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1

2 **Increased joint mobility is associated with impaired transversus abdominis**

3 **contraction**

4

5

6 **ABSTRACT**

7 Increased joint mobility is a risk factor for joint injury, but muscle function may be able to compensate
8 for it. Current evidence suggests reduced force production capacity in people with hypermobility.
9 However, little is known about the lumbar spine. The purpose of this cross-sectional study was to assess
10 if there was a link between joint mobility and transverse abdominis and multifidus muscles contraction,
11 muscles ascribed a core-stability role.

12 Using a modified quantitative version of the Beighton scale (BOM score), we measured joint mobility
13 of 30 middle-aged individuals without low back pain. These scores were correlated with MRI-derived
14 measures of transverse abdominis and multifidus muscle contraction during a spinal loading
15 manoeuvre. The level of significance was set for $p \leq 0.05$.

16 The results showed greater joint mobility (higher BOM score) correlated ($r = 0.468$; $p = 0.009$) with
17 reduced transversus abdominis shortening during contraction (i.e. less muscle shortening in people with
18 greater joint mobility). The trunk subdomain score exhibited a correlation of 0.354 with transversus
19 abdominis length change, but this did not reach statistical significance ($p = 0.055$). The subdomains of
20 the BOM score did not correlate **significantly** with each other ($p \geq 0.097$). No association was seen
21 between multifidus contraction and joint mobility.

22
23 The results suggest that greater general joint mobility is associated with impaired contraction of the
24 transversus abdominis muscle. This should be considered when coaching athletes or treating patients
25 with (functional) spinal instability. The quantitative approach to measuring joint mobility we developed
26 could be used in the future studies of global flexibility.

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28
29
30 **Key words:** Muscle; Rehabilitation; Physiotherapy; Physical Therapy; Fascia; Laxity

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33

34 **INTRODUCTION**

35 The transversus abdominis muscle (TrA) is ascribed a role in stabilising the lumbar spine (26). The TrA
36 arises from the inner surface of the 7th to 12th costal cartilages, the thoracolumbar fascia, the iliac crest,
37 and the inguinal ligament and attaches to the linea alba. Due to the muscle's insertions and largely
38 transverse fiber orientation it tightens the thoracolumbar fascia when it contracts, thus increasing intra-
39 abdominal pressure (12) and spinal stiffness (6, 13). Reduced or delayed TrA contraction has been
40 linked to a greater lumbar spine "neutral zone" motion in flexion, which was explained by reduced
41 tension in the thoracolumbar fascia (2). The importance of the muscle and its role in low back pain and
42 rehabilitation has been the subject of discussion, mostly in regard to its ability to contract prior to
43 extremity movements (feedforward function) (10, 14). The lumbar multifidus muscle acts as a force
44 couple partner to the TrA in stabilizing the spine. It is a four-layer muscle with origins on the spinous
45 process, mammillary process and superior articular process and insertions on facet capsule and
46 mammillary process. In addition, it features interlaminar fibers (15). There is a positive relationship
47 between the ability to contract the multifidus and the TrA muscles (11).

48

49 Hypermobility of joints is postulated to be a risk factor for joint injuries (17, 18). Hypothetically, greater
50 joint laxity results in a higher likelihood of excessive joint translations, subluxations and dislocations
51 and hence damage to articular and periarticular structures. A joint is considered to be hypermobile when
52 its range of motion exceeds the expected normalized standard (8). When several joints are affected and
53 when accompanied by musculoskeletal pains the condition is commonly referred to as generalized joint
54 hypermobility (GJH) (7). The primary cause of this benign disorder is ligamentous laxity due to a
55 connective tissue disorder and is genetically anchored (8). GJH has been found to be associated with
56 decreased isokinetic (20) and isometric (21) muscle strength in shoulder abductors, finger flexors (grip
57 strength), knee extensors and ankle dorsiflexors (20, 21). The impact of local or widespread joint
58 (hyper)mobility on transversus abdominis and multifidus muscle function has not been studied.

59

60 Criteria for assessing GJH were first described by Carter and Wilkinson in 1964 (5) and should therefore
61 be considered the original assessment tool. The scale was then modified by Beighton and Horan in 1969
62 (3), and amended in 1973 by Beighton et al. (4). Currently, GJH is commonly measured with the latter
63 (4), a 9-point scale that assesses the end ranges of motion of four joints on each extremity and of the
64 spine. Beighton et al. (4) **intended** the scale to be an easily used and uncomplicated epidemiological
65 screening tool that uses dichotomous categorical yes/no questions. The Beighton-score was not,
66 however, designed to quantify hypermobility or to assess for subtle mobility differences within- and
67 between participants (22). To assess the relationship between TrA contraction and joint laxity, we
68 implemented a modified, quantitative, version of the Beighton scoring system, referred to as [redacted
69 for review purposes] (BOM) score.

70

71 The purpose of this study was to assess TrA and multifidus length changes with contraction in healthy
72 middle-aged participants and correlate this to their mobility. The participants were not chosen for their
73 mobility. We hypothesized that the TrA would, to account for the increased laxity and compliance of
74 the connective tissue, demonstrate greater contraction (shortening) in more mobile participants. We also
75 hypothesized that multifidus contraction would not correlate with increased mobility given that the
76 muscle does not attach to soft tissue. A secondary purpose was **to perform an exploratory analysis**, i.e.
77 to assess if this new version of the Beighton scale has, in principle, the potential of being used in the
78 clinical field. We defined 'success' as the ability for our new scale to demonstrate a significant
79 correlation with parameters of TrA and MF contraction.

80

81 **METHODS**

82

83 **Experimental Approach to the Problem**

84 This **exploratory analysis** uses a cross-section design.

85

86 **Subjects**

87

88 The University Faculty of Health Human Ethics Advisory Group approved this study. All participants
89 were informed of the benefits and risks of the investigation prior to signing the institutionally approved
90 informed consent document to participate in the study. Exclusion criteria included: history of or current
91 shoulder, thoracic, neck or lumbar spine pain for which treatment was sought (“treatment” was defined
92 as having seen a physiotherapist, chiropractor, osteopath or medical doctor for the condition), known
93 scoliosis or osteoporosis, and inability to communicate in English. Thirty participants (N = 18 males
94 and 12 females) were analysed. Participants had a mean(standard deviation; SD) age of 43(7) years,
95 height of 170.7(9.0) cm and weight of 67.9(10.9) kg.

96

97 **Procedures**

98 Magnetic resonance imaging (MRI), image processing and analysis

99 MRI was performed under two conditions in a supine position, with the participant: 1) at rest with knees
100 slightly flexed over a rolled towel and 2) performing an isometric narrow chest press with arms
101 maintained torso width apart, while simultaneous raising the sternum (Fig 1). Resistance bands were
102 used to provide loading through the arms during the exercise condition, with a resistive load at an
103 estimated 20% one-repetition maximum based on the threshold between ‘fair’ and ‘good’ normative
104 values for age, sex and weight (1) achieved when the hands were 28 cm anterior to the chest. Resistance
105 was determined by digital force gauge (Digital Scale 40 kg, Rogue, China, Australia). This exercise
106 was to increase intra-abdominal pressure and stimulate TrA contraction (14) in a more functional way
107 compared to the abdominal drawing-in maneuver. Hence, position 1) was used to scan the TrA at rest,
108 position 2) was used to scan the TrA during contraction. Each scan lasted about 30 seconds. Rolled
109 towels were placed under the cervical and lumbar spine to ensure that a neutral spine position was
110 maintained throughout the scan. A rolled towel was positioned under the knees to prevent knee
111 straightening. During both conditions participants were instructed to hold their breath after breathing in
112 and remain static during scans.

113

114

< Figure 1 about here >

115

116 To quantify muscle morphology on a 3T Phillips Ingenia scanner (Amsterdam, Netherlands) a T2-
117 weighted sequence (thickness, 3 mm; interslice distance, 7 mm; repetition time, 2643 ms; echo time,
118 60ms; field of view, 347 x 347 mm, 768 x 768 pixels) was used with spinal coils to collect 14 axial
119 images encompassing the volume of the transversus abdominis from the perineum up to the rib cage.
120 Data were exported for offline processing. To ensure blinding of the examiner, each subject was
121 assigned a random numeric code (obtained from www.random.org). ImageJ 1.48v
122 (<http://rsb.info.nih.gov/ij/>) was used to perform all quantitative MRI measures.

123

124 After tracing around the transversus abdominis muscle (Fig 2), a custom written ImageJ plugin (“ROI
125 Analyzer”; <https://github.com/tjrantal/RoiAnalyzer> and
126 <https://sites.google.com/site/daniellbelavy/home/roianalyser>) was used to fit a fourth order polynomial
127 to the region of interest and the curvature from the muscle was removed. Mean muscle length and
128 thickness were calculated in both conditions (at rest and during contraction). Similarly, the multifidus
129 was traced around (Fig 2), peak anteroposterior and mediolateral thicknesses were calculated. Data were
130 averaged across all slices, as well as between the left and right sides.

131

132 < Figure 2 about here >

133

134 [redacted for review purposes] (BOM) score

135 Our modified, **quantitative**, version of the Beighton score (4) was calculated as the sum of nine **variables**
136 **that consisted of measurements on a continuous scale**, as opposed to the sum of nine categorical
137 (positive test = 1; negative test = 0) **variables. Hence, a score closer to ‘0’ indicated no or little**
138 **hypermobility, whereas a score closer to ‘1’ indicated greater hypermobility.** The nine **variables** and
139 their calculations are as follows:

140 *Variables 1 and 2: Passive extension of the fifth fingers (digitus minimus)*

141 These two **variables** examined passive extension of the little fingers (left and right) with the subject
142 sitting, their forearm in a pronated position and hand placed firmly on a solid surface (lower limit = 0
143 degrees). The angle of extension was obtained to the nearest degree (test outcome). As per criteria

144 proposed by Beighton et al. (4), 90 degrees corresponded with a positive test and was considered the
 145 upper limit. To obtain the score for these variables, the test outcome was divided by the upper limit.
 146 Values beyond the accepted upper limit were not used for calculations (e.g. angles of extension >90
 147 degrees were recorded as 90 degrees; hence resulting in a score of 1).

148

$$149 \quad \text{Item 1 and 2 (score)} = \frac{\text{test outcome [range, 0 - 90]}}{90}$$

150

151 < Figure 3 about here >

152

153 *Items 3 and 4: Passive apposition of the thumb (right and left pollux) to the ventral aspect of the forearm*
 154 *in the sagittal plane*

155 These two variables examined passive apposition of the thumbs (left and right). The subject apposed
 156 their thumb passively to the ventral aspect of the forearm. The distance from the most distal aspect of
 157 the thumb to the ventral aspect of the forearm was measured to the nearest 0.1 cm (test outcome). A
 158 positive test according to Beighton et al. (4) would correspond with 0 cm (upper limit). For calculations
 159 of the lower limit, the wrist was held in flexion, which provided a 90-degree angle between the
 160 metacarpal (and first and second phalanx) of the thumb and ventral surface of the forearm. The average
 161 distance from the carpometacarpal joint to the most distal aspect of the second phalanx of the thumb in
 162 humans is 11.7 cm (9). Using these data, we calculated the arc length (lower limit) between the most
 163 distal aspect of the second phalanx of the thumb to the ventral aspect of the forearm [Arc length =
 164 $2\pi r \left(\frac{C}{360}\right) = 2\pi(11.7) \left(\frac{90}{360}\right) = 18.4$]. Given these data, the score for these variables was calculated by
 165 subtracting the test outcome from the lower limit, which was then divided by the lower limit. Values
 166 beyond the accepted lower limit were not used for calculations (e.g. test outcomes >18.4 cm were
 167 recorded as 18.4 cm; hence resulting in a score of 0).

168

$$169 \quad \text{Item 3 and 4 (score)} = \frac{18.4 - \text{test outcome [range, 18.4 - 0]}}{18.4}$$

170

171

< Figure 4 about here >

172

173 *Variables 5 and 6: Hyperextension of the elbows*174 These two **variables** examined hyperextension of the elbows (left and right) with the subject sitting, the

175 shoulder flexed to 90 degrees, the forearm supinated. The angle of hyperextension beyond 180 degrees

176 was obtained to the nearest degree (test outcome). As per criteria proposed by Beighton et al. (4), 10

177 degrees corresponded with a positive test and was considered the upper limit. To obtain the score for

178 these **variables**, the test outcome was divided by the upper limit. Values beyond the accepted upper limit

179 were not used for calculations (e.g. hyperextension >10 degrees were recorded as 10 degrees; hence

180 resulting in a score of 1).

181

182
$$\text{Item 5 and 6 (score)} = \frac{\text{test outcome [range, 0 - 10]}}{10}$$

183

184 *Variables 7 and 8: Hyperextension of the knees*185 These two **variables** examined hyperextension of the knees (left and right) whilst the patient was in

186 supine position. The angle of hyperextension beyond 0 degrees was obtained to the nearest degree (test

187 outcome). As per criteria proposed by Beighton et al. (4), 10 degrees corresponded with a positive test

188 and was considered the upper limit. To obtain the score for these **variables**, the test outcome was divided

189 by the upper limit. Values beyond the accepted the upper limit were not used for calculations (e.g.

190 hyperextension >10 degrees were recorded as 10 degrees; hence resulting in a score of 1).

191

192
$$\text{Item 7 and 8 (score)} = \frac{\text{test outcome (range, 0 - 10)}}{10}$$

193

194 *Variable 9: Forward flexion of the trunk with knees straight*

195 This variable examined forward flexion of the trunk with knees straight whilst the patient was standing

196 on a flat solid surface. The distance from the **distal carpal row** to the ground was obtained to the nearest

197 0.1 cm (test outcome). A positive test according to Beighton et al. (4) would correspond with 0 cm
 198 (upper limit). For calculations of the lower limit, several referent values were utilised. Normative values
 199 for the sit-and-reach test, a test that similarly assesses flexibility during trunk forward flexion, were
 200 determined. The average (“good”) reach value for adults aged 40-49 years is 4.5 cm beyond the level
 201 of the toes (1). This measurement is taken from the most distal point of the distal phalanx of the third
 202 digit, not from the carpals, as it is done in Beighton’s forward flexion test. Therefore, the average
 203 distance from the most distal point of the distal phalanx of the third digit to the carpals (18.6 cm in
 204 humans (9)) was subtracted from this result, which determined that 14.1 cm was the average lower limit.
 205 Given these data, the score for these variables was calculated by subtracting the test outcome from the
 206 lower limit, which was then divided by the lower limit. Values beyond the accepted lower limit were
 207 not used for calculations (e.g. test outcomes > 14.1 cm were recorded as 14.1 cm; hence resulting in a
 208 score of 0).

209

$$210 \quad \text{Item 9 (score)} = \frac{14.1 - \text{test outcome} [\text{range}, 14.1 - 0]}{14.1}$$

211

212 Data for joint subdomains were calculated as follows: 1) left plus right little fingers [two variables
 213 combined], 2) left plus right thumbs [two variables combined], 3) left plus right elbows [two variables
 214 combined], 4) left plus right knees [two variables combined], and 5) trunk [single variable].

215

216 To obtain test-retest reliability of the BOM score, it was measured six times each on six different
 217 volunteers which is sufficient to attain a precise measure of repeatability (9). All measurements were
 218 performed on the same day. The intraclass correlation coefficients (ICC)^{2,1} and standard error of the
 219 measurement (SEM) were as follows:

220 BOM score: ICC=0.99 (SEM=0.4)

221 Right little finger: ICC=0.98 (SEM=2.9)

222 Left little finger: ICC=0.98 (SEM=2.6)

223 Right thumb: ICC=0.96 (SEM=0.3)

224 Left thumb: ICC=0.96 (SEM=0.3)

225 Right elbow: ICC=0.99 (SEM=1.4)

226 Left elbow: ICC=0.99 (SEM=1.1)

227 Right knee: ICC=0.84 (SEM=1.4)

228 Left knee: ICC=0.98 (SEM=1.2)

229 Trunk flexion: ICC=0.99 (SEM=1.8)

230

231 **Statistical analyses**

232 All analyses were conducted using STATA statistical software version 15 (College Station TX, USA).

233 Transversus abdominis and multifidus contraction were quantified as the difference between the

234 “contraction condition” and “rest condition” for transversus abdominis peak length and mean thickness,

235 and multifidus peak anteroposterior and mediolateral thickness. All data were distributed normally, as

236 assessed by Shapiro-Wilk test. Independent t-tests were employed to compare outcomes (Beighton

237 scores [0/ >0] and BOM scores) stratified by sex (male/female). Pooled data from male and female were

238 used for the correlation analysis. The strength and direction of associations between all variables were

239 assessed by Pearson correlation coefficient. An alpha-level of 0.05 was adopted for all statistical tests.

240

241 **RESULTS**

242

243 Beighton score

244 The majority (N = 24; 80%) of participants had a Beighton score of zero, whereas five participants

245 (16.7%) had a score of one and one participant (3.3%) had a score of two. No Beighton scores greater

246 than two were observed (Fig 5).

247 < Figure 5 about here >

248

249 BOM score (modified quantitative Beighton score)

250 Mean(SD) BOM score was 2.95(0.87) for the total sample (N = 30). Participants who had a Beighton

251 score of zero had a lower (p = 0.006) mean(SD) BOM score, 2.74(0.68), than the participants with a

252 Beighton score of greater than zero, 3.80(1.09). Males (N = 18) had a mean(SD) BOM score of
253 2.73(0.73), whereas females had 3.28(1.00). There was no significant difference in BOM score between
254 sexes (p = 0.100). Mean(SD) BOM subdomain scores were 1.45(0.26) for little fingers, 0.67(0.25) for
255 thumbs, 0.48(0.43) for elbows, 0.11(0.19) for knees and 0.24(0.41) for the trunk.

256

257 Muscle length and thickness changes

258 Percent mean(SD) change in transversus abdominis and multifidus length and thickness between the
259 two conditions (i.e. contraction state compared to rest state) are shown in Table 1. In participants with
260 a Beighton score greater than zero, transversus abdominis demonstrated less shortening of length than
261 in those with a Beighton score of zero (p = 0.026). No other muscle activity outcomes differed based
262 on Beighton score. Moreover, no muscle activity outcomes differed between sexes.

263

264 < Table 1 about here >

265

266 Correlations

267 Correlations between differences in transversus abdominis and multifidus muscle length and thickness
268 changes between conditions are presented in Table 2. Total BOM score (r = 0.468; p = 0.009) and the
269 subdomain for elbows (r = 0.456; p = 0.011) correlated with transversus abdominis length (i.e. less
270 muscle shortening). The trunk subdomain score exhibited a correlation of 0.354 with transversus
271 abdominis length change, but this did not reach statistical significance (p = 0.055). No other measures
272 of muscle activity were significantly correlated with total BOM score. The subdomains of the BOM
273 score did not correlate with each other (p ≥ 0.097).

274

275 < Table 2 about here >

276

277

278 **DISCUSSION**

279

280 The current study was the first, to our knowledge, to consider the relationship between joint mobility
281 and lumbo-pelvic muscle contraction. We developed a scale that is based on the original Beighton-
282 scoring system (4) for measuring joint mobility, but with a more quantitative approach. The advantage
283 of our BOM score is that it has a greater sensitivity for changes within or between individuals and could
284 be used in the future studies of general joint laxity.

285 The results suggest that greater joint mobility (as measured by a Beighton score greater than zero)
286 demonstrated less TrA shortening. This finding was supported when we applied the BOM score, which
287 also correlated negatively with TrA shortening. Our first hypothesis was therefore rejected, but the
288 secondary hypothesis was met in part.

289

290 Hypermobility is often a result of a more compliant connective tissue, rendering fasciae and ligaments
291 less stiff and more yielding. A muscle that is at least partially inserted to said connective tissue, such as
292 the TrA, would have to shorten more during a concentric contraction for its contraction to be translated
293 into the desired action. In addition, some of the shortening force may not reach the intended target
294 because it is attenuated by the lengthening of the fascia. Other authors have found a connection between
295 strength and hypermobility. For example, Sahin et al. (20) found that knee extensor muscle strength
296 was significantly lower in patients with GJH, compared to the controls. The authors hypothesized that
297 the muscle weakness was connected to the lengthening of the quadriceps muscle. Scheper et al. (21)
298 found decreased muscle strength in subjects with GJH in shoulder abductors, finger flexors (grip
299 strength), knee extensors and ankle dorsiflexors. In line with this prior work, the current study shows
300 that less shortening during contraction of the TrA muscle is also associated with increased joint
301 mobility. As indicated earlier, the participants of this study were not selected because they exhibited
302 increased joint range of motion, but rather represented a sample of convenience.

303

304 The findings of the current study deepen our understanding of why increased joint mobility may be
305 associated with greater risk of injury. Other than the bony anatomy of a synovial articulation (e.g.
306 congruency between the two joint partners), passive structures, like the articular capsule and ligaments,
307 play an important role in determining the potential and available range of motion. They maintain the

308 integrity of a joint and, together with the surrounding muscles, stabilize it during activity. A more
309 mobile joint, by definition, has laxer stabilizing structures. Thus, the guiding restraints of the passive
310 structures are reduced and the joint is exposed to altered biomechanics. Intra- and extra-articular
311 structures therefore undergo increased strain and damage will likely ensue. Increased joint mobility has
312 been named a risk factor for injury (e.g. for the knee (24)) and for recurrence of injury (e.g. for the
313 shoulder (25)). Muscle contraction may, to a certain extent, be able to compensate for this, but
314 attenuation of force transmission via connective tissues will remain a problem. With regard to spinal
315 hypermobility, Panjabi introduced the concept of an increased “neutral zone” (18). A weakened
316 stabilizing system, for example by weakened TrA and multifidus muscles, increases the available
317 passive range of motion with the spine in neutral position (i.g. not in extension nor in flexion) and
318 subjects the segment to potentially damaging forces (19).

319

320 The change in TrA length was associated with the BOM score, but not the change in TrA thickness.
321 This is most likely due to the small change in thickness (< 1mm) compared to the greater change in
322 length (> 10mm). As hypothesized, we did not find any association between the BOM and change in
323 MF thickness. Again, these changes were small (anteroposterior thickness change < 2 mm; mediolateral
324 thickness change < 1 mm) and therefore potentially not sensitive enough to be detected with current
325 methods.

326

327 There were no associations between the different subdomains of the BOM score. This is of interest,
328 because it implies that laxity in different parts of the body are not correlated. Notably, participants were
329 not recruited because of their hypermobilities, but because they were healthy and free from
330 impairments. Similarly, the little finger BOM subdomain score did not correlate to the overall BOM
331 score. This suggests that the little finger ROM test might not be needed in the overall BOM score and
332 could possibly be removed as a test **variable**. This would decrease the number of test **variables** by two.
333 At the very least it suggests that this particular subdomain is likely not mediating the overall BOM
334 score.

335

336 There was a strong, albeit non-significant, correlation between the trunk subdomain score and the
337 change in TrA length. Future studies in participants with low back pain (LBP) are therefore warranted
338 to assess if there is an association between these two variables. Those findings could possibly add to
339 the highly debated subject of whether or whether not motor control of the TrA (16) or its “feed forward
340 feature” (6) are directly associated with LBP. Given our participants were all pain free, we cannot make
341 any inferences on this matter.

342

343 A strength of our study was the use of MRI, which in this specific study was further strengthened by
344 the large sample size and blinded assessment of images. However, it is appropriate to consider some of
345 the limitations of the current study. Firstly, we did not directly measure TrA muscle contraction force
346 or intra-fascial forces, as this would require technically challenging and invasive procedures. Whether
347 intra-fascial force was equivalent with greater shortening of the TrA muscle in people with greater joint
348 mobility remains open. Moreover, we only considered healthy individuals and therefore it unknown
349 whether our BOM score would also provide greater sensitivity in those with diseases known to influence
350 joint mobility. In this study we did not explicitly recruit people with joint hypermobility. Whether the
351 impediments of muscle contraction are greater in people with diagnosed joint hypermobility is open.
352 Further, we did not collect information on history of pregnancy, which could have an impact on core
353 strength and transversus abdominis activation (23). Further methodological developments, such as the
354 assessment of validity of the assessment of joint mobility and more detailed study of reliability than
355 what we assess here, would be appropriate.

356

357 PRACTICAL APPLICATIONS

358 People with increased joint mobility activate their anterior-lateral core stabilizing muscles less than
359 those with less mobility. This should be considered when coaching athletes or treating patients with
360 (functional) spinal instability. However, the cause and effect relationship is not clear.

361 Our new approach to measuring general joint mobility (BOM score) could be used to quantify the
362 qualitative Beighton score.

363

364

365

366

367 **ACKNOWLEDGMENTS**

368 The authors thank the participants for taking part in this study and the staff at the MRI center for their

369 support implementing this study. The current study was conducted as secondary data analysis of a wider

370 (as yet unpublished) study funded by a commercial organisation. The organisation had no role in the

371 design of the current study or the decision to publish.

372

373

374

375 **FIGURE LEGENDS**

376

377

378 **Figure 1.** Exercise performed in the MR scanner to activate the transversus abdominis muscle

379 A MR-compatible custom-made vest was used with elastic bands and grips which, based on

380 practice tests prior to entering the MR-scanner, provided the required load at 28 cm of

381 extension.

382

383 **Figure 2.** MR image with manual tracings of the transverse abdominis (TrA) and multifidus

384 muscles

385

386

387

388 **Figure 3.** Measuring passive extension of fifth finger

389

390

391 **Figure 4.** Measuring passive apposition of the thumb

392

393

394 **Figure 5.** Beighton score vs. BOM score for each participant

395

396

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