Proprioception Assessment in Subjects with Idiopathic Loss of Shoulder Range of Motion: Joint Position Sense and a Novel Proprioceptive Feedback Index

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ABSTRACT: We examined the effects of elevation range and plane on shoulder joint proprioception in subjects with idiopathic loss of shoulder range of motion (ROM). Joint position sense (JPS) and a novel proprioceptive feedback index (PFI), including difference magnitude and the similarity index, were used to assess proprioception. Twelve subjects (eight male, four female) with involved stiff shoulders and normal opposite shoulders were recruited from a university hospital. Subjects attempted to repeat six target positions. Target positions consisted of arm elevation in three planes (frontal, scapular, and sagittal planes) and two ranges (end/mid range). Six trials of each target position were used to determine acceptable trials for stabilization of the data, less than 5% of the cumulative mean values for at least three successive trials. The data stabilized at the sixth repetition. Compared to control shoulders, involved shoulders had enhanced proprioception during end range movements ($p < 0.05$). The magnitude of the repositioning error and difference magnitude decreased (1.6°–3.5° for repositioning error and 22.2°–62.1° for difference magnitude), whereas similarity index improved at end range movements compared to mid range movements ($p < 0.05$) in involved stiff shoulders. Results of JPS and PFI suggest that both capsuloligamentous and musculotendinous mechanoreceptors play an important role in proprioception feedback during active movements in subjects with idiopathic loss of shoulder ROM. © 2008 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 26:1218–1224, 2008

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Proprioception is a type of feedback from the limbs to the central nervous system[1] that has been described as a sensory modality with combination of joint position sense (JPS), the ability of a person to identify and reproduce limb position in space, and kinesthesia, the perception of limb motion.[2] Stimuli from peripheral mechanoreceptors in joints, muscles, and skin provide the central nervous system with information regarding JPS and kinesthesia to modify motor control.[3,4] Proprioceptive mechanisms are essential in maintaining joint stability, especially for the shoulder, where stability is sacrificed for a large range of motion.[5,6]

JPS is commonly tested using either active or passive reproduction of joint positioning, whereas kinesthesia studies have been limited to identifying the threshold to detect limb motion using a passive motion. For detecting JPS, the shoulder joint of a blindfolded subject is moved through an active or passive range of motion to a predetermined position and held for 5 to 10 s. Upon return to the starting position, subjects attempt to replicate the target position when they feel the presented position has been matched. The difference between the presented and reproduced position is the repositioning error. For kinesthesia proprioception, movement detection is identified using passive movement.[7,8] This method cannot measure proprioceptive feedback during active motion. In our study, we assessed proprioception during active limb motion with a novel method, the proprioceptive feedback index (PFI), comprised of the total absolute difference between target and replicate trials (magnitude) and the kinematic distribution of the movement (similarity index, SI).

Deformation of capsuloligamentous tissue is believed to stimulate mechanoreceptors and provide the central nervous system with proprioceptive information.[9] In the shoulder, this hypothesis is supported by studies examining JPS, which have reported that subjects reproduce position accurately and consistently near the end of motion.[10–13] To our knowledge, however, this effect has not been studied in patients with shoulder stiffness. Previous investigations assessed JPS in one specific plane; we measured JPS and proprioceptive feedback in an unconstrained shoulder model. Our purpose was to examine the effect of arm elevation range and plane on repositioning error and our newly developed PFI. We hypothesized that near the end range of arm elevation and in frontal and saggital planes, proprioception (JPS and PFI) would be enhanced. Additionally, we investigated the effect of increasing numbers of trials in the assessment of shoulder joint proprioception.

MATERIALS AND METHODS

Twelve adult subjects (>18 years) with unilateral stiff shoulders were analyzed (Table 1). The diagnosis was defined as a limited range of motion and pain and/or stiffness in the shoulder. Patients who had concomitant cervical radiculopathy, evidence of bone spurs on radiographs, or a history of traumatic injury were excluded. No shoulder symptoms were present on the contralateral side. Subjects signed informed consent forms approved by an internal review board (IRB).

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Table 1. Subject Demographics (Eight Male and Four Female; 10 Frozen Shoulders and 2 Impingement Syndrome)

Demographic	Mean (Control)	Standard Deviation	Range
Age (years)	51.8	9.8	43–69
Weight (kg)	63.9	6.8	57–69
Height (cm)	166.3	7.9	162–182
Duration (m)	30.3	10.2	1–66
Flexion (°)	143 (177)	24 (2.3)	92–165 (175–182)
Abduction (°)	108 (175)	13 (3.2)	83–135 (172–183)
Interior rotation (°)	40 (87)	20 (4.5)	35–75 (85–93)
Exterior rotation (°)	25 (88)	13 (3.5)	10–25 (84–95)
FLEX-SF[a] scores	36.5 (48.2)	6.1 (1.5)	28–43 (47–50)

[a]Flexilevel scale of shoulder function.

Instrumentation

The FASTRAK motion analysis system (Polhemus Inc., Colchester,VT) with six-dimensional (6D) research software (Skill Tech. Inc., Phoenix, AZ) was used to detect shoulder movements. Sensors were attached to bony landmarks with adhesive tape at the sternum and at the flat superior surface of the scapular acromial process, and by the Velcro straps to the distal humerus between the lateral and medial epicondyles. Another sensor attached to a stylus was used to digitize anatomical coordinates (sternal notch, xiphoid process, seventh cervical vertebra, eighth thoracic vertebra, acromioclavicular joint, root of the spine of the scapula, inferior angle of the scapula, lateral and medial epicondyles). The glenohumeral joint rotation center was determined by the anterior and posterior humeral joint. The absolute axes defined by the sensor were converted to anatomically defined axes derived from the bony landmarks (Fig. 1). Raw kinematic data were low-pass filtered at a 6-Hz cutoff frequency and converted into anatomically defined rotations. Humeral orientation relative to the scapula was described using an Euler angle sequence in which the first rotation represented the plane of elevation, the second defined the amount of elevation, and the third described the amount of axial rotation. The high reliability [ICC (2, k) = 0.91–0.99), similarity index (0.78–0.97), and accuracy (<2° standard error) of this approach have been described previously.[14–17]

Procedure

Patients removed their shirts (females wore sports bras). They were seated on a chair without back support to minimize

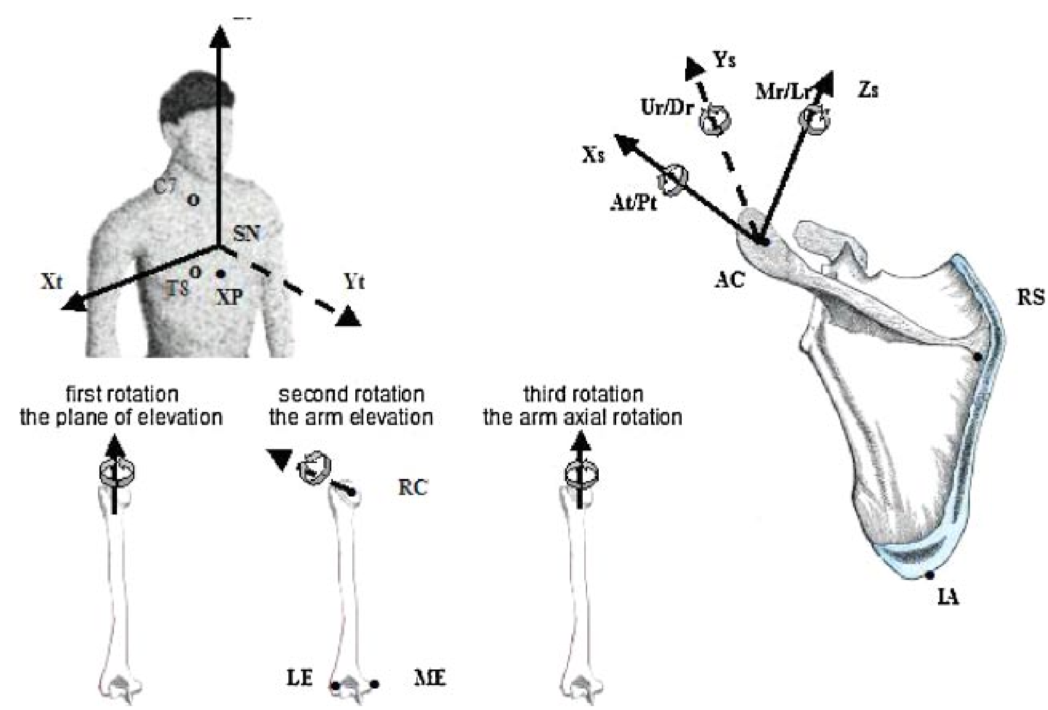

Figure 1. Coordinate systems for the thorax, scapula, and humerus. Surface sensor were placed on the sternum inferior to the sternal notch, on the scapular acromial process, and at the point on the distal humerus between the lateral and medial epicondyles. C7, spinous process of the seventh cervical vertebra; T8, spinous process of the eighth thoracic vertebra; XP, xiphoid process; SN, sternal notch; RS, root of the spine of the scapula; IA, inferior angle of the scapula; AC, acromioclavicular joint; ME, medial epicondyle; LE, lateral epicondyle; RC, rotation center of the glenohumeral joint; At/Pt, anterior tipping/posterior tipping; Ur/Dr, upward rotation/downward rotation; Mr/Lr, medial rotation/lateral rotation. Trunk axes are aligned with cardinal planes. Xt is directed laterally, Yt is directed anteriorly, and Zt is directed superiorly. Xs is directed laterally from RS to AC, Ys is directed anteriorly perpendicular to the plane of the scapula, Zs is directed superiorly perpendicular to Xs and Ys.

cutaneous tactile cues from the lower back. To address effects of end/mid range and plane on unconstrained JPS and PFI, six target positions were presented: elevation to end range and mid range in the frontal, scapular (45° anterior to the fontal plane), and sagittal planes. Patients were required to self-select an end/mid range target position with the hand with the verbal cue "Please move your hand to where you assume the end/mid range position to be." The objective was to move the limb to the target position as accurately as possible without visual guidance (subjects were blindfolded). As the target was reached, a trigger button was pressed to synchronize the kinematic data. The testing targets were presented in random order, using a balanced Latin square design.[18] To investigate the effect of number of trials, each subject chose a target once and then attempted to replicate it six times. The involved and the normal opposite shoulders were both tested.

Outcomes of JPS and Kinesthesia

For the analysis, the calculated angles (plane of elevation, amount of arm elevation, amount of axial arm rotation; humeral orientation relative to the scapula) were defined as the instant movement. For JPS, the angle between targeted and reproduced positions was calculated (square root of sum by square difference in plane, elevation, and rotation) for each trial and assumed to represent the absolute magnitude of the repositioning error. We used a newly developed PFI to interpret movement patterns. The normalization of the response instant movement, as generated in Equation (1), quantitatively describes the relative motion every 10% of the movement during each trial of each test. The instant movement of each target test was used as a prototype instant movement for each trial. The PFI is comprised of two numbers: the total absolute angle difference between targeted and reproduced trials of movements {the sum of 10% movement difference, square root of [(target − reproduced plane)^2 + (target − reproduced elevation)^2 + (target − reproduced axial rotation)^2)]} recorded for movement (difference magnitude), and the correlation between response instant movement and prototype instant movement on arm elevation (similarity index, SI). To follow the Nyquist–Shannon sampling theorem, we separated the test (completion about 1 s) into 10% movements to reconstruct the movement (one third of this reconstruction sample rate exceeds the bandwidth of the signal being sampled, 30 Hz). This approach provides quantitative analysis and elementary pattern recognition of proprioception feedback during movements.

$$R_{\mathrm{norm}} = \frac{[R_1 R_2 R_3 R_4 R_5 R_6 R_7 R_8 R_9 R_{10}]}{\sqrt{\sum_{\mathrm{i}} R_{\mathrm{i}}^2}} \tag{1}$$

Where R_1 = average of 10% movement as an instant movement, R_2 = average of 10% to 20% movement as an instant movement, R_{i} = average of i * 10% = (i = 1) * 10% movement as an instant movement, R_{10} = average of 90% to 100% movement as an instant movement.

Data Analysis

The Kolmogorov–Smirnov test confirmed that the data were normally distributed. The effect of the number of trials was investigated by calculating the means and standard deviations (SD) of all subjects for each angle. The change in SD for each subsequent trial was calculated and described as a percentage change of the cumulative means:

$$\begin{aligned} &\text{percentage change in SD} \\ &= (\mathrm{SD}_{n+1} = \mathrm{SD}_n) * 100/\text{cumulative mean}_{n+1} \end{aligned} \tag{2}$$

Table 2. Mean Error from Target Angle

Target Angle	Repetition 1 Involved	Repetition 1 Normal	Repetition 2 Involved	Repetition 2 Normal	Repetition 3 Involved	Repetition 3 Normal	Repetition 4 Involved	Repetition 4 Normal	Repetition 5 Involved	Repetition 5 Normal	Repetition 6 Involved	Repetition 6 Normal
Elevation in frontal plane end range	3.9 (2.0)	4.8 (2.2)	4.7 (2.9)	5.5 (2.0)	5.1 (3.3)	6.8 (3.2)	5.5 (2.2)	7.1 (2.8)	5.2 (3.0)	6.7 (2.2)	5.1 (3.4)	8.1 (3.3)
Elevation in frontal plane mid range	4.2 (2.4)	5.2 (3.2)	6.5 (3.0)	6.0 (2.7)	7.7 (3.0)	7.1 (3.2)	8.4 (3.0)	8.6 (3.4)	8.5 (3.7)	8.5 (2.9)	9.6 (3.7)	8.8 (3.9)
Elevation in scapular plane end range	3.4 (2.8)	6.5 (3.0)	4.3 (3.8)	5.9 (3.0)	4.0 (4.2)	6.2 (2.6)	4.8 (3.8)	5.4 (1.2)	5.1 (4.7)	5.9 (2.0)	5.0 (3.8)	4.7 (3.5)
Elevation in scapular plane mid range	5.2 (3.7)	6.2 (2.3)	6.4 (3.0)	6.1 (3.2)	6.3 (2.7)	5.4 (3.3)	7.2 (3.2)	6.2 (3.3)	6.8 (4.5)	5.2 (3.6)	8.6 (3.9)	7.4 (3.0)
Elevation in sagittal plane end range	3.4 (2.4)	4.9 (2.6)	3.9 (2.0)	4.8 (2.7)	3.5 (2.9)	5.3 (2.6)	4.0 (1.9)	5.2 (2.1)	4.6 (2.7)	5.3 (1.9)	4.6 (2.4)	5.9 (2.1)
Elevation in sagittal plane mid range	4.0 (2.0)	4.2 (2.9)	4.7 (2.9)	4.9 (3.2)	5.1 (3.3)	4.7 (3.9)	5.5 (2.2)	5.7 (3.9)	5.2 (3.0)	5.3 (2.4)	5.1 (3.4)	6.7 (3.9)

Values are shown as mean (SD).

Plots of the cumulative means and SDs against trial number determined the point at which the mean and SD stabilized. Sufficient trials were collected when the SD varied in absolute terms by <5% of the cumulative mean values for ≥3 successive trials.[17]

To test if a proprioception difference existed between involved and control shoulders, paired t-tests were calculated on the mean of acceptable trials for JPS (SD varies less than 5%), similarity index, and difference magnitude. To determine if a proprioception difference existed at different elevation angles and planes in involved shoulders, two-way repeated ANOVA (two ranges and three planes) were calculated on the mean of acceptable trials for JPS, similarity index, and difference magnitude. Bonferroni follow-up analyses were used at a significant alpha level of 0.05 to adjust for multiple pairwise comparisons where appropriate.

RESULTS

Based on glenohumeral joint motion, the mean error from the target angle, for each repetition, is presented in Table 2. The percentage change in cumulative SDs is presented in Figure 2. For the end range testing movements, data stabilized at the sixth repetition; data for the mid range testing movements stabilized at the fifth or sixth repetition. Thus, we used the mean of the fourth, fifth, and sixth repetitions on the JPS, SI, and difference magnitude for analysis.

Compared to control shoulders, involved shoulders had enhanced proprioception during end range movements (decreased JPS, decreased difference magnitude, and higher movement pattern similarity, $p < 0.05$). For the JPS, there was no interaction or plane main effect. The

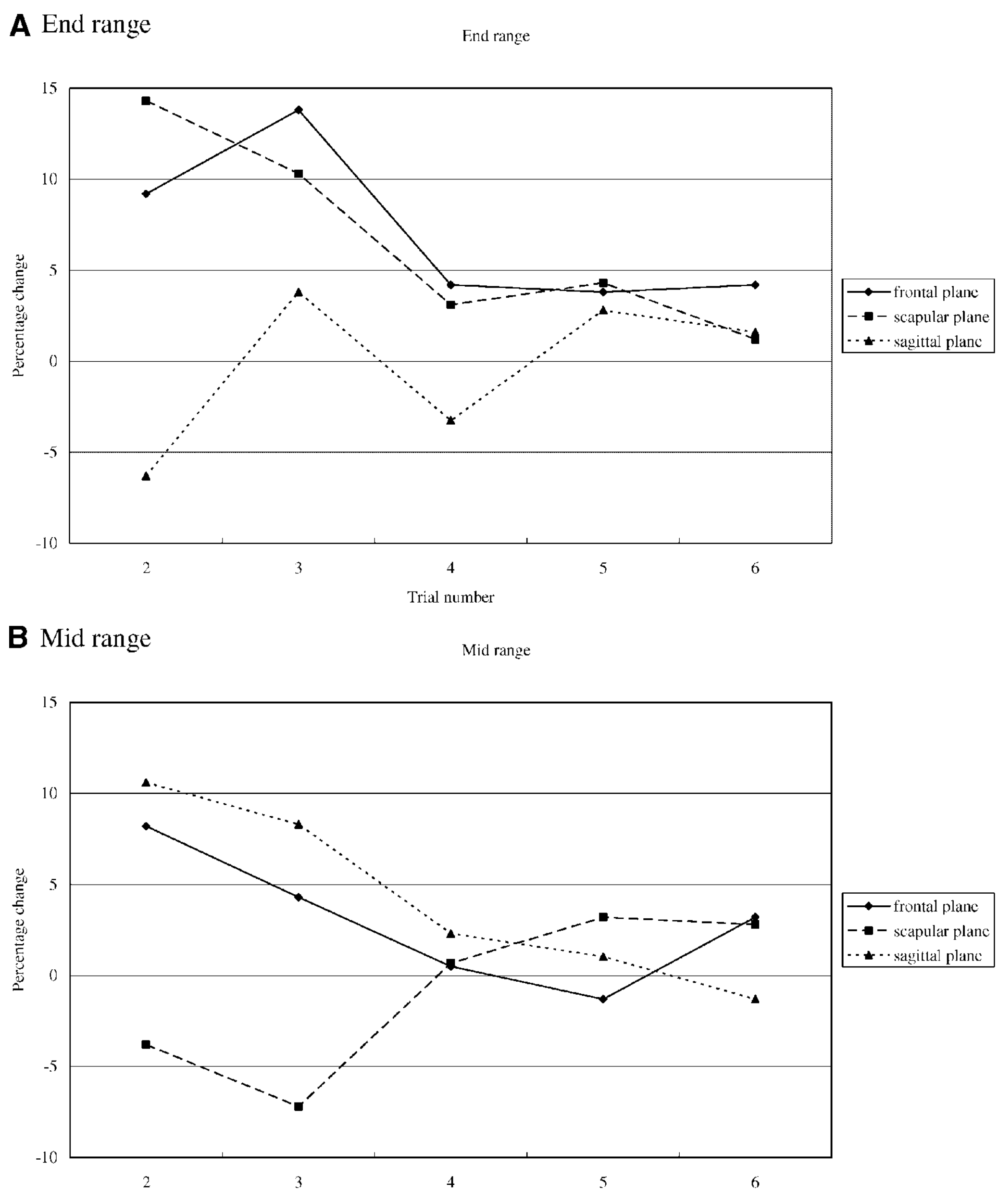

Figure 2. Percentage change in cumulative standard deviation during testing movements.

Table 3. Difference of Measurement Values for Joint Reposition Error, Difference Magnitude, and Similarity Index in Involved Shoulders

Parameter	Plane of Elevation	End Range Mean (SD)	Mid Range Mean (SD)	Average between Two Ranges
Joint reposition error (°)	Frontal plane	6.4 (4.2)	8.4 (3.4)	7.4 (3.8)
	Scapular plane	4.8 (3.5)	8.3 (3.3)	6.6 (3.4)
	Sagittal plane	3.8 (2.1)	5.4 (2.7)	4.6 (2.4)
	Average across three planes	4.9 (3.3)[a]	7.6 (3.0)	
Difference magnitude (°)	Frontal plane	93.2 (36.6)	122.1 (51.8)	107.7 (44.2)[b]
	Scapular plane	137.4 (41.1)	169.5 (57.3)	153.5 (49.2)
	Sagittal plane	102.4 (36.7)	115.2 (41.3)	109.3 (38.9)[b]
	Average across three planes	111.2 (38.1)[a]	135.6 (49.8)	
Similarity index	Frontal plane	0.86 (0.11)	0.83 (0.15)	0.90 (0.07)
	Scapular plane	0.85 (0.13)	0.86 (0.13)	0.89 (0.09)
	Sagittal plane	0.90 (0.07)	0.92 (0.06)	0.95 (0.04)
	Average across three planes	0.87 (0.11)[a]	0.87 (0.12)	

[a]There was a significant difference between mid and end range movements. [b]The difference magnitude was significantly lower than that in scaption.

magnitude of the repositioning error decreased at end range movements compared to mid range movements (1.6°–3.5°, $p < 0.05$; Table 3). The PFI was computed by a pair of elements (SI and difference magnitude, Fig. 3). For the difference magnitude, there was no interaction effect. The difference magnitude reduced at end range movements compared to mid range movements (22.2°–62.1°, $p < 0.05$) and also decreased in elevation in the sagittal/frontal planes compared to the scapular plane (39.7°–45.8°, $p < 0.05/3$). For the SI, there was no interaction or plane main effect. The movement pattern similarity was better at end range movements than that at mid range movements (0.91–0.93 for end range and 0.85–0.89 for mid range, $p < 0.05$).

DISCUSSION

We examined the effects of elevation range and plane on proprioception, including repositioning error and a newly developed PFI, in an unconstrained testing condition in subjects with shoulders with restricted range of motion and normal opposite shoulders. We hypothesized that proprioception would increase as movements approached the end range or extreme planes (frontal and sagittal planes) due to stretching of the capsule and ligaments in the involved shoulders. Our results supported this hypothesis, as repositioning error and difference magnitude decreased, and SI increased, during end range movements. The difference magnitude also decreased during elevation in the frontal and sagittal planes. This result matches that of previous studies.[20–22] Studies of joint position sense have found enhanced repositioning precision as the position approaches the end range of movement. Decreased threshold to detection of motion was also observed as the starting position approached the end range.[21,23]

Our newly developed PFI, including SI and difference magnitude, is appropriate and more effective than repositioning sense to represent proprioception. In our study, similar results were observed between JPS and PFI as replication accuracy. SI and magnitude similarity were enhanced during end range movements. A significant effect of plane on difference magnitude was also found. These results indicate that PFI is more sensitive than reposition sense to represent proprioception. Further, our PFI can detect proprioception during active movement in addition to JPS at static position. This is especially worthy when considering proprioception input from both capsuloligamentous receptors andmuscle spindles during movement. Voight and colleagues[24] claimed that afferent input from muscle spindles may be the primary contributor to joint position sense. Suprak and colleagues[25] further proposed that information provided by muscle spindles may override that provided by capsuloligamentous receptors to explain the nonsignificant effect of plane on repositioning error in their study. Our results on enhanced PFI, but not on repositioning error, during frontal and sagittal planes, supported some of this proposition. The contribution of enhanced PFI in our study may come dominantly from afferent input from muscle spindles, with the contribution from capsuloligamentous receptors less likely.

The magnitudes of the repositioning errors in our study are comparable to those previously reported. In studies exploring JPS at the shoulder in uniplane movements, the repositioning errors ranged from 2° to 5°.[24,26,27] Suprak and colleagues[25] examined JPS on unconstrained shoulder movements and reported 4° to 9°. We demonstrated the errors ranged from 3° to 10°. The differences may be due to the unconstrained nature of our protocol and that of Suprak and colleagues,[25] whereas in the other studies, subjects were required to reposition the joint in only one plane.

Our results have implications for clinicians and researchers who examine shoulder joint proprioception as part of functional measurement for patients with shoulder dysfunction. Because error and variability are common in measuring proprioception, accurate assessment is needed to provide clinical decision making and

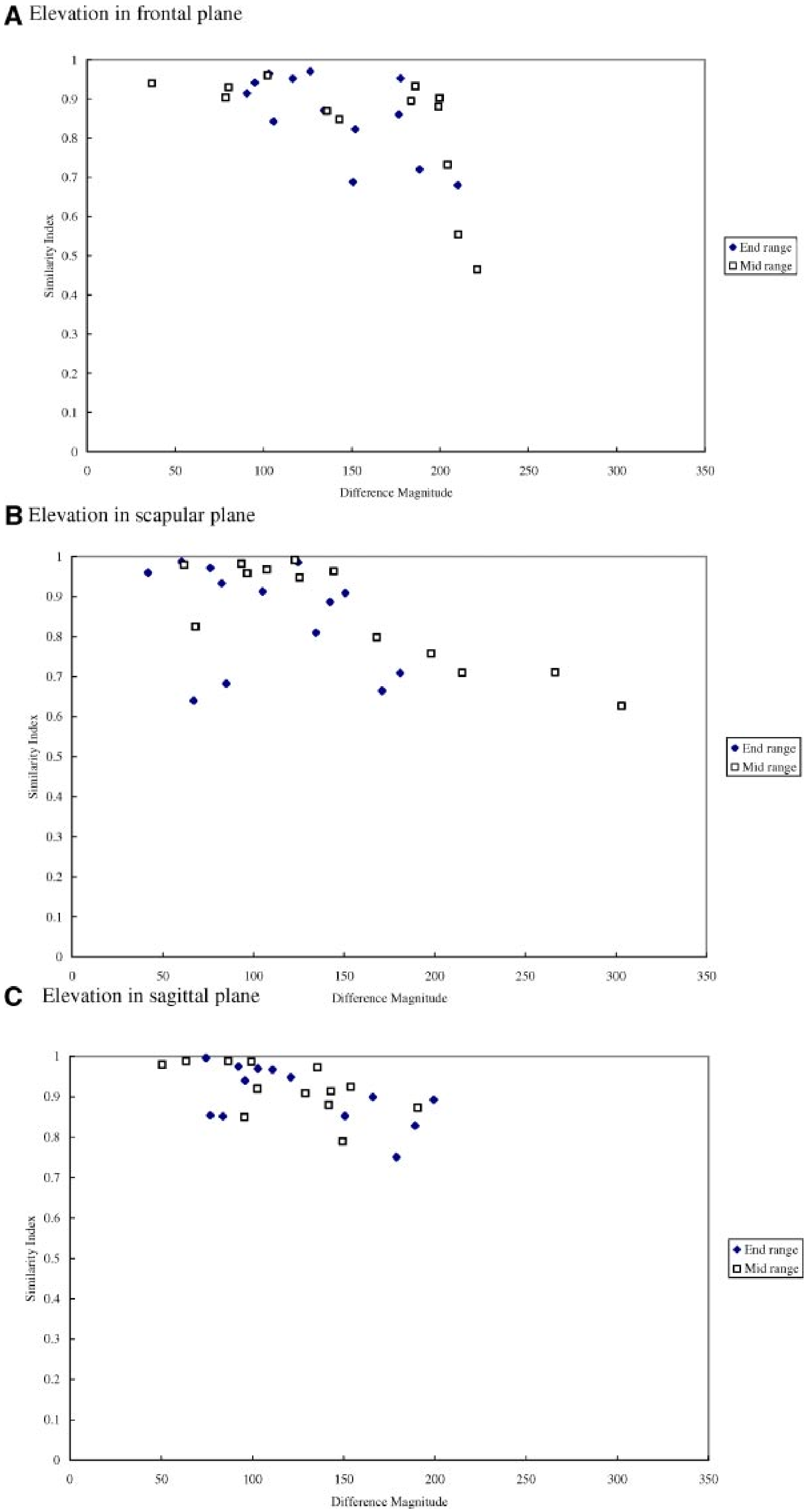

Figure 3. Proprioceptive feedback index obtained from patients' involved sides during testing movements.

rehabilitation strategies. Based on a protocol that sets a threshold of variation in magnitudes of $<5\%$ of the SD for the cumulative mean for at least three straight trials,[19] we suggested that the mean of the fourth, fifth, and sixth trials can represent shoulder proprioception where stability in magnitude was been obtained in our study. This result is similar to the Selfe and colleagues study,[19] which that the same trials can represent knee proprioception. Additionally, the newly developed PFI can provide different aspects of proprioception feedback, such as input from musculotendinous mechanoreceptors, to evaluate dynamic shoulder stability.

Limitations of our study should be noted. Our sample included subjects with limited range of motion. Results of proprioception would likely be different in subjects with shoulder instability, who commonly have proprioception impairment. However, our sample, with restricted range of motion and normal controls, provides a rationale for validating our developed PFI and JPS, because involved shoulders were assumed to have enhanced proprioception during end range movements. Also, our index may reflect both stored motor control patterns and peripheral proprioception during active movement. The PFI, however, should be appropriate for partial support of examination of kinesthesia as the perception of limb movement. On the analysis of movement accuracy in three-dimensional (3D) space, visual information, spatial working memory, and proprioceptive feedback are the three major components that guide movements. In our protocol, subjects were blindfolded to block visual information. Subjects were also asked to target movement once every 2 to 3 s, which limited the effect from spatial working memory. Thus, we believe that the accuracy of movement indicated proprioceptive feedback related to the perception of limb movement. Caution should be considered regarding the use of this index. Furthermore, the use of skin-based motion trackers for arm elevations above 120° in asymptomatic sides was invalid. Future research should focus on different samples with and without shoulder dysfunction using PFI and JPS in our experimental paradigm.

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