed by SEM [38,40], CMC$_2$ and concurrent MDD values [38] and ICC [40]) and good inter-protocol agreement (as assessed with RMSE and LoA) for scapulothoracic medial-lateral rotation up to 120° of elevation in the sagittal and frontal plane [37]. Scapulothoracic protraction-retraction was in agreement between protocols for a smaller range of humeral elevation [37]. However, in this last study, very strict conditions for inter-protocol agreement were followed [37]. Furthermore, van den Noort et al. (2015) evaluated the effect of additional calibration, by means of a scapula locator with an inertial sensor [39], on scapulothoracic joint angles. Additional calibration resulted in similar protraction and lateral rotation angles during arm elevation in the frontal and sagittal plane and increased anterior tilt in all elevation angles [39]. These results might indicate that, when using the standard ISEO-protocol calibration, anterior tilt angles can be under-estimated [39]. It might be of interest to further investigate in which situations the application of such an additional calibration is of interest, like in persons with higher body mass indexes where soft-tissue artefacts can be expected [39].

Furthermore, the paper of Cutti et al. (2014) on reference values of scapulothoracic joint angles, assessed by means of the ISEO protocol, is highly valuable from both a clinical and research perspective [20,67]. It provides monolateral and differential reference data of different age-categories, which are fundamental for the assessment of kinematics of pathologic shoulders and can be used to further fine-tune rehabilitation strategies based on rehabilitation outcomes. Moreover, based on this work [20], a modified version of the Constant-Murley Score could be developed, i.e. the Scapula-Weighted Constant-Murley Score [8] which accounts for scapulothoracic movement as assessed by the ISEO-protocol. In this Scapula-Weighted Constant-Murley Score, two factors which are calculated based on kinematic scapulothoracic data of an individual with respect to the reference values as reported in [20], were added to the original Constant-Murley Score. The fact that the Scapula-Weighted Constant-Murley Score is responsive to change and measures differences which are higher than the minimal clinical important difference [8], makes it appropriate to use in rehabilitation.

4.2.2. Humerothoracic joint angles

Based on research with substantial to high quality, the maturity of IMUs to measure humerothoracic joint angles with sufficient reliability and intra- and inter-protocol agreement, was only assessed and proven to a limited extend. During an analytical measurement protocol, intra- and inter-protocol agreement was low for humeral internal/external rotation [48], and reliability results were high for ab-adduction [22]. During functional movement protocols in a laboratory setting, inter-protocol agreement for the three humerothoracic rotations seemed good but reliability or repeatability results were lacking [24,25,29,44,57]. In a long-term field assessment, i.e. daily parlour work [41], the intra- and inter-protocol agreement of the degree of shoulder elevation was reported to be acceptable. However, 3D humerothoracic joint angles were not examined.

Yet, apart from the incomplete data about the psychometrics of IMUs to measure humerothoracic joint angles, there is only limited added value for humerothoracic joint angle measurement in the assessment of shoulder function, i.e. there is only clinical relevance if a distinction between humerothoracic and glenohumeral joint angles is made.

4.2.3. Other outcomes

Low to moderate agreement results (i.e. results from correlation analysis, as summarized in Table 2) and high discriminative validity results (i.e. results from the comparative studies, as summarized in Table 3) indicate that other outcomes, such as quantity and quality of arm use [30–32], might have an added value to assess arm function, next to currently used questionnaires. However, whether these scores and outcomes can be assessed reliable and in a repeatable manner is currently not known. Furthermore, as mentioned above, the clinical value of these outcomes is limited since they are not able to differentiate between glenohumeral or scapulothoracic functioning. Furthermore, apart from Jolles et al. (2011) [35], all research on these other outcomes only applied a humeral sensor to make their calculations.

4.2.4. Future directions

Portable sensors do not suffer from space constraints, and thereby make in-field measurements possible, e.g. in ambulatory settings, work places, sport centers, patients home, etc. This was already the case for several measurements, which were included in this review, e.g. [8,20,26–28,30,32,38,43]. Future research using IMUs should thus further profit from this advantage of IMUs. Constraint analytical tasks do not resemble daily living tasks. Ideally, future assessment protocols are developed for patient-specific functional tasks and are combined with long-term monitoring of shoulder characteristics during daily activities. This objective information would enhance shoulder evaluation as it assesses the natural and voluntary movement of the patient in an unconstrained setting. However, the repeatability and reproducibility from such functional protocols has to be assessed first.

The evaluation of shoulder functionality based on IMUs should furthermore go further than the assessment of joint angles, range of motion and outcomes based on velocity and acceleration. The outcomes 'movement smoothness', 'movement path' and 'trajectory length' might to be considered as well since they might also represent the functional status of a joint [68]. These parameters are already assessed in neurological disorders, such as stroke, but are probably also relevant parameters in musculoskeletal rehabilitation, in case of motor control disorders, like scapular dyskinesia or secondary subacromial impingement. Furthermore, outcomes should be chosen in accordance with the specific needs of the clinician. Range of motion is probably more important in pathologies such as frozen shoulder, whereas trajectory length and movement fluency are of value when motor control is impaired. Finally, outcomes from multiple segments in the upper limb chain (trunk, shoulder complex, elbow), or at least from all segments being part of the shoulder complex (trunk, scapula, humerus), need to be captured. Results of all segments can then be integrated to enhance correct clinical decision making and therapy planning.

5. Conclusion

In conclusion we can state that different IMU-outcomes are introduced and assessed during protocols located on the ICF function and activity level. Scapulothoracic joint angles can be assessed in a repeatable, reliable and reproducible manner, and a scapulothoracic valuable reference data set of different age categories is available. Furthermore, a questionnaire, which takes scapulothoracic kinematics into account, is developed. Former results are moreover assessed in highly qualitative papers. However, the clinical relevance of most research is still limited due to (1) methodological limitations in terms of correct psychometric properties assessment, (2) the focus on the humerothoracic joint instead of the scapulothoracic and glenohumeral joint, (3) the limited research assessing the complete upper limb chain in shoulder patients and (4) the limited number of high quality study protocols located on the 'actual performance sublevel' of the ICF activity level. As such, the assessment of the whole upper limb chain, including the scapulothoracic and glenohumeral joint, during analytical and functional tasks, might be implemented in future research to provide clinical meaningful information for shoulder research and clinical practice.

Conflict of interest statement

None to declare.

Acknowledgements

This study is part of the Limburg Clinical Research Program (LCRP) UHasselt-ZOL-Jessa, supported by the foundation Limburg Sterk Merk, province of Limburg, Flemish government, Hasselt University, Ziekenhuis Oost-Limburg and Jessa Hospital. The funding organizations did not have a contribution to the creation of this systematic review.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2017.06.025.

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