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► **To cite this version:**

Roxanne Dubé-Cyr, Carl-Éric Aubin, Isabelle Villemure, Rohan-Jean Bianco, Yves Godio-Raboutet, et al.. Biomechanical analysis of two insertion sites for the fixation of the sacroiliac joint via an oblique lateral approach. *Clinical Biomechanics*, 2020, 74, pp.118-123. 10.1016/j.clinbiomech.2020.02.010 . hal-03226860

HAL Id: hal-03226860

<https://amu.hal.science/hal-03226860v1>

Submitted on 15 May 2021

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1 **Biomechanical analysis of two insertion sites for the fixation of the sacroiliac joint via an**
2 **oblique lateral approach**

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19 **Declarations of interest:** Medtronic provided the implants and surgical kit for the study. Carl-Éric Aubin
20 is currently receiving funding from the Natural Sciences and Engineering Research Council of Canada
21 (Industrial Research Chair program with Medtronic of Canada). The other authors have no conflict of
22 interest to declare.

23

24 **Research Ethics Committee:**

25 Polytechnique Montreal: CÉR-1617-30

26

27 **Word count:**

28 Abstract : 250 words

29 Manuscript: 3123 words

30

31 **Abstract**

32 *Background.* The sacroiliac joint is an important source of low back pain. In severe cases, sacroiliac joint
33 fusion is used to reduce pain, but revision rates can reach 30%. The lack of initial mechanical stability may
34 lead to pseudarthrosis, thus not alleviating the patient's symptoms. This could be due to the damage
35 induced to the interosseous ligament during implant insertion. Decoupling instrumentation steps (drilling-
36 tapping and implant insertion) would allow to verify this hypothesis. Moreover, no biomechanical studies
37 have been published on sacroiliac joint fixation with an oblique lateral approach, while it has important
38 clinical advantages over the lateral approach.

39 *Methods.* Eight cadaveric human pelves with both ischia embedded were tested in three sequential states:
40 intact, drilled-tapped and instrumented with one cylindrical threaded implant with an oblique lateral
41 trajectory. Specimens were assigned one of two insertion sites (distal point; near the posterior superior iliac
42 spine, and proximal point; anterosuperior to the distal point) and tested in compression and flexion-
43 extension. Vertical and angular displacements of the sacroiliac joint were measured locally using digital
44 image correlation methods.

45 *Findings.* In compression, instrumentation significantly reduced vertical displacements (17% (SD 22%),
46 $P=0.04$) but no difference was found for angular displacements or flexion-extension loads ($P>0.05$).
47 Drilling-tapping did not change the stability of the sacroiliac joint ($P>0.05$); there was no statistical
48 difference between the insertion sites ($P>0.05$).

49 *Interpretations.* Insertion of one implant through either the distal or proximal insertion site with an oblique
50 lateral approach significantly reduced vertical displacements of the sacroiliac joint in compression, a
51 predominant load of this joint.

52

53 *Key words.* Sacroiliac joint, sacroiliac joint fixation, sacroiliac joint fusion, arthrodesis, biomechanics,
54 minimally invasive surgery

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58 **1. Introduction**

59 The sacroiliac joint (SIJ) ensures the transmission of important forces from the spine and upper body to the
60 lower limbs. The SIJ generates pain in 15 to 30% of patients suffering from low back pain ¹. Treatment
61 options include anti-inflammatory medication, physical therapy, sacral belt, and in last resort, surgical
62 fusion. For the latter, implants are inserted across the sacrum and ilium through the SIJ to allow mechanical
63 stability. An osseointegration process begins and the opposing bony surfaces start to biologically fuse. In a
64 meta-analysis evaluating five clinical outcome measures, minimally invasive SIJ fusion was proven
65 effective for alleviating girdle pain ². Minimally invasive SIJ surgeries limit tissue exposure during surgery
66 and only necessitate a 3-cm long incision while offering greater pain relief than open surgeries ³. Still, the
67 fusion rate ranges from 25 to 88% after 12 months ⁴⁻⁸. Patients with persistent or recurrent pain may require
68 a revision surgery, with revision rates reaching 30% after 4 years ⁹.

69 As the quality of the biological fusion and osseointegration is linked to the initial mechanical stability ¹⁰,
70 researchers have investigated the effect of instrumentation on SIJ range of motion (RoM). In cadaveric
71 studies, instrumentation with either two cylindrical and threaded implants, or three implants with a
72 triangular cross-section significantly decreased the RoM by 27% to 54% ¹¹⁻¹⁴. However, the SIJ RoM is not
73 significantly reduced for all specimens. Counterintuitively, the SIJ RoM is sometimes increased following
74 fixation ^{11,12,14}. In a clinical setting, an insufficient reduction in SIJ RoM may lead to pseudarthrosis, which
75 does not alleviate the patient's symptoms. Increased RoM could be explained by the damage to the
76 interosseous ligament (IOL), the strongest and largest of SIJ ligaments ¹⁵ during implant insertion. The IOL
77 directly connects the SIJ surfaces together, so a modification to its integrity could lead to a loss of stability
78 greater than the stability gain provided by the implants. This hypothesis could be verified by isolating the
79 effects of drilling and tapping on SIJ stability, which has not been done before. Decoupling instrumentation
80 steps (drilling-tapping and implant insertion) would allow a better understanding of SIJ biomechanics and
81 SIJ fixation.

82 SIJ initial mechanical stability also depends on certain surgical choices like the surgical approach and
83 implant trajectory, as well as the type, size, and number of implants. For instance, the two main surgical
84 approaches for minimally invasive SIJ fixation are the direct lateral and the oblique lateral approaches,

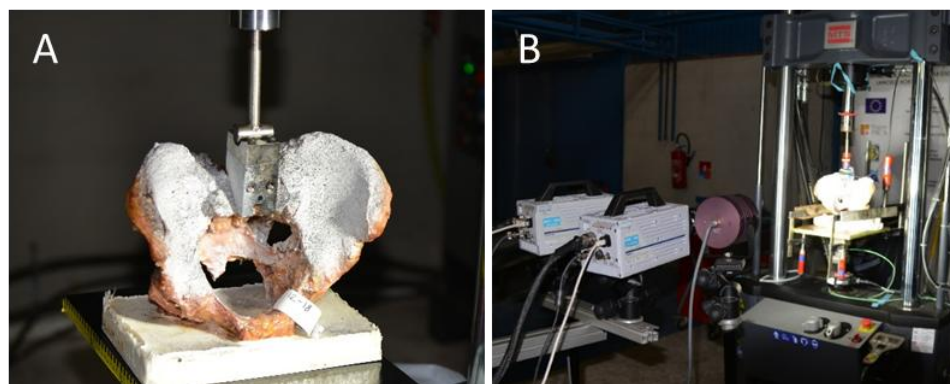
85 respectively referred to as lateral and oblique in the text for simplicity. Compared to the oblique approach,
86 the lateral approach requires considerably more dissection of the gluteal muscles (medius and maximus).
87 However, most of the recent clinical studies have used the lateral approach with triangular dowel implants
88 and are industry-sponsored ¹⁶. Recently, two retrospective studies have compared the lateral and oblique
89 approaches, using triangular implants and cylindrical threaded implants respectively. Majd et al. found the
90 oblique approach to be superior for some clinical outcomes (higher rate of significant improvement on the
91 visual analogue scale (VAS) (65% vs 45%), lower estimated blood loss (33cc vs 60cc), lower adverse event
92 rate (6.7% vs 20%) ¹⁷. However, significance was not mentioned. Claus et al. found that both approaches
93 led to a significant improvement of the Oswestry Disability Index (ODI) and SF-12 (Short Form-12 health
94 survey) scores, without a significant difference between the two techniques ¹⁸. Length of stay, estimated
95 blood loss were not statistically different between the groups but the oblique approach had a significantly
96 longer surgery (60 min vs 41 min) ¹⁸. Revision rate was higher for the oblique approach compared to the
97 lateral approach (6.1% vs 2.4%), but the difference was not statistically significant. Many experimental and
98 numerical studies have been conducted on the lateral approach ^{11-14,19-21} compared to only one numerical
99 study on the oblique approach ²². Bruna-Rosso et al. simulated an oblique SIJ instrumentation using a finite
100 element model of the pelvis with one to two threaded implants and compared two insertion sites and two
101 implant orientations ²². Placing the implant farther from the SIJ center of rotation (CoR) (located at the
102 axial interosseous ligament according to Farabeuf's theory ²³) and using an orientation more parallel to the
103 SIJ CoR led to a better stabilization of the SIJ subjected to compression loads. No cadaveric studies have
104 been published on this approach, but such study would allow a better understanding of oblique fixation and
105 help further reduce revision rates.

106 Hence, the current study aimed to experimentally measure the isolated effects of drilling and tapping as
107 well as the effects of oblique SIJ fixation on SIJ RoM while comparing two possible insertion sites. It was
108 hypothesized that instrumenting the SIJ with one implant would lead to significant motion reduction and
109 that there would be a significant difference between the two tested insertion points.

110 **2. Methods**

111 *2.1 Specimen preparation*

112 The pelves (sacrum and iliac bones) of eight human specimens (age ranged from 73 to 94 years old; Table
113 1) embalmed with a zinc chloride solution were harvested. They were thawed at room temperature and
114 cleaned of muscle tissue while keeping the ligaments of the SIJ intact (anterior, posterior, IOL,
115 sacrotuberous and sacrospinous ligaments). CT-scans were taken to ensure there were no anomalies like
116 bone bridging. Bone mineral density was measured with a calibration phantom (Model 062M Electron
117 Density Phantom, CIRS Inc., Virginia, USA). Specimens were wrapped in saline-soaked gauze, placed in
118 plastic bags and stored at -20 °C. The day before testing, they were thawed at room temperature and placed
119 in neutral position (i.e. anterior superior iliac spine in line with the pubic symphysis in the vertical plane).
120 The inferior part of the specimens was embedded in a bloc of fast-curing resin (1:1 mixture of F18 Polyol
121 and F18 Isocyanate, Axson Technologies, Cergy, France) up to the obturator foramina in a double-leg
122 stance model (Fig. 1A). They were wrapped in saline-soaked gauze and put in a refrigerator (4 °C) until the
123 next day. Right before the beginning of the tests, a random speckle pattern was produced on the anterior SIJ
124 surfaces using a black spray paint over uniform white paint (Fig. 1A).



125
126 Fig. 1 Experimental set-up: A) Double-leg stance model and B) camera position

127 2.2 Test procedure

128 Specimens were randomly divided into two equal groups (n=4/group) and assigned one of two insertion
129 sites. The distal point was located near the posterior superior iliac spine (PSIS) (Fig. 2). The proximal point
130 was positioned anterosuperiorly to the distal point²².

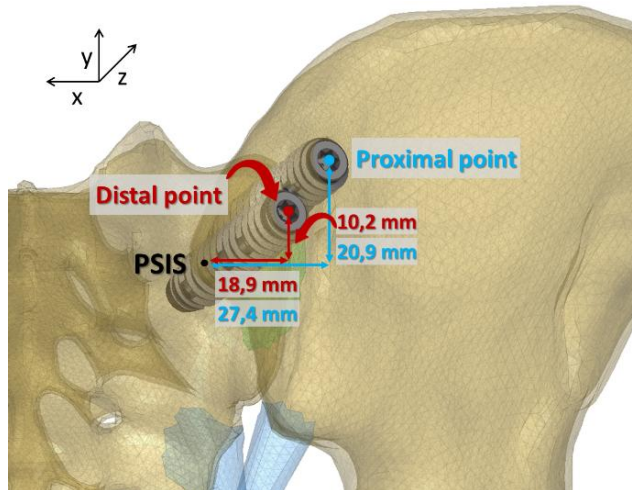


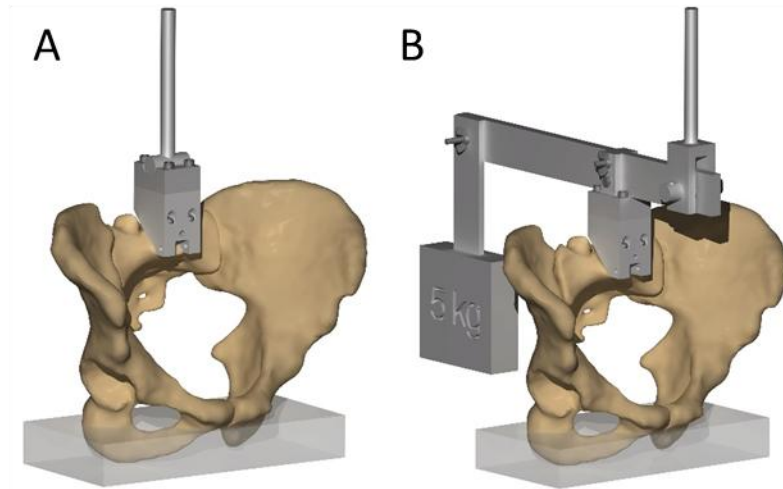
Fig. 2 Insertion points tested and implant trajectory – Posteroanterior view

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132

133 Metal bars and clamps rigidly fastened the resin bloc to a 370.02-15kN MTS servohydraulic system (MTS
134 Systems, Créteil, France) (Fig. 1B). A custom metal piece was firmly fixed on the endplate of S1 with
135 wood screws. The displacements between the sacrum and the ilium were measured in three states. First, the
136 specimens were tested in the “intact state” under compression and flexion-extension (FE) loads (see next
137 paragraph) to obtain a reference RoM and allow subsequent comparison. Next, using a posteromedial
138 approach (Fig. 2)²², we positioned a guidewire using a template to ensure repeatability of the insertion sites.
139 Then, a drill and a depth-stop were used over the guidewire to drill a 12-mm diameter hole for a 50-mm
140 long threaded, cannulated and fenestrated implant (RIALTO™ Sacroiliac Joint Fusion System, Medtronic,
141 Memphis, TN, USA). With a surgical tap, we threaded the insertion hole and tested the specimens for the
142 “drilled state”. Finally, the implant was inserted and specimens were tested again in the “instrumented
143 state”. All implants were inserted on the right side. Implant position was confirmed with a CT-scan after
144 testing.

145 Specimens were tested in compression and FE under quasi-static loads (10 N/s) preceded by 15
146 preconditioning cycles (0.5 Hz) of 40 N. The compression loads (i.e. vertical axis) reached 500 N and were
147 applied with a hinge joint (Fig. 3A). The two cycles of FE (i.e. sagittal plane) ranging from -7.5 Nm to 7.5
148 Nm were applied with a pivot joint. The FE moments were achieved with a lever arm and a 5-kg weight,
149 resulting in a combined compression ranging from 25 to 175N respectively (Fig. 3B). A total of six tests
150 were performed for each specimen. On average, it took 120 minutes to perform the tests (time ranged from
151 80 to 185 minutes). To avoid dehydration during testing, saline-soaked gauzes were applied posteriorly on

152 the sacrum, covering the posterior portion of the SIJs. It was not possible to apply saline-soaked gauzes on
153 the anterior portion of the SIJs because of the speckle pattern.



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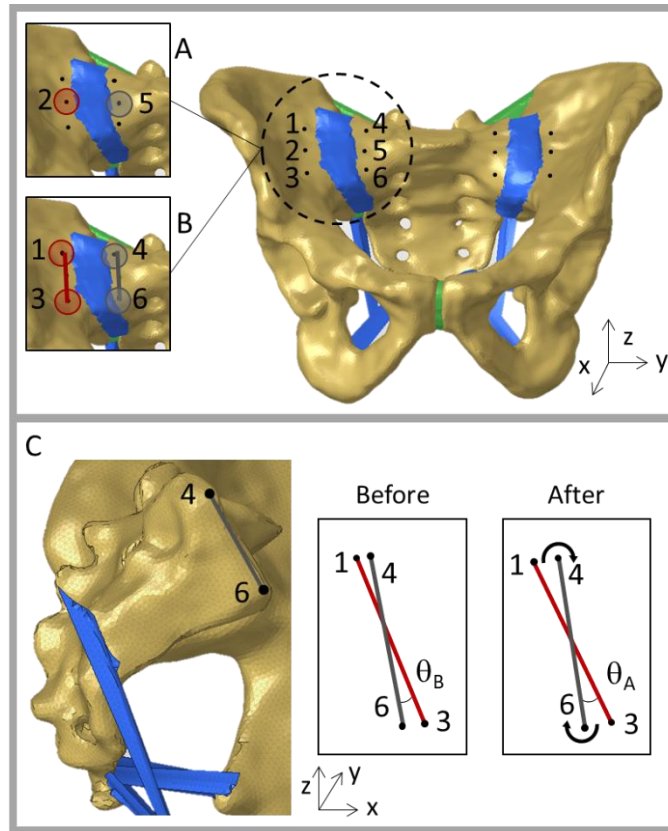
155 Fig. 3 Experimental devices for A) compression and B) flexion-extension loads (combined with compression)

156 *2.3 Data measurement and analysis*

157 Two 1MP cameras (FASTCAM SA3 Model 120K, Photron Europe Limited, West Wycombe, UK) were
158 placed with a 20° to 25° angle between them (Fig. 1B). The intra-articular displacements were measured
159 locally with the Correlated Solutions VIC-3D measurement system (Correlated Solutions Incorporated,
160 Columbia, SC, USA). This system calculated the three-dimensional displacements on the surface nearby
161 the joint based on the principle of digital image correlation (DIC). In-plane precision was under 0.005 mm
162 while out-of-plane precision was 0.01 mm.

163 Using the VIC-3D software, we numerically selected sets of three points along the right SIJ (three on the
164 ilium and three on the sacral ala) for a total of six points (Fig. 4). The relative vertical displacements (VD)
165 (z-axis) of the sacrum was computed with regards to the ilium. The vertical displacement of the ilium (pt.
166 2) was subtracted from the vertical displacement of the sacrum (pt. 5) throughout loading, and the
167 maximum value over time was reported. To measure the relative angular displacements (AD) in the sagittal
168 (x-z) plane, lines connecting the top and bottom points for each set of points (1-3; 4-6) were virtually
169 drawn. Next, the angle between the sacral ala and the ilium was computed before (θ_B) and throughout
170 loading (θ_A) using the lines' slopes. The angle difference over time ($\Delta AD = \theta_A - \theta_B$) was measured. For

171 the FE loads, the values reported represent the total RoM, i.e. the maximum AD in flexion added to the
172 maximum AD in extension. Both VD and AD were computed for each loading scenarios.



173
174 Fig. 4 Representation of the selected points for the measurement of SIJ relative A) vertical displacements (VD) and B) angular
175 displacements (AD). C) Side view of the sacrum for the measurement of AD. For visualization purposes only.

176 2.4 Statistical analysis

177 Statistical analysis was made with Statistica (v13.3; TIBCO Software Inc., Palo Alto, CA, USA). A
178 Wilcoxon signed rank test was applied to compare the “drilled state” and the “instrumented state” to the
179 “intact state” and check for significant differences. This type of analysis takes into account the inter-
180 variability that is inherent to cadaveric testing. The two insertion sites were compared by applying a Mann-
181 Whitney U test on the normalized data (percentage change with regards to the “intact state” of each
182 specimen). For all statistical tests, the significance level was set at 0.05.

183 3. Results

184 Seven specimens completed the testing protocol (Table 1). One specimen (ID1) deteriorated at the end of
 185 the second test and was therefore not included in the analysis. The age ranged from 73 to 94 years. No bone
 186 bridging was detected from the CT-scans.

187 Table 1 Specimen information

<i>Specimen</i>	<i>Sex</i>	<i>Age (yr)</i>	<i>Bone mineral density (mg/cm³)</i>
*ID1	H	88	90
ID2	F	74	155
ID3	H	73	200
ID4	H	73	105
ID5	H	76	90
ID6	H	83	35
ID7	H	94	95
ID8	F	83	80
*Mean		79.4	108.6
SD		7.8	53.7

188 Note: *Means and SD calculated without ID1

189 Intra-articular displacements of adjoining sacrum and ilium of the “intact state” ranged from 0.08 mm to
 190 2.20 mm for VD (translation) and from 0.15° to 2.83° for AD (rotation) (Table 2). No significant difference
 191 was found in compression or in FE between the “intact state” (CI: 0.14 – 1.36 (compression, VD), 0.05 –
 192 0.40 (FE,VD), CI: 0.01 – 1.70 (compression, AD), 0.16 – 0.75 (FE, AD)) and the “drilled state” (CI: 0.14 –
 193 1.19 (compression,VD), 0.06 – 0.41 (FE,VD), CI: -0.01 – 1.52 (compression, AD), 0.14 – 0.79 (FE, AD),
 194 ($P>0.05$). In compression, insertion of the implant led to a significant decrease of VD compared to the
 195 “intact state” (CI: 0.08 – 1.16, $P=0.04$). It had no significant effect on AD (CI: 0.001 – 1.56) ($P>0.05$). In
 196 FE, the implant had no significant effect on VD (CI: 0.06 – 0.36) or AD (CI: 0.21 – 0.68) ($P>0.05$). There
 197 was no significant difference between the two insertion sites in compression (CI: -37.37 – 2.96 (VD), CI: -
 198 23.25 – 19.81(AD)) or in FE (CI: -35.50 41.33 (VD), CI: -22.41 – 35.94 (AD), $P>0.05$) (Table 3).

199 Table 2 Relative SIJ displacements of the instrumented side

<i>Specimen</i>	<i>Insertion point</i>	<i>Compression</i>			<i>Flexion-extension</i>		
		Intact	Drilled	Instrumented	Intact	Drilled	Instrumented
<i>Vertical displacement - VD (mm)</i>							
*ID1	1	0.21	-	-	0.04	-	-
ID2	2	0.55	0.37	0.33	0.10	0.12	0.10
ID3	1	0.49	0.48	0.25	0.19	0.23	0.11
ID4	2	0.56	0.42	0.46	0.16	0.14	0.20

ID5	1	0.48	0.49	0.45	0.19	0.16	0.11
ID6	2	0.72	0.71	0.67	0.25	0.28	0.30
ID7	1	0.23	0.28	0.27	0.08	0.08	0.13
ID8	2	2.20	1.91	1.90	0.64	0.63	0.53
*Mean		0.75	0.66	0.62	0.23	0.24	0.21
SD		0.66	0.56	0.58	0.19	0.19	0.16
<i>Angular displacement - AD(°)</i>							
*ID1	1	0.23	-	-	0.33	-	-
ID2	2	0.27	0.36	0.32	0.15	0.20	0.23
ID3	1	0.97	0.48	0.48	0.42	0.50	0.29
ID4	2	0.48	0.56	0.54	0.42	0.21	0.49
ID5	1	0.41	0.36	0.47	0.36	0.36	0.50
ID6	2	0.82	0.75	0.79	0.50	0.59	0.48
ID7	1	0.20	0.17	0.21	0.22	0.20	0.19
ID8	2	2.83	2.58	2.64	1.13	1.19	0.94
*Mean		0.85	0.75	0.78	0.46	0.46	0.45
SD		0.91	0.83	0.84	0.32	0.36	0.25

200 Note: *Means and SD calculated without ID1

201 Table 3 Comparison of the RoM change (%) for the insertion points tested (average, and each specimen values)

Load	Displacement	Percentage change (intact vs. instrumented) (%)		
		Distal insertion point (n=4)	Proximal insertion point (n=3)	P-value (Mann-Whitney U)
Compression	VD	-20 (-41; -19; -6; -14)	-14 (-49; -6; +14)	0.63
	AD	+4 (+16; +13; -4; -7)	-10 (-50; +17; +4)	0.63
FE	VD	+9 (+6; +25; +20; -17)	-5 (-44; -43; +72)	1.00
	AD	+12 (+55; +15; -3; -17)	-1 (-31; +41; -12)	0.63

202

203 4. Discussion

204 We experimentally measured the isolated effects of drilling and tapping as well as implant insertion on SIJ
205 stability and compared two insertion sites using image correlation methods. The VD of the intact SIJs agree
206 with previous studies, which reported means ranging from 0.32 to 0.7 mm²⁴⁻²⁶. The measured AD are in
207 line with rotations measured *in vivo* (means of 0.5° and 0.8°, respectively)^{27,28} but are below AD reported
208 in most *ex vivo* studies (means ranging from 1.3° to 4.5° for similar FE loads)^{11-14,26}. Those *ex vivo* studies
209 had younger subjects and higher female to male ratios, both factors increasing SIJ mobility. Moreover, the
210 single-leg stance model used in these studies increases the shear force²⁹ and thus leads to larger SIJ
211 displacements. The rehabilitation guidelines by Dall et al. recommend to avoid single-leg stance until bony
212 fusion has occurred, which is usually within 6 to 8 weeks²⁹. Cadaveric testing aims to simulate the initial

213 postoperative stabilization; therefore, a double-leg stance model was deemed appropriate. The distance
214 from the SIJ to the reference point on the ilium may also influence the reported RoM. Lindsey et al.,
215 Soriano-Baron et al. and Jeong et al. placed their marker on the iliac wings, near the anterior superior iliac
216 spine, while Shih et al. placed it near the acetabulum^{11-13,21}. Hammer et al. quantified the RoM of the ilia
217 during compressive loading of L5 and showed motion was present between the SIJ and the pubic
218 symphysis²⁶, meaning the ilium should not be considered as a rigid body. Using a double-leg stance model,
219 they found a negligible AD of the sacrum with regards to the ilium of 0.01°. In the present study, DIC
220 allowed to select iliac reference points millimeters away from the articulation, which may give a better
221 representation of the actual relative displacements of the SIJ.

222 The loads used in this study do not represent all possible loads present in the pelvis. Compression is the
223 most important load of the SIJ because it is almost always present in most diurnal postures and motions
224 (i.e. upper body weight) and contributes to the stability of the pelvic ring³⁰. FE is also involved in several
225 tasks, and puts even more loads on the SIJ. In this study, it was modeled with a lever-arm that led to a
226 combination of FE and compression. This type of loading may be more realistic than pure moments, which
227 do not take into consideration the stability provided by the compression and force-closure mechanisms.
228 Lateral bending and axial rotation were not included, but could be tested in future studies to assess a wider
229 variety of possible loadings.

230 Drilling and tapping for one implant unilaterally did not destabilize the SIJ. Therefore, the damage to the
231 IOL created to insert an implant does not explain why some specimens lose stability after instrumentation.
232 The maximum cross-section area of IOL that was cut ($\approx 115 \text{ mm}^2$) remains relatively small compared to its
233 total section of approximately 750 mm^2 ³¹. In a study by Dall et al., transecting the entire posterior ligament
234 complex (including the IOL) led to a significant, but relatively small increase of motion, with AD staying
235 under 2° ²⁹. This could be because form-closure mechanisms such as the self-locking arrangement of the
236 pelvis and the fitting ridges and grooves of the articular surfaces provide great stability to the SIJ³⁰. Thus,
237 SIJ stability relies only partially on the IOL. Another possible explanation for the lack of initial mechanical
238 stability could be poor bone quality, but additional testing needs to be done.

239 Implant insertion significantly decreased VD for the compression load, with an average reduction of 17%
240 (SD 22%), which is likely not enough to lead to an osseointegration. Instrumentation with one implant
241 contributed relatively little to the stabilization of the SIJ, and had no significant effect on AD and for FE
242 loads. Likewise, Jeong et al. did not find a significant decrease of AD in FE following instrumentation with
243 three triangular implants²¹. Contrastingly, similar studies have reported a significant decrease of AD in FE
244 using two or three implants¹¹⁻¹⁴. However, most of them compared the RoM of the instrumented state to a
245 “destabilized” state (posterior ligaments and/or pubic symphysis cut)¹¹⁻¹³, which may amplify the action of
246 the implants. In the current study, the “instrumented state” consisted of only one implant and was compared
247 to the “intact state”. Because of the rotatory nature of the SIJ biomechanics, one fixation point may not be
248 enough to successfully restrain different types of movements, especially given the proximity of the implant
249 to the CoR of the SIJ, located near S2²³. Adding more implants may reduce this effect and further increase
250 stability, but additional testing is necessary.

251 The position of the two clinically plausible insertion sites tested did not lead to statistically different RoM
252 reduction in the case of a one-implant scenario, as opposed to the previous numerical study of Bruna-Rosso
253 et al²². The distance between the two tested sites was less than 15 mm, which might be too small to have an
254 impact on the RoM. Hence, both insertion points provided a comparable SIJ stabilization.

255 Some mobility always remains *ex vivo* following instrumentation^{11-14,21}, and it is hard to define a clinically
256 significant RoM reduction. Muscular activity further stabilizes the SIJ *in vivo*, but remaining
257 micromovements may hinder the osseointegration process. The ideal RoM restriction threshold to allow
258 proper SIJ fusion is not known. Such threshold would be relevant to define clinical significance and assess
259 the proper action of SIJ fusion implants and how it relates to the patient’s pain.

260 This experimental study has some limitations. Results may have been influenced by freeze-thaw cycles, the
261 duration of the tests and embalment. Tan et al. studied the effect of freeze-thaw cycles, and multiple
262 within- and between-day testing on human cadaveric lumbosacral spine³². They found that the initial four
263 freeze-thaw cycles had no significant effect on the RoM of the segments and that cumulative testing (8
264 tests; up to 12 hours) within a single day did not lead to significant differences in RoM. In the present
265 study, each specimen went through two freeze-thaw cycles and testing was done in a single day, in under 3

266 hours, so the impact on the results are thought to be minimal. However, because of the paint and speckle
267 pattern, it was not possible to keep the anterior part of the SIJ moist with saline-soaked gauzes once the
268 tests started. The anterior ligaments may have dried up and stiffened, possibly contributing to the small
269 displacements measured. Given that the tests were performed in 120 minutes on average, we believe that
270 the ligament of interest, the IOL, was deep enough to stay hydrated throughout testing. As for
271 embalment, it may also have stiffened the ligaments of the SIJ, which may have affected the results,
272 especially regarding the effect of drilling through the IOL. However, unlike a true synovial joint, the
273 biomechanics of the SIJ relies largely on form-closure mechanisms of the pelvis (i.e. shape of the bones)
274 that are independent of soft tissues, thus we believe the effect of soft tissue stiffening was limited. The
275 specimens were old with varying bone quality and this might have affected the SIJ RoM. However, the CT-
276 scans showed no bone bridging or other anomalies. In addition, the measured effect of the implants was
277 obtained on the basis of comparison, so the conclusions drawn likely remain valid.

278 **5. Conclusions**

279 This is the first biomechanical study to investigate SIJ fusion via an oblique approach. We measured the
280 isolated effects of drilling-tapping and instrumentation on SIJ stability and compared two different insertion
281 sites. Drilling through the IOL did not increase the intra-articular displacements of the SIJ, and thus this
282 hypothesis is rejected. Our main hypothesis was only partly accepted, as instrumenting the SIJ with one
283 implant significantly decreased vertical displacements in compression but led to no motion reduction in
284 flexion-extension and no significant difference between both insertion sites.

285 **6. Acknowledgments**

286 The authors acknowledge the support of Dr Kathia Chaumoître, MD, and the Assistance Publique-Hôpitaux
287 de Marseille, (Hôpital Nord, Marseille, France) for their radiologic expertise. The authors would also like
288 to thank: the A*MIDEX foundation, MITACS Globalink, the Fonds de recherche du Québec – Nature et
289 technologies and the Natural Sciences and Engineering Research Council of Canada (Industrial Research
290 Chair program with Medtronic of Canada – grant number: PCIPJ-346145) for their financial support and
291 Medtronic for providing the implants and surgical kit for the study.

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