Clinical assessment of shoulder joint-position sense and interactive data analysis – a pilot study

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Abstract

Background: Shoulder joint-position sense (JPS) is impaired in shoulder pathology but rarely measured in clinical practice. Challenges include finding a practical assessment method and presenting test results in a meaningful format. This pilot study investigates a modified 'laser pointer assisted angle-reproduction test' (LP-ART) for assessing JPS with interactive data analysis and presentation.

Methods: 30 healthy volunteers were recruited from orthopaedic waiting rooms. Three targets provided shoulder elevation measurements of 55°, 90° and 125°. A laser pointer was attached to the subject's forearm. Subjects pointed at each target before being blindfolded and attempting to reposition their arm. Interactive scatterplots were used to present the data.

Findings: Assessments were simple to perform, taking 10 minutes per subject. Elevations were typically below the 125° target, and above the 90° and 55° targets. There was evidence that elevation of the target affected subject elevation error in both abduction ($\chi^2(2) = 244$, $p < 0.0001$), and in flexion ($\chi^2(2) = 299$, $p < 0.0001$). Subject sex showed a statistically significant effect on the mean elevation error for both abduction ($\chi^2(3) = 38.8$, $p < 0.0001$) and flexion ($\chi^2(3) = 38.3$, $p < 0.0001$), but no significant effect on elevation error variance in either abduction ($\chi^2(3) = 5.4$, $p = 0.15$), or in flexion ($\chi^2(3) = 6.6$, $p = 0.08$).

Interpretation: Modified LP-ART provides a low-cost assessment method with clear visual representation of results. JPS acuity measurement via mean error or within-subject variance is suggested, depending upon the purpose of the analysis. Further work is required before this method can be recommended for use in clinical practice.

Keywords: shoulder, joint-position sense, JPS, proprioception, laser pointer, angle-reproduction test, LP-ART, interactive analysis

1. Background

1.1. Shoulder joint position sense

Proprioception is a sixth sense, formed by the integration of three distinct elements of internal sensory information (Boyar et al., 2007). The three components – joint position sense (JPS), awareness of force, and kinaesthesia – combine with other sensory modalities in the central

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nervous system to facilitate sensorimotor control (Myers and Lephart, 2002; Hatterman et al., 2003).

Proprioceptive impulses originate within mechanoreceptors in joint capsules, ligaments, muscles, tendons and skin (Grigg, 1994). These sensory stimuli travel via afferent neural pathways and perceived at both conscious and subconscious levels (Lephart et al., 1994), before central processing and neuromuscular response via the efferent limb of the sensorimotor system (Myers and Lephart, 2002). Proprioception is vital for coordinated movement and functional stability throughout the human body (Myers and Lephart, 2002; Hatterman et al., 2003).

In the upper extremity, shoulder proprioception has the greatest influence on motor control (Myers and Lephart, 2002). As such, the glenohumeral joint is richly endowed with proprioceptive mechanoreceptors, located within both capuloligamentous and contractile structures (Myers and Lephart, 2002; Gohlke et al., 1998; Witherspoon et al., 2014; Ide et al., 1996).

Proprioceptive neural impulses from musculotendinous receptors exceed those from capsuloligamentous structures during unconstrained movements of the shoulder (Suprak et al., 2006). This has been proposed as an explanation for the greater accuracy observed during active joint repositioning tasks when compared to passive repositioning (Lonn et al., 2000; Erickson and Karduna, 2012).

1.2. JPS across the shoulder range of motion

Several authors report a variation in proprioceptive acuity across the range of shoulder motion (Anderson and Wee, 2011). JPS appears to improve with increased upper limb elevation and tension within capsuloligamentous restraints (Ulkar et al., 2004; Janwantanakul et al., 2001; Suprak et al., 2007; Yang et al., 2008; Anderson and Wee, 2011) . However, it is unclear whether this occurs during unconstrained shoulder joint elevation, where musculotendinous mechanoreceptors provide additional afferent proprioceptive stimuli (Suprak et al., 2006; Suprak, 2011).

In keeping with this rationale, subjects with unilateral shoulder stiffness have been found to have enhanced JPS at terminal shoulder elevation, relative to their normally-mobile contralateral shoulder (Yang et al., 2008) . Although previous studies report no differences in shoulder proprioception between the sexes (Langan, 2014), the female shoulder does possess a significantly greater range of motion than the male shoulder (Schwartz et al., 2016). There have been, to our knowledge, no studies exploring differences in the upper-range of shoulder elevation, where capsuloligamentous tension may differ between male and female shoulders.

1.3. Clinical assessment of joint position sense

Shoulder disorders including osteoarthritis and instability are not only associated with impaired proprioception, but have been shown to improve following operative treatment (Zuckerman et al., 2003; Cuomo et al., 2005). Given its fundamental role in upper limb function, clinical assessment of shoulder proprioception would be desirable (Myers and Lephart, 2002). In practice, however, this remains rare; one reason for this is practicability (Balke et al., 2011). In the laboratory setting, 3D motion analysis, electromagnetic tracking and isokinetic dynamometry provide elegant yet complex solutions to proprioceptive assessment (Kasten et al., 2009; Hung and Darling, 2012; King et al., 2013; Haik et al., 2013).

Unfortunately these methods are poorly suited to the time and resource-limited environment of a busy musculoskeletal clinic. These tests also offer limited simulation of real-life function (Han et al., 2013).

The laser pointer assisted angle-reproduction test (LP-ART) is suggested as an economically viable and quicker alternative. This JPS assessment tool – which involves a small wrist-mounted laser and a target – may be practical for use in clinic, and has been shown to effectively quantify proprioceptive dysfunction in patients with shoulder instability (Balke et al., 2011; Glendon and Hood, 2015). However, previous authors cited problems mounting a suitable laser pointer. Another challenge is analysing and presenting test results in a useful and patient-friendly format.

2. Aims

We revised the LP-ART and introduced a novel interactive data analysis tool, designed for clinicians, researchers and patients. We piloted the test on 30 healthy volunteers in an orthopaedic clinic, with the aim of establishing:

1. The feasibility of using LP-ART with interactive results visualisation to test healthy volunteers in a clinical setting.
2. Reference values for upper limb repositioning accuracy in healthy individuals using LP-ART.
3. Whether differences exist in shoulder elevation accuracy for differing elevation angles in healthy subjects.
4. Whether there are differences in shoulder elevation accuracy between between male and female participants.

3. Materials and methods

3.1. Subjects

Formal ethical approval for this study was waived by St George's, University of London.

Healthy volunteers were recruited from orthopaedic waiting rooms. All subjects received both verbal and written instructions of test procedure. Informed, written consent was obtained prior to data collection in all cases. Inclusion and exclusion was based on factors that affect JPS. Inclusion criteria were:

- Healthy individuals aged 18 to 50 years (Adamo et al., 2009).
- Able to understand and consent to the tasks required.

Exclusion criteria were:

- Prior shoulder pain or injury (Fyhr et al., 2015).
- Limitation to shoulder movement (Adamo et al., 2009).
- Prior shoulder surgery (Aydin et al., 2001; Zuckerman et al., 2003; Cuomo et al., 2005).
- Any neurological impairment including areas of skin numbness.
- Any recent or regular medication.
- Any disorders affecting joint mobility, including Marfan and Ehlers-Danlos syndrome (Blasier et al., 1994).
- Any alcohol consumed in the past 24 hours (Modig et al., 2012).
- Any vigorous exercise in the past 24 hours (Iida et al., 2014).

3.2. *Testing apparatus*

Our target board consisted of three separate points marked down the centre of a millimetre lined grid made from three sheets of size A0 graph paper, the dimensions of which are 252.3×118.8 cm. The board was mounted on a flat vertical wall and positioned to locate target 2 at mid glenohumeral joint level for each subject. Target 1 was located 70 cm below this point, while target 3 was 70 cm above it, creating a between-targets angle of 35° at the shoulder of a subject standing 1 m from the target, as shown in Figure 1. This provided targets at 55°, 90° and 125° elevation. Markings on the floor ensured the subjects feet were parallel to the target for flexion, and perpendicular for abduction. Each attempt was recorded by photographing with a digital camera (Canon 350D SLR, Japan). A coordinate system based upon the millimetre grid was used to measure the error in each attempt. Unlike previous work using a simplified LP-ART, this system records the exact position of the laser pointer at each attempt, rather than simply its distance from the target (Glendon and Hood, 2015).

The pointer used in this study was a 5 mW 532 nm laser torch, weighing 55 g (JD-850, China). Due to problems encountered by Balke et al. (2011) involving the subject's hand fouling the laser beam, we attached the laser to a ventilated archery arm guard (CR6G Cartel, Korea) using an elevated mount as shown in Figure 2.

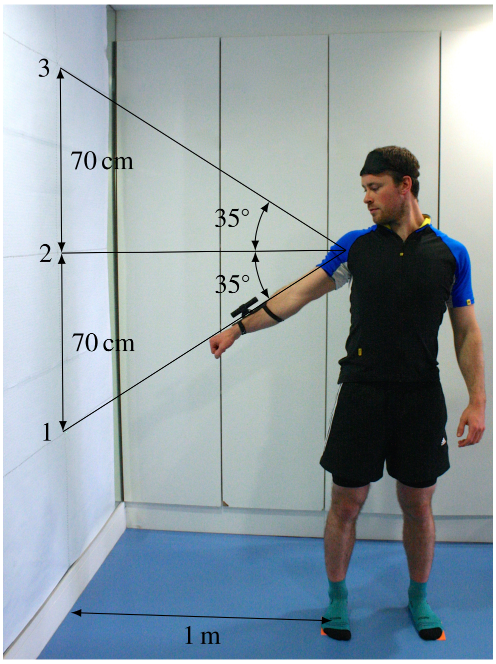


Figure 1: Subject before blindfolding – abduction position 1 (55°).

Figure 2: Laser mounted on subject's forearm – distal aspect of brace level with Lister's tubercle, laser-pointer directed towards base of third digit (beam at 55° target).

3.3. *Testing procedure*

Given that cutaneous mechanoreceptors contribute little to JPS (Grigg, 1994), we examined subjects wearing loose fitting clothing, rather than bare-chested as in the study by Balke et al. (2011).

The target vertical positions were adjusted to the subject's height as described above, via a mobile central strip. Subjects were positioned such that the centre of their shoulder joint was 1 m from target 2. Foot placements were standardized in a 30 cm wide bipedal stance via markers on the ground.

Tests were performed for flexion and abduction in each subject, and for both right and left shoulders, giving four separate tests per subject. Although the results present the targets by angle, the researcher referred to the targets only as '1', '2' and '3' throughout the trial. At the start of each test the subject was asked to point at each target in turn – in the order target 1, target 2, target 3 – with their eyes open, relaxing their arm down to their side between attempts. The subject was typically able to position the laser spot very accurately on each target with visual feedback.

The subject was then blindfolded and asked by the researcher to reposition their arm towards different targets. For abduction, the subject was advised to maintain their head in same position after blindfolding to reduce deviation due to altered head position (Guerraz et al., 2011). Before each repositioning attempt, the subject was asked to relax their arm by their side. No other feedback was given to the subject during testing. Three repositioning attempts were made per target in each test. The order of the targets requested was randomised in each test by the researcher drawing counters from a bag without replacement. The resulting position for each attempt was documented via digital photography of the laser spot on the grid, and subsequently recorded as a vertical and horizontal error from the target. Two standing positions (abduction and flexion), left and right arms, three targets, and three attempts per target, resulted in a total of 36 attempt recordings per subject. This process took around 10 min in total per subject.

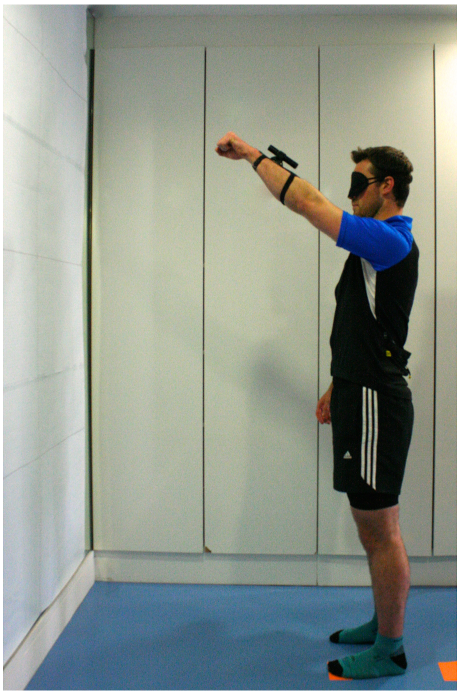
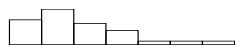
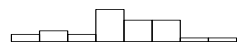
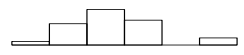


Figure 3: Blindfolded subject – flexion position 3 (125°).

4. Results

4.1. Subject demographics

A total of 30 healthy volunteers participated in this study; aged 20 to 50 years (med=28, $_{20}$  $_{55}$), 16 men and 14 women, three of whom were left-handed. Heights varied from 156 to 191 cm ($_{155}$  $_{195}$) and weights were in the range 50 to 86 kg ($_{50}$ $_{90}$). Participants had slept for between 5 and 10 hours the previous night, with the majority having had around 7 hours sleep ($_{5}$  $_{11}$). All subjects were healthy with no pain, injury or limitation to shoulder movement.

4.2. Data Analysis

Due to the non-linearity introduced through the projection onto a flat wall, the measurements were converted into an angular coordinate system about the shoulder. The shoulder coordinate system is defined as an azimuthal angle, taken as the direction of pointing projected onto a horizontal plane and measured in degrees clockwise from zero directly at the targets, and an elevation angle measured in the vertical plane (rotated with the azimuth measurement) with 0° pointing straight down. Errors in azimuth and elevation were calculated with reference to the target requested by the researcher.

The error for all separate attempts, measured in the shoulder coordinate system, was then presented in scatterplots (azimuth error on the horizontal and elevation error on the vertical), separated into the three targets and left and right arms; these are shown for all attempts, by all 30 subjects, for abduction and flexion in Figures 4 and 5 respectively.

Interactive results data from this study were presented in SVG using the D3 javascript library (Bostock, 2012), and can be viewed at: extuitive.co.uk/shoulderResearchResultsPlot. In the interactive version results may be filtered by subjects and by demographic details. Points generated by the same subject may be highlighted during interactive investigation, along with the display of ellipses to show means and standard deviations.

4.3. Elevation JPS acuity at differing target angles

In order to test the hypothesis that target angle affects JPS acuity, comparison was made between several linear mixed models fitted to the dataset using the R nlme package, with random effects to account for the multiple attempts per subject (Pinheiro et al., 2015). These within-subject attempts are assumed to be independent and free from correlation; this is based on the fact that it was a straightforward and easy task, no feedback on performance was given between attempts, all were conducted within a short space of time, and there was not sufficient repetition for fatigue to produce a significant impact (given that all subjects were healthy individuals). Three models were estimated and compared, for both flexion and abduction separately: the first model explains the elevation error only as a random effect of the multiple within-subject attempts; the second explains elevation error as a fixed effect of the target angle and the random within-subject attempts; and the third is the same as the second but it also allows the variance of the error to differ between targets. All model fits were generated using the maximum-likelihood method, so that likelihood based methods could be used to compare models. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. *P* values were obtained by likelihood ratio tests between models.

Comparing the first two models, and visible from the plots in Figures 4 and 5, there is clear evidence that the elevation of the target affects subject elevation error. This is true in both abduction ($\chi^2(2) = 244$, $p < 0.0001$), and in flexion ($\chi^2(2) = 299$, $p < 0.0001$).

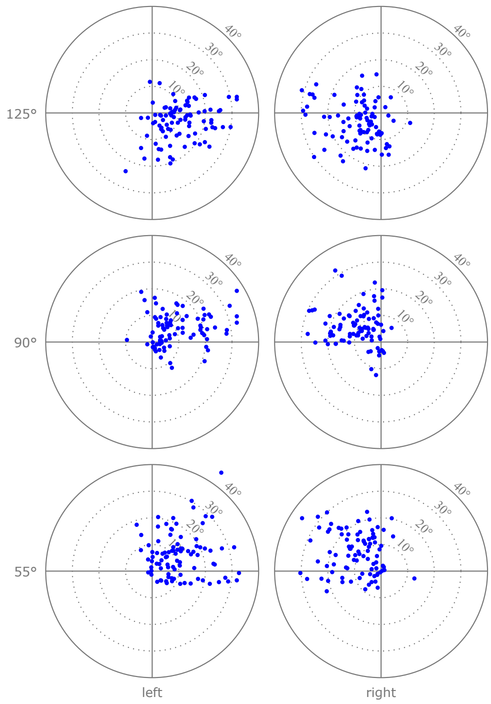


Figure 4: Results for all attempts in abduction by all subjects.

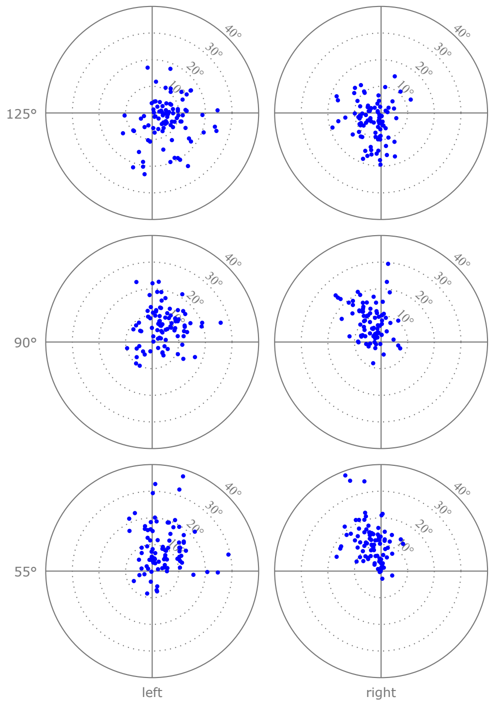


Figure 5: Results for all attempts in flexion by all subjects.

Comparing the second and third model assesses the effect of target elevation on subject elevation error variance; evidence is found that target elevation does significantly affect elevation error variance in both abduction ($\chi^2(2) = 33.0$, $p < 0.0001$), and in flexion ($\chi^2(2) = 9.4$, $p = 0.009$). In both cases the error variance is smallest at 90° and largest at 55°.

4.4. Sex differences in elevation JPS acuity

To test the hypothesis that subject sex affects elevation JPS acuity, linear mixed models were compared as detailed above; subject to the same set of assumptions, inspections and testing processes. In this case three models were compared as follows: the first equal to the third model above; a second model the same as the first, but with fixed interaction effects between target angle and sex; and a third model the same as the second, but with the addition of error variance differences between sexes.

Comparing the first two models there is evidence of subject sex having an interaction effect with target angle, for both abduction ($\chi^2(3) = 38.8$, $p < 0.0001$) and flexion ($\chi^2(3) = 38.3$, $p < 0.0001$), with the impact shown in Table 1.

Comparing the second and third model, there is no evidence of a statistically significant effect of sex on elevation error variance in either abduction ($\chi^2(3) = 5.4$, $p = 0.15$), or in flexion ($\chi^2(3) = 6.6$, $p = 0.08$).

Including the interaction effect of subject sex, the standard deviation due to between-subject differences is 4.4° in both abduction and flexion, whilst the residual within-subject standard deviation varies with target angle as shown in Table 2.

	Abduction		Flexion	
	Male	Female	Male	Female
125°	−4.5°	−2.2°	−4.5°	−1.3°
90°	4.0°	6.4°	5.2°	7.9°
55°	8.8°	4.2°	11.2°	7.2°

Table 1: Elevation errors due to target angle and sex

	Abduction	Flexion
125°	5.6°	5.8°
90°	4.2°	5.1°
55°	6.4°	6.2°

Table 2: Within-subject standard deviation due to different target angles (with subject sex interacting with target angle)

5. Discussion

Proprioception is an important aspect of shoulder function, yet no 'gold standard' method of assessment has emerged. Previous JPS research has failed to identify a useful presentation format and has not considered error variance. Our primary aim was therefore to pilot LP-ART with interactive results visualisation in healthy individuals, with a view to further clinical feasability work.

Previous work suggests that elevation angle affects JPS acuity (Anderson and Wee, 2011). However, unconstrained shoulder elevation has not been adequately studied in healthy individuals (Suprak et al., 2006). Our secondary aim was therefore to assess the effect of differing elevation angles on JPS.

Prior research suggests greater JPS acuity in stiffer shoulders. Although studies suggest no significant difference in shoulder JPS between males and females, previous methodology has not considered the potential for differences at the various angles of elevation. We therefore aimed to evaluate whether males' more limited shoulder motion is associated with a difference in JPS at progressive degrees of shoulder elevation.

5.1. Practical relevance

In everyday life, eyesight generally provides an effective feedback loop to allow compensation for minor JPS errors, hence the need to blindfold subjects during the tests; the benefit of accurate JPS is therefore likely to be magnified in situations where visual feedback is not available. An example would be entering a darkened room and reaching for a light switch. In this example, assuming the subject misses the light switch on their first attempt, they are unlikely to return their arm to their side and then reattempt location of the switch from the start. Much more likely, they will slide their hand over the wall until they locate the switch; therefore, if there is a systematic error, for example they generally do not lift their arm high enough, during successive actions of switching on the light they may learn that they need to search upwards for the switch. In fact, during regular use it may be possible for subjects to correct for systematic errors, lifting their arm higher to find the switch.

It is this feedback and compensation mechanism that motivates the investigation of error variance between attempts, alongside error magnitude. Previous shoulder JPS research has based acuity assessment only on subjects' error in reproducing a desired shoulder angle. Often the average over several attempts is taken, with no regard paid to the variance (Glendon and Hood, 2015). This variance is dependent upon JPS acuity and, unlike a systematic error, cannot be compensated for based on previous knowledge. Overall it is suggested that subject variance may be an important factor in JPS measurement and should be studied further.

5.2. *Study outcomes and implications*

We found LP-ART simple to administer to healthy subjects within a clinical environment. The test is also quicker and, with material costs of around £30, considerably cheaper than other methods. There remains scope however, for further development of the test procedure and equipment.

Previous authors found the laser beam to be obscured by wrist movement, but our elevated mount effectively avoided this. The interactive results visualisation used in this study allowed clear and detailed data analysis.

In keeping with previous studies, we found that elevation JPS acuity was affected by the angle of the upper limb in both abduction and flexion; this is true both in terms of mean error and in terms of variance (Balke et al., 2011). Studies have identified greater JPS acuity at higher degrees of shoulder elevation, a phenomenon that previous authors have attributed to increasing capsuloligamentous tension (Jerosch et al., 1996). Our results support this mechanism in respect of mean elevation error (the only measure used in previous studies), with most subjects tending to point only slightly below target 3 at 125°. Interestingly however, we found the elevation error variance to be smallest at 90° and greatest at 55°, in both abduction and flexion.

Our results are consistent with those of a focussed study of unconstrained shoulder motion that failed to demonstrate improved position sense at end-range horizontal abduction (Suprak et al., 2006). One explanation for this outcome is increased activity in myotendinous mechanoreceptors, in addition to feedback from non-contractile tissues, when testing unconstrained motion. As our study investigated shoulder elevation, the effects of gravity are likely to have caused a further increase in muscle spindle activity at 90°. We suggest that this additional feedback from muscle and tendon may have contributed to the our finding of the smallest elevation error variance at 90°. As there is evidence to suggest that upper limb anatomy has evolved for unconstrained manipulation of objects at the lower degrees of shoulder elevation, 90° and 55° might indeed be expected to show superior JPS acuity to 125° (Lewis et al., 2001). We also note that, although target 2 was never identified as 90° to subjects, familiarity with this horizontal upper limb position may have contributed to decreased variance when assessing this target.

As JD et al. (1999) note, it is impossible to compare results directly between shoulder JPS studies due to the different methods used. The LP-ART values shown in Tables 1 and 2 will provide a useful reference for future research using LP-ART, although we acknowledge the limitations of our sample size. We also emphasise the importance of considering error variance as a measure of JPS.

This work also suggests that differences in elevation JPS between males and females are significant only in terms of mean error, with females tending to undershoot less at the higher target (possibly due to their greater range of motion), but not in terms of variance. It therefore depends upon the purpose of the analysis, and accordingly the chosen definition of JPS measurement, as to whether there is a difference between the sexes. A possible explanation for females tending undershoot the higher target is a lower level of capsuloligamentous tension in the more mobile female shoulder.

Although this study did not statistically analyse JPS error in the horizonal plane, we did observe a possible trend when assessing abduction. For all targets, participants appear to deviate anteriorly into horizontal flexion/adduction. This may be explained by the anatomical orientation of the glenoid fossa. Participants appear to drift anteriorly into scapular plane elevation, rather than maintaining true abduction. Participants may also have internally rotated or pronated during abduction, thus orientating the laser anteriorly.

5.3. Study strengths

LP-ART relies upon active repositioning at various degrees of upper limb elevation. Active repositioning has greater functional relevance and is more sensitive than passive tests, as a result of targeting both myotendinous and capsuloligamentous mechanoreceptors (Anderson and Wee, 2011). The test is performed in the standing position, mimicking function, and utilising antigravity muscles that may contribute to improved proprioception (Janwantanakul et al., 2003).

The smartphone-compatible scatterplots allow investigation through demographic and physical characteristic filtering. With many readers now accessing research articles electronically, interactive data analysis is suggested as an enhancement to the overall scientific literature.

As discussed above, it is suggested that within-subject variance should be analysed in addition to mean accuracy in the assessment of proprioceptive function.

5.4. Study weaknesses

LP-ART investigates JPS, which is just one element of proprioception (Myers and Lephart, 2002). In addition, JPS may not be the only factor affecting the test results – cognitive function may also have an impact. Another weakness of LP-ART in general is its failure to collect data on medial and lateral shoulder rotation. This would be an significant issue if examining patients with shoulder instability.

While randomisation aimed to eliminate any bias in testing order induced by short-term memory, it is possible that some effect persisted. Several subjects mentioned experiencing some muscular fatigue towards the end of the testing procedure, which has been shown to have deleterious effects on the accuracy of active repositioning ability (Iida et al., 2014). Although the randomisation process aimed to minimise these effects, fatigue would be an important factor to consider if testing patients with shoulder pathology. A shorter testing procedure by reducing LP-ART to one attempt for each target, or multiple attempts at a single target, could be considered; although each of these options will introduce compromises in the results obtained. A faster testing process may also improve the clinical utility of the test.

Another potential weakness in our study design was in the measurement of the subject distance from the wall. Rather than measuring directly from the shoulder to the wall, the subjects feet were positioned 1 m away, potentially allowing trunk deviation to affect shoulder-to-wall distance. The subject may also have shifted stance slightly during the testing procedure. However, any errors introduced by these factors are expected to have been small. Attempts at restraint were avoided as we considered that this may provide additional cutaneous feedback to the participant.

Offset of the laser from the wrist eliminated the previous beam-obstruction issues experienced by Balke et al. (2011); however, as noted previously, this mounting method may have introduced minor measurement errors due to the offset and any upper limb rotation during elevation.

Other negative aspects of our experience with the modified LP-ART include a large and cumbersome paper target, 10 minute procedure, and 10 minute data entry process. Automation of this process could be attempted in future work.

5.5. Further work

Due to the possibility of a learning effect during LP-ART, a follow-up study investigating intra-tester reliability is recommended. Inter-tester reliability should also be ascertained.

Further analysis of the existing results may also be performed to investigate: azimuthal JPS acuity and the impact of target target angle and subject sex; correlation between elevation and azimuthal JPS acuity; impact of arm dominance on JPS; fatigue affects as testing progresses; and the significance of differences between flexion and abduction.

Future research may investigate the use of scatterplot result presentation with patients. By promoting patient understanding of test results this visualisation tool may be investigated as a means of facilitating surgical consent and therapy concordance (Fraval et al., 2015). Further development is also recommended to reduce the time taken to administer the test and compile the data.

Further feasibility work investigating LP-ART in patients with shoulder pain is required before this test can be recommended for use in clinical practice.

6. Conclusions

In summary, LP-ART shows early promise as a solution to measuring shoulder JPS, although further investigation is recommended. Interactive data presentation worked well in this study and is suggested for use in future work. JPS acuity measurement through mean error or through within-subject variance is suggested, depending upon the purpose of the analysis.

This study shows evidence of a statistically significant difference in mean elevation JPS error due to the vertical elevation of a target and a subjects sex, and of a significant difference in elevation JPS within-subject variance due to the target vertical elevation, but not due to subject sex.

Results show a tendency to not raise the arm high enough at high targets, but to raise the arm too high for horizontal and lower targets. Within-subject elevation variance is smallest for horizontal targets and greatest for lower targets. Reference values for shoulder elevation JPS have been proposed.

Conflict of interest

DT receives payment for lecturing, fellowship support and royalties from Arthrex. No funding or payment has been received related to the content of this paper.

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