1

Title: Assessment of abduction movement in older people with painful shoulder: an analysis based on inertial sensors.

Authors

Cristina Roldán-Jiménez, PhD[1]

Email: cristina.roldan005@gmail.com

Jaime Martín-Martín, PhD [1, 2]

Email: jaimemartinmartin@gmail.com

Paul Bennett [3]

Email: p.bennett@qut.edu.au

Steven McPhail, PhD [3,4]

Email: steven.mcphail@qut.edu.au

Antonio I Cuesta-Vargas, PhD[1, 3,*]

Email: acuesta.var@gmail.com

Graham K. Kerr, PhD [3]

Email: g.kerr@qut.edu.au

Affiliations

[1] Department of Psychiatry and Physiotherapy. University of Malaga, Faculty of Health Sciences, Spain.

[2] Unidad Central de Anatomía, Universidad Católica de Murcia, España.

[3] Institute of Health & Biomedical Innovation, Faculty of Health, Queensland University Technology, Australia.

[4] Centre for Functioning and Health Research, Metro South Health, Australia

*Corresponding author: acuesta.var@gmail.com (AIC-V)

2

Abstract

Reduced range of motion in the shoulder can be a source of functional limitation. Current quantitative evaluation systems are limited to assessing the functionality or the maximum articular amplitudes in each of the planes of movement, both in isolation. These separate clinical evaluation systems may not allow the identification of the underlying impairments contributing to the functional limitation. The use of inertial sensors to quantify movement in addition to more common clinical assessments of the shoulder may allow clinicians to understand that are potentially unnoticed by the human eye. The main objective of this cross-sectional study was to generate an explanatory model for shoulder abduction based on data from inertial sensors. Shoulder abduction of thirteen older adults suffering from shoulder dysfunction was evaluated using two inertial sensors placed on the humerus and scapula. Movement variables (maximum angular mobility, angular peak of velocity, peak of acceleration) were used to explain the functionality of the upper limb (assessed using the Upper Limb Functional Index). Abduction movement of the shoulder was explained by six variables related to the mobility of the shoulder joint complex. A manova analysis was used to explain the results obtained on the functionality of the upper limb. The MANOVA model based on angular mobility explained 69% of the variance of the ULFI value (r-squared=0.69). The most relevant variables were the abduction-adduction of the humerus and the medial and lateral rotation of the scapula. However, given the limited sample size, none of these individual variables were statistically significant in the decomposition model on their own. The method used in the present study reveals the potential importance of the analysis of the scapular and humeral

48 movements for comprehensive evaluation of the upper limb. Further research

49 should include a wider sample and may seek to use this assessment technique

50 in a range of potential clinical applications.

Introduction

52 Shoulder disorders are highly prevalent in the population and to a greater

53 extent among older adults; in many cases, biomechanical anomalies are

54 asymptomatic [1,2]. Despite the potential absence of pain, limitations caused by

55 a reduced range of motion (ROM) can have a detrimental impact on the

56 performance of activities of daily living [3]. Clinically, the evaluation of patients'

57 daily functioning in their upper limbs is often based on self-administered

58 questionnaires, such as Disability of the Arm Shoulder and Hand (DASH) [4] or

59 Upper Limb Functional Index (ULFI) [5] and functional physical assessments

60 [6]; due to the high cost of the imaging devices such as motion tracking with

61 multiple camera system or real-time ultrasound.

62 In this regard, there is increasing evidence supporting the combined use

63 of new technologies with functional physical tests or ROM assessments for

64 more comprehensive biomechanical diagnostics. Technologies used for this

65 purpose include: X-ray [7–9], magnetic resonance imaging [10], 3D imaging

66 models [11] and inertial sensors [2,12], among others. Currently, one of the

67 devices most frequently used for clinical purposes is inertial sensors due to their

68 small size, reliability, and accuracy for registering human movement (speed,

69 acceleration, and orientation) [13].

70 For the assessment of shoulder mobility with inertial sensors, it is

71 necessary to use two or three inertial sensors located on the skin adjacent to

72 the humerus, scapula, and chest [14]. Inertial sensors have been used

73 alongside other objective assessments of the quality and quantity of movement

74 in patients with chronic painful shoulders [15,16]. Similarly, these sensors have

75 sufficient sensitivity to discriminate between healthy and affected subjects,

76 complementing the results of standardized assessment scales [15–19].

77 Changes in shoulder mobility, whether symptomatic or asymptomatic, may be

78 due to bone and muscle-related disorders affecting the rotator cuff

79 [20,10,9,11,8]. This may limit upper limb functionality and, in some cases, is

80 directly associated with age [20]. Prior research has indicated there are no

81 significant differences in the neutral positioning of the shoulder in symptomatic

82 and asymptomatic subjects. However, significant changes in internal mobility of

83 the shoulder joint complex have been detected when the shoulder flexes above

84 90 degrees [18]. This is because the scapula has movement in three spatial

85 planes [21], which can change the orientation of the arm[7,9,11,19]. In addition

86 to the scapula, shoulder muscles also change their activation level according to

87 the speed and ROM of flexion or abduction[22].

88 Positive correlations between acceleration values measured with inertial

89 sensors and function-related questionnaire responses (DASH) have been

90 reported previously. Higher acceleration values reflected greater shoulder

91 functionality [16]. The asymmetry of shoulder movement assessed with inertial

92 sensors has also been correlated with patient-reported functionality; greater

93 asymmetry indicated less functionality [23].

94 Therefore, describing an approach for assessing shoulder mobility based on

95 inertial sensors in subjects who have functional limitations is an important next

96 step in advancing the field. Ideally, the assessment with multiple inertial sensors

5

97 will discriminate whether the displacement of body segments is below or above

98 the normal values and contribute to functional limitation; providing additional

99 information for clinical use. Therefore, inertial sensors could be used to

100 compliment more traditional assessments when diagnosing shoulder

101 dysfunction. The main objective of this study was to design a multivariate model

102 for upper limb dysfunction based on inertial sensors, thereby obtaining

103 predictors of upper limb dysfunction based on shoulder movements.

6

Materials and methods

Subjects

A cross-sectional study was designed to evaluate abduction movement of the shoulder with two IntertiaCube3 Sensors [24]. Thirteen participants (9 females, 4 males) were recruited from a specialized orthopedics clinic. They had previously been diagnosed with rotator cuff tears by magnetic resonance imaging and were on the waiting list for surgical intervention. Inclusion criteria were age between 18 and 75 years old, Body Mass Index (BMI) between 18 and 42 and presence of a confirmed rotator cuff tear. Participants were excluded if they declined to participate in the study or had concurrent or alternative etiologies for their shoulder dysfunction.

An a-priori sample size of 9 participants was calculated for an α error of 0.05, a statistical power of 0.8 and β error of 0.7, based on data from a systematic review on the use of inertial sensors to measure human movement [25].

The study was approved by the ethics committee of the University of Malaga (Faculty of Health Sciences) and complied with the principles of the Declaration of Helsinki [28]. All participants provided informed consent prior to taking part in the study.

Apparatus

Two IntertiaCube3 Sensors (Billerica,MA,US) [24] were used to measure shoulder abduction of each subject. This sensor has high performance: 4ms latency, 180 Hz rate, high accuracy (below 1º of error), 3 degrees of freedom (Yaw, Pitch, and Roll) and a little size and weight. Acceleration (m/s^2) and

7

129   angular mobility (°) of shoulder abduction were measured with these sensors in

130   the three spatial axes (Z-Yaw, Y – Pitch, X - Roll); each spatial axis was related

131   to the movement of the corporal segment (Table 1).

132

Table 1. Real movement by axis and plane.

Region	Axis- plane	Real Movement
Humerus	X -Roll	FL–EX
	Y - Pitch	IN–EX
	Z - Yaw	AB–AD
Scapula	X - Roll	AN–PO
	Y - Pitch	PR–RE
	Z - Yaw	ME–LA

133

134   Two inertial sensors were placed on the humerus and the scapula

135   following the protocol designed by Cutti et al. (2008) [14].To ensure the correct

136   measurement data, the skin of participants was cleaned with alcohol before

137   attaching the sensors to the skin with double-sided adhesive.

138   Before making the recordings, inertial sensors were calibrated to 0 following the

139   protocol established by the manufacturer's software [26]. This software was the

140   same as used for recording data; a low-pass filter (Kalman filter) was applied

141   while recording data.

Procedure

142

143   Prior to registration made with inertial sensors, patient characteristics

144   including the Spanish version of Upper Limb Functional Index (ULFI) [5]. ULFI is

145   an upper extremity outcome measure that consists of a 25-item scale that can

146   be transferred to a 100-point scale. It also has strong psychometric properties

147   [27]. Its Spanish version has demonstrated high internal consistency ($\alpha = 0.94$)

148   and reliability ($r = 0.93$) [5]. Placed in the standing position and with the upper

149   extremity in the neutral position, participants performed three full shoulder

150 abductions. That is, lifting the arm sideways until the hand reaches as high as

151 possible. Two sets of three repetitions were recorded; the second repetition of

152 each set was the one chosen to be analysed. Patients were told to perform

153 shoulder abduction at a natural speed until their movement had reached its end

154 of range of motion. Questionnaires were recorded. Abduction of the affected

155 shoulder was measured on the humeral and scapular sections. The main

156 variables analyzed were: maximum angular mobility (°), angular peak of velocity

157 (°/s), peak of acceleration (m/s^2).

Data analysis

159   Descriptive analyses (mean, SD) were used for participant characteristic

160 variables (weight, height, BMI, and age) to describe the sample. Based on the

161 yaw, pitch and roll values obtained by the sensor the minimum peaks obtained

162 by each sensor were subtracted from the maximum peaks for each of the

163 variables (acceleration and speed); the norm of the resultant vector (Nrv) was

164 calculated $Nrv = \sqrt{x^2 + y^2 + z^2}$ in order to obtain the mean speed and

165 acceleration of the movement performed. The means of peak of maximum

166 angular mobility inside the abduction movement in each of the 3 axes (yaw,

167 pitch and roll) were used in order to create an ANOVA multivariate analysis

168 (MANOVA) model .explaining the ULFI questionnaire results.

Results

170

171   Functional impairment of the participants was reflected by high ULFI

172 values (mean±SD) 70.96±20.93 [5]. The anthropometric characteristics of the

9

173 participants were age 52.68±9.78 years, weight 75.58±17.98 kg, height

174 1.64±0.09 m and body mass index 28.22±6.59 kg/m^2.

175   The mean maximum angular mobility in humerus abduction axis (72.97°)

176 indicated that a substantial reduction in shoulder mobility was present in the

177 sample. The reductions of the range movement, also affect to scapular section,

178 where the mean range was 12.63° for protraction-retraction (Table 2).

179

Table 2: Mean (95%*CI*) sensor peak maximum of angular mobility (°) from each axis in abduction movement.

Surface placement	HUMERUS		SCAPULA	
Axis	Motion	Mean (95%*IC*)	Motion	Mean (95%*IC*)
X	IN-EX	38.0 (16.17-59.85)	AN-PO	15.60 (2.33-13.86)
Y	AB-AD	77.56 (48.18-106.92)	PR-RE	12.63 (5.56-19.70)
Z	FL-EX	35.72 (21.12-50.31)	ME-LA	4.57 (1.87-7.28)

180

181   . The MANOVA model explained 69% of the variance of the ULFI value.

182 In an exploratory decomposition of the multivariate model, the main explanatory

183 variable was the value of the humerus AB-AD movement (*p*=0.093) followed of

184 the scapular ME-LA (*p*=0.195). However, given the limited sample size in the

185 present study, none of these individual variables were statistically significant in

186 the decomposition model on their own. On the other hand, there was less (or

187 no) indication that gender and scapular anterior–posterior tiling movement were

188 likely to have importance for the explanation of the model (Table 3).

189

10

Table 3: Decomposition of the multivariate model.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.831	0.690	0.569	16.38757

		Unstandardized Coefficients		Standardized Coefficients	t	p
		B	Std. Error	Beta		
1	(Constant)	108.320	9.569		11.320	0.000
	Gender	-3.189	8.920	-0.062	-.357	0.725
	FL–EX	-0.195	0.185	-0.295	-1.057	0.305
	AB–AD	-0.347	0.196	-0.590	-1.771	0.093
	IN–EX	0.104	0.154	0.192	0.673	0.510
	ME–LA	-0.078	0.058	-0.212	-1.347	0.195
	PR-RE	-0.312	0.569	-0.123	-0.548	0.590
	AN–PO	-0.119	1.072	-0.039	-0.111	0.913

190

191   The mean (95%CI) peak of acceleration (m/s^2) and velocity (°/s) and

192   peak from norm of the resultant vector in abduction is presented in Table 4.

193

Table 4. Mean (95%CI) peak of acceleration (m/s^2) and velocity (°/s) and peak from norm of the resultant vector in ABD.

Axis		Humerus	Scapula
Nrv	Acceleration	16.25 (9.86-222.64)	4.48(2.72-6.24)
	Velocity	109.42 (70.80-147.98)	43.71 (27.97-59.45)

194

195

11

Discussion

196

197 Shoulder abduction has been described by the use of two inertial sensors

198 in the present study. In this case, they were placed on the scapula and

199 humerus. The results obtained were used in order to create a multivariate

200 model for the description of abduction movement(s) that explained shoulder

201 function as reported by patients using the ULFI questionnaire. Thus, the overall

202 objective of the study was fulfilled. The maximum values of acceleration and

203 angular velocity refer to the normal movement performed by the participants

204 (they were asked to perform shoulder abduction at normal speed). This

205 requirement allowed us to create a model that was more faithful to shoulder

206 movement in daily living. In accordance with the results obtained, the inertial

207 sensors have potential for complementary description and quantification of

208 perceived disability in the upper limb; because of the results of MANOVA model

209 (r-squared=0.69).

210 Prior descriptions of shoulder abduction have been carried out by various

211 authors in recent decades [7–11,20]. Most of these prior studies focused on

212 rotator-cuff fatigue although some elements of biomechanical mobility during

213 shoulder abduction have been examined using X-rays [7–9], ultrasound

214 techniques [20], magnetic resonance [10] or computed tomography [11].

215 Unfortunately these previously reported approaches to examining

216 biomechanical shoulder abduction movement are likely to be too costly for daily

217 use in clinical settings and the inability to follow the movement in real time.

218 However inertial sensors do not have these limitations [13].

219 The inertial sensors used in the present study allowed an assessment

220 based on angles, speed and acceleration movements. However, they do not

221 provide the same level of insight pertaining to osseous structures involved in the

222 movement as the aforementioned imaging technologies. Nonetheless, the

223 supplementary biomechanical information provided by inertial sensors may add

224 value in the context of biomechanical diagnostics in clinical settings.

225 According to findings from the movement decomposition model reported

226 in Table 3, humerus ABD-ADD and scapula AN-PO may be the movement

227 components that have the greatest association with self-reported upper limb

228 function. This finding was not surprising; however, this was accompanied in

229 greater measure for the scapular anterior-posterior movement rather than

230 lateralization (that is to say, scapular ME-LA). These findings from the present

231 study are consistent with a previous study that focused on the scapulothoracic

232 joint which found a reduced ME-LA motion during elevation in symptomatic

233 subjects [29]. In contrast with these results, another previous study that

234 examined 3D scapula kinematics using Polhemus Fastrak found an

235 increased scapular lateral rotation as a compensatory pattern in pathological

236 shoulders [30]. A potential explanation for this observation is that the middle

237 deltoid is the muscle that performs arm elevation with greater activity over 75°

238 of shoulder abduction, while the supraspinatus is more effective at low angles

239 [11]. Likewise, Duc et al. (2014) observed different levels of muscle activation

240 for shoulder abduction in the same subject depending on the affected or healthy

241 side [31].

242 In this regard, the rotator cuff has an important role in shoulder

243 abduction[9]. Prior studies have shown tears in the rotator may or may not be

244 symptomatic or associated with functional deficits, and they are positively

245 associated with older age [10]. Several studies have demonstrated that

246   shoulder mobility does not maintain a direct relationship with the size or

247   thickness of the tear [10,20]; and in some cases there may be accommodation

248   of the humeral head in the glenoid [8,9,11].

249   In the present study, the findings presented in the Table 3 ANOVA model

250   may represent something of the accommodation or biomechanical adaptation of

251   the scapula and humerus movement using the two additional planes of

252   movement rather than abduction alone. This is consistent with prior reports from

253   other authors regarding the 3-dimensional movement of the scapula during

254   performance of shoulder abduction in symptomatic and asymptomatic subjects

255   [21]. Although the 3 dimensional movement of the scapula has been discussed

256   in prior research, the symptomatic nature of participants in the present study

257   (mean ULFI 70.96) and quantification of 3-dimensional movement using a

258   straight-forward inertial sensor setup means that finding from the present study

259   are likely to have particular relevance for this clinical population.

260   The association between the dysfunctionality of the upper limb (high values in

261   ULFI) and movement of the arm was consistent with other studies. Jolles et al

262   (2011) identified a positive coefficient of correlation (R>0.61) for 3 kinematic

263   variables in 4 different questionnaires functionality. One of the questionnaires

264   tested, the Simple Shoulder Test, obtained an excellent linear correlation

265   (R=0.80) with shoulder power [16]. The results obtained by Körver et al (2014)

266   also showed positive relationships between kinematics asymmetry scores,

267   understood as relative difference between healthy and affected side, and DASH

268   and Simple Shoulder Test Questionnaires (R=0.79); which indicated a high

269   diagnostic power to differentiate between healthy and affected side. These

270   results are consistent with those obtained in the present study in which the

14

271   values of humeral AB-AD explained almost 60% on the negative direction of the

272   variance of the questionnaire functionality (Table 3). Therefore, a lower level of

273   AB-AD was associated with a higher score obtained on the ULFI (which

274   corresponds to a less functionality).

275   In clinical contexts, shoulder assessment is usually done by traditional

276   clinical tests that are based on the premise that it is possible to isolate individual

277   structures by compressing or stretching the tissue of interest. However, this is

278   not possible without affecting the state of adjacent structures [32] because

279   rotator cuff tendons are interwoven as a functional unit [33]. For example, some

280   clinical tests that are intended to implicate supraspinatus pathology have been

281   demonstrated (using electromyography) to activate eight or nine other muscles

282   [34]. Hence, the employment of these tests leads to inaccuracy in their findings

283   [32–35].

284   Furthermore, the clinical expression of shoulder injuries is highly variable

285   [36–38]. Besides clinical test, in shoulder assessment image tests are also

286   employed. However, these too may be considered invalid at times, as there are

287   a large number of asymptomatic individuals who have structural shoulder

288   abnormalities[32]. Hence, at present, the evaluation and diagnosis of joint

289   pathology of the shoulder joint is a complex clinical endeavor prone to

290   uncertainty [33]. Results from the present study reinforce the potential use of

291   both inertial sensor and questionnaires to assess shoulder function building on

292   prior research in the field that has established each of these as independently

293   validated measurement instruments.   Research contributions that identify

294   potential predictors of upper limbs dysfunction based on validated instruments

295   may not only have a role in diagnostics, but also have additional potential in

296 quantify the effect of treatment. By extension, this may also lead to further

297 developments that assist in improving predictions of which patients are likely to

298 receive the greatest benefit from surgical or conservative interventions. To build

299 on findings from the present study, future research may also seek to measure

300 the same movement in a person twice (one on each side) and also for patients

301 to report the functionality of each of their upper limbs, as well as their global

302 upper limb functions. A study of this nature would have the potential to correlate

303 the functional capacity of each of the sides with the same kinematics values,

304 while also considering the roles of unilateral or bilateral kinematic deficits and

305 hand dominance on self-reported upper limb functioning to investigate the

306 potential mediating role of the unaffected arm.

307

Conclusions

309 The functionality of the shoulder is a key element in activities of daily

310 living. The application of complementary assessment technologies like inertial

311 sensors to traditional clinical upper limb assessments may add value for the

312 functional diagnosis of patients with shoulder pain. The method used in the

313 present study reveals the potential importance of the analysis of the scapular

314 and humeral movements for comprehensive evaluation of the upper limb. The

315 individual analysis of the planes of movement demonstrated the importance of

316 considering the relative contribution of each joint movement. Use of wireless 3-

317 dimentional sensors permitted the consideration of shoulder abduction as a

318 combination of movements dependent on each other within the joint complex of

16

319   the shoulder. Further research may seek to use this assessment technique in a

320   range of potential clinical applications.

321

322

Acknowledgments

330

331

332

17

References

1. Gill TK, Shanahan EM, Allison D, Alcorn D, Hill CL. Prevalence of abnormalities on shoulder MRI in symptomatic and asymptomatic older adults. Int J Rheum Dis. 2014;17: 863–871. doi:10.1111/1756-185X.12476

2. Louwerens JKG, Sierevelt IN, van Hove RP, van den Bekerom MPJ, van Noort A. Prevalence of calcific deposits within the rotator cuff tendons in adults with and without subacromial pain syndrome: clinical and radiologic analysis of 1219 patients. J Shoulder Elb Surg Am Shoulder Elb Surg Al. 2015;24: 1588–1593. doi:10.1016/j.jse.2015.02.024

3. Burner T, Abbott D, Huber K, Stout M, Fleming R, Wessel B, et al. Shoulder symptoms and function in geriatric patients. J Geriatr Phys Ther 2001. 2014;37: 154–158. doi:10.1519/JPT.0b013e3182abe7d6

4. Hudak PL, Amadio PC, Bombardier C. Development of an upper extremity outcome measure: the DASH (disabilities of the arm, shoulder and hand) [corrected]. The Upper Extremity Collaborative Group (UECG). Am J Ind Med. 1996;29: 602–608. doi:10.1002/(SICI)1097-0274(199606)29:6<602::AID-AJIM4>3.0.CO;2-L

5. Cuesta-Vargas AI, Gabel PC. Cross-cultural adaptation, reliability and validity of the Spanish version of the upper limb functional index. Health Qual Life Outcomes. 2013;11: 126. doi:10.1186/1477-7525-11-126

6. Roe Y, Soberg HL, Bautz-Holter E, Ostensjo S. A systematic review of measures of shoulder pain and functioning using the International

18

355   classification of functioning, disability and health (ICF). BMC Musculoskelet

356   Disord. 2013;14: 73. doi:10.1186/1471-2474-14-73

357   7. Poppen NK, Walker PS. Normal and abnormal motion of the shoulder. J

358   Bone Joint Surg Am. 1976;58: 195–201.

359   8. Teyhen DS, Miller JM, Middag TR, Kane EJ. Rotator cuff fatigue and

360   glenohumeral kinematics in participants without shoulder dysfunction. J

361   Athl Train. 2008;43: 352–358. doi:10.4085/1062-6050-43.4.352

362   9. Yamaguchi K, Sher JS, Andersen WK, Garretson R, Uribe JW, Hechtman

363   K, et al. Glenohumeral motion in patients with rotator cuff tears: a

364   comparison of asymptomatic and symptomatic shoulders. J Shoulder Elb

365   Surg Am Shoulder Elb Surg Al. 2000;9: 6–11.

366   10. Sher JS, Uribe JW, Posada A, Murphy BJ, Zlatkin MB. Abnormal findings

367   on magnetic resonance images of asymptomatic shoulders. J Bone Joint

368   Surg Am. 1995;77: 10–15.

369   11. Terrier A, Reist A, Vogel A, Farron A. Effect of supraspinatus deficiency on

370   humerus translation and glenohumeral contact force during abduction. Clin

371   Biomech. 2007;22: 645–651. doi:10.1016/j.clinbiomech.2007.01.015

372   12. Louwerens JKG, Sierevelt IN, van Hove RP, van den Bekerom MPJ, van

373   Noort A. Prevalence of calcific deposits within the rotator cuff tendons in

374   adults with and without subacromial pain syndrome: clinical and radiologic

375   analysis of 1219 patients. J Shoulder Elb Surg Am Shoulder Elb Surg Al.

376   2015;24: 1588–1593. doi:10.1016/j.jse.2015.02.024

19

377 13. Cuesta-Vargas A, Galán-Mercant A, Williams J. The use of inertial sensors
378   system for human motion analysis. Phys Ther Rev. 2010;15: 462–473.
379   doi:10.1179/1743288X11Y.0000000006

380 14. Cutti AG, Giovanardi A, Rocchi L, Davalli A, Sacchetti R. Ambulatory
381   measurement of shoulder and elbow kinematics through inertial and
382   magnetic sensors. Med Biol Eng Comput. 2008;46: 169–178.
383   doi:10.1007/s11517-007-0296-5

384 15. Duc C, Farron A, Pichonnaz C, Jolles BM, Bassin J-P, Aminian K.
385   Distribution of arm velocity and frequency of arm usage during daily
386   activity: objective outcome evaluation after shoulder surgery. Gait Posture.
387   2013;38: 247–252. doi:10.1016/j.gaitpost.2012.11.021

388 16. Jolles BM, Duc C, Coley B, Aminian K, Pichonnaz C, Bassin J-P, et al.
389   Objective evaluation of shoulder function using body-fixed sensors: a new
390   way to detect early treatment failures? J Shoulder Elb Surg Am Shoulder
391   Elb Surg Al. 2011;20: 1074–1081. doi:10.1016/j.jse.2011.05.026

392 17. Lawrence RL, Braman JP, Laprade RF, Ludewig PM. Comparison of 3-
393   dimensional shoulder complex kinematics in individuals with and without
394   shoulder pain, part 1: sternoclavicular, acromioclavicular, and
395   scapulothoracic joints. J Orthop Sports Phys Ther. 2014;44: 636–645, A1-
396   8. doi:10.2519/jospt.2014.5339

397 18. Lawrence RL, Braman JP, Staker JL, Laprade RF, Ludewig PM.
398   Comparison of 3-dimensional shoulder complex kinematics in individuals

20

399   with and without shoulder pain, part 2: glenohumeral joint. J Orthop Sports

400   Phys Ther. 2014;44: 646–655, B1-3. doi:10.2519/jospt.2014.5556

401 19. Roren A, Lefevre-Colau M-M, Roby-Brami A, Revel M, Fermanian J,

402   Gautheron V, et al. Modified 3D scapular kinematic patterns for activities of

403   daily living in painful shoulders with restricted mobility: a comparison with

404   contralateral unaffected shoulders. J Biomech. 2012;45: 1305–1311.

405   doi:10.1016/j.jbiomech.2012.01.027

406 20. Milgrom C, Schaffler M, Gilbert S, van Holsbeeck M. Rotator-cuff changes

407   in asymptomatic adults. The effect of age, hand dominance and gender. J

408   Bone Joint Surg Br. 1995;77: 296–298.

409 21. van den Noort JC, Wiertsema SH, Hekman KMC, Schönhuth CP, Dekker

410   J, Harlaar J. Reliability and precision of 3D wireless measurement of

411   scapular kinematics. Med Biol Eng Comput. 2014;52: 921–931.

412   doi:10.1007/s11517-014-1186-2

413 22. Castillo-Lozano R, Cuesta-Vargas A, Gabel CP. Analysis of arm elevation

414   muscle activity through different movement planes and speeds during in-

415   water and dry-land exercise. J Shoulder Elb Surg Am Shoulder Elb Surg

416   Al. 2014;23: 159–165. doi:10.1016/j.jse.2013.04.010

417 23. Körver RJP, Heyligers IC, Samijo SK, Grimm B. Inertia based functional

418   scoring of the shoulder in clinical practice. Physiol Meas. 2014;35: 167–

419   176. doi:10.1088/0967-3334/35/2/167

21

420   24. InterSense | Precision Motion Tracking Solutions | InertiaCube3™

421   [Internet]. [cited 10 Aug 2016]. Available:

422   http://www.intersense.com/pages/18/11/

423   25. Cuesta-Vargas A, Galán-Mercant A, Williams J. The use of inertial sensors

424   system for human motion analysis. Phys Ther Rev. 2010;15: 462–473.

425   doi:10.1179/1743288X11Y.0000000006

426   26. InterSense, LLC. Product Manual for use with InertiaCube3 and the

427   InertiaCube Processor.

428   27. Gabel CP, Michener LA, Burkett B, Neller A. The Upper Limb Functional

429   Index: development and determination of reliability, validity, and

430   responsiveness. J Hand Ther Off J Am Soc Hand Ther. 2006;19: 328–348;

431   quiz 349. doi:10.1197/j.jht.2006.04.001

432   28. WMA Declaration of Helsinki - Ethical Principles for Medical Research

433   Involving Human Subjects [Internet]. 19 Oct 2013 [cited 10 Aug 2016].

434   Available: http://www.wma.net/es/30publications/10policies/b3/

435   29. Lawrence RL, Braman JP, Laprade RF, Ludewig PM. Comparison of 3-

436   dimensional shoulder complex kinematics in individuals with and without

437   shoulder pain, part 1: sternoclavicular, acromioclavicular, and

438   scapulothoracic joints. J Orthop Sports Phys Ther. 2014;44: 636–645, A1-

439   8. doi:10.2519/jospt.2014.5339

440   30. Roren A, Lefevre-Colau M-M, Poiraudeau S, Fayad F, Pasqui V, Roby-

441   Brami A. A new description of scapulothoracic motion during arm

22

442 movements in healthy subjects. Man Ther. 2014;
443 doi:10.1016/j.math.2014.06.006

444 31. Duc C, Pichonnaz C, Bassin J-P, Farron A, Jolles BM, Aminian K.
445 Evaluation of muscular activity duration in shoulders with rotator cuff tears
446 using inertial sensors and electromyography. Physiol Meas. 2014;35:
447 2389–2400. doi:10.1088/0967-3334/35/12/2389

448 32. Lewis JS. Rotator cuff tendinopathy/subacromial impingement syndrome:
449 is it time for a new method of assessment? Br J Sports Med. 2009;43:
450 259–264. doi:10.1136/bjsm.2008.052183

451 33. Lewis J. Rotator cuff related shoulder pain: Assessment, management and
452 uncertainties. Man Ther. 2016;23: 57–68. doi:10.1016/j.math.2016.03.009

453 34. Boettcher CE, Ginn KA, Cathers I. The "empty can" and "full can" tests do
454 not selectively activate supraspinatus. J Sci Med Sport Sports Med Aust.
455 2009;12: 435–439. doi:10.1016/j.jsams.2008.09.005

456 35. Hegedus EJ, Goode A, Campbell S, Morin A, Tamaddoni M, Moorman CT,
457 et al. Physical examination tests of the shoulder: a systematic review with
458 meta-analysis of individual tests. Br J Sports Med. 2008;42: 80–92;
459 discussion 92. doi:10.1136/bjsm.2007.038406

460 36. Duckworth DG, Smith KL, Campbell B, Matsen FA. Self-assessment
461 questionnaires document substantial variability in the clinical expression of
462 rotator cuff tears. J Shoulder Elb Surg Am Shoulder Elb Surg Al. 1999;8:
463 330–333.

23

464   37. Matthewson G, Beach CJ, Nelson AA, Woodmass JM, Ono Y, Boorman

465   RS, et al. Partial Thickness Rotator Cuff Tears: Current Concepts. Adv

466   Orthop. 2015;2015: 458786. doi:10.1155/2015/458786

467   38. Giai Via A, De Cupis M, Spoliti M, Oliva F. Clinical and biological aspects

468   of rotator cuff tears. Muscles Ligaments Tendons J. 2013;3: 70–79.

469   doi:10.11138/mltj/2013.3.2.070

470

471