

Collecting shoulder kinematics with electromagnetic tracking systems and digital inclinometers: A review

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Abstract

The shoulder complex presents unique challenges for measuring motion as the scapula, unlike any

other bony segment in the body, glides and rotates underneath layers of soft tissue and skin. The ability for clinicians and researchers to collect meaningful kinematic data is dependent on the reliability and validity of the instrumentation utilized. The aim of this study was to review the relevant literature pertaining to the reliability and validity of electromagnetic tracking systems (ETS) and digital inclinometers for assessing shoulder complex motion. Advances in technology have led to the development of biomechanical instrumentation, like ETS, that allow for the collection of three-dimensional kinematic data. The existing evidence has demonstrated that ETS are reliable and valid instruments for collecting static and dynamic kinematic data of the shoulder complex. Similarly, digital inclinometers have become increasingly popular among clinicians due to their cost effectiveness and practical use in the clinical setting. The existing evidence supports the use of digital inclinometers for the collection of shoulder complex kinematics as these instruments have been demonstrated to yield acceptable reliability and validity. While digital inclinometers pose a disadvantage to ETS regarding accuracy, precision, and are limited to two-dimensional and static measurements, this instrument provides clinically meaningful data that allow clinicians and researchers the ability to measure, monitor, and compare shoulder complex kinematics.

Key words: Biomechanics; Glenohumeral; Kinematics; Reliability; Scapulothoracic; Validity

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Core tip: This review compiles the available evidence regarding the accuracy and precision of measuring glenohumeral and scapulothoracic motion with electromagnetic tracking systems and digital inclinometers. These instruments have been found to be adequately reliable and valid with the majority of measurement error originating from operator inaccuracies associated

with palpation.

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INTRODUCTION

The ability to objectively measure shoulder complex kinematics is key to gaining a thorough understanding of normal and abnormal movement, and may assist clinicians in the diagnosis and management of shoulder dysfunction^[1]. Earlier studies^[2,3] exposed participants to potentially harmful radiography in order to assess static two-dimensional motions of the shoulder complex that may inaccurately describe what is actually occurring three-dimensionally^[4,5]. Subsequently, technological advances have allowed for noninvasive three-dimensional analysis of glenohumeral and scapulothoracic kinematics utilizing electromagnetic tracking systems (ETS)^[6-11]. The main obstacle to analyzing three-dimensional shoulder movements is the difficulty of tracking the movements of the scapula. Unlike the upper and lower extremity segments, the scapula glides and rotates underneath layers of soft tissue and skin requiring investigations into the ability to accurately and repeatedly measure scapular kinematics using noninvasive measures^[7-9,11-20]. Furthermore, other real limitations exist in that these systems are neither cost effective nor practical for the clinical setting^[21,22]. Due to these difficulties, other methods of measuring shoulder complex kinematics that are easily accessible in the clinical setting have been investigated^[21-23].

The availability of reliable and valid clinical instrumentation enables clinicians to make sound clinical decisions that are effective, efficient, and safe. Clinically accessible methods have been established that qualitatively and quantitatively assess scapular resting position and scapular orientation during humeral elevation^[24-28]. Of the two, quantitative methods improve objectivity that may lead to decreased clinician error. Several studies have utilized the digital inclinometer to investigate various kinematic measures of the shoulder complex. While a three-dimensional analysis provides a thorough investigation of glenohumeral and scapulothoracic kinematics, the digital inclinometer provides clinicians with a more simplistic mean of analyzing kinematic data.

Instances in the literature exist where inclinometers were validated against three-dimensional scapular kinematic data collected by ETS^[21,23]. Other studies have established criterion-related validity and reliability of other clinical instruments against data collected with a digital inclinometer^[22]. To our knowledge no articles have been published that review the reliability

and validity of ETS and digital inclinometers as measurement tools for collecting shoulder complex kinematics. The purpose of this paper is to provide such a review, with emphasis placed on the various factors, methods and motions that affect reliability and validity, and selected clinical applications utilizing these instruments.

ETS

ETS permit investigators the ability to track the position and orientation of sensors in space. These systems utilize an electromagnetic transmitter that generates an electromagnetic field and a series of sensors tethered to a computer system. Combined, the transmitter and computer system are able to detect the location and orientation of the sensors allowing for the six degrees of freedom required for three-dimensional analysis. In the field of biomechanics, these sensors can be mounted to the surface of the skin overlying various anatomical landmarks that enables the measurement of body segment kinematics. Currently, there are two ETS (Polhemus, Colchester, VT and Ascension Technology Corporation, Burlington, VT) that are commonly used in the study of biomechanics. In order to acquire and analyze data collected by the hardware, users must either write their own code using a commercially available product such as MATLAB (The MathWorks, Inc., Natick, MA) or purchase a commercially available software interface system, such as MotionMonitor[®] (Innovative Sports Training, Inc., Chicago, IL) that is a comprehensive turnkey data acquisition and analysis system. As it relates to data acquisition and analysis, post-treatment analysis of the data is performed to quantify shoulder kinematics. Presently, in order to facilitate the reporting of shoulder kinematics among researchers and clinicians, the International Society of Biomechanics has published standards for joint coordinate systems and rotation sequences for the thorax, clavicle, scapula, and humerus^[29].

Calibration

Accuracy and precision are necessary in order to effectively utilize any data that is collected by laboratory/clinical instruments. Ascension has published information regarding accuracy for the Flock of Birds (FOB) system with root mean square (RMS) errors of 7.62 mm for linear position and 0.5° for orientation. However, the environment in which these data were attained is unclear. It is well understood that metallic objects within the vicinity of the electromagnetic transmitter will alter the magnetic field, thus affecting accuracy of the ETS^[30,31]. Milne *et al*^[30] demonstrated significant alterations in measurement accuracy (positional difference of 5.26 cm and angular difference of 9.75°, $P < 0.001$) when mild steel was introduced into the electromagnetic field of the ETS. They collected the kinematic data utilizing the default settings with a sampling frequency of 103 Hz. LaScala *et al*^[31] investigated different sampling frequencies and their effects on accuracy when aluminum

and steel were introduced into the electromagnetic field. While both materials had significant effects ($P < 0.0001$) on measurement error, a significant interaction of sampling frequency and metal type ($P < 0.0001$ - 0.0016) indicated errors in all three coordinates. The FOB system was found to be more accurate at lower frequencies (*i.e.*, 20 Hz) when aluminum was placed within the electromagnetic field, whereas the system was more accurate at higher frequencies (*i.e.*, 120 Hz) when steel was present^[31]. Therefore, users of ETS should be cognizant of their testing environment and utilize calibration procedures to adjust for interferences created in the electromagnetic field.

Earlier studies^[6,7,9,10,13] investigating scapular kinematics utilizing ETS were limited to static measurements through a given range of motion. Meskers *et al.*^[32] investigated the accuracy of the FOB system before and after a static calibration procedure. Positional measurements were collected in a 1 m³ space located 1 m above the floor utilizing a stylus. The error calculated prior to calibration was unacceptably high with RMS errors of 20.8 mm (x-coordinate), 22.2 mm (y-coordinate), and 20.4 mm (z-coordinate). The authors attributed these errors due to a large disturbance of the electromagnetic field caused by metal in the testing environment, particularly the steel reinforced concrete floors. After calibration, the RMS errors were reduced to acceptable levels of 3.24 mm (x-coordinate), 5.64 mm (y-coordinate), and 2.73 mm (z-coordinate). Further, when removing measurements taken closest (1 m) to the steel reinforced concrete floor, RMS error measurements improved to 2.07 mm (x-coordinate), 2.38 mm (y-coordinate), and 2.35 mm (z-coordinate)^[32]. Others have reported static RMS errors of 5.3 mm in position, 3.1 mm in linear displacement, and 0.23° in orientation and have suggested that system accuracy be established for each testing environment^[14].

As methodologies^[4,8,33] have evolved, the collection of dynamic scapular kinematics has become the norm; therefore, an understanding of the dynamic accuracy of the FOB is necessary. McQuade *et al.*^[34] investigated the dynamic accuracy and repeatability of the FOB utilizing a dynamic pendulum calibration technique. RMS errors were reported for position (3.7-10 mm), angular displacement (0.3°-0.5°), and angular velocity (1.1°-2.2°/s). In addition, the authors suggested that studies examining motions with speeds greater than 250°/s would incur large errors in accuracy^[34]. Therefore, studies investigating high velocity uncontrolled athletic movements should use caution in the reporting of results.

Scapula tracking methods

The ability to accurately and precisely track dynamic movements of the scapula in a noninvasive manner has been a limiting factor in analyzing detailed kinematics of the shoulder complex. The current gold standard for tracking scapular kinematics involves use of invasive, transcutaneous, cortical pins being placed in the scapular spine^[4,8]. While this method allows for

dynamic assessment of scapular motion, it is obviously undesirable in large-scale clinical studies. Nonetheless, cortical pins provide a means of directly collecting bony kinematic data that may be less comfortable for the patient. The usefulness of this methodology can be seen in the study by Karduna *et al.*^[8] in validating the scapular tracker and acromion method, both being noninvasive methods. Three noninvasive methods have been described for use with an ETS to track scapula orientation: Scapula locator, scapula tracker, and acromion method. Each of these noninvasive methods have been described and validated based on the associated measurement error when comparing novel approaches.

Scapula locator: Johnson *et al.*^[13] first described the scapula locator as a means to record three-dimensional scapular orientations in space. The measurement jig consisted of a housing that supports three rods that could be positioned over the posterolateral acromial angle, the root of the scapular spine, and the inferior angle of the scapula. An electromagnetic sensor affixed to the jig allowed orientation of the locator, relative to the thorax, to be recorded by an ETS during quasi-static trials. Quasi-static trials involved the participant moving to selected positions and holding those positions while the scapula locator was used to collect orientation data. This apparatus eliminated the need to individually digitize the three anatomical landmarks as described by van der Helm^[10], which decreased error and increased speed of analyses^[7,13].

Three studies evaluated the reliability of the scapula locator and found it to be applicable in three-dimensional kinematic studies of the scapula^[7,9,21]. Johnson *et al.*^[13] reported 95% confidence interval ranges for intra-observer and inter-observer errors. They reported intra-observer errors ranging from 0.89° to 2.34° for anterior-posterior tilt, 0.91° to 1.87° for medial-lateral tilt, and 1.05° to 2.69° for upward-downward rotation, while inter-observer errors ranged from 4.98° to 7.88°, 4.5° to 6.04°, and 5.64° to 11.02°, respectively. Following designed modifications and improvements, Barnett *et al.*^[9] reported 95% confidence intervals for inter-observer errors that ranged from 2.55° to 2.72° for anterior-posterior tilt, 3.57° to 3.63° for medial-lateral tilt, and 3.47° to 3.85° for upward-downward rotation. Similarly, Meskers *et al.*^[7] reported standard deviations for inter-observer errors, which were 2.73° to 2.87° for anterior-posterior tilt, 2.98° to 3.21° for medial-lateral tilt, and 3.80° to 3.91° for upward-downward rotation. In addition to inter-observer errors, they reported inter-trial (1.93°-1.96°; 2.26°-2.46°; 2.37°-2.53°; respectively), inter-day (2.83°-3.03°; 4.01°-4.17°; 3.43°-3.73°; respectively), and inter-subject (7.81°-8.02°; 7.86°-9.02°; 6.05°-7.04°; respectively) variability^[7].

The reported error measures for the scapula locator indicate sufficient reliability for its use in clinical research^[7,9,13]. The fairly low inter-day error measures reported by Meskers *et al.*^[7] demonstrates

the ability to reliably align the scapula locator with adequate precision, especially considering the amount of error that may be associated with identifying anatomical landmarks. In a more recent modeling study, Langenderfer *et al.*^[20] indicated that variability in scapular kinematic descriptions could range as high as 11.7° in anterior-posterior tilt, 16.6° in medial-lateral tilt, and 12.3° in upward-downward rotation when allowing for 4 mm in anatomical landmark variability. Nonetheless, Meskers *et al.*^[7] reported considerably smaller errors caused by palpation when digitizing the anatomical landmarks with the scapula locator (0.53°-1.52°). Although the scapula locator has been demonstrated to be a reliable method for measuring quasi-static scapula kinematics, its relevancy falls short given the inherent dynamics of normal human movement. Furthermore, the locator has not been compared against the gold standard method to establish accuracy.

Scapula tracker: Karduna *et al.*^[8] first described the scapula tracker as a valid method for noninvasive tracking of three-dimensional scapula motions. The scapula tracker was a custom made plastic jig made of three parts: A base, an arm, and a footpad. The base was affixed to the skin overlying the spine of the scapula. The attached arm was adjustable to reach the acromion, which was affixed to the flat part of the acromion *via* the footpad. An ETS sensor was connected to the base of the scapula tracker that allowed dynamic tracking of three-dimensional scapula kinematics. The scapula tracker was compared to simultaneous measurements captured by a sensor attached to transcutaneous cortical pins that were drilled into the spine of the scapula. In an effort to validate the scapula tracker, the authors reported RMS errors of 3.2° to 10° for all scapular orientation angles (anterior-posterior tilt, medial-lateral tilt, and upward-downward rotation) during four active motions of the shoulder complex (scapular plane elevation, sagittal plane elevation, horizontal abduction, and external rotation). Interestingly, while most efforts to validate an instrument involve an assessment of concurrent validity through correlation analyses, an evaluation of RMS error was utilized instead. In these instances, while no acceptable level of error was defined, investigators sought to define methods that resulted in as little error as possible. Given the nonlinear nature of the data, the use of RMS appears to have served as an appropriate alternative for establishing validity. No articles were found that specifically addressed reliability for the scapula tracker.

Acromion method: The acromion method is a skin-fixed method by which an ETS sensor is adhered to the flat surface of the acromion that allows noninvasive tracking of three-dimensional scapula motions^[8,33,35]. This method allows for dynamic tracking of the scapula that does not restrict the motions of subjects, is more comfortable, reduces the data collection time and

motor noise associated with other palpation methods (*i.e.*, scapula locator), and does not require a custom designed piece of equipment (*i.e.*, scapula locator and scapula tracker)^[11]. Karduna *et al.*^[8] established concurrent validity of the acromion method against an invasive method whereby an ETS sensor was attached to transcutaneous cortical pins that were drilled into the spine of the scapula. They reported RMS errors of 3.7° to 11.4° for all scapular orientation angles (anterior-posterior tilt, medial-lateral tilt, and upward-downward rotation) during four active motions of the shoulder complex (scapular plane elevation, sagittal plane elevation, horizontal abduction, and external rotation). Generally, the acromion method underestimated the bone fixed measurements; however, upward rotation was overestimated^[8]. In contrast, Meskers *et al.*^[11] found the acromion method underestimated all scapular orientation angles by an average of 6.5° (maximally 13°) when compared to measurements obtained with a scapula locator.

Karduna *et al.*^[8] found that RMS errors increased for all scapular orientation angles as humeral elevation increased indicating the presence of skin motion artifacts. Due to the relationship of error and elevation, they indicated that the acromial method was acceptable for tracking scapular motions below 120° of elevation. A systematic error pattern was identified for upward rotation; therefore, the authors presented a correction model that reduced the overall RMS error of upward rotation from 6.3° to 2°. In likeness, Meskers *et al.*^[11] was able to reduce RMS errors for scapular orientation angles to approximately 2° when applying a linear regression model to correct skin motion artifact to improve the RMS error calculated between the acromion method and scapula locator. It was confirmed that measurement error increased as elevation increased indicating the sensor was sensitive to skin motion artifact^[11]. In contrast, Lin *et al.*^[16] found no significant differences or significant correlations in scapular orientation angles that would have suggested skin motion artifact. They concluded that skin motion artifact had little impact on the scapular kinematics when evaluating four functional tasks.

Alternate methods to improve accuracy of tracking scapular motions, which have been described as less complex than skin motion artifact correction models, have been proposed in studies utilizing optoelectronics tracking systems^[36,37]. Brochard *et al.*^[36] developed a double calibration technique of the local scapula coordinate system that resulted in lowered RMS errors ranging from 2.96° to 4.48° as compared to the larger RMS errors of a single calibration (6°-9.19°). Shaheen *et al.*^[37] reported that optimal positioning of the acromial marker (the meeting point of the spine of the scapula and acromion) and angle of abduction (90° of shoulder elevation) during the initial calibration of the local scapular coordinate system resulted in improved RMS errors (3° to 5°). While the reduction in RMS errors reported by Brochard *et al.*^[36] and Shaheen

Table 1 Electromagnetic tracking system reliability of scapular measures during isolated planar motion of the humerus

Ref.	Motion studied		Reliability coefficient		Measurement error	
Thigpen <i>et al</i> ^[15]	Dynamic	Ascending	CMC		RMS	
		Sagittal	Inter-trial	0.88-0.97	1.35°-1.74°	
		Scapular	Within-day,	0.74-0.94	3.43°-5.18°	
		Frontal	Inter-session			
			Inter-day	0.68-0.94	4.27°-6.65°	
Ludewig and Cook ^[33]	Dynamic	Ascending	ICC		SEM	
		Scapular	Inter-trial	0.93-0.98	< 3.3°	
Scibek and Carcia ^[14]	Quasi-static	Ascending	ICC			
		Sagittal	Inter-trial	0.95-0.99		
		Scapular	Inter-day	0.36-0.98		
		Frontal				
Roren <i>et al</i> ^[18]	Dynamic	Ascending	ICC		SEM	SRD
		Sagittal	Inter-trial	0.83-0.98		
		Frontal	Inter-day,	0.76-0.95	0.56°-1.61°	1.54°-4.47°
			Intra-observer			
			Inter-day,	0.49-0.92	0.89°-3.57°	2.46°-9.89°
			Inter-observer			
Haik <i>et al</i> ^[19]	Dynamic	Ascending and descending	ICC		SEM	MDC
		Sagittal	Inter-trial	0.92-0.99	0.86°-3.17°	
			Inter-day	0.54-0.88	2.77°-7.44°	6.43°-17.27°

CMC: Coefficient of multiple correlation; ICC: Intraclass correlation coefficient; RMS: Root mean square; SEM: Standard errors of measurement; SRD: Small real difference; MDC: Minimal detectable change.

et al^[37] were not as substantial as Karduna *et al*^[8] and Meskers *et al*^[11], the simplicity of the techniques are appealing. Therefore, investigation into the utilization of these calibration techniques^[36,37] with ETS is warranted.

The reliability of tracking scapular motion during isolated humeral planar motions with ETS utilizing the acromion method has been relatively strong over time (Table 1). Inter-trial and within-day, inter-session reliability in both healthy and impaired subjects has been demonstrated to yield good to excellent. In addition, inter-day, intra-observer reliability demonstrated moderate to excellent results in healthy subjects with the exception of Scibek and Carcia^[14] where inter-day reliability was found to yield fair to excellent results. Instances of lower inter-session or inter-day reliability may be due to anatomical landmark digitization error^[14,20] and sensor placement error^[11,14,37]. Thigpen *et al*^[15] suggested that scapular orientation angles should be collected in the sagittal plane in order to best detect changes in kinematics due to the larger CMCs (0.82-0.94) and smaller RMS errors (3.43°-5.76°) compared to the scapular and frontal planes. With the exception of Scibek and Carcia^[14], similar results were reported by Roren *et al*^[18] (ICC = 0.77-0.93) and Haik *et al*^[19] (ICC = 0.70- 0.82) regarding inter-day, intra-observer reliability measures during sagittal plane elevation. However, less favorable results (ICC = 0.58-0.88) have been found for the

descending phase of motion in the sagittal plane^[19]. Regarding error in the sagittal plane, Roren *et al*^[18] found small SEM (0.69°-1.61°) and small real difference (SRD) (1.90°-4.47°) values, whereas Haik *et al*^[19] found relatively large SEM (2.77°-6.79°) and minimal detectable change (MDC) (6.43°-15.76°) values. These differences are likely due to the lower range of motion (0°-90°)^[18] studied as compared to the other two studies (30°-120°^[15] and 0°-120°^[19]) considering the known associated errors with higher levels of elevation^[8]. While these studies have demonstrated acceptable reliability for assessing scapular kinematics in isolated planar motion, the large SRD and MDC question the ability of ETS to detect meaningful changes in scapular kinematics. SRD and MDC measurements have substantial value to clinicians, especially when determining outcomes of an intervention.

Only two studies in the literature were found that investigated the reliability of tracking dynamic scapular orientation angles during functional movement patterns with ETS utilizing the acromion method^[16,18]. Lin *et al*^[16] investigated the reliability of tracking shoulder complex motions during four functional activities (overhead height task, shoulder height task, sliding a box task, and reaching for a salt shaker task). They reported inter-trial ICC values based on peak scapular orientation angles that ranged from 0.78 to 0.99 for kinematic descriptions of the shoulder complex (scapular orientation angles and humeral orientation angles). Measurement error

was reported with SEM values that were less than 2° for all kinematic variables. In addition, the authors reported Pearson bivariate correlation values that ranged from 0.81 to 0.97, which served as an index of similarity across the trials of the recorded movement patterns during each respective functional task. Roren *et al.*^[18] assessed the reliability of tracking two functional movement patterns (simulated back washing and hair combing) based on scapular orientation angles at rest, 30°, and 90° of humeral elevation (only rest and 30° for back washing). They reported ICC values that ranged from 0.83-0.98 for inter-trial reliability; 0.64 to 0.92 for inter-day, intra-observer reliability; and 0.35 to 0.89 for inter-day, inter-observer reliability. SEM values ranged from 0.77° (MDC = 2.12°) to 1.67° (MDC = 4.64°) for inter-day, intra-observer, and 1.05° (MDC = 2.91°) to 3.23° (MDC = 8.96°) for inter-day, inter-observer.

The repeatability of functional movement patterns has been demonstrated to yield good to excellent inter-trial reliability^[16,18]. While Lin *et al.*^[16] did not report inter-session or inter-day measures of reliability, Roren *et al.*^[18] demonstrated fair to excellent inter-day reliability. Of the two movement patterns, the hair combing movement pattern consistently demonstrated larger ICCs and smaller SEMs and MDCs. The authors speculated the less favorable measures of the back washing movement may be due to the subjects not being able to see the arm motion while looking ahead, thus not receiving visual feedback of the movement. Another note of importance that may have impacted the results of Roren *et al.*^[18] was that the authors utilized the original standardization protocol^[38] instead of the most current^[29]. Other studies have suggested higher measures of reliability were enhanced to restricting humeral elevation to one plane of motion for the collection of scapular kinematics^[14,15]. The results of these two studies have demonstrated the ability to repeatedly measure functional tasks of the upper extremity that involved multi-planar motions^[16,18]. However, some caution should be taken when comparing inter-day, inter-observer scapular kinematic data.

Humeral tracking method

As stated earlier regarding the tracking of scapular motions, the ability to accurately and precisely track dynamic movements of the humerus in a noninvasive manner is necessary to garner relevant data about shoulder complex kinematics. However, these types of studies are not applicable to large-scale clinical studies due to the invasive nature of the method. The most commonly used noninvasive method for tracking humeral kinematics with an ETS utilizes a hook-and-loop strap that secures a sensor to the surface of the upper arm (humeral cuff), and avoids the use of cortical pins making it more desirable for large-scale clinical studies.

Ludewig *et al.*^[39] simultaneously compared the tracking of humeral kinematics with a humeral cuff to a sensor affixed to an external humeral fixator in a single

subject. Dynamic three-dimensional kinematic data were collected for humeral elevation in the scapular and sagittal planes and internal and external rotation with the upper arm maintained at the side. Different Euler angle rotation sequences were used to describe humeral rotation angles with respect to the trunk (z , y' , z'') and scapula (y , x' , z''). The humeral cuff was found to closely match humeral rotation angles with maximal underrepresentation of external rotation of 5.7° during elevation in the scapular plane and 15.6° of external rotation with the arm at the side. RMS errors for humeral rotation angles ranged from 1.3° to 7.5° for all respective motions.

In an effort to establish a noninvasive method, LaScalza *et al.*^[40] compared humeral kinematic data collected with a humeral cuff against a bone-fixed sensor in five cadaver specimens. The scapula of each specimen was prevented from moving by being rigidly fixed to a testing apparatus. The arms were directed through several motions including abduction, flexion, external rotation, three simulated reaching tasks, and a simulated overhand throw. Measurement errors calculated for all humeral rotation angles between the humeral cuff and bone-fixed sensor were reported as SEMs that ranged from 0.0° to 1.5°.

Hamming *et al.*^[41] established concurrent validity of a humeral cuff against an invasive method whereby ETS sensors were attached to transcutaneous cortical pins that were placed into the clavicle, acromion, and humerus. They reported average errors for all humeral orientation angles (angle of elevation, plane of elevation, and axial rotation) during five dynamic motions of the shoulder complex (frontal plane elevation, scapular plane elevation, sagittal plane elevation, axial rotation with the arm at the side, and axial rotation with the arm at 90° abduction). For all five motions, the mean errors for the humeral orientation angles for angle of elevation and plane of elevation ranged from 1.0° to 2.3°. However, mean errors for the humeral orientation angles for axial rotation were much larger for all five motions. Mean errors during the five dynamic motions ranged from 4.8° to 5.5° for the three motions of elevation, whereas the mean errors for the two rotation motions ranged from 14.3° to 11.5° with maximal differences approaching 30°. Furthermore, the authors found that differences in body mass index impacted measurement error with significant increases when subjects had index measures greater than 25.

These studies validate the use of the humeral cuff for tracking humeral kinematics^[14,39-41]. In contrast to Ludewig *et al.*^[39], LaScalza *et al.*^[40] and Hamming *et al.*^[41] reported fairly large measurement errors for tracking humeral axial rotation during any type of shoulder complex motion. Furthermore, all three studies observed fairly slow movements (approximately $\leq 40^\circ/\text{s}$) limiting the effects of skin artifacts caused by inertial movements of the sensor during faster motions. The measurement error reported for all elevation movements may support the use of the humeral cuff based on the significant

effects that anatomical landmark digitization can have on humeral kinematic descriptions. Langenderfer *et al.*^[20] indicated that variability in humeral orientation angle descriptions could range as high as 7.3° for elevation angle, 15.8° for plane of elevation, and 11.3° for axial rotation when allowing for 4 mm in anatomical landmark variability. Nonetheless, caution should be used when interpreting measures of humeral orientation angles of axial rotation as the validity and reliability of this measure is questionable.

Although the aforementioned studies bring forth skepticism in utilizing the humeral cuff, other research has demonstrated its effectiveness in collecting kinematic data. Scibek and Carcia^[14] established criterion-related validity and reliability for their methodology of collecting shoulder complex kinematics. Quasi-static measurements of shoulder complex kinematics were collected during shoulder elevation in the sagittal, scapular, and frontal planes. Validity of the ETS was established against measurements collected with a digital inclinometer. Significant correlations ($P \leq 0.01$) determined validity of the ETS utilizing Pearson product-moment correlations that ranged from 0.85 to 0.99. The authors noted that angular measurements collected with the ETS for humeral elevation were consistently less than the inclinometer measurements ranging from -11.06° to 32.23°. Inter-trial reliability was reported with ICC values that ranged from 0.49 to 0.99, and inter-day reliability ICC values ranged from 0.05 to 0.99. While the inter-day reliability values appear to be less than favorable, the large majority of ICC values were found to be moderate to excellent.

DIGITAL INCLINOMETER

Many clinicians have limited or no access to state of the art three-dimensional biomechanical instrumentation for collecting kinematic data. Furthermore, clinicians do not have the time that is needed to set-up subjects, collect, and process the data collected with ETS. Clinicians need access to simple instrumentation that is both cost effective and practical to the clinical setting. The ability to quantitatively vs qualitatively measure shoulder movement is much more meaningful in the clinical setting. In addition, valid and reliable instruments provide clinicians with the ability to accurately measure, monitor, and compare changes in shoulder movement that may lead to better patient outcomes. The digital inclinometer has neither the ability to record three-dimensional nor dynamic shoulder movements. However, this tool provides clinically meaningful measures of two-dimensional shoulder kinematic data^[42,43].

Scapular measurements

The digital inclinometer has been demonstrated to be a valid instrument in measuring two of the three axes of scapular motion: upward rotation^[21] and anterior-posterior tilt^[23]. Johnson *et al.*^[21] and Scibek and Carcia^[23] established criterion-related validity of a modified digital

inclinometer against data collected with an ETS. Both studies utilized Pearson product moment correlations demonstrating strong relationships that ranged from 0.74 to 0.92 (mean differences 7° to 14°) for upward rotation^[21] and 0.63 to 0.86 (mean differences 3.66° to 4.75°) for anterior-posterior tilt^[23]. The smaller mean differences found with anterior-posterior tilt are most likely attributed to the smaller range of motion that occurs during humeral elevation as compared to the larger range of motion associated with upward rotation. Additionally, Johnson *et al.*^[21] compared static inclinometer measures to dynamic ETS measures with Pearson product moment correlations that ranged from 0.59 to 0.73. While the relationships were strong, the less favorable correlations reflected the expected inherent differences when comparing static to dynamic kinematics^[17]. Regression analyses indicated positive relationships between the digital inclinometer and ETS. Johnson *et al.*^[21] reported the inclinometer detected 0.92° to 1.20° of change for every 1° detected by the ETS for upward rotation while Scibek and Carcia^[23] reported slightly less favorable results with the inclinometer detected 1° of change in tilt for every 0.5° detected by the ETS for anterior-posterior tilt. It should be noted that Johnson *et al.*^[21] utilized participants with healthy and impaired shoulders while Scibek and Carcia^[23] utilized only healthy participants highlighting the need for further investigation into the clinical usefulness of measuring anterior-posterior tilt in unhealthy shoulders.

Regarding reliability, Johnson *et al.*^[21] reported intratester, inter-trial reliability with ICC values that ranged from 0.89 to 0.96, and SEM values that ranged from 2.0° to 2.8°. Similarly, Scibek and Carcia^[23] reported excellent inter-trial reliability with ICC values that ranged from 0.97 to 0.99. It appears that upward rotation can be repeatedly measured with acceptable consistency; however, no articles were found that have specifically assessed the reliability of assessing anterior-posterior tilt with a digital inclinometer.

Humeral measurements

Similar to scapular measurements, few investigations have reported on the validity of the utilization of digital inclinometers for humeral measurements. Two studies by Kolber *et al.*^[44,45] determined concurrent validity between measures collected with the inclinometer and a standard goniometer with ICC values for scaption (0.94), flexion (0.86), abduction (0.85), external rotation (0.97), and internal rotation (0.95) indicating good to excellent measures. Laudner *et al.*^[43] determined concurrent validity by measuring the relationship between horizontal adduction motion and internal rotation motion. Significant ($P < 0.01$) Pearson product moment correlations ranged from 0.52 to 0.72 between methods signifying an association of a loss of motion with contracture of the posterior capsular structures of the glenohumeral joint. While differences in methodology make comparisons difficult, these studies have demonstrated the digital inclinometer to be a valid instrument.

Two-dimensional measurements of shoulder motion utilizing a digital inclinometer has been demonstrated to exhibit moderate to excellent measures of reliability and validity. Similar to ETS, inter-observer measurements resulted in less than favorable reliability as compared to intra-observer measurements when utilizing digital inclinometers (Table 2). Therefore, caution must be taken when comparing angular measures of the shoulder complex that have been obtained by two different observers, and when measures are being compared that have been recorded from different instrumentation.

CLINICAL APPLICATIONS

Electromagnetic tracking systems and inclinometers have both shown to be both valid and reliable means of collecting shoulder complex kinematic data specific to movement of both humerus and scapula. When attempting to monitor clinical outcomes the ability to accurately quantify motions of these bony segments can provide useful data that could be used to drive clinical decision making. A variety of studies have demonstrated the usefulness of ETS in addressing clinically related questions, specifically those whose aim is to quantify shoulder kinematics associated with various shoulder patient populations.

Electromagnetic tracking systems have been useful in describing shoulder kinematics exhibited by the scapula and humerus in patients with rotator cuff pathology^[46-52]. Lukasiwicz *et al.*^[46] noted altered scapular kinematic patterns in patients presenting with shoulder impingement when compared to participants with healthy shoulders. Similarly, in a study designed to compare three-dimensional shoulder kinematics in subjects with and without shoulder impingement, McClure *et al.*^[52] noted differences in scapular kinematics between groups, which were attributed to compensation strategies utilized for glenohumeral weakness and shoulder motion loss. In a treatment based study McClure *et al.*^[48] assessed scapular kinematics in patients with shoulder impingements before and after a six week intervention. While patients noted improvements in pain and shoulder function, no changes were noted in scapular kinematics following the intervention program^[48]. Mell *et al.*^[47] utilized an ETS to identify variations in scapulohumeral rhythm between rotator cuff tear, tendinopathy, and healthy control subjects. Using the same equipment, others have investigated the role that pain and rotator cuff tear size has on scapulohumeral rhythm^[49,50] and shoulder movement velocity^[51]. Similarly, ETS have been utilized to capture three-dimensional scapular kinematics in patients with multidirectional instability^[53], in a patient that had undergone shoulder arthroplasty^[54], and in patients with frozen shoulders^[55,56]. In all but one case^[54], a noninvasive approach was utilized in conjunction with the ETS. In each case, data were obtained that enabled the clinicians to quantify the three-dimensional motion associated with the shoulder complex.

Electromagnetic tracking systems have also been

useful in some clinically based studies designed to monitor three-dimensional scapular kinematics following an intervention. Wang *et al.*^[57] utilized an ETS to monitor alterations in scapular orientation following a stretching and strengthening protocol in a small sample of subjects presenting with forward shoulder posture. Similarly, Ebaugh *et al.*^[58,59], in two separate studies, evaluated the impact of shoulder muscle fatigue on the glenohumeral and scapular kinematics in samples of twenty healthy subjects. Others have also utilized ETS to monitor changes in scapular kinematics and scapulohumeral rhythm following fatigue protocols^[60-62]. When evaluating the impact of glenohumeral internal rotation deficit (GIRD) in the shoulders of 23 subjects, Borich *et al.*^[63] noted that a significant relationship exists between GIRD and scapular orientation.

Although, ETS have been utilized in a variety of clinically based studies, the number of participants in these studies is relatively small. Often, access to these testing systems is limited due to the financial and physical resources necessary to own and operate this sophisticated equipment. Furthermore, although there are a variety of software packages and platforms that allow for data capture and analysis, the amount of time that must be invested in learning how to utilize these systems along with the time associated with setting up subjects is considerable and likely exceeds the available time for most clinicians. Still, investigators continue to utilize this equipment for their research; however, the number and size of these clinically based shoulder studies is limited. Interestingly, many of the studies involving the shoulder and ETS are validation studies designed to verify the clinical usefulness of a new, clinically available method of kinematic assessment. Johnson *et al.*^[21] took this approach when validating the digital inclinometer for use with assessing scapular upward rotation, which was replicated by Scibek and Carcia^[23] for the monitoring of scapular anterior-posterior tilt. Still others have utilized ETS to establish the validity of a visual and clinically based scapular dyskinesis screening^[26,27]. Ultimately, while ETS allow for accurate quantification of three-dimensional shoulder kinematics, accessibility limitations, along with physical and financial limitations make other tools and systems, such as inclinometers, an attractive option for clinical use and for addressing clinical questions.

In addition to the work of Johnson *et al.*^[21] and Scibek and Carcia^[23], other investigators have suggested that inclinometers offer a cost effective and clinically useful means by which to quantify shoulder and scapular kinematics^[64,65]. A number of studies involving assessment of the shoulder have relied on the use of inclinometers to quantify both scapular motion and glenohumeral motion. Borsa *et al.*^[66] utilized a digital inclinometer to quantify scapular upward rotation during humeral elevation in subjects with healthy shoulders. Scibek and Carcia^[42] utilized a digital inclinometer to evaluate scapulohumeral rhythm in unimpaired subjects. A variety of clinically based studies have

Table 2 Digital inclinometer reliability of humeral range of motion measurements

Ref.	Motion	Reliability	ICC	SEM	MDC
Kolber <i>et al</i> ^[74]	Flexion	Intra-day, inter-observer	0.58	3.24°	8°
		Inter-day, intra-observer	0.83	1.64°	
	Abduction	Intra-day, inter-observer	0.95	1.63°	4°
		Inter-day, intra-observer	0.91	2.26°	
	Internal rotation	Intra-day, inter-observer	0.93	3.39°	8°
		Inter-day, intra-observer	0.87	4.27°	
Kolber <i>et al</i> ^[44]	External rotation	Intra-day, inter-observer	0.88	3.98°	9°
		Inter-day, intra-observer	0.94	2.63°	
	Scaption	Intra-day, inter-observer	0.89	3.4°	9°
		Inter-day, intra-observer	0.88	3.4°	
Laudner <i>et al</i> ^[43]	Horizontal adduction	Intra-observer	0.93	1.64	
		Inter-observer	0.91	1.71	
de Winter ^[65]	Abduction	Inter-observer	0.28–0.83		
	External rotation	Inter-observer	0.56–0.90		

ICC: Intraclass correlation coefficient; RMS: Root mean square; SEM: Standard errors of measurement; MDC: Minimal detectable change.

incorporated inclinometers when quantifying scapular motion and glenohumeral motion in overhead athletes and in patients with shoulder pathologies^[43,67-72]. Dover *et al*^[67] utilized inclinometers to measure glenohumeral range of motion and to evaluate proprioception in female softball athletes. Witwer and Sauers^[68] evaluated scapular upward rotation in a group of collegiate water polo players. Similarly, Laudner *et al*^[72] incorporated a digital inclinometer when comparing scapular upward rotation between baseball pitchers and positions players. Another inclinometer-based study examined scapular kinematics in 72 overhead athletes, with healthy and injured shoulders^[69]. Interestingly, these studies where clinical data were obtained using an inclinometer routinely presented with larger sample sizes as compared to those clinically based studies that utilized ETS. Certainly, the statistical designs of these studies that utilized inclinometers may have required larger sample sizes; however, the ease of use associated with the inclinometer made it feasible to test large pools of subjects.

While there are few studies where ETS were used to measure changes in shoulder kinematics following an injury intervention program^[48], inclinometers have been shown to be plausible options. Following the establishment of the digital inclinometer as a valid and reliable tool for assessing posterior shoulder tightness^[43], Laudner *et al*^[71] evaluated the acute effects of a sleeper stretch designed to increase posterior shoulder flexibility. Using the inclinometer, the investigators were able to observe significant increases in shoulder internal rotation and posterior shoulder motion following the stretching intervention^[71]. Similarly, utilizing an inclinometer, McClure *et al*^[73] compared the effectiveness of two stretching protocols, a sleeper stretch and cross body stretch, to increase shoulder range of motion. Although the randomized controlled trial utilized smaller sample sizes, they were able to detect significant and clinically meaningful increases in shoulder motion using an

inclinometer^[73]. Although not an intervention based study, Thomas *et al*^[70] utilized a digital inclinometer to monitor changes in shoulder range of motion and scapular upward rotation in overhead athletes over the course of their competitive seasons. Based upon the observed changes in glenohumeral and scapular motion across their sport seasons, it was suggested that changes in motion should be monitored during their competitive seasons so as to address any changes that might contribute to the occurrence of shoulder injuries^[70]. While both ETS and inclinometers can be utilized to monitor changes in shoulder complex kinematics over time or following intervention strategies, inclinometers provide an accessible, affordable, and clinically useful strategy for monitoring various aspects of shoulder motion.

CONCLUSION

The ability to gain valuable insight into the kinematics of the shoulder complex is heavily reliant on the accuracy and precision of the instrumentation utilized. The evidence presented in this review demonstrates that ETS and digital inclinometers are reliable and valid instruments. Similarly, it is apparent that ETS have an advantage regarding accuracy, precision, and the ability to capture three-dimensional and dynamic analyses, while digital inclinometers are much more cost effective and practical in clinical settings. Reliability of both of these instruments is highly dependent on the user as inter-rater measures were found to be less desirable when compared to intra-rater measures, with palpation error likely contributing to the increased variability. Although some evidence has been presented regarding the minimal detectable changes captured with ETS for scapular kinematics, further study is warranted to expand our understanding of the clinical usefulness of ETS. Conversely, inclinometers provide a clinically useful means to monitor kinematic changes during outcomes-based studies.

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