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► To cite this version:

Maëva Retailleau, Floren Colloud. New insights into lumbar flexion tests based on inverse and direct kinematic musculoskeletal modeling. *Journal of Biomechanics*, 2020, 105, pp.109782. 10.1016/j.jbiomech.2020.109782 . hal-03490473

HAL Id: hal-03490473

<https://hal.science/hal-03490473>

Submitted on 20 May 2022

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1 New insights into lumbar flexion tests based on *inverse*
2 *and direct kinematic* musculoskeletal modeling

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6 Category: Original Article.

7 Number of words in the abstract: 249.

Number of words in the text (Introduction through Discussion): 3496.

8 **Abstract**

9 Measurement of maximal lumbar flexion is considered to be a crucial ele-
10 ment in the assessment of lumbar spine mechanics in situations as diverse as
11 physiotherapy, orthopaedics, ergonomics, sport or aging. However, currently,
12 there is no consensus on a reference test.

13 This study aims to characterise five maximal lumbar flexion tests (four
14 classical tests and a new, specifically-developed test designed to constrain
15 pelvic retroversion) based on a three-dimensional, participant-specific mus-
16 culoskeletal model.

Preprint submitted to Journal of Biomechanics

March 10, 2020

17 Twenty-six male and female participants performed the five tests. Move-
18 ments were modelled in OpenSim to estimate change in length in lumbar,
19 hamstring and *gluteus* muscles, together with lumbar flexion and pelvic tilt.
20 These so-called “inverse” kinematic results were compared using a two-way
21 ANOVA (*sex* × *test*). In a second step, lumbar muscle change in length was
22 computed using a direct kinematic method.

23 Lumbar flexion and lumbar muscle change in length were found to be
24 greater when participants were in seated postures, with little pelvic retro-
25 version. Female participants were observed to have less lumbar flexion than
26 male participants ($77 \pm 14^\circ$ and $91 \pm 12^\circ$, respectively). Hip extensor muscles
27 (hamstrings and *gluteus*) were fully stretched during each of the five tests.
28 Our results highlight the specific roles of hamstrings, *gluteus* and lumbar
29 muscles into reaching maximal lumbar flexion.

30 Coupling inverse and direct kinematic methods proved to be a useful tool
31 to enhance our knowledge of lumbar tests. Our findings help to characterise
32 the role of the muscles involved in lumbar flexion, and we propose some
33 recommendations for improving and standardising these tests.

34 *Keywords:* Three-dimensional kinematics, Joint, Range of motion, Muscle,
35 Asymptomatic participant

36 1. Introduction

37 The assessment of lumbar spine mobility is currently used in clinical
38 screening routines for people with and without low back pain, in contexts
39 as diverse as physiotherapy (Toppenberg and Bullock, 1986; Zuberbier et al.,
40 2001), orthopaedics (Post and Leferink, 2004; Stephens et al., 2015), er-
41 gonomics (Keegan, 1953; Yasukouchi and Isayama, 1995), sport (McKeag,
42 1985; Keogh, 1999) or aging (Intolo et al., 2009; Arshad et al., 2019). The
43 diagnosis enables clinicians to establish normative values (Dvorak et al., 1991;
44 Youdas et al., 1996; Troke et al., 2001; Laird et al., 2014), determine whether
45 an abnormal limitation exists (Loebl, 1967; Mayer et al., 1984; Cornbleet
46 and Woolsey, 1996), identify risk factors for injuries (Keogh, 1999; Du Rose
47 and Breen, 2016), develop a rehabilitation program and evaluate the patients
48 response over time (Shahvarpour et al., 2017, 2018).

49 However, there is still no consensus regarding baseline tests to estimate
50 maximal lumbar flexion. Historically, tests have been performed either in a
51 standing (Kim et al., 2013) or sitting posture (López-Miñarro et al., 2007),
52 with knees either flexed (Kim et al., 2014) or extended (Reese and Bandy,
53 2016). In particular, maximal lumbar flexion is facilitated when the pelvis is
54 retroverted (Cornbleet and Woolsey, 1996; Esola et al., 1996; Youdas et al.,
55 1996; Lee and Wong, 2002), suggesting that hip extensors may play a crucial
56 role in constraining pelvic anteversion by decreasing lordosis.

57 Currently, most tests are characterised by minimal, inexpensive measure-
58 ment devices (e.g. ruler, inclinometer, goniometer and/or potentiometer).
59 Although these devices are a convenient way to screen participants, they are
60 poorly-suited to establishing baseline, reference tests. Firstly, they do not

61 characterise the bias induced by compensatory movements of the trunk (axial
62 rotation), pelvis (axial rotation), hips (external rotation and abduction) and
63 knees (flexion) observed at maximal lumbar flexion. Secondly, at maximal
64 joint range of motion (RoM), many structures (muscles, tendons, ligaments,
65 joints and bones) interact three-dimensionally. Compensatory movements
66 allow the participant to extend their RoM by decreasing the length of the
67 tissues stretched. Thirdly, [greater flexion is observed in males](#), suggesting a
68 sex-specific lumbar RoM (Troke et al., 2001). Consequently, [different baseline
69 tests could be used for females and males](#).

70 A reliable reference lumbar flexion test should investigate compensatory
71 movements and interactions between joint angles and tissue lengths. Con-
72 sequently, both lower limb and trunk joint kinematics (Troup et al., 1968;
73 Lee and Wong, 2002), and the extensibility of tissues in the lumbar region
74 must be assessed. Current frameworks that combine [inverse and direct kine-
75 matic methods](#), based on participant-specific musculoskeletal modelling are
76 providing new insights into bone-tissue interactions (Delp et al., 1990). This
77 combined strategy is useful as the [experimental](#) approach, [used](#) alone, is lim-
78 ited to understanding the passive functions of muscles; the aim is to find
79 significant [inter-participant differences](#) that are due to complex interactions
80 between their anthropometry, muscle extensibility and the tested posture.
81 On the other hand, a participant-specific [predictive simulation, based on di-
82 rect kinematic over](#) the full range of flexion enables the angle-muscle length
83 relationship to be characterised, while avoiding interactions.

84 The literature reports four tests to assess maximum lumbar flexion: Hand-
85 Shank (HS) (Reese and Bandy, 2016), Toe-Knee-Extended (TKE) (Esola

86 et al., 1996; McClure et al., 1997), Toe-Knee-Flexed (TKF) (Keegan, 1953;
87 Dunk et al., 2009) and Sit-and-Reach (SR) (Mayorga-Vega et al., 2014; Reese
88 and Bandy, 2016). In this study, we introduce a fifth, Row-and-Reach (RR)
89 test that mimics the catch posture in rowing, and is designed to constrain
90 pelvic retroversion (figure 3). The aim is to compare these five tests using [in-](#)
91 [verse and direct kinematic methods](#) of lumbar flexion, based on a participant-
92 specific musculoskeletal model. We hypothesise that: (i) lumbar flexion and
93 lumbar muscle length is greater in tests that favour pelvic retroversion; (ii)
94 hip extensor muscles (e.g. hamstrings and *gluteus*) are fully stretched in
95 these tests; (iii) lumbar muscle length as a function of lumbar flexion is
96 participant-specific; and (iv) lumbar flexion [is](#) greater in males [than](#) females.

97 **2. Methods**

98 *2.1. Musculoskeletal model*

99 We developed a musculoskeletal model for the lower limbs and lumbar
100 spine in OpenSim 3.3., based on models developed by Raabe and Chaudhari
101 (2016) and Christophy et al. (2012). Our model consisted of a total of 118
102 musculotendon actuators, [13 segments](#), and [33 degrees of freedom \(DoF\)](#)
103 [connected by 12 joints](#) (figure 1).

104 [Figure 1 about here.]

105 Since the RoM found during our lumbar tests was greater than that de-
106 scribed by earlier authors, sagittal plane RoM was increased for lumbar (from
107 -115° to 40°), hip (from -45° to 150°), knee (from -160° to 10°) and an-
108 kle (from -70° to 60°) joints. We also added an ellipsoid wrap embedded

109 to the femur head for the *gluteus*, six conditional points embedded to four
110 multifidus lines of action for large lumbar flexion, and a conditional point
111 embedded to each line of action of *gluteus* (*maximus* and *minimus*) and to
112 those of the hamstrings for large hip flexion (Retailleau et al., 2018). Muscle
113 moment arms were carefully checked, to fit those of the initial model. For
114 flexions performed outside the boundaries of the initial model, we checked
115 that moment arm patterns were close to those reported in the literature
116 (Buford et al., 1997), and muscle lines of action respected bone constraints.

117 *2.2. Participants and experimental procedure*

118 Twenty-six healthy females and males (table 1) provided informed consent
119 to participate in the IRB-approved protocol. All participants declared that
120 they had been free from any self-reported musculoskeletal limitations or pain
121 within the previous six months.

122 [Table 1 about here.]

123 Forty-four reflective markers were placed on the participants head (4),
124 trunk (8), pelvis (9), right femur (7), right tibia (4), right foot (4), left femur
125 (5) and left tibia (3) (figure 2). An optoelectronic camera system (T40,
126 Vicon, UK) sampled at 100 Hz recorded three-dimensional trajectories.

127 Participants performed six functional movements, which made it possible
128 to calculate each joint centre using the SCoRE method (Ehrig et al., 2006).
129 They first performed a standing trial designed to scale their anatomical pose
130 to the generic musculoskeletal model (figure 2) .

131 [Figure 2 about here.]

132 After a standardised warm-up, the participant performed seven static,
133 passive stretching tests:

- 134 • maximum lumbar flexion was assessed with the five lumbar tests (fig-
135 ure 3), performed in a balanced, randomised order;
- 136 • maximum length of the *gluteus* and hamstrings were assessed with the
137 Hip-Maximum-Flexion (HMF) and Passive-Straight-Leg-Raise (PSLR)
138 tests, respectively (figure 4).

139 Each participant performed three trials, during which they maintained
140 the maximal stretching posture for four seconds. Starting postures and tests
141 are summarised in table 2.

142 [Figure 3 about here.]

143 [Figure 4 about here.]

144 [Table 2 about here.]

145 Electromyographic (EMG) signals were recorded to ensure that [stretch-](#)
146 [ing tests](#) were performed without voluntary contraction for seven muscles
147 (right and left lumbar, right *gluteus medius*, *rectus femoris*, *vastus lateralis*,
148 long head of the *biceps femoris* and *semitendinosus*) with surface electrodes
149 (Trigno, Delsys, USA) sampled at 2000 Hz. To normalise EMG signals, the
150 participant performed maximum voluntary contractions during four specific
151 tests that placed the targeted muscles in a stretched posture. EMG signals
152 were integrated by a [bandpass filter](#) ranging from 20 Hz to 500 Hz. Through-
153 out [each stretching test and for each participant, post-treatment](#) normalised
154 EMG values were [maximum at](#) close to 5%.

155 2.3. Inverse kinematic approach

156 Inverse kinematics modelling and muscle analysis were performed with
157 OpenSim 3.3. Lines of action for the lumbar muscles (*iliocostalis lumborum*,
158 *longissimus thoracis*, *quadratus lumborum* and *multifidus*), *gluteus* and ham-
159 strings are illustrated in figure 1. Muscle lengths were calculated as the mean
160 of the length of their line of action.

161 Two trials with the greatest RoM were selected and averaged. Muscle
162 lengths reached during each stretching test (ℓ_{test}) and the anatomical posture
163 (ℓ_{static}) test were calculated. Maximal length ($\ell_{maximal}$) was defined as the
164 length reached during the best of the five lumbar tests (for lumbar muscles),
165 or HMF or PSLR (for *gluteus* and hamstrings, respectively). To overcome
166 differences between participants' anthropometry and their own extensibility,
167 muscle length change ($\delta\ell_{test}$) was calculated during each of the seven stretch-
168 ing tests taking into account maximal change ($\delta\ell_{maximal}$) as follows:

$$\delta\ell_{maximal} = \ell_{max} - \ell_{static}$$

$$\delta\ell_{test} = \frac{\ell_{test} - \ell_{static}}{\delta\ell_{maximal}} \times 100$$

169 Pelvic tilt (the sagittal angle between the reference frame and the pelvis
170 frame) was computed in OpenSim. The pelvis frame was based on Brand
171 et al. (1982). Anterior pelvic tilt was assigned a positive value.

172 Lumbar flexion, muscle length change and pelvic tilt were compared with
173 a two-way ANOVA ($sex \times test$), followed by the Tukey-Kramer *post-hoc* test,
174 where appropriate. *Gluteus* and hamstring change in length were compared

175 with a one-way ANOVA, for each lumbar test, with those obtained during
176 HMF and PSLR tests. The significance threshold was set at 5%.

177 2.4. Direct kinematic approach

178 For each participant, the change in length of the four lumbar muscles was
179 computed by increasing lumbar flexion from 0° to 115° with a 1° increment,
180 based on their scaled model. Mean change in length and standard deviation,
181 as a function of lumbar range were then calculated based on results from all
182 participants.

183 3. Results

184 Significant differences were found for lumbar flexion as a function of *sex*
185 ($p < .001$) and *test* ($p < .001$), while no interaction was found ($p = .992$).
186 Lumbar flexion was greater for males (table 3 and figure 5). *Post-hoc* tests
187 revealed that lumbar flexion was significantly lower for the HS test compared
188 to the other tests for females and males.

189 [Figure 5 about here.]

190 [Table 3 about here.]

191 Lumbar muscle change in length was significantly different depending on
192 *test*: *iliocostalis lumborum* and *longissimus thoracis* ($F(1, 4) = 54, p < .001$);
193 *quadratus lumborum* ($F(1, 4) = 48, p < .001$); and *multifidus* ($F(1, 4) =$
194 $65, p < .001$) while no effect was found for *sex* ($p = .788$) or the interaction
195 of the two factors ($p = .850$). *Post-hoc* tests revealed that it was significantly
196 lower for both the HS and TKE tests compared to TKF, SR and RR tests
197 (table 4).

198

[Table 4 about here.]

199 The same change in length, computed by direct kinematics, increased
200 continuously as a function of lumbar flexion. With respect to mean change
201 in length, a quasi-linear pattern was found for the *longissimus thoracis*, *il-*
202 *iocostalis lumborum* and *quadratus lumborum* up to 50° of lumbar flexion,
203 followed by a curvilinear pattern until full lumbar flexion. Here, we present
204 results for the *longissimus thoracis* (figure 5, top). In this case, across the
205 sample of participants, standard deviations of 11.5° and 11.8° were found for
206 lumbar flexion of 20° and 100°, respectively, compared to 11.3° and 11.7°
207 for the *iliocostalis lumborum* and *quadratus lumborum*. For each participant,
208 inverse and direct kinematic data fitted well (overall mean RMS $2.0 \pm 0.5^\circ$),
209 as illustrated in figure 5 (bottom) for participant 13 (P13, female) and par-
210 ticipant 21 (P21, male).

211 For the *multifidus*, the pattern was linear (figure 6, top). Slopes were
212 1.16, 1.07 and 1.25 for the mean, and the mean plus and minus the standard
213 deviation, respectively. Similar patterns were observed for inverse and direct
214 methods. This is illustrated in figure 6 (bottom) for the two participants
215 who exhibited the largest (P13; 1.37 vs. 1.33 for inverse and direct methods)
216 and smallest (P21; 1.05 vs. 1.11 for inverse and direct methods data) slope.

217

[Figure 6 about here.]

218 A significant main effect of test was found for pelvic tilt ($F(1,4) =$
219 $3.96, p < .001$) while no effect was found for *sex* ($p = .822$) or interaction
220 ($p = .778$). The *post-hoc* analysis highlighted that posterior pelvic tilt
221 was significantly lower for RR ($-21 \pm 14^\circ$) and SR ($-15 \pm 16^\circ$) than TKF

222 ($15 \pm 16^\circ$), TKE ($39 \pm 42^\circ$) and HS ($39 \pm 33^\circ$) tests. Furthermore, pelvic tilt
223 observed during the TKF was significantly lower than that reached during
224 TKE and HS tests. For the HS test, one female (P01) exhibited particularly
225 low lumbar flexion and, consequently, little lumbar muscle change in length
226 (figures 5 and 6, top). She was only able to reach this position with a much
227 larger anterior pelvic tilt (89°) than other participants.

228 Maxima were reached during the two tests where the hip is flexed (TKF
229 and RR) for *gluteus*, and during the three tests where the lower limb is fully
230 extended (HS, TKE and SR) for hamstrings (table 5).

231 [Table 5 about here.]

232 4. Discussion

233 In our study, lumbar flexion was calculated with the inverse kinematic
234 method for two standing posture tests (HS and TKE) and three seated posture
235 tests (TKF, SR and RR). Flexion was greater for male than female
236 participants, and posterior pelvic tilt was identified as an indicator of perfor-
237 mance. The combination of inverse and direct kinematic approaches was able
238 to highlight individual specificities with respect to muscle length for lumbar,
239 hamstring and *gluteus*.

240 Results using the direct kinematic method confirmed those using the indi-
241 rect method. Specifically, they highlighted muscle-specific patterns of change
242 in length as a function of lumbar flexion: a curvilinear pattern was identified
243 for the *longissimus thoracis*, *iliocostalis lumborum* and *quadratus lumborum*
244 (figure 5, top), while a linear pattern was observed for the *multifidus* (fig-

245 ure 6, top). These patterns are geometrically related to the insertion point
246 of the respective muscles, and to differences in lumbar and sacral curvatures.

247 The direct kinematic approach also highlighted participant specificities.
248 For the *longissimus thoracis*, *iliocostalis lumborum* and *quadratus lumborum*,
249 constant standard deviation was observed over the full range of lumbar flex-
250 ion; the curvilinear pattern is related to the extensibility of the participants
251 posterior chain structures, but not to their anthropometry. This finding is
252 illustrated in figure 5 (bottom) for the participant with the smallest (P13,
253 59°) and largest (P21, 111°) lumbar flexion. A quasi linear pattern was ob-
254 served for P13 over the whole RoM while the pattern was curvilinear for
255 participants with largest lumbar flexion, especially beyond 60°.

256 *Multifidus* change in length was related to both the extensibility of the
257 participants posterior chain structures (slope of the linear function, see fig-
258 ure 6 bottom) and their anthropometry (standard deviation increasing with
259 lumbar flexion, see figure 6 top).

260 Participants performing a maximal lumbar test are asked to flex their
261 trunk as far as possible. Trunk flexion is a combination of both hip and
262 lumbar flexion (Gajdosik et al., 1992; Esola et al., 1996; Lee and Wong,
263 2002; Laird et al., 2014). Hence, a test that constrains hip flexion by placing
264 the participant in a posture that maximally extends the hip extensor muscles
265 (e.g. *gluteus* or hamstrings) may help them to extend the range of lumbar
266 flexion. We observed significant differences as a function of the test, notably
267 whether the *gluteus* (TKF and RR) or hamstrings (HS, TKE and SR) were
268 maximally stretched. The link between hamstrings extensibility and trunk
269 flexion has been clearly demonstrated in the literature (Gajdosik et al., 1992;

270 Rodriguez-Garcia et al., 2008; Mayorga-Vega et al., 2014). However, only
271 two studies have investigated the influence of *gluteus* extensibility on pelvic
272 tilt (Toppenberg and Bullock, 1986; Yasukouchi and Isayama, 1995), while
273 there appears to be none on lumbar flexion. Our results show that female
274 participants had greater hamstrings and *gluteus* extensibility than males,
275 while lumbar flexion was maximal or close to maximum (table 5). *Gluteus*
276 stiffness may alter the coordination of hip and lumbar joints, and may be
277 a risk factor for lower back injuries. Therefore, therapeutic interventions
278 should consider the influence of both *gluteus* and hamstrings length on the
279 range of flexion of these joints.

280 Earlier studies (Troup et al., 1968; Mellin, 1988; Shephard et al., 1990;
281 Arshad et al., 2019) have found that short hamstrings limit pelvic anteversion
282 (Gajdosik et al., 1992), while increasing lumbar lordosis and lumbar flexion
283 (Intolo et al., 2009; Dreischarf et al., 2014). Our results suggest a sex-specific
284 aetiology of low back pain, requiring a tailored rehabilitation program. At
285 the same time, our study shows that the same lumbar flexion test is valid for
286 both females and males.

287 Our results confirm the crucial role of pelvic tilt in lumbar flexion (Es-
288 ola et al., 1996; Youdas et al., 1996; Cornbleet and Woolsey, 1996; Lee and
289 Wong, 2002). No participant reached maximum lumbar flexion (table 3, fig-
290 ures 5 and 6) during the two standing tests (HS and TKE), in which large
291 pelvic anteversion was observed. Compared to maximum values, we found
292 a relative difference of 11 to 88 % and 2 to 26 %, respectively, in these tests.
293 Lumbar flexion was maximum in one of the three seated tests, where pelvic
294 anteversion (TKF) or retroversion (SR and RR) was limited. Maximum rel-

295 ative differences compared to maximum lumbar flexion were 13 %, 12 % and
296 8 % for TKF, SR and RR, respectively. Although we did not find significant
297 differences between these three tests, maximum lumbar flexion was found for
298 TKF and SR within a restricted range (73° to 98° and 76° to 104° , respec-
299 tively), while results for the SR test were bounded by both extrema (59° and
300 111°). Neither the TKF nor the SR were ever the best test for either the
301 stiffest or most flexible participants.

302 The HS test is only described in the professional literature (Reese and
303 Bandy, 2016). Although the support provided by placing the hands on the
304 knees has no effect on pelvic tilt variability, it does reduce the passive effect
305 of gravity on the trunk. In this case, an operator pushing on the participants
306 shoulders might improve lumbar flexion (Dvorak et al., 1995).

307 For decades, the TKE has been the most popular test for assessing lumbar
308 flexion (e.g. Intolo et al., 2009; Laird et al., 2014; Arshad et al., 2019). It is
309 the only test used in gold standard protocols based on imaging technologies
310 to estimate the reliability of simple devices (Mayer et al., 1984; Burton,
311 1986; Newton and Waddell, 1991; Saur et al., 1996; Samo et al., 1997; Lee
312 and Wong, 2002) and to characterise the rotation and translation of lumbar
313 vertebrae (Dvorak et al., 1991; Pearcy and Whittle, 1982; Du Rose and Breen,
314 2016). As in the HS test, the participant has to control both pelvic tilt and
315 balance while flexing the trunk. Using a tool to constrain pelvic tilt (Dvorak
316 et al., 1991; Ng et al., 2001; Du Rose and Breen, 2016) may help participants
317 to reach maximal lumbar flexion in these standing postures.

318 The TKF test was introduced by Keegan (1953) in a working ergonomics
319 context and has only been used in a few studies since then (Loebl, 1967;

320 Mellin, 1986; Burton, 1986; Yasukouchi and Isayama, 1995; Youdas et al.,
321 1996). We identified two potential biases in the TKF. The first is the conse-
322 quence of the fixed height of the seat. Our study suggests that this should be
323 adapted to the participants anthropometry so that pelvic tilt is not related
324 to shank length. The second is observed for participants with either a large
325 belly or flexible hips. In this case, the chest can come into contact with the
326 thighs, thus limiting lumbar flexion. Consequently, we do not recommend
327 the TKF for clinical use, because this second bias cannot be corrected.

328 The SR is a global test that is used to estimate the [extensibility](#) of the pos-
329 terior chain, and has been used in a number of large-scale population surveys
330 (Jackson and Baker, 1986; Shephard et al., 1990; Keogh, 1999). Our study
331 suggests that it is useful as a measure of lumbar RoM, although this result
332 is not supported by previous findings (Jackson and Baker, 1986; Cornbleet
333 and Woolsey, 1996; Mayorga-Vega et al., 2014). In our study, the SR metric
334 was lumbar RoM rather than the classic, fingertip position. Although easy
335 to set up, the position of the fingertips is very sensitive to segment length
336 and joint DoF, especially shoulder abduction (Cornbleet and Woolsey, 1996;
337 Mayorga-Vega et al., 2014). Our results suggest that a more reliable SR met-
338 ric is the lumbar flexion angle. Moreover, in this test compared to the PSLR,
339 females have less flexion than males (mean 92% vs. 97%). This difference
340 might be due to the reduced passive action of gravity as the trunk is heavier
341 in males, or a lack of force in hip flexors. The intervention of an operator
342 should correct these biases (Dvorak et al., 1995).

343 Two studies have examined postures similar to those used in the RR
344 test. Troup et al. (1968) placed the participants feet at the same level as

345 the seat, which introduces a bias that is very similar to that reported above
346 for the TKF. Nevertheless, our results were similar to those reported by
347 Troup (maximal lumbar flexion $79 \pm 13^\circ$ and $80 \pm 15^\circ$ for females and males
348 respectively, with a range of 38° to 128°). Bridger et al. (1989) simulated
349 a position on a low stool. However, the latter study only reported lumbar
350 angles for a sitting position and for some participants, the abdomen was in
351 contact with the thighs. Further improvements to the RR test could be made
352 by investigating the impact of feet placement. More specifically, in clinical
353 use, the position and orientation of the feet must be standardised according
354 to the participants lower limb anthropometry.

355 Our inverse and direct approaches, proved to be a powerful way to char-
356 acterise the role of the muscles involved in lumbar flexion. However, we must
357 bear in mind that the musculoskeletal model is a generic model based on
358 anthropometric data for a male (Delp et al., 1990). Similarly, Christophy’s
359 lumbar curvature model (Christophy et al., 2012) is based on a standard pop-
360 ulation. Greater fidelity could be obtained by implementing a generic female
361 model and participant-specific lumbar curvature. Furthermore, our recom-
362 mendations regarding the five lumbar tests are limited to the population
363 studied (young, healthy females and males) and the method of measurement
364 used. Any direct implications for other groups (e.g. those with low back
365 pain) and the validity of measurement devices used to assess muscle lengths
366 in clinical practice must be the subject of further research.

367 To conclude, our study highlighted the specific role of hamstring, *gluteus*
368 and lumbar muscles during maximal lumbar flexion, and could help in the
369 design of participant-specific therapeutic programs. We confirmed the crucial

370 role of pelvic tilt, as greatest lumbar flexion was achieved during one of
371 the three seated tests (TKF, SR and RR). For each test, we offered some
372 recommendations to improve their standardisation. In particular, our new
373 RR test, designed to constrain the pelvis in retroversion, appears to be a
374 very promising assessment method for both the stiffest and most flexible
375 participants.

376 **5. Conflict of interest**

377 The authors do not have any financial or personal relationships with other
378 individuals or organisations that could inappropriately influence the study
379 reported in this manuscript.

380 **6. Acknowledgements**

381 Dr Maëva Retailleau was supported by a PhD scholarship from the Min-
382 istère de la Recherche et de l'Enseignement Supérieur (France). The funder
383 played no role in the study's design, data collection and analysis, decision to
384 publish, or preparation of the manuscript.

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Table 1: Descriptive statistics for participants (mean, standard deviation (SD), minimum and maximum values).

	Females (n=13)	Males (n=13)	Total (n=26)
	Mean \pm SD	Mean \pm SD	Mean \pm SD
	[min; max]	[min; max]	[min; max]
Age (years)	24 \pm 4 [19; 31]	23 \pm 4 [19; 28]	24 \pm 4 [19; 31]
Height (m)	1.63 \pm 0.06 [1.55; 1.72]	1.80 \pm 0.07 [1.69; 1.91]	1.72 \pm 0.11 [1.55; 1.91]
Mass (kg)	55 \pm 6 [45; 68]	74 \pm 10 [54; 95]	65 \pm 12 [45; 95]
BMI	22 \pm 2 [18; 25]	23 \pm 2 [19; 26]	22 \pm 2 [18; 26]

BMI = body mass index.

Table 2: Starting postures and test for lumbar, *gluteus* and hamstring assessments.

	Starting posture	Test run
Hand-Shank (HS)	Stand with hands on shanks	Maximally flex lumbar region Keep the trunk raised
Toe-Knee-Extended (TKE)	Stand on a box	Maximally flex lumbar region Place hands along the box while keeping knees fully extended
Toe-Knee-Flexed (TKF)	Seated on a plinth with hips and knees flexed and feet positioned flat on a box	Maximally flex lumbar region Place hands on the box without rotation and abduction of the hips
Sit-and-Reach (SR)	Seated on the floor with knees extended and feet positioned flat against a box (0.35 m height)	Maximally flex lumbar region Keep knees fully extended
Row-and-Reach (RR)	Seated on a rowing ergometer (model C, Concept2, Morrisville, USA) with heels positioned at the level of the sliding bar and feet oriented at 45°	Maximally flex hips and knees without rotation or abduction of the hips Maximally flex lumbar region
Hip-Maximum-Flexion (HMF)	Lying on the back with the right knee flexed	Maximum flexion of the right hip induced by an operator applying force to the top of the femur until passive resistance is felt or rotation or abduction of the hip is observed
Passive-Straight-Leg-Raise (PSLR)	Lying on the back with the right knee extended	Maximum flexion of the right hip induced by an operator applying force above the ankle until passive resistance is felt, rotation or abduction of the hip is observed, or the right knee begins to flex

Table 3: Lumbar flexion (mean, standard deviation (SD), minimum and maximum values (in degrees)) for females and males observed during the five tests.

	Females	Males	Total
	Mean \pm SD	Mean \pm SD	Mean \pm SD
	[min; max]	[min; max]	[min; max]
HS ($^{\circ}$)	53 \pm 18 [7; 73]	65 \pm 7 [54; 80]	60 \pm 10 [7; 80]
TKE ($^{\circ}$)	65 \pm 13 [47; 89]	78 \pm 10 [62; 101]	72 \pm 10 [47; 101]
TKF ($^{\circ}$)	74 \pm 14 [52; 97]	85 \pm 8 [74; 99]	81 \pm 10 [52; 99]
SR ($^{\circ}$)	74 \pm 4 [53; 95]	88 \pm 11 [72; 109]	82 \pm 12 [53; 109]
RR ($^{\circ}$)	77 \pm 14 [59; 102]	91 \pm 12 [75; 111]	84 \pm 12 [59; 111]

Table 4: *Post-hoc* results for lumbar muscles change in length for the factor *test*.

	HS	TKE	TKF	SR
TKE	< .05			
TKF	< .05	< .05		
SR	< .05	< .05	.976	
RR	.935	< .05	.560	.873

Table 5: p – values for *gluteus* and hamstring change in length.

	<i>Gluteus</i>	Hamstrings
HS	< .05	1.000
TKE	< .05	.880
TKF	.832	< .05
SR	< .05	.293
RR	.935	< .05

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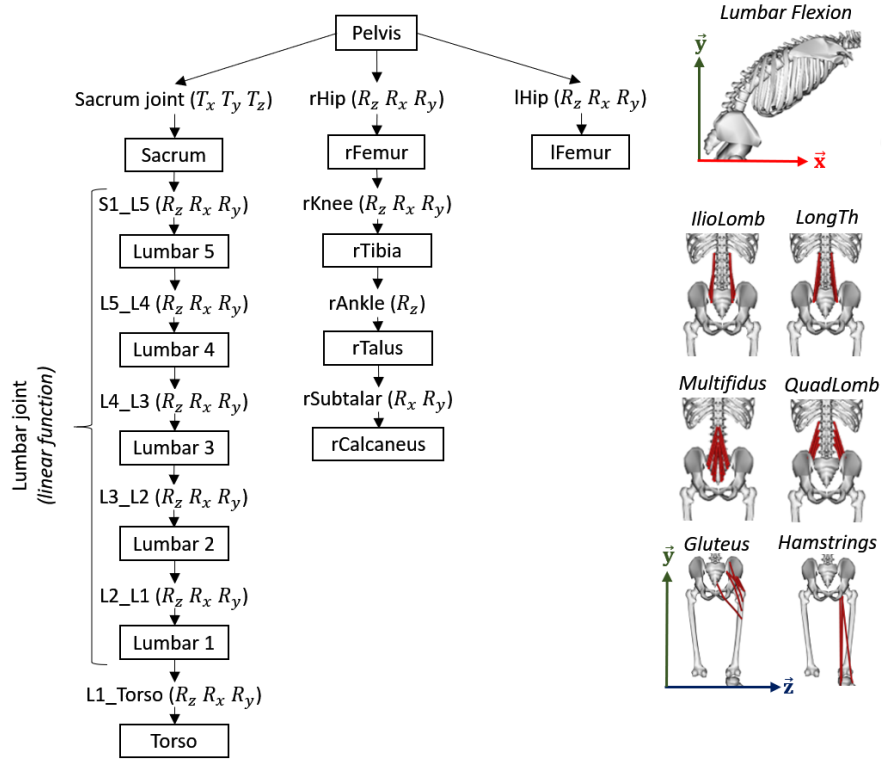


Figure 1: Segments, DoF and muscles implemented in the OpenSim model. Rotations and translations are noted as R_x , R_y , R_z and T_x , T_y and T_z , respectively. Lumbar flexion is implemented as a linear repartition along the 5 lumbar joints, based on Christophy et al. (2012). Lumbar flexion, and lines of action for the *ilio lomborum* (*IlioLomb*, 8), *longissimus thoracis* (*LongTh*, 10), *multifidus* (40), *quadratus lomborum* (*QuadLomb*, 14), *gluteus* (9×2) and *hamstrings* (3×2) are illustrated on the right.



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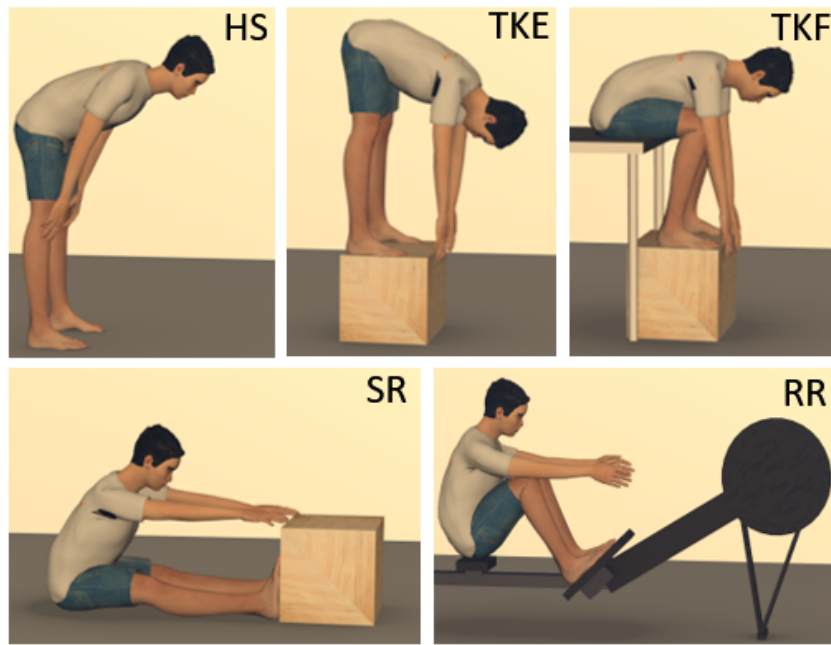


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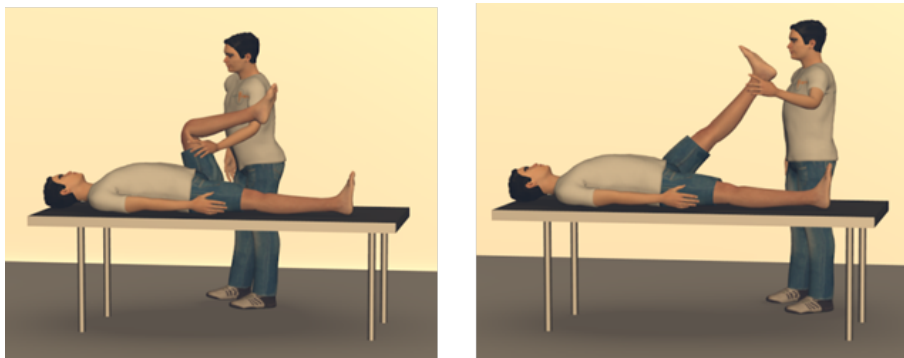


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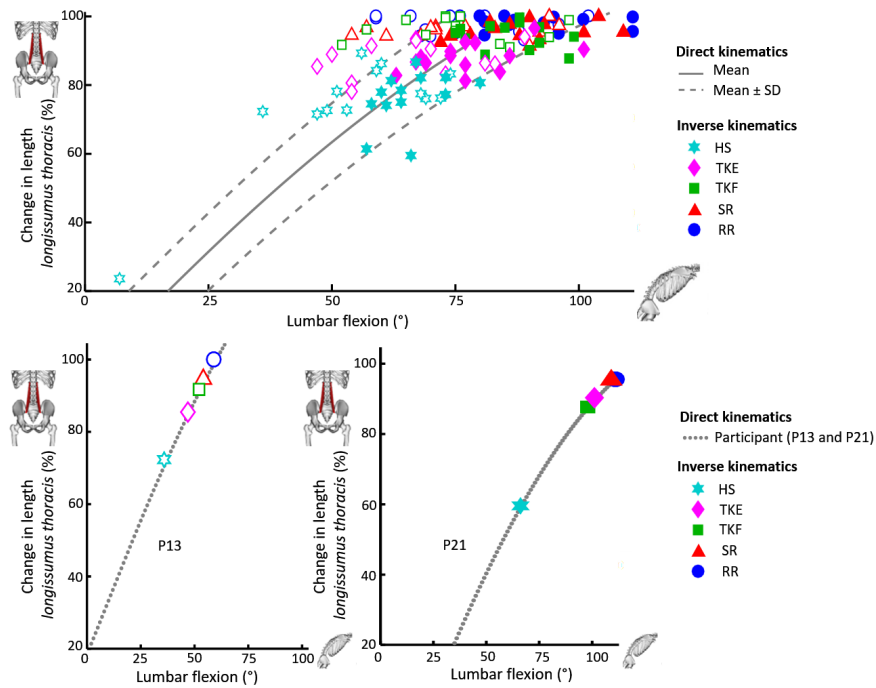


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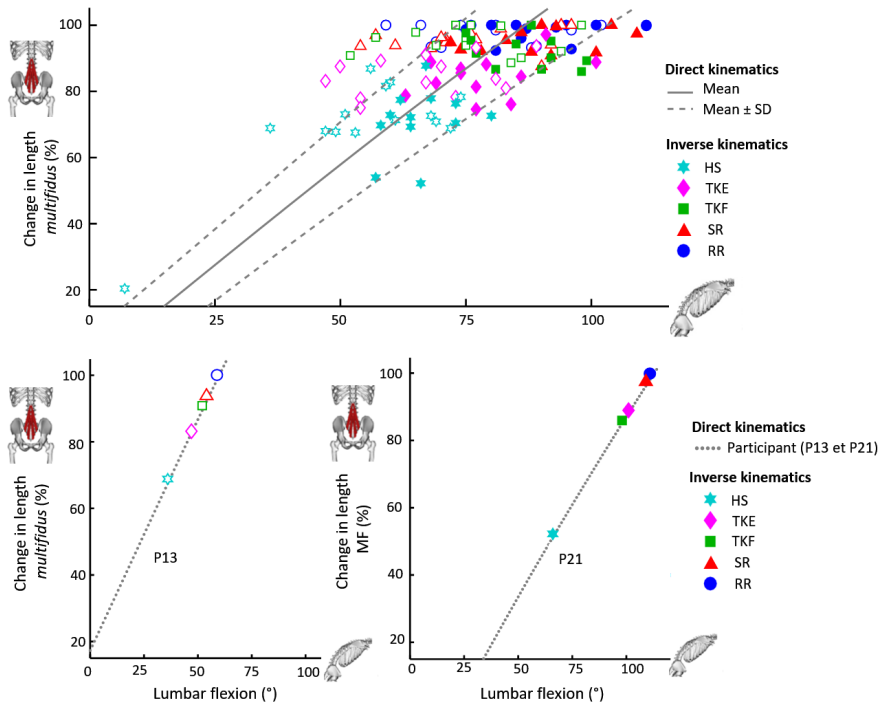


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