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Additional Information

ABSTRACT

This cross-sectional study analyzed the influence of chronic shoulder pain (CSP) on movement variability/kinematics during humeral elevation, with the trunk and elbow motions constrained to avoid compensatory strategies.

For this purpose, 37 volunteers with CSP as the injured group (IG) and 58 participants with asymptomatic shoulders as the control group (CG) participated in the study. Maximum humeral elevation (Emax), maximum angular velocity (Velmax), variability of the maximum angle (CVEmax), functional variability (Func_var) and approximate entropy (ApEn) were calculated from the kinematic data. Patients' pain was measured on the visual analogue scale (VAS). Compared with the CG, the IG presented lower Emax and Velmax and higher variability (i.e. CVEmax, Func_var and ApEn). Moderate correlations were achieved for the VAS score and the kinematic variables Emax, Velmax and variability of curve analysis, Func_var and ApEn. No significant correlation was found for CVEmax. In conclusion, CSP results in a decrease of angle and velocity and an increased shoulder movement variability when the neuromuscular system cannot use compensatory strategies to avoid painful positions.

Key terms: Shoulder pain, variability, humeral elevation, neuromuscular control system.

1. INTRODUCTION

Human movement is variable in nature, meaning that the same gesture repeated by the same person does not always perform in the same way (Schwartz, Trost, & Wervey, 2004). This variability has been associated with the stability of the neuromuscular system (Clark & Phillips, 1993) and its magnitude may be different in people with injury or pain (Bergin, Tucker, Vicenzino, Van Den Hoorn, & Hodges, 2014).

The analysis of movement variability in upper limb motion shows seemingly contradictory results. While some authors have reported an increased variability in kinematics in people with shoulder pain (Jayaraman et al., 2014; Lomond & Côté, 2010), others have reached the opposite conclusion (Bergin et al., 2014; Moon et al., 2013; Rice, Jayaraman, Hsiao-Wecksler, & Sosnoff, 2014). These conflicting results are a restriction for the use of movement variability as a clinical measure in the assessment and treatment of patients with chronic shoulder pain (CSP).

Two main issues should be considered when analyzing the results of the aforementionaed studies: (i) movement variability is directly associated with the task under investigation (Bates, James, & Dufek, 2004) and (ii) the result of movement variability may depend on the metrics used to measure it (Srinivasan & Mathiassen, 2012).

With respect to the task under investigation, with upper limb motion it is often possible to achieve the same goal through several anatomical configurations. According to the uncontrolled manifold hypothesis (Scholz & Schöner, 1999), the nervous system allows variations in task performance in order to relieve the dysfunction of the injured structure, increasing the mobility of the adjacent joints (i.e. the trunk, elbow and wrist)

and decreasing the shoulder motion and movement variability without compromising the success of the task (Jayaraman et al., 2014; Lomond & Côté, 2010; Madeleine & Madsen, 2009). Therefore, decreased variability of movement in injured people would be more closely related to these compensation strategies involving the neighboring joints, which may help to successfully accomplish the task, than to the effect of the injury itself. Consequently, an appropriate analysis of the effect of CSP on movement variability would require the restriction of compensatory strategies involving other joints with the aim of focusing only on the shoulder joint motion. This would reduce the nervous system's options for managing pain, hypothetically resulting in an increased variability of shoulder movement, as no other compensation strategies are available. However, no previous studies have used this approach.

Regarding the metrics, the interpretation of movement variability largely depends on the method used to measure it (Srinivasan & Mathiassen, 2012). Usually, cycle-to-cycle variability of discrete variables (e.g. range of motion, maximum force) is quantified using linear measures (e.g. standard deviation (SD) or coefficient of variation (CV)) (Harbourne & Stergiou, 2009). To avoid problems associated with the use of discrete values (e.g. wrong identification or limited information) it is also possible to use full-waveform data to study the between-cycle variability by means of functional measurements (Duhamel et al., 2004). Furthermore, other authors have proposed the use of nonlinear tools (e.g. approximate entropy (ApEn)) to analyze the temporal structure of variability. These tools study temporal variations in movement and are supposed to provide information about the adaptability of the neuromuscular system to external perturbations (Harbourne & Stergiou, 2009).

There is evidence of the usefulness of both linear and nonlinear measures to quantify differences in variability between people with and without shoulder pain (Madeleine & Madsen, 2009; Rice et al., 2014; Srinivasan & Mathiassen, 2012). Each method may provide different and complementary information about motion performance, but there are no clear indications about which metric it is better to use in each case (Srinivasan & Mathiassen, 2012). The results of Rice et al. suggest that intra-individual variability analysis is sensitive to shoulder pain (Rice et al., 2014), but no study has analyzed the correlation between variability metrics and perceived pain, which may give an indication of their suitability for assessing CSP.

The main aim of this work is to compare the extent and characteristics of movement variability between individuals with and without CSP during humeral elevation, without the possibility of using contiguous joints, i.e. constraining trunk and elbow motions. The hypothesis is that movement variability will be greater in patients than in healthy people, due to the difficulties of the nervous system finding compensatory strategies to reduce the pain experienced during the task. This is based on the assumption that pain is responsible for the variability.

Secondarily, we intend to explore the usefulness of different variability metrics (i.e. variability of discrete values, waveform variability and temporal structure variability), establishing relationships with the intensity of perceived pain in people with CSP.

2. METHODS

2.1. Participants

The study included a group of 37 individuals with right shoulder injury (IG), 27 men and 10 women within the same age range, all of whom were suffering pain at the time of the assessment, which lasted for at least three months. The CSP presented different etiologies: supraspinatus tendinitis (n=19), supraspinatus tears (n=9), resolved anterior dislocation (n=3), consolidated humerus fracture (n=2), arthritis (n=2), suprascapular lipoma and supraspinatus and infraspinatus muscle atrophy (n=1) and shoulder ligament sprain (n=1). They were all diagnosed by an experienced physician and clinical and imaging tests were used.

The control group (CG) comprised 58 individuals (33 men and 25 women). None of them had a structural pathology with shoulder, cervical or thoracic pain at least three months before their assessment and they did not present a psychiatric disorder. All the participants in the CG and IG were right handed.

All of the procedures were conducted in accordance with the principles of the World Medical Association's Declaration of Helsinki and were approved by the ethics committee of our institution. Involvement was voluntary and the participants signed an informed consent form before data were collected.

2.2. Pain assessment

The intensity of pain was measured at the beginning of assessment by a 100 mm visual analog scale (VAS) (Carlsson, 1983). The VAS consisted of a continuous line between two end-points, with 0 being "no pain" and 100 being "maximum tolerable pain".

2.3. Kinematic analysis

The participants sat on a rigid seat with a height-adjustable backrest, with their trunk upright. The backrest was fixed at the middle of their thorax, providing maximum support approximately at the level of the T4-T5 vertebrae. To avoid movement compensations, the participant' pelvis, trunk and left arm were fastened with straps to fix their position, allowing only the right arm to move. Elbow flexion-extension was also constrained by means of a splint in the region of the forearm. The motions of the arm and trunk were analyzed with seven reflective markers (Figure 1), according to the procedures described in (López-Pascual, Cáceres, De Rosario, & Page, 2016).

Figure 1 near here

The trunk reference frame was defined in the initial posture as follows: the y-axis of the trunk is coincident with the vertical direction, given by the global reference frame; the x-axis is perpendicular to the plane formed by the y-axis and the line LA-RA; The z-axis is computed as the cross product of the x-axis and the y-axis, resulting in the

141 transverse axis. The motion of the trunk was tracked by a technical cluster of markers
142 located on LA, the second dorsal vertebrae (D2), and the medial third of the scapular
143 spine (SC) (López-Pascual et al., 2016).

144 The starting position of the arm was fixed with its axis at 37.5º anteriorly to the coronal
145 plane of the trunk, and 45º down the transverse plane, with the aid of a guide marked on
146 a height-adjustable table and an electronic inclinometer. Thus, the initial orientation of
147 the humeral frame was defined as plane of elevation $\alpha = 37.5^{o}$, amount of elevation
148 $\beta = 45^{o}$, and axial rotation $\gamma = 0^{o}$.
149 The participants were instructed to lift their arm as much as they could, at a self-
150 determined comfortable speed, and maintain the maximum elevation for 3 seconds. This
151 gesture was repeated 5 consecutive times by each subject, holding a 250 g mallet to
152 standardize the starting and ending positions. The entire procedure was controlled by a
153 physiotherapist.
154

155 **2.4. Data analysis**

156

157 The motion of the markers was recorded by a stereophotogrammetry system (Kinescan-
158 IBV), with 4 CCTV cameras at 50 fps (Page, Candelas, & Belmar, 2006), and global
159 fixed frame aligned with the initial thoracic frame. Custom-written software in Matlab
160 R2010a (MathWorks, Natick, MA, USA) was used for the data processing.
161 The rotations of the thorax and the humerus from the starting position at any instant
162 were calculated using Rodrigues' vectors, according to the procedures described in
163 (López-Pascual et al., 2016). Humerothoracic motion for each subject was represented

using the XZ'Y'' Euler sequence, due to its better performance in terms of reliability compared with YX'Y'' (López-Pascual et al., 2016).

Only the first rotation $\alpha_i(t)$ (humeral elevation) and its angular velocity $\dot{\alpha}_i(t)$ were used in this study. The $\dot{\alpha}_i(t)$ waveforms were used to split out the j=5 repetitions of the ascent phase of the elevation gesture. Times were normalized by means of a cubic spline to represent the elevation cycles as intervals from 0% to 100% (n=101 data points for each repetition), obtaining $\alpha_{ij}(n)$ and $\dot{\alpha}_{ij}(n)$.

The following variables were calculated for each subject (Table 1): maximum humeral elevation (Emax), maximum angular velocity (Velmax), coefficient of variation of the maximum angle (CVEmax), functional variability (Func_var) and approximate entropy (ApEn). Parameters m and r for the calculation of ApEn were chosen according to the empirical approach described in Ramdani et al. (Ramdani, Seigle, Lagarde, Bouchara, & Bernard, 2009), obtaining the value m = 2 and r = 0.2, with N = 1500, where N is the input data points, m is the length of compared runs, and r is the tolerance.

Table 1 near here

2.5. Statistical analysis

Statistical analysis of the data was performed by SPSS v21 (SPSS Inc, Chicago, IL, USA).

First, we described the data. Standard statistical methods were used to obtain the mean and standard deviation of the mean, the minimum and maximum.

An independent-samples Student's t-test was performed to explore the differences in the dependent variables (kinematic variables) between the study groups (i.e. IG and CG) as the independent factor. We evaluated the normality assumption with the Shapiro-Wilk test and the homoscedasticity using a Levene test. If homoscedasticity was assumed, we used Student's t-test. In case of heteroscedasticity, we used the Satterthwaite approximation that adjusted the degrees of freedom. The effect size was reported with a Pearson's r estimator.

After checking the normality assumption of the pain score distribution in the IG, Spearman's correlation test was performed to establish the relationship between kinematic variables and pain score (measured with the VAS). All tests of hypotheses were conducted at the alpha = 0.05 level (Type I error of 5%).

3. RESULTS

3.1. Participants

The CG was comprised of 58 healthy people (33 men, 25 women) with a mean (SD) age of 42.47 (11.55) years, range 20 - 60; mean BMI of 25.12 (3.38) kg, range 19.20 - 33.65. The IG was comprised of 37 injured people (27 men, 10 women) with a mean (SD) age of 49.81 (11.55) years, range 23 - 64; mean BMI of 27.71 (4.32) kg, range 19.88 - 41.28. In this group the mean (SD) for the VAS was 5.16 (2.06), range 0.5 - 8. There were statistical differences between groups, both in age ($t(93) = -3.05$, $p<0.01$) and BMI ($t(93) = -3.27$, $p<0.01$). Although the differences in mean were small (2.59 points for BMI and 7.34 years), we aimed to rule out the possibility that this could

influence the results of the study. To this end in each group we analyzed the association between age and all the kinematic variables and also between BMI and all the kinematic variables. We obtained no significant correlation with the kinematic data for age and BMI ($p>0.05$), so the results presented below are not influenced by the effect of age or BMI.

3.2. Kinematic analysis

To address the first goal of the study, a comparison between the two groups was conducted of the assessment of kinematic variables during the defined analytical movement. Table 2 shows the descriptive results of all the kinematic variables depending on the grouping and the significant differences found between groups. As can be observed, the CG showed a significantly greater Emax and Velmax and lower movement variability, computed with three metrics (CVEmax, Func_var and ApEn).

Table 2 near here

Figure 2 is presented with the intention of better illustrating the characteristics of movement performance of the CG (healthy case) and the IG (chronic shoulder pain case). It can be observed that the healthy case achieved higher Emax and Velmax values than the CSP case (maximum values in the y axes). The phase-plane plot (below) shows that the curves corresponding to the five elevation cycles are almost superposed in the healthy case, which results in a low Func_var value. In contrast, the CSP case shows greater between-cycle variability and, therefore, a higher Func_var value. There are also

differences in the shape of the curves, which are smoother in the healthy case than in the CSP case. This feature is related to the magnitude of ApEn, which is greater in the IG. Smooth curves are believed to represent typical neuromuscular control, while irregular curves with rapid increases or decreases in angular velocity are believed to be indicative of poor control (Spinelli, Wattananon, Silfies, Talaty, & Ebaugh, 2015).

Figure 2 near here

3.3. Relationship between pain and kinematic variables

Regarding the secondary goal of the study, in which the relationship between pain and kinematic data was explored, significant Spearman's correlations were found between pain (measured with VAS) and all kinematic variables except CVEmax (i.e. variability of the discrete variables) ($p > 0.05$). Therefore, the pain intensity score was significantly correlated with Emax ($r = - 0.44$, $p < 0.01$), Velmax ($r = - 0.47$, $p < 0.01$), Func_var ($r = 0.48$, $p < 0.01$) and ApEn ($r = - 0.52$, $p < 0.01$).

4. DISCUSSION

This study aimed to analyze the impact that CSP has on movement performance and, specifically, on its variability. Given the controversy about the relationship between variability and shoulder pain, a novel methodological approach was used in this work. We focused specifically on the target joint, isolating the shoulder movement by limiting possible compensations by trunk and elbow motions. With this approach, we found

greater movement variability in the IG than in the CG and a significant correlation between movement variability and perceived pain.

While previous works have focused on the analysis of activities of daily living (ADL) or work-related activities (WRA), our study was the first to analyze the variability pattern in people with CSP who were asked to perform a humeral elevation, limiting the possible compensatory movements of the adjacent upper body structures.

This is based on the results of previous authors, who observed how patients with CSP naturally develop optimal motor solutions for everyday tasks with the aim of avoiding painful positions (Srinivasan & Mathiassen, 2012). The motion of the injured joint is then constrained to small deviations around the optimal solution, resulting in reduced shoulder ROM and variability (Bates et al., 2004). As a consequence, there is an increase in the motion of other body segments in order to successfully accomplish the task. These compensations were observed for the elbow, wrist and trunk in the study conducted by Lomond and Côté in a repetitive reaching task (Lomond & Côté, 2010) and by Madeleine and collaborators in a deboning task (Madeleine & Madsen, 2009) and in a repetitive arm movement (Madeleine, Mathiassen, & Arendt-Nielsen, 2008). In contrast, when pain was experimentally induced in healthy people, movement variability increased (Madeleine et al., 2008). The explanation given to this different behavior is that healthy individuals do not have a known compensatory strategy, thus the neuromuscular system would be continuously searching for the optimal solution, resulting in increased movement variability.

In our study, the movement executed by the participants is not an ADL or WRA and the compensatory movements of the elbow and trunk were constrained. This is a new situation for patients with CSP who, like healthy individuals with induced pain, do not

have a known optimal strategy for completing the task. As a consequence, we observed lower Emax and Velmax values and increased movement variability in the IG compared to the CG. The patients presented a 32.95% reduction in shoulder elevation and 69.02% reduction in maximum angular velocity. Limitation of shoulder elevation is one of the most common signs in patients suffering from shoulder pain and has already been reported in previous studies with different pathologies: Illyés and Kiss in patients with shoulder instability (Illyés & Kiss, 2006); McClure et al. in shoulder impingement (McClure, Michener, & Karduna, 2006); Mell et al. in shoulder cuff tears (Mell et al., 2005); and Rundquist et al. and Yang et al. in frozen shoulder (Rundquist, Anderson, Guanche, & Ludewig, 2003; Yang, Chang, Chen, & Lin, 2008).

The lower angular velocity shown by the IG is in line with previous studies such as Scibek et al., who showed that a reduction in patients' pain by means of a subacromial lidocaine injection resulted in significant increases in humeral elevation velocity (Scibek, Mell, Downie, Palmieri-Smith, & Hughes, 2010).

Regarding movement variability, there were higher values in the IG than in the CG, irrespective of the approach used to calculate the variability (i.e. linear and nonlinear methods). The three variability metrics computed in this study resulted in significant differences between the CG and IG, with large effect sizes. The capability of this type of variables for distinguishing between healthy and pathological individuals had already been reported by Rice et al. (CVEmax) (Rice et al., 2014), Delval et al. (Func_var) (Delval et al., 2008) and Stergiou et al. (ApEn) (Stergiou, Harbourne, & Cavanaugh, 2006). It should be mentioned that in our work both methods based on analysis of motion curves (Func_var and ApEn) presented a greater effect size (Pearson's correlation coefficient) than the CVEmax, which was computed using only the 5 values

307 of maximum elevation. These results are consistent with the study of correlations
308 between kinematic variables and pain intensity conducted.
309 In our study, significant negative correlations were achieved between the VAS score
310 and Emax and Velmax, as described in a previous study (Sarig Bahat, Weiss, Sprecher,
311 Krasovsky, & Laufer, 2014), in which correlation coefficients close to 0.5 were
312 obtained between VAS score and neck mobility.
313 Regarding variability metrics, moderate positive correlations were also found between
314 waveform variability (i.e. Func_var) and pain, and also for the temporal structure of
315 variability (i.e. ApEn) and pain. Nevertheless, pain and variability of discrete values
316 (CVEmax) were not significantly correlated. This suggests that variability metrics based
317 on curve analyses are more suitable for the study of the influence of pain on movement
318 performance.
319 Although some previous studies found differences in movement variability between
320 people with and without shoulder pain (Lomond & Côté, 2010; Madeleine & Madsen,
321 2009; Rice et al., 2014), so far no study has investigated the correlation between VAS
322 score and variability metrics.
323 Previous authors have already pointed out the clinical importance of the measurement of
324 angular velocity and movement variability to complement range of motion, strength and
325 muscle activity (Scibek et al., 2010; Spinelli et al., 2015). These variables may provide
326 relevant information to support decisions regarding the prescription and monitoring of
327 rehabilitation strategies (Scibek et al., 2010), as is the case with gait analysis (Yogev-
328 Seligmann, Giladi, Brozgol, & Hausdorff, 2012). It is in this regard that further studies
329 could explore variability patterns in pathologies that present similar clinical symptoms
330 (i.e. reduction of range of motion and /or pain) but different etiologies, such as

musculoskeletal disorders themselves or neuromuscular impairments, in order to understand the pathology-specific variability in behavior and to better manage rehabilitation.

Furthermore, the results of this work support the use of methods based on curve analysis (Func_var and ApEn) rather than discrete values (CVEmax) to measure shoulder movement variability in relation to CSP. However, no answer can be derived from this study regarding the suitability of applying linear methods (Func_var) or nonlinear methods (ApEn), as similar results were obtained. All the results should be used with caution because we did not explore the possibility of obtaining different patterns depending on the age or BMI.

5. CONCLUSIONS

As has been described above, movement variability is related to the stability of the neuromuscular system (Clark & Phillips, 1993). Our findings support this, as we have found increased variability in patients with CSP and a significant correlation with perceived pain. These results support the importance of using constrained movements for the assessment of CSP. This approach seems to be more adequate for evaluating the effect of the injury on movement variability, which may be disguised by compensatory strategies when executing ADL or WRA.

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FIGURE CAPTIONS

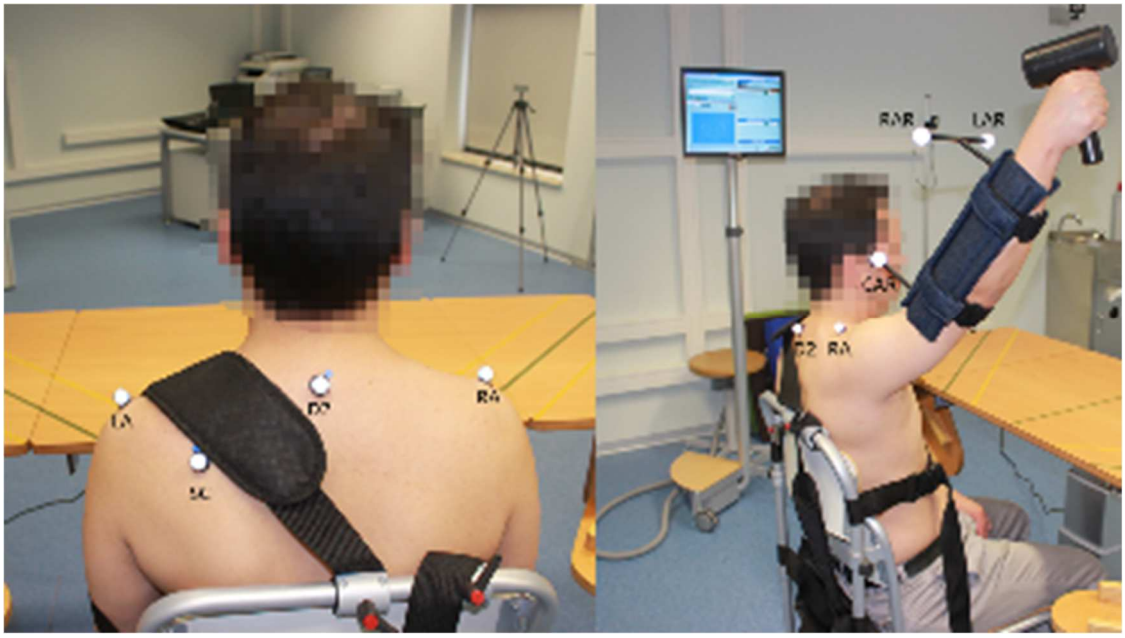
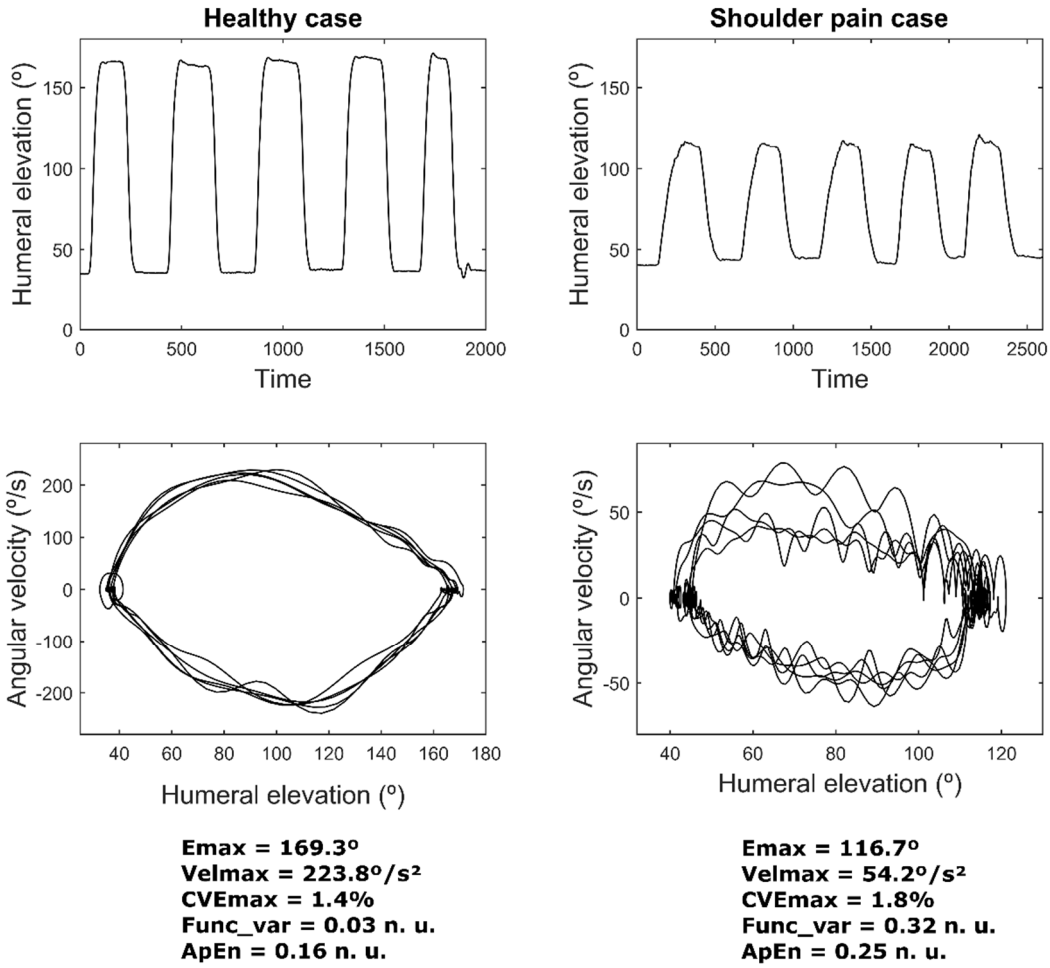


Figure 1. Instrumentation settings and markers.

LA: Left acromion; RA: Right acromion; SC: Medial third of the scapular spine; D2: Second dorsal vertebra; CAR: Central arm; LAR: Left arm; RAR: Right arm; (Xt;Yt;Zt): Trunk coordinate system; (Xh;Yh;Zh): Humerus coordinate system.

460 Figure 2. Movement performance of the two representative participants, one from the

461 control group and another from the injured group



462

463 Graphical representation of five cycles of humeral elevation in the scapular plane.

464 Angle vs time (above) and angular velocity vs angle (below). Emax: maximum

elevation; Velmax: maximum velocity; CVEmax: coefficient of variation of the maximum elevation; Func_var: functional variability; ApEn: approximate entropy.

Table 1: Description of the variables used in the study

Code	Description	Calculation
Emax (°)	**Maximum elevation:** Mean of the maximum angles of humeral elevation achieved in the N repetitions	$\frac{1}{N}\sum_{j=1}^{N}\max(\propto_j)$
Velmax (°/s)	**Maximum velocity:** Mean of the maximum angular velocities in humeral elevation achieved in the N repetitions	$\frac{1}{N}\sum_{j=1}^{N}\max(\dot{\propto}_j)$
CVEmax (%)	**Coefficient of variation** of the maximum angle of humeral elevation, as a measure of between-cycles variability using discrete variables.	$\frac{\sqrt{\frac{1}{N}\sum_{j=1}^{N}(\max(\propto_j)-\mathrm{Emax})^2}}{Emax}$
Func_var (n.u.)	**Functional variability**, between-cycles variability computed using $\dot{\propto}(n)$ waveform data as: $1-ICC_{func}(\dot{\propto}_J,..,\dot{\propto}_N)$ (Duhamel et al., 2004)	$1-\frac{MST_j-MSE_j}{MST_j+(N-1)\times MSE_j}$
ApEn (n.u.)	**Approximate entropy**, as a measure of temporal structure of variability, computed from $\propto(t)$ waveform data.	$\phi^m(r)-\phi^{m+1}(r)$ (Pincus, 1991) Where: $\phi^m(r)=(\mathrm{N}-\mathrm{m}+1)^{-1}\sum_{i=1}^{\mathrm{N-m+1}}\log \mathrm{C}_i^m(\mathrm{r})$

Where *N* is the total number of j repetitions of shoulder elevation performed in the test (5 for this study); $\propto$ is the angle of elevation waveform (°) ; $\dot{\propto}$ is the elevation angular velocity waveform (°/s); *MST* is the between-time mean square and *MSE* the within-time mean square from a one-way ANOVA per subject (Duhamel et al., 2004); The $C_i^m(r)$ values measure within the tolerance r the frequency of patterns similar to a given pattern of window length m (Pincus & Goldberger, 1994).

Table 2: Comparative analysis of the kinematic variables of the control group and the injured group

	CG	IG	t-test results	Effect size (r)
Emax (°)	167.82 (7.15)	112.53 (28.73)	*T(38.86) = 11.48, p < 0.01*	0.88
Velmax (°/s)	240.71 (63.37)	74.58 (55.24)	*T(93) = 13.08, p < 0.01*	0.80
CVEmax (%)	1.25 (0.88)	3.33 (1.88)	*T(46.14) = -6.32, p < 0.01*	0.68
Func_var (n.u.)	0.06 (0.03)	0.36 (0.22)	*T(37.15) = - 8.28, p < 0.01*	0.81
ApEn (n.u.)	0.16 (0.03)	0.30 (0.10)	*T(39.30) = -8.11, p < 0.01*	0.79

Data are expressed as mean (SD); CG: control group: IG: injured group; n.u.=no units; Emax: Maximum humeral elevation; Velmax: Maximum angular velocity; CVEmax: Variability of the maximum angle; Func_var: Functional variability; ApEn: Approximate entropy.