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TECHNICAL NOTE

Validation and Repeatability of a Shoulder Biomechanics Data Collection Methodology and Instrumentation

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The purpose of our study was to establish criterion-related validity and repeatability of a shoulder biomechanics testing protocol involving an electromagnetic tracking system (Flock of Birds [FoB]). Eleven subjects completed humeral elevation tasks in the sagittal, scapular, and frontal planes on two occasions. Shoulder kinematics were assessed with a digital inclinometer and the FoB. Intrasession and intersession repeatability for orthopedic angles, and humeral and scapular kinematics ranged from moderate to excellent. Correlation analyses revealed strong relationships between inclinometer and FoB measures of humeral motion, yet considerable mean differences were noted between the measurement devices. Our results validate use of the FoB for measuring humeral kinematics and establish our testing protocol as reliable. We must continue to consider factors that can impact system accuracy and the effects they may have on kinematic descriptions and how data are reported.

Keywords: electromagnetic tracking system, humerus, kinematics, reliability, scapula, validity

Electromagnetic tracking systems, or the Flock of Birds (FoB) technology, have become the gold standard for shoulder kinematic analysis.[1] Validity and reliability studies have assessed the overall usability of these systems.[2–5] Similarly, studies involving bone pins have been conducted to establish the accuracy of these skin-based tracking systems to quantify bony segment motion;[5–7] yet, concerns over tissue artifact, joint center estimation, movement velocity and movement task have been raised relative to kinematic description accuracy.[6,8]

While manufacturers routinely provide data to reflect the static accuracy of their tracking systems,[9] many have established the accuracy,[2,10–12] validity, reliability of the FoB systems within their own testing environments.[5,6,10,11] The pressure to publish "meaningful" clinical studies likely contributes to others relying solely on these manufacturer provided values. Failure to provide accuracy and reliability data may result in added scrutiny of laboratory findings and conclusions. Although evidence supports use of the FoB for evaluating shoulder kinematics, it is critical to ensure that our methodologies are appropriate. Given potential sources of error we must also be cognizant of how our results are being interpreted and the implications they have relative to clinical practice. Therefore, the purpose of this study was to establish criterion-related validity and reliability of a shoulder biomechanics testing protocol when comparing goniometric measures to an electromagnetic tracking system.

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Methods

Five male and six female subjects were recruited (21.44 ± 1.42 years, 1.76 ± 0.12 m, 74.93 ± 21.72 kg, 9 right & 2 left hand dominant). Subjects were healthy, reporting no history of neck, upper extremity, back or lower extremity pathology in the last six months. Subjects reported on two occasions, separated by at least 12 hours and not more than 48 hours, and refrained from any strenuous exercise between testing sessions. Exclusion criteria included any neurological conditions affecting muscle strength and/or upper extremity function, surgery involving the dominant shoulder, use of a pacemaker or device that could be affected by an electromagnetic field, allergies to adhesives, potential pregnancy or rheumatoid arthritis.

Subjects completed an informed consent document approved by the University's Institutional Review Board and a health history questionnaire. A physical screening was performed to confirm the absence of any shoulder pathology. The screening included measures of shoulder range of motion, strength, and a series of orthopedic special tests to ensure the absence of previous or current injury.[13] The production of pain or clinical findings suggesting compromised tissue integrity would have resulted in disqualification.

A digital inclinometer (Pro 360, Baseline, Fabrication Enterprises, White Plains, NY) was used to assess shoulder range of motion during static humeral elevation trials. Specially designed extensions were affixed to the inclinometer that allowed for alignment of the inclinometer with the shaft of the humerus. (Figure 1) A bubble level was affixed to the top of the inclinometer to maintain alignment in the vertical plane.[14]

Three-dimensional shoulder kinematic data were collected using an electromagnetic tracking system (Ascension Technology, Burlington, VT), and Motion Monitor software (Innovative Sports Training, Chicago, IL). The system's short range transmitter was fixed to a nonmetallic scaffolding to minimize system interference.[15] We established the position and orientation accuracy of the FoB within our laboratory during a pilot study. The root mean squared error for linear position, angular orientation and linear displacement were 5.3mm, 0.23°, and 3.1mm, respectively. The position and orientation values are consistent with values reported previously.[9,11] Metal mapping was performed each data collection session.[2,15,16]

Three electromagnetic sensors were used. The trunk sensor was affixed to the subject's cervical spine (proximal to the spinous process of C_7) using double-sided tape and reinforced with 1" athletic tape. The scapula sensor was mounted on the acromion process in a similar fashion, and the humeral sensor was strapped distally on the humerus with the manufacturer strapping system. Twelve bony landmarks, approved by the International Society of Biomechanics (ISB),[17] were digitized to calculate position, orientation and displacement of the scapula and humerus. Kinematic data were collected at 100 Hz.

Subjects were seated during testing to minimize compensatory lower extremity and trunk motion. Subjects were provided with standard verbal cues to maintain similar postures throughout testing. Subjects moved their hands to selected points along a screen corresponding to rest, 30°, 90°, 120° of humeral elevation. Shoulder motion was monitored with the inclinometer and hand placement was marked on the screen specific to subject shoulder ranges of motion, thereby ensuring repeatable arm placement. Humeral elevation and lowering speed were performed in concert with a metronome set at 88 beats per minute, resulting in subjects moving at a rate of approximately 60°/second. Data collection occurred in the sagittal, frontal and scapular plane. Testing order was randomized by plane and arm position. Subjects began with the dominant arm at rest and were then asked to move the arm to a selected position and maintain that position for two metronome counts. This procedure was repeated 3 times at each point along the screen. Subjects were provided with 2 minutes of rest between each plane.

Humeral and scapular kinematics were computed from the sensor data using ISB approved Euler angle sequences.[17] Shoulder flexion and glenohumeral flexion relative to the sagittal plane, shoulder abduction relative to the frontal plane, and upper arm vertical angles for the sagittal, frontal and scapular planes were also obtained using the Motion Monitor software. Upper arm vertical angle was defined as the angle of the humeral sensor and segment relative to the transmitter world axis. A Butterworth filter with a cutoff frequency of 8 Hz was used to smooth the data.[18]

Figure 1 — Modified digital inclinometer for humeral elevation measures. A custom-made plate (Lexan, SABIC Innovative Plastics, Pittsfield, MA) was attached to the inclinometer to allow for space adjustment of the wooden extensions used to align the inclinometer with the humeral shaft. A bubble level was also affixed to maintain vertical alignment of the inclinometer.

Tracings and values associated with humeral elevation were observed visually in the Motion Monitor to confirm stability of the data when the subject achieved the desired arm position. Stability of the data were defined by fluctuations of ≤1° for a minimum of 100 consecutive data points for the upper arm vertical angle. Motion Monitor processed data were exported to Excel (Microsoft Corporation, Redman, WA) where means for all humeral and scapular kinematics were calculated.

Intrasession and intersession reliability were assessed for each kinematic variable using intraclass correlation coefficients ($ICC_{(3,1)}$). Criterion-related validity was assessed via Pearson product-moment correlations, comparing orientation data of the inclinometer and the electromagnetic tracking system data for shoulder flexion, glenohumeral flexion, and abduction, humeral elevation with respect to the thorax and scapula and upper arm vertical angle. Mean differences between devices were calculated for shoulder flexion, abduction, and upper arm vertical angle. SPSS version 17.0 (IBM Corporation, Armonk, NY) was used for data analyses with $\alpha = .05$ set a priori.

Results

Data were collected on the dominant shoulder of 11 subjects. Data from two subjects were incomplete due to system error, reducing our sample size for the analysis to nine subjects.

Reliability data indicates that our methodology is repeatable, both within and between sessions. Intrasession reliability for orthopedic angles, humeral and scapular kinematics, and upper arm vertical angle ranged from fair to excellent [$ICC_{(3,1)} = 0.486$–0.999] (Tables1–3).[19] Intersession reliability ranged from $ICC_{(3,1)} = 0.047$ to $ICC_{(3,1)} = 0.997$, with most relationships reflecting moderate to excellent results (Tables 1–3).

Correlation analyses revealed that the FoB is valid for quantifying humeral and glenohumeral elevation kinematics (Table 4). Significant correlations were identified for each elevation variable with the majority suggesting strong relationships between the devices. Differences between the orthopedic, humerus w.r.t. thorax, and the upper arm vertical angles when measured by both devices were noted. (Figure 2A–C) Both devices recorded increases in humeral elevation angles, regardless of elevation plane. The FoB routinely exhibited less humeral elevation, as compared with the inclinometer. Mean differences between measurement devices ranged between –11.06° and 32.23° [Mean = 16.83°, SD= 13.22°].

Discussion

We chose to compare values obtained from the FoB to standard shoulder goniometric measures obtained with a digital inclinometer, which are established measures used in clinical practice and research to quantify human motion. We noted strong relationships for all other measures of humeral elevation when comparing the measurement systems. These findings confirm that the FoB is a valid means of capturing shoulder kinematic data. Overall, these favorable results were due in part to the standardization in terminology and upper extremity Euler angle sequences[17] as advocated by the ISB. Similarly, manufacturers have responded with software that allows for the integration of data capture systems and the ISB shoulder protocol, further enhancing this consistency. In addition, standardizing subject positioning, arm placement, planes of motion and shoulder elevation speeds facilitated our within and between session reliability efforts, which is consistent with the literature.[20,21] Scapular kinematic reliability was consistently high throughout, while humeral kinematic reliability was slightly lower. Langenderfer et al (2008) suggested that landmark digitization can have considerable influences on shoulder kinematic descriptions, with thorax digitizing errors being closely linked to humeral kinematic description variability. Langenderfer et al indicated that digitization variability (4 mm) can result in increased variability for humeral (7.3° to 15.8°) and scapular (11.7° to 16.6°) kinematic descriptions.[22] A combination of digitizing variability and sensor placement variability may have contributed to reduced intersession reliability.

While we noted favorable validity and reliability results, there were multiple factors that could have contributed to the differences between measures between the devices. Though both devices recorded steady increases in humeral elevation angles, accuracy of our system has been noted to be slightly less than the manufacturer reported values; yet, these values are consistent with values reported by others.[10] Some inaccuracies have been reported during dynamic testing[9] and when testing occurs outside of an optimal transmitter specific testing range.[23] Digitizing variability can also have significant effects on shoulder kinematic descriptions.[22] The interaction between skin-based sensor systems and soft tissue artifacts also have been suggested to negatively impact accuracy,[6] with some employing correction factors to control for systematic error in kinematic descriptions.[5] Ludewig et al (2002) identified peak under-representations of bone movement ranging from 5.7° to 15.6° during elevation tasks and reported root means square errors of < 8° using skin-based sensors. Furthermore, it was suggested that the extent of these errors could be influenced by subject demographics and movement characteristics.[6]

Other clinically-oriented studies have identified discrepancies between the FoB and other clinical measurement devices.[12,14,24] Assink et al (2008) noted measurement differences in cervical range of motion between the FoB and an inclinometer.[24] Another study involving cervical motion reported between session differences that were not pathologically oriented.[12] While validating the digital inclinometer for measuring scapular upward rotation, Johnson et al (2001) identified mean differences (7.0°–14.4°) between a digital inclinometer and a FoB system.[14] While the FoB is valid and reliable for assessing shoulder kinematics, the degree of clinical accuracy may be limited, bringing to light questions regarding how this kinematic data should be reported and integrated into patient care.

Table 1 Shoulder elevation kinematics: intrasession and intersession reliability

Plane and Elevation Angle	Intrasession Reliability				Intersession Reliability			
	Shoulder Flexion	Glenohumeral Flexion	Shoulder Abduction	Upper Arm Vertical Angle	Shoulder Flexion	Glenohumeral Flexion	Shoulder Abduction	Upper Arm Vertical Angle
Sagittal								
30°	0.955	0.920	0.993	0.966	0.721	0.648	0.560	0.657
90°	0.667	0.754	0.953	0.650	0.777	0.688	0.779	0.876
120°	0.956	0.921	0.935	0.945	0.327*	0.626	0.482	0.593
Frontal								
30°	0.956	0.957	0.961	0.973	0.850	0.433	0.827	0.329*
90°	0.891	0.944	0.965	0.985	0.751	0.346*	0.693	0.784
120°	0.919	0.941	0.910	0.974	0.681	0.716	0.682	0.823
Scapular								
30°	0.753	0.918	0.940	0.959	0.493	0.144*	0.618	0.787
90°	0.958	0.959	0.947	0.989	0.616	0.717	0.652	0.743
120°	0.956	0.987	0.935	0.983	0.183*	0.828	0.578	0.628

Note. Correlation coefficients represent the strength of the relationships for each shoulder elevation variable when assessed within and between trials. Assessments of correlation strength were rated based upon the range described by Portney and Watkins (2000) where 0.00–0.25 represents no or little relationship; 0.25–0.50 represents a fair relationship; 0.50–0.75 signifies a moderate to good; and values > 0.75 considered good to excellent. All relationships were statistically significant (*except) at the level of $P \leq .001$ to $\leq .05$.

Table 2 Humeral elevation kinematics: intrasession and intersession reliability

Plane and Elevation Angle	Intrasession Reliability						Intersession Reliability					
	Humerus w.r.t. Thorax			Humerus w.r.t Scapula			Humerus w.r.t. Thorax			Humerus w.r.t Scapula		
	Plane	Elevation	Rotation	Plane	Elevation	Rotation	Plane	Elevation	Rotation	Plane	Elevation	Rotation
Sagittal												
30°	0.795	0.778	0.811	0.998	0.999	0.999	0.491	0.519	0.047*	0.978	0.988	0.968
90°	0.986	0.993	0.982	0.998	0.988	0.996	0.679	0.996	0.671	0.957	0.996	0.961
120°	0.998	0.992	0.997	0.990	0.999	0.995	0.994	0.994	0.959	0.960	0.997	0.967
Frontal												
30°	0.983	0.993	0.975	0.945	0.996	0.945	0.855	0.951	0.574	0.307*	0.948	0.854
90°	0.961	0.999	0.997	0.971	0.999	0.998	0.561	0.991	0.891	0.659	0.997	0.898
120°	0.987	0.999	0.996	0.955	0.999	0.995	0.777	0.995	0.937	0.571	0.997	0.935
Scapular												
30°	0.486	0.991	0.498	0.991	0.994	0.998	0.100*	0.621	0.437*	0.687	0.937	0.912
90°	0.685	0.999	0.612	0.975	0.999	0.999	0.330	0.825	0.694	0.639	0.994	0.920
120°	0.588	0.812	0.669	0.977	0.999	0.999	0.273*	0.768	0.670	0.509	0.995	0.823

Note. Correlation coefficients represent the strength of relationship between trials (intrasession) or between sessions (intersession) for Euler-angle-based humeral and glenohumeral kinematics. Assessments of correlation strength were rated based upon the range described by Portney and Watkins (2000). All relationships were statistically significant (*except) at the level of $P \leq .001$ to $\leq .05$; w.r.t. represents the phrase “with respect to.”

Table 3 Scapular kinematics: intrasession and intersession reliability

Plane and Elevation Angle	Intrasession Reliability Scapula w.r.t Thorax			Intersession Reliability Scapula w.r.t Thorax		
	ML Tilt	Rotation	AP Tilt	ML Tilt	Rotation	AP Tilt
Sagittal						
30°	0.999	0.988	0.991	0.967	0.439	0.550
90°	0.996	0.969	0.981	0.983	0.493	0.611
120°	0.999	0.987	0.966	0.983	0.824	0.524
Frontal						
30°	0.996	0.994	0.990	0.907	0.739	0.335
90°	0.995	0.987	0.962	0.925	0.680	0.409
120°	0.985	0.984	0.953	0.925	0.835	0.304
Scapular						
30°	0.999	0.994	0.964	0.914	0.824	0.709
90°	0.996	0.990	0.983	0.920	0.674	0.654
120°	0.999	0.994	0.986	0.894	0.702	0.438

Note. Correlation coefficients represent the strength of relationship between trials (intrasession) or between session (intersession) for scapular kinematics. Assessments of correlation strength were rated based upon the range described by Portney and Watkins (2000). All relationships were statistically significant (*except) at the level of $P \leq .001$ to $\leq .05$; w.r.t. represents the phrase "with respect to."

Table 4 Humeral elevation kinematics: correlation coefficients for three planes of motion*

	Plane	Shoulder Flexion	Glenohumeral Flexion	Shoulder Abduction	Humerus w.r.t. Scapula	Humerus w.r.t. Thorax	Upper Arm Vertical Angle
Pretest	Sagittal	0.978	0.949	—	0.916	0.982	0.989
	Frontal	—	—	0.975	0.910	0.980	0.989
	Scapular	0.959	0.872	0.970	0.849	0.984	0.986
Posttest	Sagittal	0.959	0.886	—	0.888	0.946	0.985
	Frontal	—	—	0.972	0.863	0.952	0.983
	Scapular	0.960	0.899	0.973	0.872	0.846	0.983

Note. Correlation coefficients represent the strength of relationship between digital inclinometer and electromagnetic tracking system humeral elevation kinematics. Assessments of correlation strength were rated based upon the range described by Portney and Watkins (2000). All relationships were statistically significant (*) at the level of $P \leq .01$; w.r.t. represents the phrase "with respect to."

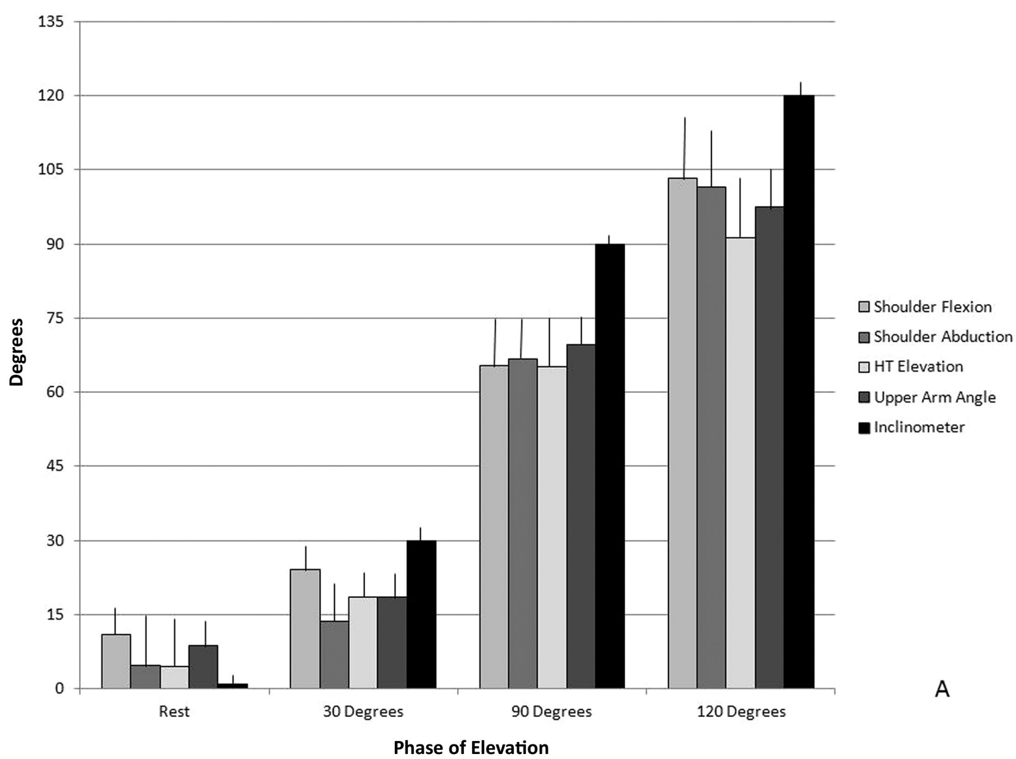

Figure 2 *(continued)*

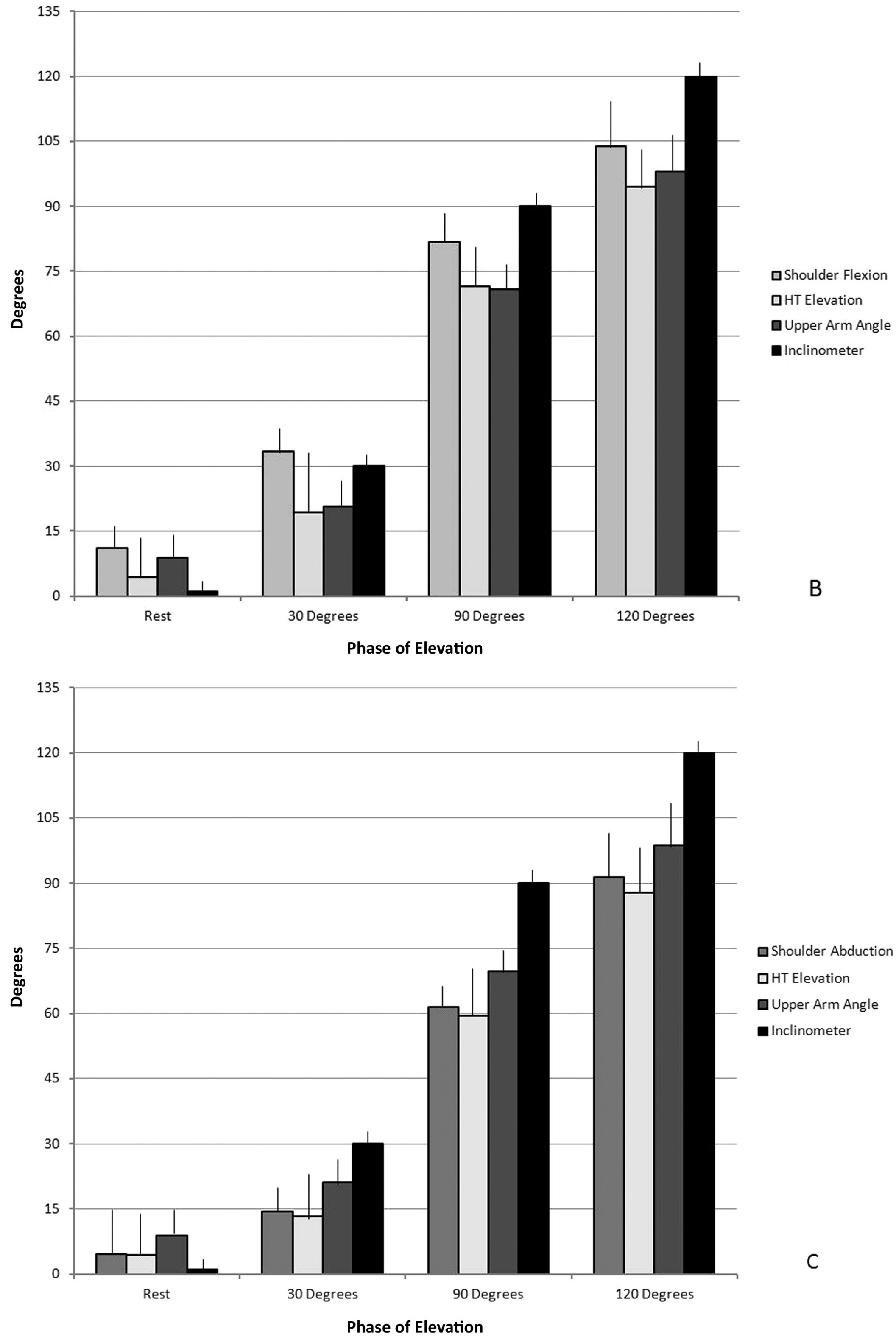

Figure 2 — A–C: Mean shoulder kinematics for three planes of elevation assessed by an electromagnetic tracking system and a digital inclinometer. Kinematic data collected using the electromagnetic tracking system included shoulder flexion, shoulder abduction, elevation of the humerus with respect to the thorax (HT elevation) and upper arm vertical angle (Upper Arm Angle). Using the digital inclinometer, humeral elevation angles were obtained (Inclinometer). Kinematic data were observed at four intervals (Rest, 30 degrees of elevation, 90 degrees of elevation and 120 degrees of elevation), with all data recorded in degrees. The figures depict a consistent upward elevation trend in shoulder kinematic data for both measurement devices. Differences between devices for each kinematic variable are also apparent. Vertical bars represent standard deviations. (A) Represents scapular plane, (B) sagittal plane, and (C) frontal plane data.

Given the noted differences between the recorded FoB and inclinometer measures it may be advisable to report shoulder kinematic findings in a relative fashion such that they reflect the relative movement of the bony segments being observed, as opposed to actual joint measures.

The procedures we have described should serve as a template for other investigators to use to validate and establish reliable testing protocols involving the FoB. Considering the discrepancies identified between the FoB and inclinometer, and the potential sources of error that could impact kinematic description accuracy, there are likely limitations associated with the equipment and our testing protocol. As investigators continue to use this technology to explore shoulder kinematics they will need to be mindful of both digitization accuracy and subject set up to mitigate their deleterious effects on data being collected. Furthermore, investigators will need to evaluate how their findings are being reported to ensure that their results accurately reflect synchronous shoulder movement.

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