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1 **Can shoulder impairments be classified from three-dimensional kinematics using**  
2 **inertial sensors?**

3

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1 **Abstract**

2 Inertial sensors may help clinicians to assess patients' movement and potentially support  
3 clinical decision-making. Our aim was to determine whether range of shoulder motion during  
4 movement tasks measured using inertial sensors are capable of accurately discriminating  
5 between patients with different shoulder problems. Inertial sensors were used to measure  
6 three-dimensional shoulder motion during six tasks of 37 patients on the waiting list for  
7 shoulder surgery. Discriminant function analysis was used to identify whether the range of  
8 motion of different tasks could classify patients with different shoulder problems. The  
9 discriminant function analysis could correctly classify 91.9% of patients into one of the three  
10 diagnostic groups based. The tasks that associated a patient with a particular diagnostic group  
11 were: subacromial decompression: abduction; rotator cuff repair with tears  $\leq 5$  cm: flexion  
12 and rotator cuff repair with tears  $> 5$  cm: combing hair, abduction and horizontal abduction-  
13 adduction. The discriminant function analysis showed that range of motion measured by  
14 inertial sensors can correctly classify patients and could be used as a screening tool to support  
15 surgery planning.

16

17 **Keywords:** Inertial sensors, shoulder, rotator cuff, discriminant function analysis

18

19 **Word count:** 1779

20 **No. Figures:** 1

21 **No. Tables:** 3

## 22 Introduction

23 Treatments for shoulder problems include physiotherapy, injections and surgery.<sup>1</sup> To  
24 help with clinical decision-making, imaging examinations are often used to confirm diagnosis  
25 and treatment planning. Both Ultrasound Imaging (USI) and Magnetic Resonance Imaging  
26 (MRI) are used in the detection of various problems, including rotator cuff tears. A Cochrane  
27 systematic review reported that there were no differences in sensitivity and specificity  
28 between MRI and USI for detecting full- or partial-thickness rotator cuff tears.<sup>2</sup> Imaging such  
29 as Magnetic Resonance Imaging (MRI), can be costly and if there is great demand, may delay  
30 treatment.<sup>3</sup> During clinical examination, the use of a screening tool that accurately identifies  
31 cases where imaging is required for surgical planning could potentially help to reduce waiting  
32 lists for imaging procedures. Three-dimensional motion analysis using inertial sensors has  
33 been shown to be able to aid clinicians in identifying altered movement patterns in patients  
34 with shoulder problems.<sup>4</sup> Inertial sensors are a relatively new tool that can be used in the  
35 clinical setting due to their good ecological validity.<sup>3</sup> Thus, they have potential to be used as  
36 an alternative to imaging.<sup>5,6</sup> Other studies have used inertial sensors to compare movement  
37 patterns of patients with various shoulder disorders though they only assessed single-plane  
38 movements in unloaded conditions.<sup>7-9</sup> For example, Roldán-Jiménez, Cuesta-Vargas, Martín  
39 <sup>9</sup> used inertial sensors to investigate which kinematic variable had best diagnostic accuracy to  
40 identify shoulder problems; however, only the scaption movement was assessed. The aim of  
41 this study was to determine whether measuring range of shoulder motion (ROM) during  
42 common clinical and daily tasks using inertial sensors is capable of accurately discriminating  
43 patients with various degrees of rotator cuff tendon problems.

44

45

## 46 **Method**

47 We recruited patients aged between 40 and 70 years old, which is the usual age range  
48 for patients with symptomatic rotator cuff tears,<sup>10</sup> who were on the waiting list for shoulder  
49 surgery in a single hospital. Patients were classified into one of three groups according to the  
50 surgery they were listed for: subacromial decompression (SAD), rotator cuff repair with tears  
51 of up to 5 cm ( $\text{RCR} \leq 5\text{cm}$ ), and tears greater than 5 cm ( $\text{RCR} > 5\text{cm}$ ). Size and classification  
52 of the rotator cuff tear was determined by the attending clinician using MRI or USI according  
53 to local clinical pathways and clinician preference. We excluded patients who had had  
54 previous shoulder surgery and/or other musculoskeletal impairment in the assessed limb or  
55 cervical and thoracic spine, people who were unable to understand instructions or non-  
56 English speakers. This study received ethical approval (University of Central Lancashire  
57 STEMH 462).

58 Each patient performed five repetitions of six tasks, while standing, in a randomised  
59 order:<sup>7,11,12</sup>

- 60 1) Combing hair: simulated combing movements taking the hand from the front to the back  
61 of the head.
- 62 2) Abduction: Maximum abduction in the coronal plane.
- 63 3) Horizontal abduction-adduction: horizontal shoulder abduction and adduction holding a  
64 1kg dumbbell with the elbow in extension.
- 65 4) Reaching behind back: the participants tried to reach their opposite back pocket.
- 66 5) Flexion-extension: maximal forward flexion and extension in the sagittal plane.
- 67 6) Lifting: with the arm resting beside their body, the participant raised a 1kg dumbbell to the  
68 highest point above their head.

69

70 These tasks were chosen based on what is generally used during routine clinical assessments  
71 and common tasks used in everyday life that were assessed in similar studies.<sup>11,13</sup> The  
72 Xsens/MVN system (Xsens Tech®, Enschede, Netherlands) was used to collect 3D  
73 movements of the shoulder at 120 Hz. The manufacturer has reported that pitch and roll was  
74 accurate to  $<0.5^\circ$  and yaw was accurate to  $1^\circ$ , and confirmed by independent research <sup>14</sup>. All  
75 sensors were attached to the patient's body with Velcro® strips over their clothes (Figure 1).  
76 The sensor placement, body acquisition configuration (upper body) and calibration  
77 procedures followed the recommendations from the equipment manual.<sup>15</sup> For each task,  
78 ROM was calculated by subtracting the glenohumeral joint angle at the final position of the  
79 task from the glenohumeral joint angle at the initial position of the task.

80

81 **Insert Figure 1 about here**

82

83 Mean and standard deviation of the ROM was calculated for each task. Discriminant  
84 function analysis using the Wilk's Lambda method was used to identify which of the tasks  
85 would be able to discriminate between the three groups, SAD,  $RCR \leq 5\text{cm}$  and  $RCR > 5\text{cm}$   
86 using cut-off points from the function at group centroids. Those tasks whose standardized  
87 canonical discriminant function coefficients were greater than the cut-off points were selected  
88 to discriminate between the three groups. The matrices of homogeneity were tested using  
89 Box's M test, and a classificatory analysis and cross-validation was used to check allocation  
90 accuracy for the discriminant function analysis.<sup>16 17</sup>

91

92 **Results**

93 Thirty-seven patients were recruited. The descriptive data for each task and surgical  
 94 group is detailed in Table 1.

95 **Table 1.** Mean and standard deviation of the ROM of each task for each surgical group  
 96 (discriminant tasks for each group are in bold).

Task (degrees)	Subacromial decompression (n=15) x (SD)	Rotator cuff tears ≤ 5 cm (n=18) x (SD)	Rotator cuff tears > 5 cm (n=4) x (SD)
Combing	113.02 (8.73)	84.73 (24.19)	<b>73.67 (23.83)</b>
Abduction	<b>110.03 (23.09)</b>	72.23 (34.40)	<b>75.01 (40.56)</b>
Horizontal abduction- adduction	73.08 (14.59)	51.41 (25.27)	<b>45.56 (31.0)</b>
Reaching behind back	-19.94 (5.37)	-21.47 (6.08)	-17.80 (4.26)
Flexion-extension	125.65 (22.09)	<b>115.31 (36.08)</b>	83.62 (36.53)
Lifting	116.76 (33.78)	103.20 (37.25)	77.99 (39.73)

97

98 The first function was chosen as the best to discriminate groups based on its capacity  
 99 to explain the percentage of variance and the high canonical correlation value (0.854). The  
 100 test of function indicated an ability to significantly discriminate groups (Wilks Lambda:  
 101 0.196, Chi-square 51.4, P<0.001). The function at group centroid cut-off points were; -1.580,  
 102 0.587 and 1.740 for the RCR ≤ 5, RCR > 5 and SAD groups, respectively.

103 The standardized canonical discriminant function coefficients used to select the discriminant  
 104 variables for each group are detailed in Table 2.

105

106

107 **Table 2.** Standardized canonical discriminant function coefficients and the associated  
108 surgical group for each task.

	Function		Associated group for each task
	1	2	
Combing	1.062	0.799	RCR>5cm
Abduction	1.775	-0.794	RCR>5cm / SAD
Horizontal abduction-adduction	0.689	0.001	RCR>5cm
Reaching behind back	-0.514	-0.199	-----
Flexion-extension	-3.033	1.025	RCR≤5cm
Lifting	0.084	-0.263	-----

109 SAD: subacromial decompression. RCR: rotator cuff repairs.

110

111 The Function at Group Centroids were 1.740 for SAD, -1.580 for  $RCR \leq 5$ , and 0.587  
112 for  $RCR > 5$ . The values of Function 1 were chosen if they exceeded the threshold value for a  
113 specific group

114 The discriminant variables for each group were, SAD: abduction,  $RCR \leq 5$  cm:  
115 flexion-extension and  $RCR > 5$  cm: combing, abduction and horizontal abduction-adduction.  
116 Based on these discriminant variables the classificatory analysis could correctly classify  
117 91.9% of the individuals, while the cross-validated analysis showed an accuracy of 75.7%  
118 (Table 3).

119



120 **Table 3.** Classificatory and cross-validation analyses.

		Predicted Group Membership				
			SAD	RCR≤5cm	RCR>5cm	Total
Classificatory <sup>a</sup>	Count	SAD	15	0	0	15
		RCR≤ 5	1	16	1	18
		RCR>5	1	0	3	4
	%	SAD	100.0	0	0	100.0
		RCR≤ 5	5.6	88.9	5.6	100.0
		RCR>5	25.0	0	75.0	100.0
Cross-validated <sup>b</sup>	Count	SAD	13	1	1	15
		RCR≤ 5	2	14	2	18
		RCR>5	2	1	1	4
	%	SAD	86.7	6.7	6.7	100.0
		RCR≤ 5	11.1	77.8	11.1	100.0
		RCR>5	50.0	25.0	25.0	100.0

SAD: subacromial decompression. RCR: rotator cuff repairs

<sup>a</sup>. 34 out of 37 (91.9%) of original grouped cases correctly classified.

<sup>b</sup>. Cross-validation is done only for those cases in the analysis. In cross-validation, each case is classified by the functions derived from all cases other than that case.

121

122 **Discussion**

123 Our aim was to investigate whether the measurement of shoulder ROM during six  
 124 tasks using 3D kinematics could accurately classify patients according to their shoulder  
 125 problems.

126 Classificatory accuracy of the kinematic data from inertial sensors was compared to the  
127 imaging results prior to listing for surgery, whether that was USI or MRI. However, as MRI  
128 and USI have similar sensitivity and specificity for detecting full- or partial-thickness rotator  
129 cuff tears this wasn't thought to affect the comparisons. Almost 92% of the cases were  
130 correctly classified and cross-validation confirmed the discriminant capacity of the  
131 assessment protocol using the four discriminant tasks: abduction, flexion, combing hair and  
132 horizontal abduction-adduction. These values are high and substantially greater than a  
133 classification by chance, which in this analysis of three groups would be 33.33%. Successful  
134 classifications should be above 80%;<sup>18</sup> the classificatory analysis fulfilled this criteria, but the  
135 cross-validation, which checks the discriminant function analysis accuracy case-by-case, was  
136 just under that threshold. One possible reason for the cross-validation not reaching at least  
137 80% might be due to the low number of patients in the RCR>5 group.

138 The discriminant function analysis showed great applicability for the use of inertial sensors  
139 when assessing four tasks which could be used to classify patients based on their shoulder  
140 ROM. To the authors' best of knowledge, the only other study that has used discriminant  
141 function analysis to classify patients with shoulder disorders was Colliver, Wang, Joss, Ebert,  
142 Koh, Breidahl, Ackland <sup>19</sup>, In their study, discriminant function analysis was used to  
143 determine whether surgical repair integrity could be determined by the results of clinical  
144 questionnaires. Their results showed that questionnaires could only classify 36% of the intact  
145 repairs. The low accuracy may be attributed to using a generic upper limb questionnaire, the  
146 QuickDASH instead of a specific questionnaire for shoulder problems. Roldán-Jiménez,  
147 Cuesta-Vargas, Martín <sup>9</sup> investigated the discriminating precision of inertial sensors during  
148 scaption. They assessed people with no shoulder complaints compared to a group of patients  
149 with various shoulder problems. They found that scapular protraction-retraction ROM had  
150 83.3% specificity and 90.9% specificity to diagnose shoulder problems. However, their study

151 only investigated one task and did not try to differentiate shoulder problems; only differences  
152 between people with affected and unaffected shoulders.

153 Similar to our study, Kolk, Henseler, de Witte, van Zwet, van der Zwaal, Visser, Nagels,  
154 Nelissen, de Groot <sup>7</sup> performed an analysis where inertial sensors were used to assess  
155 movement differences between patients with shoulder pain but no anatomical alterations to  
156 cuff muscles or tendons, an isolated supraspinatus tear, or a massive rotator cuff tear of  
157 greater than 5cm. They found that patients with a massive rotator cuff tear had a greater  
158 reduction in flexion and abduction compared to the other two groups. However, they did not  
159 find any group differences in movement in patients with either shoulder pain or an isolated  
160 supraspinatus tear. In contrast, we found that patients undergoing subacromial decompression  
161 had better ROM than those with a tear smaller than 5 cm; however, our  $RCR \leq 5$  cm group  
162 included patients with tears spanning beyond the supraspinatus tendon only.

163 Using inertial sensors to classify shoulder disorders based on four movement tasks has  
164 potential to be used as a screening tool to accurately identify which patients require further  
165 imaging when classified into one of the three surgical groups assessed in our study. In the  
166 future, it may be possible to incorporate such analysis within smartphones or wearable  
167 sensors, allowing access to initial diagnostic assessments. However, further studies are  
168 needed to prove its diagnostic capacity.

169 As this paper looked at the allocation accuracy of the discriminant function analysis only,  
170 further work is needed to prove its diagnostic capacity to fully establish the sensitivity and  
171 specificity of inertial sensors as a diagnostic tool. Further studies could investigate the  
172 accuracy of smartphone or other cheap wearable sensors with the Xsens system used in this  
173 study. Other studies could focus on including inertial sensor data from the four movement  
174 tasks alongside MRI or USI to improve diagnosis and surgical decision making. A limitation

175 of our study was to look at only one kinematic variable, ROM, and the glenohumeral joint.  
176 Future studies should investigate scapular movements and other kinematic variables such as  
177 acceleration and velocity.

178 The use of inertial sensors to assess shoulder ROM appear to be a valuable tool to accurately  
179 classify patients with different shoulder problems. The tasks that associated a patient with a  
180 particular diagnostic group were: subacromial decompression, abduction; rotator cuff repair  
181 with tears  $\leq 5$  cm, flexion; and rotator cuff repair with tears  $> 5$  cm, combing hair, abduction  
182 and horizontal abduction-adduction.

183

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247

248

249 **Figure caption**

250

251 **Figure 1.** Xsens sensors placement, A) front view, B) back view