Volumetric definition of shoulder range of motion and its correlation with clinical signs of shoulder hyperlaxity. A motion capture study

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Background: Shoulder hyperlaxity (SHL) is assessed with clinical signs. Quantification of SHL remains difficult, however, because no quantitative definition has yet been described. With use of a motion capture system (MCS), the aim of this study was to categorize SHL through a volumetric MCS-based definition and to compare this volume with clinical signs used for SHL diagnosis.

Method: Twenty-three subjects were examined with passive and active measurement of their shoulder range of motion (SROM) and then with an MCS protocol, allowing computation of the shoulder configuration space volume (SCSV). Clinical data of SHL were assessed by the sulcus sign, external rotation with the arm at the side (ER\textsubscript{1}) > 85° in a standing position, external rotation > 90° in a lying position, and Beighton score for general joint laxity. Active and passive ER\textsubscript{1}, EIR\textsubscript{2} (sum of external and internal rotation at 90° of abduction), flexion-extension, and abduction were also measured and correlated to SCSV.

Results: Except for the sulcus sign, SCSV was significantly correlated with all clinical signs used for SHL. Passive examination of the different SROMs was better correlated to SCSV than active examination. In passive examination, the worst SROM was ER\textsubscript{1} (R = 0.36; P = .09), whereas EIR\textsubscript{2}, flexion, and abduction were highly correlated to SCSV (P < .01).

Conclusion: SCSV appears to be an appealing tool for evaluation of SHL regarding its correlation with clinical signs used for SHL diagnosis. The sulcus sign and ER\textsubscript{1} > 85° in a standing position appear less discriminating and should be replaced by EIR\textsubscript{2} measurement for SHL diagnosis.

Level of evidence: Basic Science, Kinematics.

Keywords: Shoulder; shoulder kinematics; shoulder laxity; hyperlaxity; shoulder instability

Shoulder hyperlaxity (SHL) is considered a main risk factor for shoulder instability\textsuperscript{2} and can be associated with different clinical shoulder instability presentations, such as multidirectional instability or unstable painful shoulder.\textsuperscript{15} Interestingly, quantification of shoulder laxity and hyperlaxity, particularly during physical examination, still remains an unsolved problem.\textsuperscript{6,20,21,26} Increased shoulder
laxity, so-called hyperlaxity, can be defined as an increased amount of manual glenohumeral translation of the shoulder\textsuperscript{11} or a global increased range of joint movement.\textsuperscript{9} Currently, no shoulder laxity clinical test appears completely reliable\textsuperscript{13,17} because of the spectral distribution of shoulder laxity in the population. Furthermore, only a few studies have described SHL from a biomechanical or a motion capture analysis point of view\textsuperscript{7,15,16} but confirmed the possible use of a motion capture system (MCS) as an appropriate tool for quantitative assessment of multiaxial shoulder motion.

The lack of shoulder laxity quantification motivated this study. We hypothesized that the total volume of shoulder range of motion (SROM) is correlated to SHL. The aim of our study was to assess the 3-dimensional (3D) shoulder motion analysis in an asymptomatic population to know whether range of motion and, above all, external rotation are correlated to SHL. Finally, we tried to correlate actual clinical signs used for SHL diagnosis to this volumetric definition of SROM.

**Materials and methods**

This is an observational motion capture study.

**Subjects**

Twenty-three healthy female volunteers (medical or sports students; age, 24.5 ± 2.5 years [range, 20.2-29.9 years]; height, 165 ± 6 cm [range, 157-175 cm]; body mass index, 18.5 kg/m\textsuperscript{2} ± 1) were selected for study. All subjects were right-hand dominant. Exclusion criteria were a positive apprehension test result or symptoms of instability, positive Neer test result or pathologic rotator cuff test result (Jobe, Yocum, palm-up, and lift-off tests), previous history of shoulder surgery or complaint, shoulder trauma (including acromioclavicular joint), sensitivity to adhesive tape, pregnancy, Marfan syndrome, psychological voluntary subluxation (including acromioclavicular joint), sensitivity to adhesive tape, pregnancy, Marfan syndrome, psychological voluntary subluxation, and neck pain (complaint or surgery). Written informed consent was obtained from all subjects before participation.

**Clinical examination**

Before MCS analysis of SROM, SHL was searched for in every subject by different clinical criteria. Each clinical sign was elicited and assessed jointly by 2 shoulder senior orthopedic surgeons (M.R. and H.T.). Before examination and experimentation, all subjects sustained upper limb preparatory movements realizing complete circular movements of their dominant right arm in maximal SROM.

Signs considered for SHL diagnosis were the following:

- Passive hyperrotation with external rotation with the arm at the side (ER1) >85° in a standing position.\textsuperscript{7}
- Passive hyperrotation with ER1 >90° in a lying position.\textsuperscript{18}
- Sulcus sign >2 cm (yes or no).
- Sulcus sign grades 0, +, ++, ++++.\textsuperscript{9}
- Beighton scale for general joint laxity >5 points: passive metacarpophalangeal joint hyperextension of small

**Figure 1** Overview of marker placement with rigid purpose-built splint at 90° of elbow flexion in neutral prone supination.

- Finger > 90° (2 points); passive thumb apposition to forearm (2 points); elbow hyperextension >10° (2 points); knee hyperextension >10° (2 points); trunk flexion, knee extension, and palms to the floor (1 point).\textsuperscript{3}

Active and passive ER1 measurements in a standing position were performed with a physiotherapist goniometer.

**Instrumentation: motion analysis protocol**

A 12-camera MCS (Vicon MX40; Oxford Metrics Ltd, Oxford, UK) was used to track the 3D displacements of markers of the whole upper limb to obtain 3D kinematics data. The upper limb and thoracic markers were positioned on the subjects by the same experienced physician for all the procedures and placed by the recommendations of the International Society of Biomechanics.\textsuperscript{25} All measurements were realized with a purpose-built splint at 90° of flexion in a neutral forearm position (supination = 0°) (Fig. 1) to avoid coupling between elbow flexion/extension and shoulder motion analysis. The splint was designed with windows allowing shoulder examination and positioning of anatomic landmarks used for positioning markers tracked during motion capture analysis.

During MCS recording, subjects were first examined with measurement of ER1, EIR2 (external plus internal rotation at 90° of abduction), flexion, extension, and abduction. All measurements were performed in a standing position. First, the same senior shoulder orthopedic surgeon performed a passive examination. After this passive examination, subjects performed the same set of measures actively. Finally, the subject (active measure) or the examiner (passive measure) was asked to perform combined rotations in extreme SROM to explore all the shoulder joint reachable space, allowing determination of the passive and active shoulder configuration space volume (SCSV) (Fig. 2), expressed in 10\textsuperscript{6} deg. This volume was defined as the smallest convex hull of a polyhedron including all measures in the 3D angular space proposed by the International Society of
Biomechanics (orientation, elevation, axial rotation). Data analysis of MCS experimentation was processed with MATLAB.

**Statistical analysis**

Statistical analysis was performed with SigmaStat (Systat Software Inc, San Jose, CA, USA). Concerning quantitative values, the Pearson or Spearman correlation coefficient was assessed between each studied value and SCSV, with an associated $P$ value indicating a significant correlation ($P < .05$).

For yes/no qualitative variables issuing from a thresholding evaluation, the SCSV was analyzed through the comparison of each of the 2 subgroups by a Student $t$ test. The difference for those mean comparisons was considered significant for a $P$ value $< .01$.

**Results**

According to MCS measures, passive amplitudes were found to be higher than active ones in all SROMs except for abduction (mean values for SROM are summarized in Table I).

In comparison between an increased SCSV and amplitudes recorded during MCS, despite a significant correlation between SCSV and most of the measures performed (Table II), passive EIR2 ($P = .0002$) and passive abduction ($P = .004$) were considered the most representative SROMs for assessment of SCSV compared with the respective active SROM measures. ER1 was not considered a representative sector for SCSV assessment. However, this lack of correlation was not described for ER1 measured in a standing position ($P = .005$). General joint laxity according to the Beighton scale was also correlated to SCSV ($P = .007$). Table III provides the result of comparison between positive and negative subgroups for the 3 threshold tests. SHL was discriminated by the criteria ER1 standing $>85^\circ$ ($P = .016$) and ER1 on table $>90^\circ$ ($P = .004$). The sulcus sign, whether graded with crosses (Table II) or classified $>2$ cm (Table III), was never considered representative of SCSV (Table IV).

**Discussion**

Definition and quantification of shoulder laxity still remain an unsolved clinical problem. This lack of characterization induces difficulties in classifying a shoulder as lax, and there are not one but many spectral distributions for hyperlaxity. Conversely, SHL is now recognized as a main risk factor for shoulder instability and its treatment outcome. In this unstable shoulder context, shoulder laxity testing is recommended for patients undergoing shoulder surgery stabilization. Currently, most authors consider a diagnosis of SHL in association with at least 2 positive signs of shoulder laxity, such as an increased external rotation and a positive sulcus sign. The main problem is that no laxity tests symbolize the “gold standard” measurement. In fact, quantifying shoulder laxity is still a challenge, and intraobserver and interobserver reproducibility of shoulder laxity tests remains controversial.11 Interestingly, this study aimed first to give a method to objectively measure shoulder laxity before defining SHL.

This study reported a new model of SHL definition through the concept of a clinical reachable space, as reported by Klopčar et al, who proposed use of the arm-reachable workspace for SROM evaluation. Arm-reachable workspace is the volume measured in the cartesian space, which includes all the positions that can be in use by the wrist with respect to the shoulder. Several attempts have been made to develop a global index of shoulder mobility, that is, some kind of 3D range. The advantage of SCSV is that it can give a proposal only for shoulder articulation.
This monarticular selection is devoted to SHL diagnosis in this work; even if it is not accessible in clinical practice, this new tool seems interesting for other shoulder pathologic processes or treatment evaluation, such as total shoulder arthroplasty evaluation.

Regarding clinical signs currently used for SHL diagnosis, our conclusions underline the possible misuse of ER1 for SHL diagnosis. Indeed, ER1 has the advantage that it can be evaluated even when shoulder pain and movement restriction prevent examination with 90° of abduction (EIR2). ER1 rotation is subsequently particularly relevant for diagnosis and evaluation of treatment in patients with adhesive capsulitis. Interestingly, ER1 is a common tool in decision making for shoulder instability. Many studies have proposed that an increased ER1 >85° in a sitting position or 90° in a lying position is a criterion to determine the diagnosis of SHL. Accordingly, Balg and Boileau developed a 10-point preoperative instability severity index score to identify patients who should develop recurrent anterior shoulder instability after an arthroscopic (Bankart) procedure. In this score, among 4 other items, hyperlaxity is considered a main risk of recurrence after arthroscopic stabilization. On the topic of this score, SHL is diagnosed with the single criterion of ER1 >85°, which can increase the instability severity index score and change the surgical procedure indication of an arthroscopic to an open surgical procedure. Nevertheless, the diagnosis of SHL based on a definition of increased rotation of the shoulder measured through ER1 has never been confirmed in the literature and is highly questioned after our study. In fact, according to our findings, the ER1 amplitude appears to be the worst SROM for estimating SCSV or indirectly SHL description and certainly overestimates SHL diagnosis. According to our results, EIR2, abduction and flexion, or the association in a scoring system of both of those SROMs should replace ER1.

Furthermore, our study showed that the sulcus sign, examined by grading with crosses or >2 cm, is definitely not the most pathognomonic tool for SHL diagnosis. As shown, to assess for global shoulder mobility and indirectly SHL, we have proposed the use of preferably other clinical signs or SROMs, such as passive hyperrotation ER1 >90° in a lying position, that do not necessitate a goniometric measure. Our study also highlighted the superiority of passive measurements compared with active ones in all rotational SROMs and also in flexion/extension sectors. Finally, general joint laxity recorded according to the Beighton scale appears correlated to SCSV. In this female population, usually considered by many authors the preferential population for general joint laxity prevalence, we found that patients with higher SCSV had an increased Beighton score in comparison to patients with a low SCSV. Conversely, there is still a conflict in data regarding general joint laxity, shoulder laxity, and gender. Beighton and Brown reported also that females are more mobile than males at any age.
Table IV  Correlation between SCSV ($10^6 \text{ deg}^3$) and MCS amplitudes

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<tr>
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<th>Passive</th>
<th>Active</th>
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<td>Flexion/extension</td>
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<td><img src="image2" alt="Graph" /></td>
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<tr>
<td>ER1 (standing position)</td>
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<td>ER1 (lying position)</td>
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<td>ER2/IR2 amplitude</td>
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We acknowledge several limits to our study. Only female subjects were included in the study to explore the wider SCSV definition, as female subjects tend to be more lax than male subjects. Our conclusions should therefore be considered with caution in considering the general population, especially because only young volunteers were included to get closer to the age of patients presenting with an anterior shoulder instability. We also did not study particular clinical signs sometimes used for SHL testing, such as the hyperabduction test reported by Gagey. This choice was motivated by the fact that Gagey’s sign should be considered a clinical sign of instability more than a sign of SHL. Drawer tests were not used because of the impossibility of optimizing their assessment for the experimentation protocol (irradiation). In addition, one could criticize the choice of the MCS used, regarding the risk of error due to skin motion of the markers. Moreover, we chose also to place the subjects in a standing position to ensure the maximal ability to move the upper limb in the surrounding space. This would probably have been more difficult in the sitting and supine positions, which are usually used for assessment of a particular SRM, such as EIR2. Our methodology may not be directly transposable in clinical routine as we used a 3D motion capture device that is more dedicated to research and needs some technical skills. However, as mentioned before, our primary goal was to show the interest of SCSV in shoulder laxity evaluation. The question of simplifying the measurement device is beyond the scope of our study, but innovative techniques are being developed by other research teams. When such simpler devices are successfully completed, SCSV will reasonably be measurable in clinical routine. Finally, it would surely be interesting to have a threshold for hyperlaxity diagnosis in measuring the sum of the passive external rotation/internal rotation at 90° of abduction. In our opinion, hyperlaxity can be defined only through statistics, that is, as being over normal distribution. One can imagine, for example, that hyperlaxity would mean being within the upper 5% of laxity range. Therefore, a larger database would be necessary to provide a reliable threshold.

**Conclusion**

There is no simple method available to identify patients who present with SHL, but the association of different clinical signs should help in identifying those subjects.
Most of the actual clinical signs used for SHL diagnosis were correlated to SCSV, which appears to be an interesting tool for evaluation of SHL. Nevertheless, the sulcus sign appeared to be fairly accurate, and ER1 >85° in a standing position remains less discriminate and should, at least, be replaced by ER1 >90° on table in a lying position for SHL diagnosis.

Disclaimer

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References