Original Article

Shoulder Motion Analysis During Codman Pendulum Exercises

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Purpose: To quantify shoulder motion during Codman pendulum exercises. **Methods:** Shoulder kinematics were analyzed in 17 healthy volunteers using a validated biomechanical model coupling patient-specific imaging and motion capture. Participants were instructed to perform medio-lateral, antero-posterior and circular pendulum exercises. Glenohumeral (GH), scapulothoracic (ST), thoracohumeral (TH) ROM and overall exercise amplitude were calculated for each sequence. Linear regression analyses were carried out to determine association between different components of shoulder motion. **Results:** Mean overall exercise amplitude was 40.59±11.24° (range, 25.38 to 70.25°) for medio-lateral exercises, 46.5±22.02° (range, 20.68 to 100.24°) for antero-posterior exercises, and 20.28±7.13° (range, 10.9 to 35.49°) for circular exercises. Mean GH and ST involvement remained minimal, ranging from 6.74 to 13.81°, and 1.5° to 5.12°, respectively. There was no significant correlation between overall exercise amplitude and GH ($R = 0.31$, $p = 0.01$) or ST ROM (adjusted $R2 = 0.57$, $p < 0.001$), but a moderate correlation with TH ROM ($R = 0.73$, $p < 0.001$). **Conclusion:** This study demonstrates that Codman pendulum exercises depend mainly on truncal movement and produce very little movement in the GH and ST joints. Although they may be a safe way to promote early general stretching of the upper limb, they may be of limited further use in restoring passive shoulder ROM. **Clinical Relevance:** This study quantifies motion during frequently administered shoulder rehabilitation exercises and shows that they do not produce significant movement in the shoulder. Their use in restoring passive range of motion is thus questionable.

Pendulum exercises, eponymously known as Codman exercises,[1] have been widely used for decades with the intention of passively mobilizing the glenohumeral (GH) joint while not compromising recently injured or repaired tissues. These exercises involve the patient standing with a flexed trunk and the affected arm hanging downwards, using the momentum of truncal movement to move the arm without contracting muscles of the shoulder girdle. Using this technique, the arm can be moved forward and backward, from side to side or in a circular motion. The exercises have formed an integral part of many rehabilitation protocols.

Neurophysiological and clinical studies have confirmed the largely passive nature of the exercises,[2-6] but there is limited evidence about where or if motion takes place in the shoulder. The purpose of this study was to employ a patient-specific measurement technique combining medical imaging and motion capture[7] to analyze and quantify shoulder motion in subjects performing Codman exercises. We hypothesized that Codman pendulum exercises involve little, if any, glenohumeral motion.

Methods

Subjects

Following institutional ethics committee approval (AMG Ethic Commission for Clinical Research, Protocol

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The authors report the following potential conflicts of interest or sources of funding: A.L. reports grants from Fondation la Colline pour le Soutien de la Recherche Médicale. Full ICMJE author disclosure forms are available for this article online, as supplementary material.

Received November 10, 2019; accepted April 23, 2020.

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2666-061X/191337

https://doi.org/10.1016/j.asmr.2020.04.013

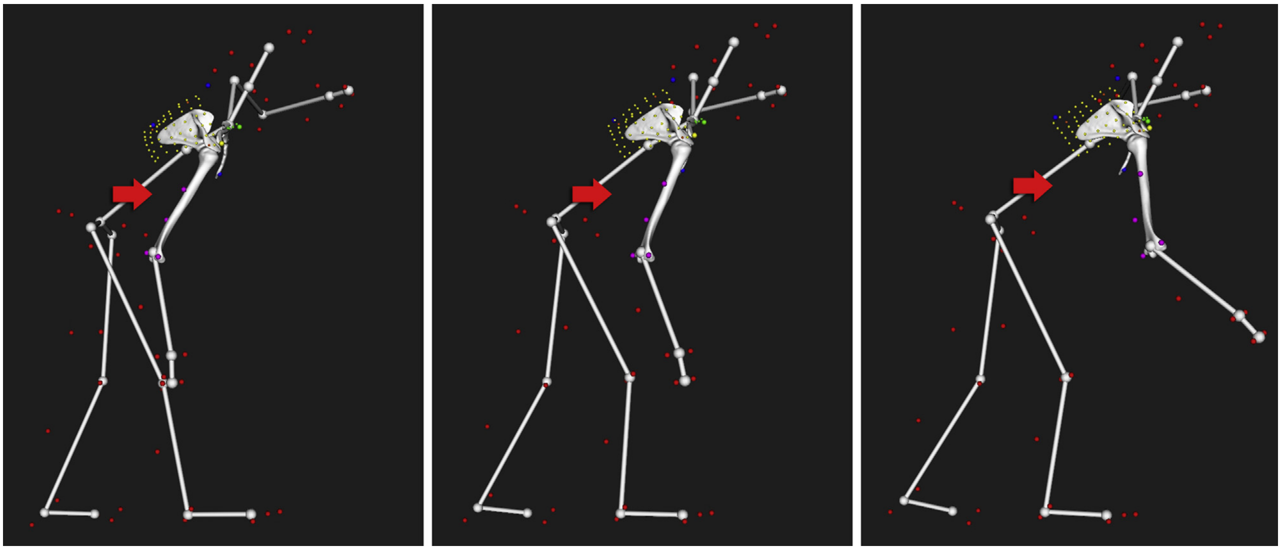

Figure 1. Animation sequence showing a patient-specific kinematic model based on 3-dimensional reconstruction of shoulder computed tomography scan performing anteroposterior pendulum exercises. The colored dots represent the retro-reflective skin markers. Note how the impulse of truncal movements (red arrow) results in a passive swing of the arm.

12-18) and obtaining informed consent, 17 healthy volunteers were recruited for this study (2 females, 15 males) between 2016 and 2018, with a mean age of 36.2 years (range, 18 to 58), and mean BMI of 23.2 kg/m^2 (range, 19.4 to 28.4). All participants had a clinically normal shoulder at the time of the study with no pain, restriction in range of motion, or GH hyperlaxity.

3D Reconstruction and Motion Capture

The subjects were fitted with 69 retro-reflective skin markers according to a previously established shoulder markers protocol,[8] including 57 markers on the scapula (1 marker on the acromion and a regular grid of 56 markers), 4 markers on the humerus (lateral and medial epicondyles, 2 markers far from the deltoid), 4 markers on the clavicle, and 4 markers on the thorax (sternal notch, xyphoid process, C7 and Th8 vertebrae). Additional markers were placed on the non-dominant arm and both legs to provide a global view of the motion (Figure 1). Kinematic data was recorded using a Vicon MX T-Series motion capture system (Vicon, Oxford Metrics, UK) consisting of 24 cameras (24 × T40S) sampling at 120 Hz.

Patient-specific 3-dimensional (3D) models of each participant's shoulder (including humerus, scapula, clavicle, and sternum), based on 0.63-mm-thick slice shoulder computed tomography scan (LightSpeed VCT 64 rows, General Electric Healthcare, Milwaukee, WI), were reconstructed by 1 of the authors (CC, biomechanical engineer specializing in human motion

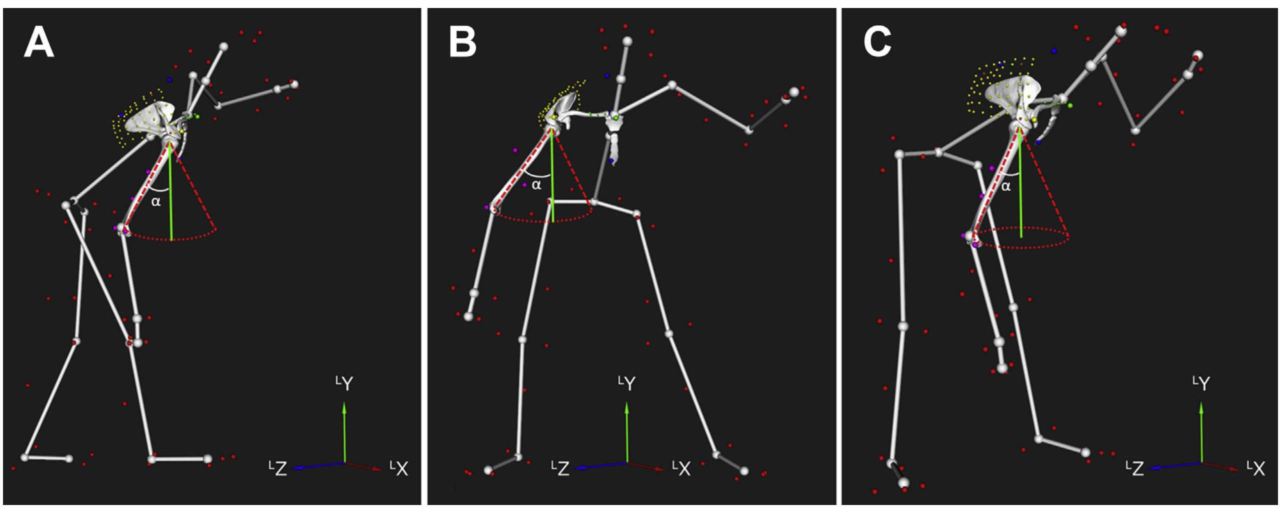

Figure 2. Image of a 3-dimensional reconstructed model of a right shoulder performing pendulum exercises. Definition of the humerus angle (α) with respect to the laboratory vertical axis (LY) during anteroposterior (A), mediolateral (B), and circular (C) exercises.

Table 1. Summary of Mean Amplitudes for Mediolateral Pendulum Exercises

	Mediolateral Exercises (°)					
	Humerus	GH (ABAD)	TH (ABAD)	ST (PR)	ST (ML)	ST (AP)
Participant 1	30.37	8.61	30.56	3.65	3.49	4.09
Participant 2	44.04	3.31	73.58	5.62	0.67	6.08
Participant 3	43.69	14.10	55.75	7.92	4.57	6.64
Participant 4	49.77	3.39	40.10	5.05	0.56	5.14
Participant 5	41.60	6.16	51.21	3.22	0.96	2.21
Participant 6	39.76	0.79	33.37	3.03	0.86	0.97
Participant 7	46.38	16.64	50.05	4.46	5.82	1.55
Participant 8	27.31	1.21	11.90	1.89	0.62	1.36
Participant 9	46.38	16.64	50.05	4.46	5.82	1.55
Participant 10	41.66	1.32	21.39	2.56	0.25	1.34
Participant 11	28.62	11.13	0.63	3.39	0.56	0.34
Participant 12	25.38	2.17	33.32	1.14	0.15	0.40
Participant 13	56.39	8.48	53.40	4.59	0.31	2.19
Participant 14	38.52	6.40	33.83	4.14	2.05	2.92
Participant 15	37.90	1.62	26.16	1.75	1.42	3.11
Participant 16	32.84	1.15	16.74	1.76	0.63	3.01
Participant 17	29.76	11.16	35.36	5.37	2.19	4.30
Mean	40.59	6.74	36.89	4.04	1.83	3.02
SD	11.24	5.38	17.84	2.03	1.87	2.13
Minimum	25.38	0.79	0.63	1.14	0.15	0.34
Maximum	70.25	16.64	73.58	8.66	5.82	7.23

Humerus: angle of the humerus relative to the laboratory vertical axis (overall exercise amplitude). Abbreviations: ABAD, abduction-adduction; AP, anterior-posterior tilt; GH, glenohumeral; ML, mediolateral rotation; PR, protraction-retraction; ST, scapulothoracic; TH, thoracohumeral.

capture, 15 years of experience) using Mimics software (Materialize NV, Leuven, Belgium).

During motion capture, participants were instructed by the same author to perform pendulum exercises according to Codman's initial description,[1] with their trunk flexed >45° and the arm hanging directly downwards, using the impulse of truncal movements to passively swing the arm. A precise target for exercise amplitudes was deliberately not set to prevent subjects from actively correcting their pendulums, which would have impeded the passive nature of these exercises, and to reflect the way patients perform these exercises freely and unsupervised. Moreover, this allowed correlation analysis between exercise amplitudes and involvement of different joint components. Exercises included mediolateral, anteroposterior, and circular movements. Volunteer performed the different movements at their own speed for a duration of 10 to 15 seconds. They undertook a training session before motion capture to ensure that the exercises were correctly performed. Movement initiation and ending were not included in the analyzed sequence.

Kinematic Analysis

Shoulder kinematics were computed from the recorded markers' trajectories using a validated biomechanical model[7,8] that accounted for skin motion artifacts. The model was based on a patient-specific kinematic chain using the 3D models reconstructed from participants' imaging data and a global optimization algorithm with loose constraints on joint translations. Figure 1 shows an animation sequence example of resulting computed postures.

GH, scapulothoracic (ST), and thoracohumeral (TH) ranges of motion (ROMs) were quantified for each exercise and expressed in clinical terms (e.g., flexion/extension, abduction/adduction).[9] This was achieved by calculating the relative orientation between 2 local coordinate systems (between the scapular and humeral coordinate systems for the GH joint, between the thoracic and scapular coordinate systems for the ST joint, and between the thoracic and humeral coordinate systems for TH ROM). The local systems were created using anatomic landmarks identified on the participant's bony 3D models and imaging, based on definitions suggested by the International Society of Biomechanics.[10] The GH joint center was calculated based on a sphere-fitting method.[11] Finally, to quantify the overall amplitude of the exercise, motion of the humerus relative to the laboratory vertical axis was also calculated, as shown in Figure 2.

Statistical Analysis

Descriptive statistics are reported as means and standard deviations (SDs). Mean amplitudes for each component of shoulder motion (GH, ST, and TH), as well

Table 2. Summary of Mean Amplitudes for Anteroposterior Pendulum Exercises

	Anteroposterior Exercises (°)					
	Humerus	GH (FE)	TH (FE)	ST (PR)	ST (ML)	ST (AP)
Participant 1	35.48	17.25	34.01	2.66	1.08	2.00
Participant 2	39.01	9.75	29.95	0.58	4.67	5.40
Participant 3	42.30	29.41	46.14	3.66	1.76	4.40
Participant 4	100.24	25.23	52.05	4.45	20.63	12.35
Participant 5	45.29	12.97	39.59	3.09	2.15	0.73
Participant 6	35.92	16.29	32.17	2.75	1.16	3.01
Participant 7	63.98	13.11	42.40	7.74	5.49	7.30
Participant 8	23.99	6.17	16.65	1.60	2.30	2.19
Participant 9	64.99	13.34	42.92	7.72	5.45	7.39
Participant 10	38.87	8.99	25.47	3.60	3.15	2.68
Participant 11	40.07	6.34	25.63	5.14	5.36	5.71
Participant 12	20.68	7.24	20.81	0.11	0.48	0.03
Participant 13	52.07	19.69	45.86	5.56	5.46	4.61
Participant 14	54.05	24.64	34.51	3.85	2.85	5.22
Participant 15	36.74	3.33	26.61	4.17	5.43	4.81
Participant 16	21.81	3.47	14.93	3.09	3.03	2.56
Participant 17	29.76	14.98	44.99	7.05	6.39	6.07
Mean	46.50	13.81	35.17	4.33	5.12	4.67
SD	22.02	7.54	12.23	2.74	5.10	2.94
Minimum	20.68	3.33	14.93	0.11	0.48	0.03
Maximum	100.24	29.41	58.44	11.13	20.63	12.35

Humerus: angle of the humerus relative to the laboratory vertical axis (overall exercise amplitude). Abbreviations: ABAD, abduction-adduction; AP, anterior-posterior tilt; GH, glenohumeral; ML, mediolateral rotation; PR, protraction-retraction; ST, scapulothoracic; TH, thoracohumeral.

Table 3. Summary of Mean Amplitudes for Circular Pendulum Exercises

	Circular Exercises (°)							
	Humerus	GH (ABAD)	GH (FE)	TH (ABAD)	TH (FE)	ST (PR)	ST (ML)	ST (AP)
Participant 1	18.43	11.08	14.45	11.58	19.91	3.43	1.45	3.43
Participant 2	18.76	18.77	11.17	13.15	23.42	1.26	2.16	3.31
Participant 3	17.82	16.25	26.25	24.20	34.19	5.35	0.01	6.01
Participant 4	21.27	11.58	12.95	6.26	20.98	1.19	2.45	3.46
Participant 5	15.30	8.57	14.19	17.25	13.25	1.33	1.14	1.27
Participant 6	15.15	4.63	13.99	16.11	6.95	1.16	1.36	0.51
Participant 7	10.90	3.14	1.21	3.01	6.00	0.47	0.30	0.73
Participant 8	19.58	8.14	10.30	0.04	16.02	2.13	0.63	1.96
Participant 9	15.66	8.51	1.15	9.77	1.12	0.25	0.16	0.22
Participant 10	14.74	6.68	10.18	17.31	5.23	0.81	2.67	0.91
Participant 11	23.36	2.54	14.15	16.96	10.08	2.43	2.83	2.30
Participant 12	14.94	11.58	6.02	7.35	13.71	0.39	2.46	1.07
Participant 13	35.49	15.23	16.86	11.67	26.73	5.32	0.93	3.06
Participant 14	14.01	4.27	13.32	12.48	13.68	2.86	0.10	1.27
Participant 15	22.58	11.23	7.89	2.19	15.43	0.80	1.69	1.12
Participant 16	33.84	12.10	15.86	5.11	24.97	2.31	3.81	3.72
Participant 17	20.25	9.89	11.96	8.08	20.43	4.07	2.24	2.93
Mean	20.28	11.23	12.40	12.99	17.55	2.32	1.50	2.18
SD	7.13	8.01	6.14	11.43	10.70	1.86	1.10	1.48
Minimum	10.90	2.54	1.15	0.04	1.12	0.25	0.01	0.22
Maximum	35.49	37.91	26.25	51.36	43.85	6.20	3.81	6.01

Humerus: angle of the humerus relative to the laboratory vertical axis (overall exercise amplitude). Abbreviations: ABAD, abduction-adduction; AP, anterior-posterior tilt; GH, glenohumeral; ML, mediolateral rotation; PR, protraction-retraction; ST, scapulothoracic; TH, thoracohumeral.

as mean overall exercise amplitudes, were calculated from the computed ROMs based on the troughs and peaks of each recorded sequence. GH and TH motions are reported in abduction-adduction motion for mediolateral pendulum exercises, flexion-extension for anteroposterior exercises, and both abduction-adduction and flexion-extension for circular exercises. As ST motion is more complex and follows different planes, all were reported for each exercise: protraction-retraction, medial-lateral rotation, and anterior-posterior tilt.[9]

Linear regression was carried out to analyze the association between overall exercise amplitude and each component of shoulder motion. Single linear regression (R) was used for GH and TH motion, and multiple linear regression (adjusted R^2) was used for the different components of ST motion. Analyses were performed with StatPlus version 7 (AnalystSoft, Walnut Grove, CA), and statistical significance was set at $p < .05$.

Results

Results are detailed in Tables 1, 2, and 3. Mean overall exercise amplitude was 40.59° ± 11.24° (range 25.38° to 70.25°) for mediolateral exercises, 46.5° ± 22.02° (range 20.68° to 100.24°) for anteroposterior exercises, and 20.28° ± 7.13° (range 10.9° to 35.49°) for circular exercises. GH and ST involvement were minimal in all exercise types (Figure 3): mean GH amplitudes ranged from 6.74° to 13.81°, mean ST amplitudes from 1.5° to 5.12°.

Linear regression analyses showed only a moderate to strong association of overall exercise amplitudes with TH amplitudes ($R = 0.73$, $p < .001$), whereas no association was observed with GH ($R = 0.31$, $p = .01$) or ST (adjusted $R^2 = 0.57$, $p < .001$) amplitudes (Figure 4).

Discussion

This study demonstrates that Codman pendulum exercises produce minimal GH and ST motion, confirming our hypothesis that they are mainly the result of truncal movement. These exercises are, however, part of the routine armamentarium of shoulder rehabilitation programs, being regarded as a safe way to restore passive shoulder motion without compromising the underlying surgical work.

Rehabilitation after shoulder surgery, particularly rotator cuff repair, is subject to much debate and controversy.[12-14] A wide range of techniques of passive shoulder mobilization have been recommended, including simple passive stretching, table slides, pulley therapy, and Codman exercises.[15] These exercises can be weighted or unweighted,[16] be self- or therapist-assisted, or serve as adjuncts to continuous passive motion machines. There is clearly a need to better define which exercises are useful in shoulder rehabilitation, and these results suggest that although they may be a safe way to stretch the upper limb in early phases of shoulder rehabilitation, pendulum exercises may not be an efficient way to restore passive ROM in the GH or ST joint.

Several electromyographic studies have shown that pendulum exercises result in very little rotator cuff

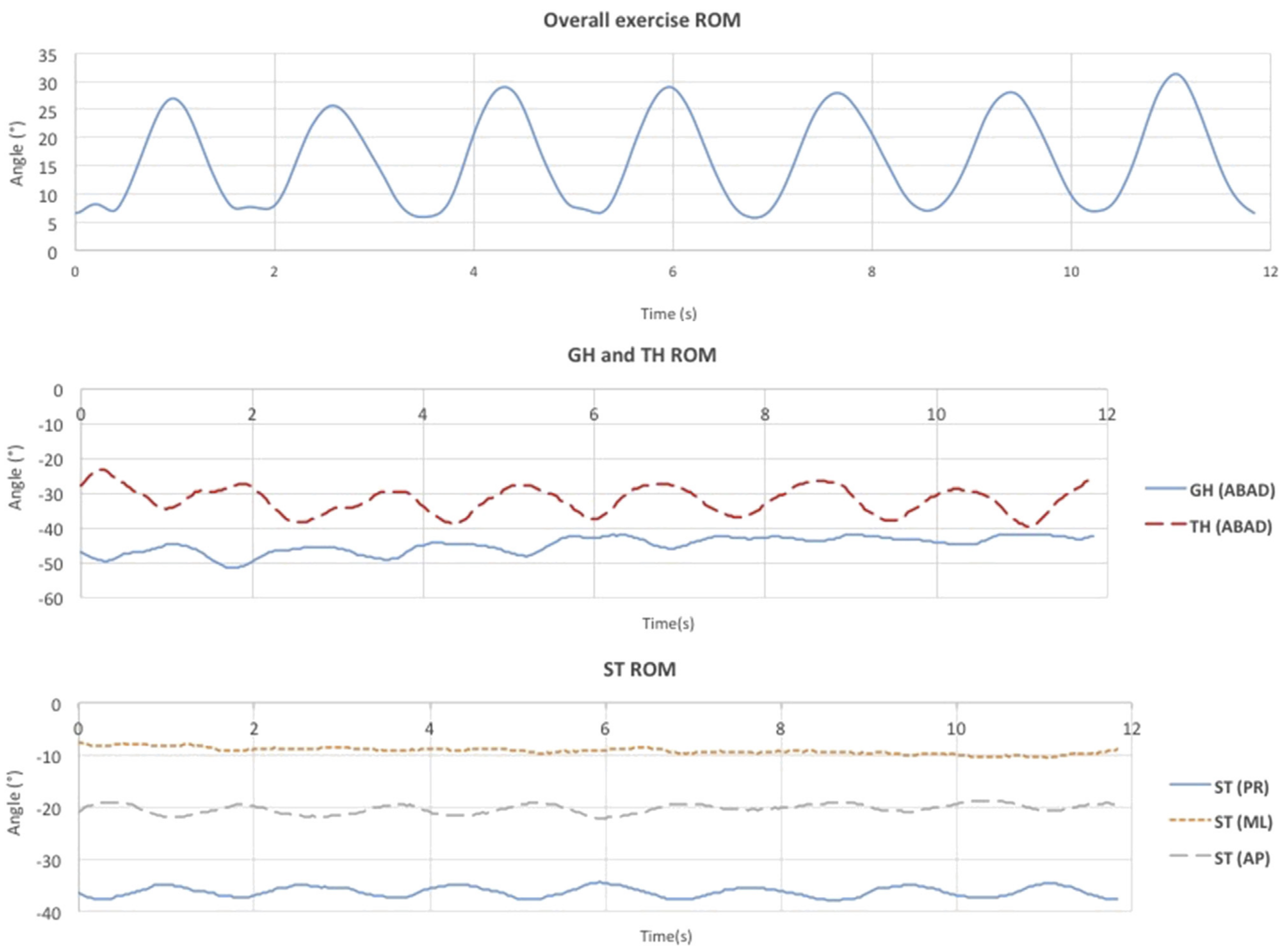

Figure 3. Illustration of variation in amplitude. The scale values are positional references, and the actual range of motion resulting from the exercises is the mean difference between the peaks and troughs. For instance, actual range of motion is only a few degrees for the GH joint (flat blue line). Abbreviations: ABAD, abduction-adduction; AP, anterior-posterior tilt; GH, glenohumeral; ML, mediolateral rotation; PR, protraction-retraction; ST, scapulothoracic; TH, thoracohumeral.

muscle contraction.[2-6] A recent study by Gurney et al.[4] used indwelling electromyography to measure rotator cuff activity in healthy volunteers during several tasks, common rehabilitation exercises, and ambulation. They found that pendulum exercises induced the least muscle contraction, whereas donning and doffing a shirt induced the highest. Even ambulation produced substantially higher muscle activity than pendulum exercises. Although these studies certainly confirm the passive nature of these exercises, they also suggest a lack of GH involvement. Long et al.[5] warned, however, that improperly performed exercises (when the movement is directly generated from the shoulder rather than the trunk), as well as performing larger pendulum circles, increased rotator cuff muscle activity.

Although the latter could also suggest an increase in shoulder motion, we found no statistically significant association between GH or ST motion and overall exercise amplitude. The latter was correlated only with TH motion, proving that Codman exercises are mainly the result of truncal movement.

Limitations

This study was not without limitations. First, the sample size was limited by the extensive time needed for subject equipment, motion capture, and post hoc analysis, which could lead to type II error. Second, the sample was composed of healthy volunteers, and thus does not necessarily represent shoulder motion in a postoperative setting. However, the latter may exhibit even less GH or ST involvement because of stiffness and motor inhibition. Moreover, these results suggest that the gain in shoulder ROM would be minimal given the low level of participation of the shoulder during these exercises in normal shoulders. Similarly, it would have been informative to quantify shoulder kinematics in patients with shoulder arthrodesis, but surgical hardware would have caused too many imaging artifacts, and the authors were not able to recruit enough patients with removed hardware. A third limitation is the lack of accurate description of these exercises in the literature, including Codman's original description.[1] The authors chose 45° of trunk flexion, as it is an easy angle to control visually.

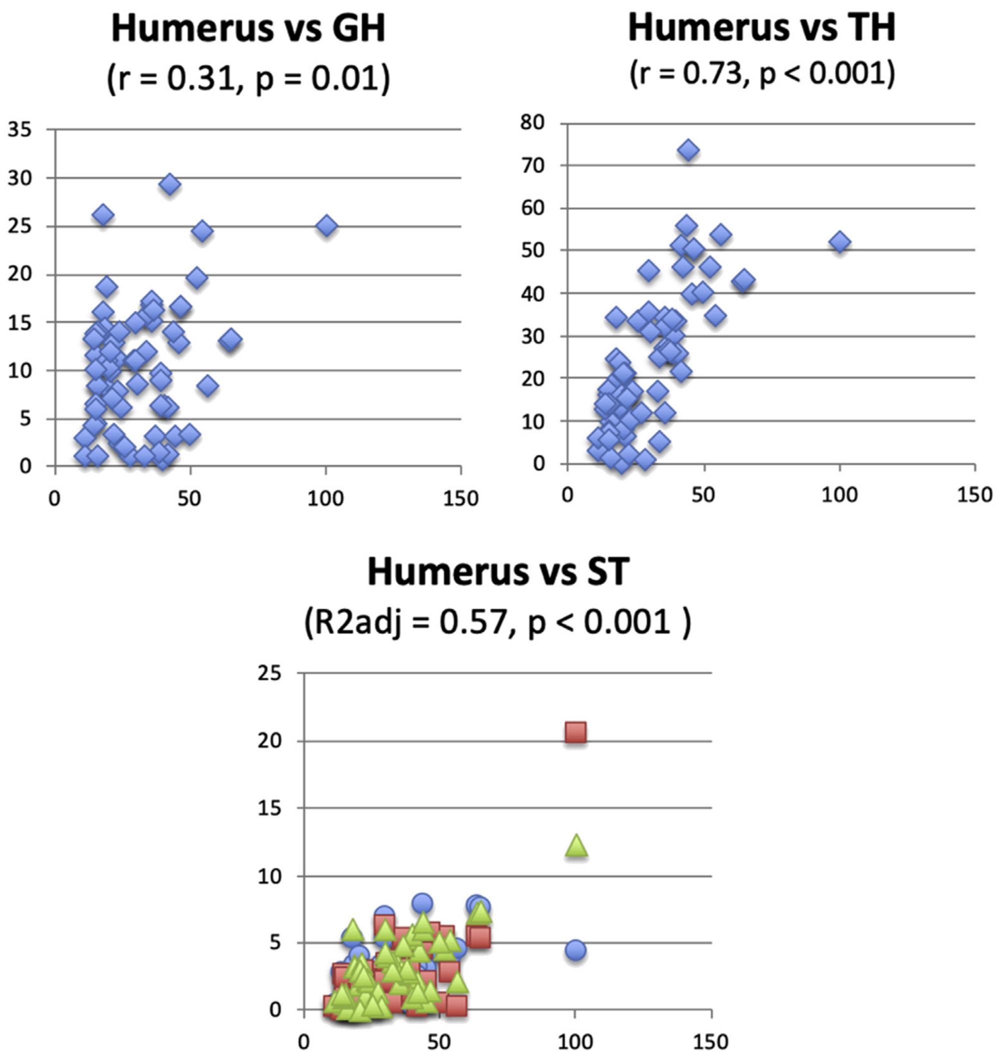

Figure 4. Scatterplots showing the association between the overall exercise amplitude and the different components of shoulder motion. Humerus: angle of the humerus relative to the laboratory vertical axis (overall exercise amplitude). Abbreviations: GH, glenohumeral; ST, scapulothoracic; TH, thoracohumeral.

Conclusion

This study demonstrates that Codman pendulum exercises depend mainly on truncal movement and produce very little movement in the GH and ST joints. Although they may be a safe way to promote early general stretching of the upper limb, they may be of limited further use in restoring passive shoulder ROM.

Acknowledgments

This study was financed by Fondation la Colline pour le soutien de la recherche médicale.

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