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Research Article

A New Neurocognitive Interpretation of Shoulder Position Sense during Reaching: Unexpected Competence in the Measurement of Extracorporeal Space

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Background. The position sense of the shoulder joint is important during reaching. *Objective*. To examine the existence of additional competence of the shoulder with regard to the ability to measure extracorporeal space, through a novel approach, using the shoulder proprioceptive rehabilitation tool (SPRT), during reaching. *Design*. Observational case-control study. *Methods*. We examined 50 subjects: 25 healthy and 25 with impingement syndrome with a mean age [years] of 64.52 +/− 6.98 and 68.36 +/− 6.54, respectively. Two parameters were evaluated using the SPRT: the integration of visual information and the proprioceptive afferents of the shoulder (Test 1) and the discriminative proprioceptive capacity of the shoulder, with the subject blindfolded (Test 2). These tasks assessed the spatial error (in centimeters) by the shoulder joint in reaching movements on the sagittal plane. *Results*. The shoulder had proprioceptive features that allowed it to memorize a reaching position and reproduce it (error of 1.22 cm to 1.55 cm in healthy subjects). This ability was lower in the impingement group, with a statistically significant difference compared to the healthy group ($p < 0.05$ by Mann–Whitney test). *Conclusions*. The shoulder has specific expertise in the measurement of the extracorporeal space during reaching movements that gradually decreases in impingement syndrome.

1. Introduction

Every single movement, depending on the goal, is the expression of various processes, such as attention, perception, motivation, and memory [1, 2]. An example of such a complex action is the control of reach-to-grasp movements, which are divided into specific sequences that integrate visual and proprioceptive afferent information with motor efferent of the upper limb [3, 4].

During the reaching phase, the function of the shoulder joint must be considered, notably in relation to the task of measuring the direction and distance that the upper limb must cover to grasp an object [5, 6]. Conversely, the shoulder joint and its position sense might be significant proprioceptive elements during reaching. Thus, the scapula is a strategic joint during anteposition movements of the shoulder regarding lateral-medial displacement and counter-balance of the trunk through changes in its center of rotation.

The organization of the center of rotation of the scapula is necessary, allowing the glenoid to move into the most suitable position to effect movements of the humerus space [7, 8].

Imbalances in musculoskeletal activity in the scapular stabilizers of subjects with subacromial impingement syndrome (SIS) have been described in restricted tasks and specific populations [9, 10]. Further, the kinematics of upper limb movements and the coordination of eye and hand movements are affected by aging, forcing older adults to use a task-dependent eye movement strategy [11]. The subtle changes that occur with age thus appear to reflect a strategy that develops to compensate for deterioration in other systems, such as visual and proprioceptive activity [12].

Visual information on the size of the body is accessed by the body schema and is prioritized over proprioceptive inputs for motor control [13]. Articular proprioception, defined as a specialized sensory function that includes the sensation of movement and joint position, must integrate with visual afferents for correct static and dynamic joint activity [14, 15].

Some groups have examined the resolution of discrepancies between visual and proprioceptive estimates of arm position, finding that the magnitude of changes in sensory estimates is greater for proprioception (20%) versus vision (<10%) [16].

Further, proprioceptive performance has been linked to improved motor performance; thus, active movement alone does not determine proprioceptive reproducibility compared with active and passive movement. External stimuli tactile input or a reference angle that is chosen by the examiner can diminish reproducibility [17].

However, several studies have attempted to describe the method by which shoulder position sense is measured in asymptomatic adults and its percentage error during movement, particularly in reaching tasks [18, 19].

We wondered whether the shoulder actually measures the distance that is covered by the upper limb during reaching the reproducibility with which it does so and how the shoulder joint integrates visual afferents and the sense of position. The aim of this research is to assess the competence of the shoulder position sense with regard to the ability to measure extracorporeal space, between patients with and without rotator cuff disease, through a novel approach using a shoulder proprioceptive rehabilitation tool (SPRT), during reaching.

2. Materials and Methods

This case-control observational study examined the proprioception of the shoulder joint and its ability to memorize a reaching position and reproduce it and to integrate visual and proprioceptive information through a specific evaluative and rehabilitative device, the SPRT.

This study was performed according to the guidelines of the Helsinki Declaration on human experimentation and was approved by the ethical committee of "Sapienza" University of Rome (registration number 3826, ClinicalTrials.gov identifier NCT02646306). All subjects gave written informed consent after receiving detailed information on the study's aims and procedures.

From July 2015 to January 2016, 50 subjects—25 who were affected by shoulder impingement syndrome (IG) and 25 controls (HG)—were recruited from the Physical Medicine and Rehabilitation Outpatient Clinic of Policlinico Umberto I Hospital, Sapienza University of Rome, Italy. The mean age [years] was 64.52 +/− 6.98 for the HG and 68.36 +/− 6.54 for the IG (see Table 1). The IG comprised 25 patients aged between 40 and 75 years with shoulder pain that had lasted for at least 3 months with a visual analog scale (VAS) score ≥ 3 for pain and a diagnosis of shoulder impingement syndrome (SIS), Neer stage 2 or 3 [20–22], established by clinical examination; X-ray images of the anteroposterior, axillary, and outlet views; and magnetic resonance imaging (MRI) or echography of the affected shoulder (right-sided dominance). The HG comprised 25 healthy subjects without any rotator cuff disease and shoulder pain with a visual analog scale (VAS) score = 0 (right-sided dominance). The healthy controls were volunteers afferent to ambulatory of the physical medicine and rehabilitation as caregivers to other patients not included in the study: the healthy state was determined by medical history and clinical examination by a physician specialist in physical medicine and rehabilitation and only right-handed persons were enrolled as in IG as in HG.

The exclusion criteria were the inability or unwillingness to give informed consent; previous surgery on the affected shoulder; inflammatory, neurological (systemic or local), or infectious disease; cognitive or psychiatric disorders; local tumor metastasis or application of radiotherapy; use of antidepressants, anxiolytics, or other medications that could have affected attentional and sensory processes; the presence of refractive errors that were improperly compensated; and patients with sternoclavicular joint dysfunction and cognitive impairment or memory.

For each case, one control was recruited, and all subjects underwent two consecutive tests: one to examine the integration of visual information and proprioceptive afferents at the shoulder level and another to determine the capacity of the shoulder to perform proprioceptive discrimination. During each task, the spatial error of the shoulder joint during reaching movements on the sagittal plane was measured using the SPRT. Each test was performed with the right arm, which was the dominant side.

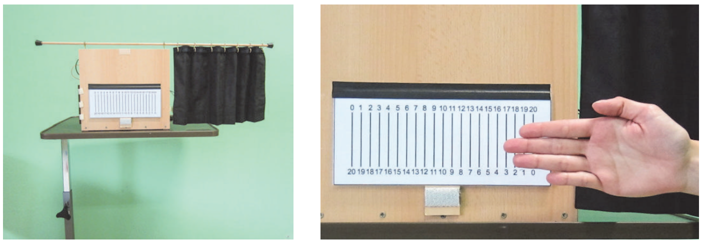
The SPRT (see Figure 1) consists of 2 panels that are joined together; on the top of the 2 panels lies a wand that is attached to a curtain to hide the limb from the subject in the test that required the exclusion of visual information. Two graduated masks (cm) were placed on the inside and outside to measure the subject's shoulder anteposition movement, with a precision of up to 0.5 centimeters. A line of holes was applied to correspond to the mask to allow the introduction of a mobile LED device that can be seen by the subject.

2.1. The Task. The subjects performed two assessment tests in succession in the forearm pronation-supination neutral position, with extended elbows, shoulder flexion of 90° in the sagittal plane, and wrist and fingers extended along the axis of the shaft of the humerus (*reference position*). The subject began by sitting with his back resting against a comfortable chair in a fixed position, with his feet parallel

Table 1: Demographic and clinical data of participants at baseline. Mean and standard deviation for clinical scores are reported with an assessment of the statistical significance of comparisons.

Baseline data	HI (N = 25) (mean +/− SD)	IG (N = 25) (mean +/− SD)	p value	Test
Age [years]	64,52 +/− 6,98	68,36 +/− 6,54	0,047	*
Body mass index = BMI [kg/m^2]	24,94 +/− 3,05	26,87 +/− 3,97	0,082	*
Constant-Murley score, pain	14,76 +/− 0,43	7,76 +/− 4,00	<0,001	*
Constant-Murley score, daily life activities	19,60 +/− 0,98	11,32 +/− 3,60	<0,001	*
Constant-Murley score, ROM	39,52 +/− 0,85	28,72 +/− 9,08	<0,001	*
Constant-Murley score, strength	20,08 +/− 4,03	6,40 +/− 3,88	<0,001	*
Constant-Murley score, total	93,97 +/− 4,23	54,20 +/− 16,61	<0,001	*
Dash score	4,76 +/− 7,01	53,24 +/− 20,48	<0,001	*
VAS [cm]	0,52 +/− 0,74	4,67 +/− 2,46	<0,001	*
Employment rate [%]	68%	44%	—	nc
Qualitative variables	N (%)	N (%)		
Gender				
Male	16 (64%)	9 (36%)	0,048	**
Female	9 (36%)	16 (64%)		
School attendance				
Basic school	0 (0%)	1 (4%)	—	nc
Middle school	7 (28%)	13 (52%)		
High school	11 (44%)	11 (44%)		
Graduated	7 (28%)	0 (0%)		

* p value by Mann–Whitney test.
** p value by chi-square test.
nc: not computable.



(a) (b)

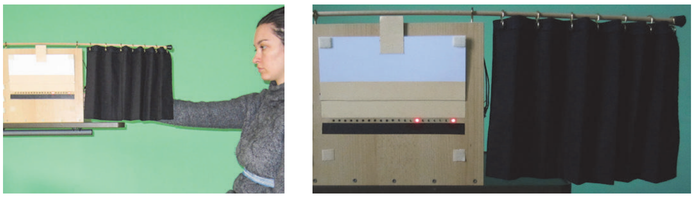
Figure 1: The shoulder proprioceptive rehabilitation tool (SPRT) and the graduated mask for the measurements.

to the ground. Then, the physiotherapist placed the patient in the *zero* reference position. To avoid fatigue, a 30-minute break between tests was given to the subject. The evaluation lasted for 10 minutes for the first test and 20 minutes for the second test.

For each test, the SPRT device was calibrated to a suitable height for the participant and his upper limb length, allowing him to bring the tip of the middle finger of the right hand to the "zero" position on the graduated mask of the SPRT (see Figure 1). The sequence of tests was alternated for each participant; for example, if subject 1 performed Test 1 before Test 2, the following subject performed the tests in reverse order to avoid any bias that could be linked to eyestrain or the learning task.

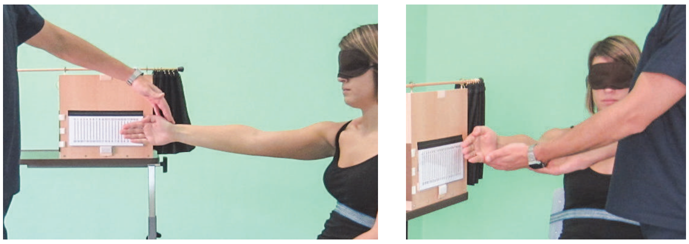
A participant performed various tasks for each test per the examiner's demands; the positions that were required always differed and were based on a standardized sequence.

Test 1: Integration of Visual Information and Proprioceptive Afferents of the Shoulder. Test 1 was carried out in complete darkness and silence to focus the patient attention's on a red LED and to eliminate other distractions (e.g., noise). Starting from the reference position, with the hand hidden from sight by the black curtain, the subject had to actively reach the positions that were instructed by the examiner through the red LED light (see Figure 2). Before starting the test, the subject performed the task once with the guidance of the physiotherapist, reaching forward through a



(a) (b)

Figure 2: Examining the integration of visual information and the proprioceptive afferents of the shoulder.



(a) (b)

Figure 3: Study of the discriminative proprioceptive capacity of the shoulder (active phase (a) and passive phase (b)).

shoulder anteposition movement, starting from the *reference position*, and then reaching back. Also, the target position was indicated on the side of an unnumbered template of the device by a red LED. The subject was placed in a dark room to eliminate any visual distractions, allowing him to focus his visual attention on the red signal that indicated the positions that were to be reached. We assumed that vision would permit positions to be estimated with high reproducibility; thus, we did not include full-vision conditions [23].

The positions that were to be attained by the subject were as follows: 2 triplets (5-2-7 and 3-6-1 cm), the first one made in a forward reaching movement, starting from reference position 0, and the second triplet made in a reaching back movement, starting from reference position 8. The patient was cued with the instruction "join hand with the red light signal."

Test 2: The Discriminative Proprioceptive Capacity of the Shoulder. Test 2 was performed in dark surroundings, with the subject blindfolded (see Figure 3). The participant, starting from the reference position, had to actively reach the position asked by the examiner with a forward reaching movement first and a reaching back movement after. This test comprised an active and passive component, in which the upper limb was aided by the examiner to increase the participant's focus on the position recognition task.

The passive section of Test 2 was preceded by a preparatory stage in which the subject perceived the 6 positions in succession in a single action in the reaching forward and reaching back movements, with the upper limb guided and supported by the physiotherapist (in the passive position, the limb was supported by the physiotherapist for the duration of the test).

Then, the same physiotherapist placed the participant's arm in one of the perceived positions and verbally asked the subject to define the number of positions with respect to the device mask.

In the active component, the researcher verbally instructed the participants to reach one of the six positions outward and in the return movement.

The following positions were to be reached: the passive section comprised 2 triplets of measurements (7-2-5 and 3-6-1 cm), as did the active component (5-2-7 and 1-6-3 cm). The patient was prompted by "join hand with position number X" in the active phase versus "in what position is your hand?" in the passive phase.

2.2. Assessment of Error. Both tests entailed six assessments: three reaching forward and three reaching back. At the end of each evaluation, the examiner noted the error by the subject, defined as the GAP in precision (cm). The average error in the two tests was considered to be the total score (i.e., the average score for reaching forward movements and that for reaching back movements). The error was expressed numerically as a percentage of the difference between the position that was instructed by the examiner and that achieved by the participants as follows:

$$\text{GAP} = \text{measure requested}_{\text{cm}} - \text{measure done}_{\text{cm}}$$

$$\text{relative GAP (RGAP)} = \text{ABS}\,(\text{measure requested}_{\text{cm}} - \text{measure done}_{\text{cm}})/\text{measure requested}_{\text{cm}}$$

$$\text{RGAP\%} = (\text{measure requested}_{\text{cm}} - \text{measure done}_{\text{cm}})/\text{measure requested}_{\text{cm}} \times 100$$

The measurement was based on the position that was reached by the tip of the middle finger on the graduated mask (see Figure 3).

The measurements that were requested to the participants (total of 18 measurements for both tests) were based on the same predetermined sequence for each participant to ensure full comparability between healthy and pathological subjects and to avoid measurement tasks that were separated by only 1 centimeter. No verbal aid was provided to the subject during the trial.

2.3. Outcome Measures. Clinical data were collected at baseline, and all subjects were evaluated before the tests. The VAS was used to measure outcomes with regard to shoulder function before the tests. Patients were asked to mark the point that corresponded to their perceived pain intensity on a 10 cm line, with 0 indicating the absence of pain and 10 reflecting the most severe pain [24]. The short form of the Disabilities of the Arm, Shoulder, and Hand (DASH) questionnaire (Quick-DASH), measuring physical ability and symptoms of the upper extremities and examining the impact of functional impairment and pain on daily-living tasks, social and recreational activities, work, and sleep, was also used; scores ranged from 0 to 100 points, with 0 reflecting no disability and 100 corresponding to the most severe disability [25, 26]. The Constant-Murley score is based on subjective (sleep, work, and recreational activities) and objective (ROM and strength) components, adjusted for age and sex, according to normative values per Yian et al. [27], with scores ranging from 0 (worst result) to 100 (best result) [28].

Two experimenters administered the tests and questionnaires, both of whom were blinded to the patient's group.

2.4. Statistical Analysis and Sample Size Calculation. Based on data from a pilot study, an average precision GAP of 1.43 cm (SD ± 0.55) (i.e., reaching forward + reaching back) was calculated in 10 healthy right-handed subjects (5 females and 5 males) with a mean age of 68 years (SD ± 5.84).

Assuming an average increase in error of 30% in patients with shoulder impingement by two-tailed t-test with a power of 80% and a 0.05 alpha error, 22 patients were needed for each group (PASS Software©). We also considered a dropout rate of 10%.

The descriptive analysis was performed using means and standard deviations (SDs) for quantitative variables and percentages and frequencies for qualitative factors.

The analysis considered the reproducibility of the following groups of the measurements of the relative error (RE) that was computed:

(i) 450 measurements of RGAPs in global reaching (test 1 + test 2 and forward + back)

(ii) 250 measurements of RGAPs reaching forward and 250 reaching back in the 2 tests overall (test 1 + test 2)

(iii) 150 measurements of RGAPs in global reaching for single tests

(iv) 75 measurements of RGAPs in reaching, considering reaching forward and reaching back movements in the single tests separately

Boxplots with whiskers were drawn to describe the RE between groups during the reaching forward + reaching back movements.

Univariate analysis was performed to examine differences between the HG and IG with regard to sociodemographic characteristics by Mann–Whitney and chi-square tests when possible.

2.4.1. Analysis within Group. In order to compare the RGAP reaching forward versus reaching back in all tests (1 and 2 active-passive) in the same group, we applied the t-test for paired samples, and the comparison between the three tests (independently for reaching forward and reaching back) in each group was performed using MANOVA. A linear regression model was performed to evaluate the possible predictors of dependent variable RGAP considered followed independent variables: gender, age, and impingement syndrome.

2.4.2. Analysis between Groups. To analyze differences in RGAP between groups (HI versus IG), Student's t-test was applied. Student's t-test for independent samples, assuming equal variances or not, was applied according to the p values by Levene's test for equality of variances.

A diagram of linear regression was carried out for RGAP independently of the type of tests between groups.

2.4.3. Analysis of Correlation. Spearman correlation was used to estimate the direct or indirect linear correlation between precision GAP and quantitative variables (age, VAS).

To determine whether the probability distribution of GAP in the HG and IG assumed that 2 or more values of RE were independent of each other or whether the occurrence of any one of them affected the occurrence of others, chi-square's test was performed, assuming that GAP values followed a discrete probability distribution.

The significance level was set to $p < 0.05$. The statistical analysis was performed using SPSS 20.

2.4.4. The Analysis of Differences between Tests: Bland and Altman Method. Bland-Altman analysis and plotting were used to evaluate the bias between mean differences and to estimate the agreement interval between two tests (Test 1 versus Test 2 active; Test 1 versus Test 2 passive) [29].

The visualization of the difference of the measurements made by the two tests was shown, plotting the differences (diff) or the bias (Y-axis) versus the mean (mean) of the two readings (X-axis). In addition, additional reference lines were overlaid on the same scatter plot: the mean of differences or bias line and 95% upper ($+1.96 * \text{SD}$ of differences) and 95% lower ($-1.96 * \text{SD}$ of differences).

3. Results

Fifty subjects were enrolled and divided into 2 groups: 25 in the healthy group (HG) and 25 in the impingement group (IG) (64% massive rupture of the rotator muscle cuff, 20% partial rupture, and 16% mild injury). No subject was withdrawn due to failure to test for increased pain or difficulty with the test.

The 2 groups were not perfectly matched with regard to gender and age and clinical characteristics at baseline ($p > 0.05$; Table 1).

3.1. Analysis of the Tests. Conversely, as reported in Table 2, there was a significant difference in mean RGAP in Tests 1 and 2, in reaching forward and reaching back, between groups.

TABLE 2: Description of RGAP (mean ± SD and median with min–max) in the two groups stratifying by tests (Test 1 and Test 2 in active and passive modality) and overall (all tests).

Tests and modality	RGAP[a] HG						RGAP[a] IG						Test to compare HG versus IG	
	N	Mean[d]	SD[d]	Median[d]	min–max[d]	p	N	Mean[d]	SD[d]	Median[d]	min–max[d]	p	p[f]	Test
All tests														
Reaching forward + reaching back	450	0,62	0,57	0,5	0–3,39	—	450	1,01	0,7	0,92	0–3,44	—	**<0,001**	b
Reaching forward	225	0,29	0,22	0,28	0,02–1,30	**<0,001**[b]	225	0,46	0,3	0,49	0–1,62	**<0,001**[b]	**<0,001**	b
Reaching-back	225	0,62	0,57	0,5	0–3,39		225	1,01	0,7	0,61	0–3,44		**<0,001**	b
Reaching forward + reaching back														
Test 1	150	0,47	0,34	0,28	0–1,33	0,352[e]	150	0,75	0,65	0,48	0–3,44	0,505[e]	**0,01**	b
Test 2 passive	150	0,38	0,29	0,23	0–1,22		150	0,66	0,45	0,33	0,11–1,83		**<0,001**	b
Test 2 active	150	0,5	0,66	0,19	0,03–3,39		150	0,79	0,68	0,35	0–2,78		**0,033**	c
reaching forward														
Test 1	75	0,4	0,32	0,28	0,02–1,3	**<0,001**[e]	75	0,59	0,38	0,47	0,03–1,62	**0,016**[e]	0,055	c
Test 2 passive	75	0,27	0,13	0,23	0–1,33		75	0,4	0,24	0,33	0,16–0,95		**0,022**	b
Test 2 active	75	0,19	0,1	0,19	0–0,39		75	0,37	0,23	0,35	0–0,76		**0,001**	b
reaching back														
Test 1	75	0,55	0,35	0,5	0,0–1,3	0,095[e]	75	0,91	0,82	0,61	0–3,44	0,224[e]	0,055	b
Test 2 passive	75	0,49	0,36	0,44	0–1,22		75	0,91	0,47	0,88	0,11–1,83		**0,001**	c
Test 2 active	75	0,8	0,82	0,56	0,06–3,39		75	1,2	0,73	1,17	0,06–2,78		0,075	c

[a] The RGAP reported the relative error computed considering the difference between the measure requested and the measure done by the patients on measure requested.

[b] t-student for paired samples.

[c] t-student for independent sample with equal variances assumed.

[d] The mean and the median GAP are computed relativizing the absolute value (=the absolute number value) of the gap value of the measure requested.

[e] p value of MANOVA test.

[f] p value for two independent samples; the specific test is reported in the last column.

N: number of measurements tested.

Table 3: Multivariate regression models for RGAP score adjusted by impingement syndrome, age, and gender (β and significance = p).

RGAP	Impingement syndrome	Age	Gender	R^2
Test 1 reaching forward	0,213 *(0,167)*	0,163 *(0,269)*	0,056 *(0,703)*	0,102
Test 1 reaching back	0,317 *(0,410)*	0,052 *(0,723)*	−0,194 *(0,187)*	0,114
Test 2 active Reaching forward	0,252 *(0,096)*	0,128 *(0,373)*	0,135 *(0,348)*	0,137
Test 2 active Reaching back	0,395 *(0,007)*	0,147 *(0,279)*	0,068 *(0,618)*	0,230
Test 2 passive Reaching forward	0,329 *(0,015)*	0,317 *(0,015)*	0,171 *(0,180)*	0,333
Test 2 passive Reaching back	0,230 *(0,134)*	0,200 *(0,173)*	−0,112 *(0,443)*	0,114

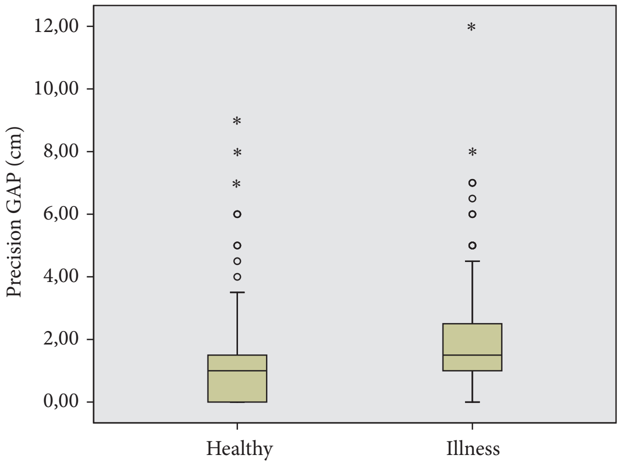


Figure 4: Box and whiskers plots of reproducibility GAP for the two groups. The boxes show the first quartile, median (middle line in box), and third quartile values. The whiskers represent the most extreme values within 1.5 times the interquartile range from the ends of the box, and the circles indicate data with values beyond the ends of the whiskers. Outliers identified with a circle are greater than 1.5 times the IQR and outliers identified with an asterisk are greater than 3 times the IQR.

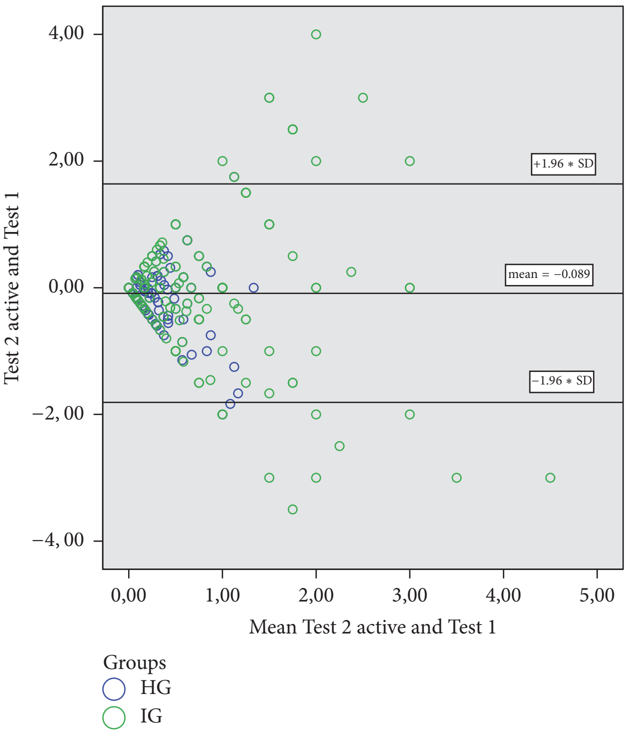


Figure 5: Bland-Altman agreement analysis between Test 1 and Test 2 (active phase). Plot of differences between Test 1 and Test 2 versus the mean of the two measurements RGAP was shown. Both graphs have shown heteroscedasticity: the difference of the RGAP in the two test increases with increment of mean of RGAP.

Specifically, over the 450 measurements of the precision GAP, the average error for the HG was 0.62 (±0.57 SD) versus 1.01 (±0.70 SD) in the IG ($p < 0.05$) (see Figure 4 box plot). Between independent Tests 1 and 2 ($N = 150$, reaching total), both groups measured better blindfolded and in the active phase, with average errors of 0.47 ± 0.34 in the HG and 0.75 ± 0.65 in the IG in Test 1 and 0.38 ± 0.29 and 0.66 ± 0.45, respectively, for active modality and 0.50 ± 0.66 and 0.79 ± 0.68 for passive modality in Test 2. Both groups measured better reaching forward ($N = 75$) in Test 2 in the passive modality, whereas performance in reaching back ($N = 75$) was better in Test 2 in the active modality. By Spearman's correlation, there was no link between precision GAP and age and pain ($r = -0.005$, $p = 0.982$ and $r = 0.124$, $p = 0.554$, resp.). No significant difference in mean error was observed between genders ($p = 0.734$).

The GAP distribution was not equally likely ($p < 0.001$); disparate distributions in GAP values were observed. No side effects were recorded during the test, and the investigator never had to stop the subject.

In Table 3 for the linear regression model we found that the RGAP computed in reaching back Test 1, Test 2 active reaching back, and Test 2 passive reaching forward were significantly associated with presence of impingement syndrome while the RGAP computed in Test 2 passive reaching forward was significantly associated with age too.

In Figure 7 the diagram of linear regression shows that, independently of the type of tests, with a $R^2 = 0.96$ and slope of the line of (1.5131) the averages of the IG-RGAP are always, and in any case, about 50% higher than those of HG.

3.2. Bland-Altman Analysis.

The plot of differences between Test 1 and Test 2 versus the mean of the two RGAP measurements is shown in Figures 5 and 6.

The mean difference between Test 2 active versus Test 1 (bias between mean differences) was −0.089, and the limits of agreement (−1.81 to 1.64) were small enough to be confident that one test could be used in place of the other for RGAP

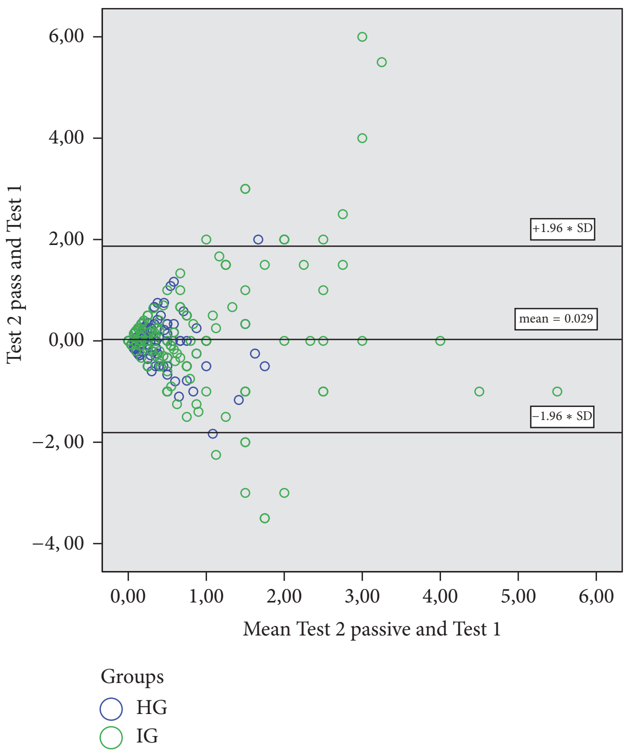


Figure 6: Bland-Altman agreement analysis between Test 1 and Test 2 (passive phase). Plot of differences between Test 1 and Test 2 versus the mean of the two measurements RGAP was shown. Both graphs have shown heteroscedasticity: the difference of the RGAP in the two test increases with increment of mean of RGAP.

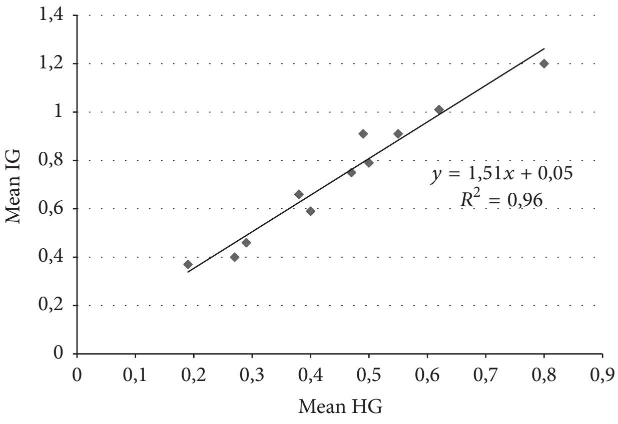


Figure 7: Regression diagram of RGAP between HG and IG.

measurements. The mean difference between Test 2 passive versus Test 1 was also minor: 0.029 with limits of agreement of −1.81 to 1.87.

Both graphs showed heteroscedasticity: the difference in RGAP in the two tests increased with greater RGAP values.

Bland and Altman recommend that 95% of data points lie within ±2 SD of the mean difference; in our cases, the outliers were 2% Test 2 active versus Test 1 (24 out of 900) and 3% Test 2 passive versus Test 1 (20 out of 900) (Figure 5).

4. Discussion

Our primary question was whether the shoulder has a proprioceptive ability in memorizing a reaching position and reproducing it. Our results indicate that HG and IG subjects estimate an average error concerning the reaching movement that is required of 1.11 ± 1.16 in the HG and 1.82 ± 1.58 in IG ($p < 0.001$), suggesting that the shoulder has its own proprioceptive ability that is reduced in impingement syndrome.

Other researchers have merely surmised the existence of this important proprioceptive aspect of the shoulder but have not studied its ability to measure during reaching.

A systematic review by Fyhr et al. showed moderate evidence of a higher threshold in detecting passive motion for involved shoulders in patients with posttraumatic glenohumeral instability compared with control groups and the contralateral uninvolved side, indicating decreased movement sense. Movement sense is most likely to be impaired after shoulder injury that involves posttraumatic instability versus the contralateral shoulder and controls, whereas deficits in active and passive joint reposition sense are more apt to be evident compared with the contralateral shoulder in participants with glenohumeral musculoskeletal disorders [30].

Other results suggest that capsule ligamentous and musculotendinous mechanoreceptors in the shoulder joint have significant function in proprioception feedback during active movements in subjects with idiopathic loss of range of motion in the shoulder [31].

The mechanisms by which modifications in peripheral proprioceptive inputs from an injured structure can determine a deficit in joint position sense have been reported by Valeriani et al., who showed that lesions to peripheral mechanoreceptors of the knee can functionally modify the central somatosensory pathways, based on involvement of the cortex in the complex integration of articular proprioceptive inputs [32].

Giachritsis et al. reported that reproduction errors and discrimination thresholds of the shoulder and elbow improve with surface length during motion, implying that the proprioceptive shoulder-elbow system integrates redundant spatial information from extended arm movements to improve orientation judgments during reaching [33].

In the IG, the errors that were computed during the tasks were not related to pain intensity, emphasizing how the loss of the ability to measure is linked to a deficiency in proprioceptive sense in those with shoulder impingement syndrome. Other studies reported that the same proprioceptive shoulder sense is influenced by strength training of the shoulder muscle, suggesting that it improves the sensitivity of muscle spindles and thus effects better neuromuscular control in the shoulder [34].

Also, healthy subjects appear to develop strategies to compensate for fatigue-induced deficits in an individual joint to maintain endpoint reproducibility in a multijoint task during repetitive arm motion, wherein the induced endpoint position sense is unaffected by shoulder fatigue [35].

With regard to how the proprioceptive sense of the shoulder integrates visual control, our results indicate that subjects perform better in the blindfolded test as in HG as in IG; in particular, the average error was minor in the blindfolded test for reaching forward in Test 2 in the passive modality in both groups.

Visual feedback has been proposed to control bodily movements in the absence of proprioceptive feedback, however erroneous the visual feedback might be [36].

Kinesthesis, strictly meaning movement sense, can make "*an invisible hand visible,*" as some researchers have written, such that, even in the absence of external visual input, the brain can predict the visual consequences of actions [37].

In the dark, distance cues might be derived from hand position signals by an efference copy of the motor command to the moving hand or by proprioceptive input; with no visual information, proprioceptive feedback from the arm also affects the perception of size [38, 39].

In certain sports, such as basketball, training to shoot with the lights off has been proposed to improve the reproducibility of the jump shot, because training without a visual input could further improve performance by allowing one to work on his sense of movement and proprioception [40, 41].

Judkins et al. concluded that, when the senses, vision, and proprioceptive feedback are used separately, subjects better adapt to perturbations, based on personal sensorimotor memories, when performance feedback is limited to solely proprioceptive or visual information channels. Their findings support a switched-input, multisensory model of predictive load compensation, wherein visual feedback of transient performance errors overwhelmingly dominates proprioception in determining adaptive reach performance [40, 42].

Our results demonstrate that the effects of visual action interfere with the motor modality but that those of proprioceptive action do not influence visual modality [43–45].

For reaching forward, both groups measured better in Test 2 in the active modality, whereas with only reaching back, performance was better in Test 2 in the passive modality. However, the function of learning in the preliminary phase of tests and the significant differences between the movements of reaching forward and reaching back in both active and passive modality remain to be determined.

One limitation of our study is the lack of analysis of muscle shoulder activation by surface electromyography to control for the absence of muscle contraction in the passive condition.

It was not possible to perform stratification of the IG by the degree of injury per Neer, because the sample size was inadequate with the lack of a match between cases and controls by age and gender. However, only for Test 2 in passive modality during reaching forward the RGAP computed was significantly associated with age.

On the other hand, patients with impingement syndrome seem to lose a specific measuring capacity that is not random, for the Bland and Altman analysis and according to the linear regression diagram independently of the tests used. In addition to describing percentage agreement for the average error between tests, there was confidence that one test could be used in place of the other test for RGAP measurements: this result is indicative of a good agreement of the tests. However, to avoid the learning of the tests by the subject enrolled in the study, we cannot perform an accurate measure of reliability: each subject performed the test only once, so there were no more repeated measures on the same subject for the same task.

Nevertheless, our results should prompt the consideration of a new rehabilitative strategy to restore shoulder function, given the important proprioceptive properties of this articulation.

In conclusion, the shoulder has specific expertise in measuring extracorporeal space during reaching that decays gradually in impingement syndrome.

Competing Interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interests.

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