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RESEARCH ARTICLE

Three-dimensional shoulder complex kinematics in individuals with upper extremity impairment from chronic stroke

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Purpose: To evaluate shoulder complex kinematics in persons with chronic upper extremity (UE) impairments due to stroke and determine if kinematics predicts motor function based on the Fugl-Meyer Motor Assessment (FMA). _Method:_ Sixteen stroke survivors with chronic UE impairments (age range = 46–80 years, male = 8, female = 8, mean (SD) 66 (40) months post-stroke) performed the UE portion of the FMA with the shoulder/elbow subscale (FM_se) documented. Three-dimensional kinematics of the shoulder complex was collected with the Motion Monitor™ (Innsport, Chicago, IL, USA). Participants performed three repetitions of arm elevation in the frontal, sagittal and self-selected planes. The third repetition was analyzed. Scapular and humeral kinematics were calculated in the self-selected plane. Scapulohumeral rhythm was analyzed at peak elevation. Backward stepwise regression analysis predicted kinematic contributions to the FM_se. _Results:_ Mean (SD) FM_se score was 25.3 1(10.9). Peak humeral elevation ranged from 45.6° to 129.2° (median 106.7°). Scapulohumeral rhythm was 4.1:1 when humeral elevation ranged from 45° to 50°, 1.5:1 from 80° to 95° and 2.1:1 from 105° to 130°. Humeral elevation, scapular upward rotation and scapular internal rotation predicted 65.4% of FM_se score variability. _Conclusion:_ Persons with chronic UE impairments from stroke demonstrated reduced peak elevation and altered scapulohumeral rhythm. Three predictors of the FM_se were humeral elevation, scapular upward rotation and scapular internal rotation.

Keywords: Kinematics, motor function, shoulder, stroke

Implications for Rehabilitation

- Three-dimensional analyses of shoulder elevation in stroke survivors with chronic upper extremity impairments reveal altered scapulohumeral rhythm in their paretic limb.
- Those with greater elevation limitations demonstrate larger scapular contribution. Humeral elevation, scapular upward rotation and scapular internal rotation predict motor function as measured by the Fugl-Meyer Motor Assessment.
- Clinicians should include examination of and intervention to all the components of the shoulder complex to address functional deficits.

Introduction

Stroke is a leading cause of disability in the United States affecting approximately 800,000 people and leading to approximately 1 of 18 deaths per year [1]. It is possible for individuals to fully recover from a stroke; however, more than two-thirds of stroke survivors will experience some type of residual impairment [2]. Abilities that may be affected include speech, memory and movement [2]. Impairments may include, but are not limited to, muscle weakness, muscle paralysis, spasticity, decreased sensation or proprioception [3–8].

Scapulohumeral rhythm (SHR) is the ratio of glenohumeral motion to scapulothoracic motion during humerus to trunk elevation. Glenohumeral motion is movement of the humerus on the glenoid fossa of the scapula, whereas scapulothoracic motion is movement of the scapula in relation to the trunk [9]. SHR was originally described by Inman et al. [10] in 1944. They evaluated one healthy individual utilizing roentgenography and bone pins and determined SHR as 2:1. In 1998, McQuade and Smidt [11] described SHR using three-dimensional kinematics as a nonlinear relationship between the head of the humerus and the glenoid fossa of the scapula that changes during different phases of elevation. The ratios they found ranged from 7.9:1 during the first 26 degrees of elevation to 3.0:1 between 104 and 130 degrees of elevation [11].

Using three-dimensional kinematic evaluation techniques, researchers have determined scapular movements during specific upper extremity (UE) motions in individuals without shoulder pathology. During humerothoracic elevation, the scapula upwardly rotates, posteriorly tilts and

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externally rotates with the majority of these motions occurring at end range [12–15]. In studies using similar techniques, individuals with deficits following stroke demonstrated less glenohumeral elevation and more scapular upward rotation during humerothoracic elevation in their affected upper extremities [6,16,17].

The Fugl-Meyer Motor Assessment (FMA) evaluates level of motor recovery post-stroke by rating their ability to complete specific motions and tasks. The FMA is divided into six subgroups which include UE, lower extremity, sensation, balance, range of motion and pain [18]. Each subgroup has an individual score that can then be added together for the total score. The maximal score of the UE FMA is 66, and the total for the shoulder and elbow subscale (FM_se) is 42 [19–21]. Research has shown the UE portion of the FMA to have intra-rater reliability of 0.995, inter-rater reliability of 0.992, test-retest of 0.94–0.99 and internal consistency of 0.97 [18,22,23].

Several authors have investigated three-dimensional shoulder complex kinematics in individuals following stroke [6,16,17,24]. However, none have determined if three-dimensional kinematic analysis of the shoulder complex can predict a person's level of motor function after a stroke. Therefore, the first purpose of this study was to demonstrate that individuals with stroke have altered SHR in comparison to previously reported age-matched healthy population. Based on previous research, the first hypothesis was that the SHR would be decreased secondary to an increased scapulothoracic component. The second purpose was to determine if glenohumeral and scapulothoracic motions could predict an individual's motor function based on the FMA. The second hypothesis was that a significant portion of the variation in FM_se could be predicted.

Materials and methods

Study participants

Sixteen volunteers with chronic stroke and UE impairment from the local community were recruited as a sample of convenience and participated in this study. The research was approved by the local Institutional Review Board and all participants signed a letter of informed consent prior to participation. The inclusion criteria were (i) community dwelling individuals with a diagnosis of stroke, (ii) chronic stroke (having occurred at least 6 months prior to data collection) [25], (iii) first-time stroke, (iv) at least 18 years of age, (v) ability to understand and agree to informed consent, (vi) no history of orthopedic shoulder pathology unrelated to the stroke, (vii) no pacemaker and (viii) ability to understand verbal commands and instructions. Brief medical histories were taken for each participant before beginning data collection. Relevant demographic information is presented in Table I.

Table I. Participant demographic information.

Gender	Age (years)	Onset duration (months)	FM_se score
Male ($n=8$)	59.6 (11.0)	68.3 (51.1)	24.3 (9.3)
Female ($n=8$)	61.5 (11.9)	64.1 (28.5)	27.4 (11.1)
Overall	60.6 (11.1)	66.2 (40.0)	25.8 (10.0)

FM_se = Fugl-Meyer shoulder and elbow subsection.
All data presented as mean (SD).

Procedure

Participants' cervical and shoulder range of motion (ROM) and ability to raise both (UEs) against gravity were evaluated. Neer (sensitivity = 0.89) [26] and Hawkins–Kennedy (sensitivity = 0.87) [26] impingement tests, as well as glenohumeral load and shift (anterior ICC = 0.53, posterior ICC = 0.68) [27] were performed on both shoulders prior to data collection to rule out potential nonstroke-related shoulder pathologies. Participants performed the UE portion of the FMA (FM_UE), with the shoulder and elbow subscale (FM_se) used for analysis [19–21]. The FMA was utilized in this study due to high test-retest reliability, high internal consistency, ease of use and specificity to post-stroke impairments.

Three-dimensional kinematics of the scapula, humerus and trunk were collected for the paretic UE (at 100 Hz) with the Motion Monitor™ short range transmitter system (Innovative Sports Training, Inc., Chicago, IL, USA) with use of "mini-bird" sensors. This system has a reported root mean square position accuracy of 0.07 inches/0.5 degrees at a 36-inch range with a resolution of 0.03 inches/0.1 degrees [28]. Based on International Society of Biomechanics (ISB) recommendations, sensors were placed on the most lateral portion of the acromion process while avoiding deltoid generated movement artifact, distal to the sternal notch of the manubrium and via a cuff placed just superior to the epicondyles of the affected UE [29]. Figure 1 depicts the experimental setup.

Participants were positioned with their back directly in front of the transmitter which was set at the height of the paretic UE's spine of the scapula. Participants were instructed to perform three repetitions of UE elevation in the frontal plane (defined as 0° plane), sagittal plane (defined at 90°) and a self-selected, preferred plane of motion between the others with their affected UE. Each participant was instructed to perform these motions at a steady, self-selected pace. The planes of motion were randomized. A guide was positioned in the frontal or sagittal planes to provide the participant with a tactile cue to encourage correct motion performance. Tactile

Figure 1. Experimental setup.

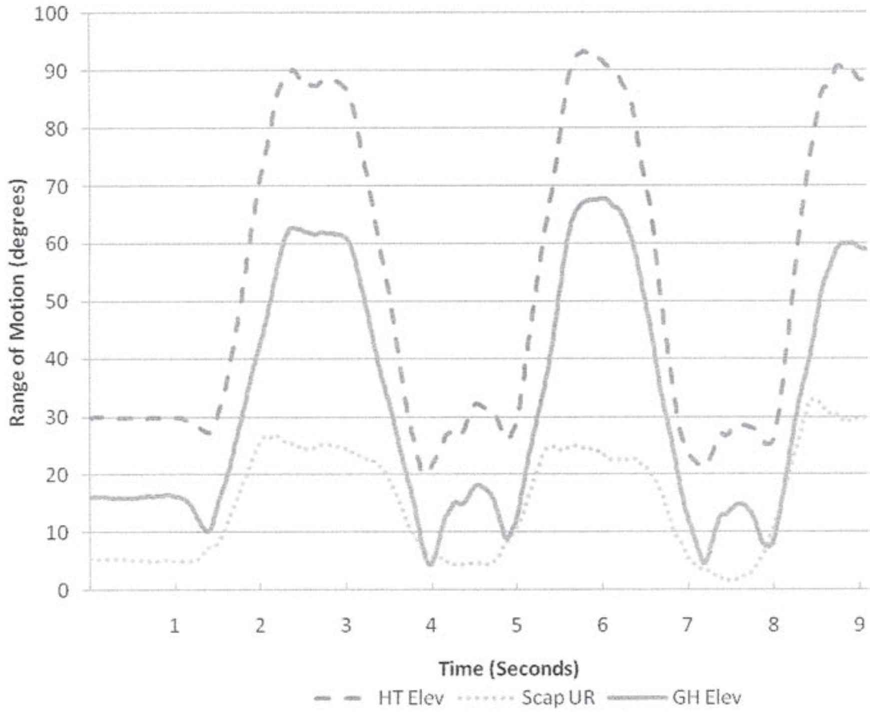

Figure 2. Representative participant humeral and scapular kinematic data during humeral elevation of one participant. HT, Humerothoracic; Scap, Scapulothoracic; GH, Glenohumeral; Elev, Elevation; UR, Upward Rotation.

cues, such as passively taking participant through correct range of motion prior to collection, were provided if patient did not fully understand the motion.

Data reduction

Using the collected data from the bony landmarks, the Motion Monitor™ program mapped the three-dimensional position and relative rotation of the shoulder complex and established local coordinate systems (LCS) for the humerus, scapula and thorax. The osteokinematics between segments were defined as rotations of one LCS moving on a more proximal LCS. The orientation of the humerothoracic and glenohumeral joints were described through a z (plane of elevation), y′ (angle of elevation), z″ (long axis rotation) Euler angle sequence. The scapulothoracic orientation was defined through a z (internal rotation/external rotation), y′ (downward rotation/upward rotation), x″ (posterior tipping/anterior tipping) Cardan angle sequence. Both rotation sequences were consistent with ISB recommendations [29]. Following data collection, the raw data was exported to a Microsoft Excel (Redmond, WA, USA) spreadsheet where the ROM values were extracted using peak humerothoracic elevation of each trial and plane of motion. Glenohumeral and scapulothoracic values were found using the corresponding peak humerothoracic elevation value, which were used to calculate SHR [29–31]. Figure 2 depicts a representative participant's glenohumeral elevation, scapular upward rotation and humerothoracic upward rotation.

Data analysis

Statistical Package for the Social Sciences version 16 (SPSS Inc., Chicago, IL, USA) was used for all analyses with a significance value defined as $p \le 0.05$. Descriptive statistics for all motions and the FMA were calculated. Correlation coefficients were calculated to determine relationships among the peak elevations across each plane. Repeated measures analysis was calculated to determine if there was a difference between trials. SHR was calculated as the ratio between glenohumeral and scapulothoracic elevation during humerothoracic elevation and was evaluated based on similar divisions as McQuade and Schmidt [11]. A forward stepwise multiple regression was attempted to predict scapulothoracic and glenohumeral kinematic contributions to the FM_se. However, it yielded no significant single factor. Therefore, a backward stepwise multiple regression analysis was performed.

Results

Mean (SD) FM_se score was 25.3 (10.9). Based upon the Shapiro–Wilk test of normality, peak elevation in abduction ($p = 0.140$) and flexion ($p = 0.152$) were normally distributed; however, Peak elevation in the self-selected plane was not ($p = 0.036$). The Spearman's correlation (r) value between self-selected and abduction planes was 0.724 ($p = 0.002$) and between self-selected and flexion planes was 0.829 ($p < 0.001$). The Pearson's correlation (r) value between abduction and flexion planes was 0.693 ($p = 0.004$). This, in combination with participants being most functional in the self-selected plane, led to the decision to use the self-selected plane for analysis.

Based upon the Shapiro–Wilk test of normality, the peak motion of the first repetition of elevation in the self-selected plane was normally distributed ($p = 0.054$). The peak motion in the other two repetitions were not ($p = 0.025$ and 0.016, respectively). Friedman's ANOVA determined that there was significant difference in peak elevation between repetitions (p = 0.019). Post-hoc analyses with Bonferroni correction (0.05/3 = 0.0167) yielded a significant difference in peak elevation between repetitions 1 and 2 (p = 0.008). Repetition 1 was consistently less than repetition 3. There was no significant difference between repetitions 1 and 3 (p = 0.063) or repetitions 2 and 3 (p = 0.679). The third repetition was chosen for further analysis. Descriptive statistics for and correlations between the third repetition of all three planes of motion can be found in Table II.

Participants unable to reach greater than 50° of humerothoracic elevation in the self-selected plane demonstrated less than 10.5°of scapulothoracic upward rotation. Participants able to reach 80° or more of humerothoracic elevation were able to achieve 23.0° or more of scapulothoracic upward rotation. SHR was 4.1:1 in participants whose peak humeral elevation ranged from 45° to 50°, 1.5:1 from 80° to 95° and 2.1:1 from 105° to 130°. The comparison of glenohumeral motion to scapulothoracic motion is shown in Figure 3. The backward stepwise multiple regression determined that scapular internal rotation, glenohumeral elevation and scapular upward rotation together were the three best predictors of impairment on the FM_se with an R^2 value of 0.652. The resultant regression equation was: predicted FM_se = −4.494 + 0.117*scapular IR + 0.122*scapular upward rotation + 0.338*glenohumeral elevation.

Table II. Descriptive statistics of third repetition of peak elevation.

Plane	Mean (x)	Median	SD	Range	r to self-selected
Self-selected	95.6°	106.7°	27.6°	45°–129°	1
Flexion	91.5°	103.8°	28.8°	44.0°–128.4°	0.829
Abduction	91.3°	101.5°	28.4°	46.6°–130.5°	0.724

SD = standard deviation.

Discussion

These results supported the two hypotheses that individuals with chronic stroke would demonstrate an altered ratio of glenohumeral elevation to scapular upward rotation of their affected UE and that their shoulder complex kinematics would significantly predict their FM_se scores. Additionally, the current findings support previous authors' discovery of decreased humeral elevation and decreased SHR in the paretic UE. Meskers et al. [16] found maximal humeral elevation in controls as 138° and in participants with stroke paretic shoulders as 126°. The peak elevation in the current study was 130.5°. Niessen et al. [6] found increased scapulothoracic upward rotation during abduction and flexion in participants with stroke with and without shoulder pain. As the authors published figures rather than actual values, direct comparisons between their study and the current study are difficult.

Price et al. [17] documented three different SHR relationships across paretic limbs of individuals with stroke. In 16 of 30 participants, the SHR was the same as their non-paretic UE. Eight of 30 demonstrated decreased scapular upward rotation and six of 30 demonstrated increased scapular upward rotation. The current results consistently fit in the increased upward rotation category. One difference between the studies is gender distribution. Price et al. had a 2:1 male to female distribution, while the current study was 1:1.

Current results regarding SHR were consistent with the findings of McQuade and Smidt [11], showing that SHR was not a consistent 2:1 ratio (Table III). McQuade and Smidt [11] found that SHR in healthy individuals is different throughout various ranges of glenohumeral elevation. The inability

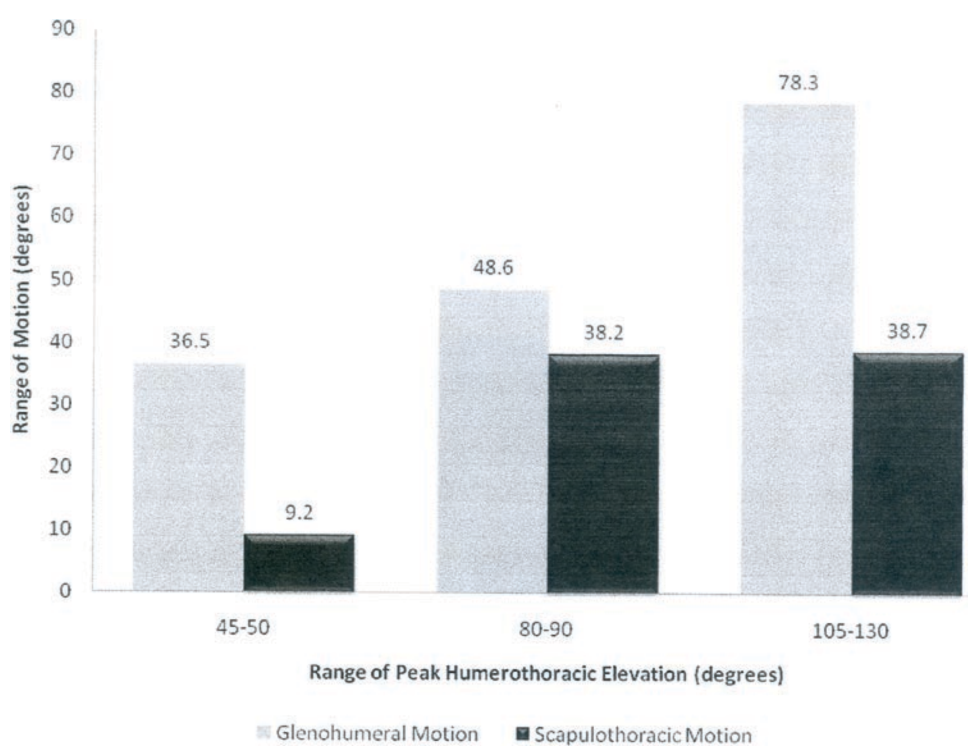

Figure 3. Comparison of glenohumeral to scapulothoracic motion.

Table III. SHR comparison between healthy individuals (McQuade) and individuals with stroke.

McQuade and Schmidt [11] Elevation (degrees)	SHR	Present study Elevation (degrees)	SHR
Phase 2 (26–52)	6.7:1	45–50	4.1:1
Phase 4 (78–104)	3.6:1	80–95	1.5:1
Phase 5 (104–130)	3.0:1	105–130	2.1:1

SHR, Scapulohumeral rhythm.

of all participants to reach full humerothoracic elevation in this study resulted in the inability to assess elevation through the full range of motion; therefore, data is discussed for the accomplished ranges.

The results of this study demonstrated a scapular contribution to shoulder function in individuals with stroke. Therefore, in clinical practice, it is important to focus treatment not simply on glenohumeral motion but to also include examinations and interventions that address the abnormalities in scapular motion.

One limitation of this study may be low generalizability. Our ratio of males to females (1:1) was inconsistent with the national demographics (1:1.5) [1], as was our age [1,2]. Nine out of 16 of the participants in this study were under the age of 65 years compared with national statistics stating 75% of persons with stroke are over 65 years of age [1,2]. Additionally, the overall different etiologies and extent of stroke were not taken into consideration. This may have affected the participant's level of function, in turn, skewing the results. A final limitation of this study could be that individually the FM_se is not validated. However, while not validated, it has been used in previous research [19–21].

Investigation of scapular mobility and its association to impairment and function in individuals with similar presentation could be an additional area for further research. Furthermore, there is a need for rehabilitation to address scapular mobility, as well as humeral motion, when treating individuals with chronic UE impairments from stroke.

Conclusion

Persons with UE impairments from stroke demonstrated reduced peak humeral elevation with altered SHR. Participants with a greater limitation in elevation demonstrated a larger scapular contribution to the SHR. The three major predictors of the FM_se were humeral elevation, scapular upward rotation and scapular internal rotation. Based on the results of this study, it is important for clinicians to include examination of and intervention to all of the components of SHR in everyday practice to address functional deficits.

***Declaration of interest*:** The authors report no conflicts of interest.

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