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L4 fixation is not necessary in L5-Iliac spinopelvic fixation after trauma, but coadjutant transilio-transsacral fixation is

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ABSTRACT

Introduction: Spinopelvic dissociation (SPD) is a severe injury characterized by a discontinuity between the spine and the bony pelvis consisting of a bilateral longitudinal sacral fracture, most of the times through sacral neuroforamen, and a horizontal fracture, usually through the S1 or S2 body. The introduction of the concept of triangular osteosynthesis has shown to be an advance in the stability of spinopelvic fixation (SPF). However, a controversy exists as to whether the spinal fixation should reach up to L4 and, if so, it should be combined with transiliac-transsacral screws (TTS).

Objective: The purpose of this study is to compare the biomechanical behavior in the laboratory of four different osteosynthesis constructs for SPD, including spinopelvic fixation of L5 versus L4 and L5; along with or without TTS in both cases.

Material and methods: By means of a formerly described method by the authors, an unstable standardized H-type sacral fracture in twenty synthetic replicas of a male pelvis articulated to the lumbar spine, L1 to sacrum, (Model: 1300, SawbonesTM; Pacific Research Laboratories, Vashon, WA, USA), instrumented with four different techniques, were mechanically tested. We made 4 different constructs in 5 specimen samples for each construct. Groups: Group 1. Instrumentation of the L5-Iliac bones with TTS. Group 2. Instrumentation of the L4-L5-Iliac bones with TTS. Group 3. Instrumentation of L5-Iliac bones without TTS. Group 4: Instrumentation of L4-L5-Iliac bones without TTS.

Results and conclusions: According to our results, it can be concluded that in SPD, better stability is obtained when proximal fixation is only up to L5, without including L4 (alternative hypothesis), the addition of transiliac-transsacral fixations is essential.

Introduction

Spinopelvic dissociation (SPD) is a severe injury characterized by a discontinuity between the spine and the bony pelvis consisting of a bilateral longitudinal sacral fracture, most of the times through sacral neuroforamen, and a horizontal fracture, usually through the S1 or S2 body [1–3]. Since SPD results after high energy injuries, like a fall from height, traffic accidents or blast injuries [4], most of the times it is found in a polytraumatized patient, associated with other life-threatening injuries [5].

Conservative treatment is chosen only in patients who are not fit for surgery or have concomitant injuries that will require a period of immobilization longer than three months and in those presenting mild displacement at the fracture sites [6]. Otherwise, SPD lesions are best treated by surgical procedures.

Classical surgical techniques, such as iliosacral screws, provide good horizontal stabilization. However, since injury mechanisms provoking SPD are due to vertical shearing forces, these fixations do not seem to provide enough stability to counteract rotational and vertical shearing forces through the fracture planes. For that purpose, spinopelvic fixation (SPF), a surgical technique extending from the lumbar spine to the pelvis, provides vertical buttressing stability, allowing early weight

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bearing after surgery in many cases [7]. Nowadays, there are different surgical fixation techniques for the treatment of SPD, initially designed for spinal deformities, simple sacral fractures, or pelvic ring injuries [8–12]; being the concept of triangular osteosynthesis the current gold standard. Triangular osteosynthesis consists of the combination of SPF with transiliac-transsacral screws (TTS) [13].

Despite these new concepts, there is a significant rate of mechanical failures, hardware prominence and non-unions, which means that there are still many controversies. [14–18]. On the other hand, only one third of these patients achieve pre-traumatic functional outcomes one year after the injury [19].

One of the controversies is whether the spinal fixation should reach L4 and, if so, it should be combined with TTS [20]. The purpose of our study is to compare the biomechanical behavior of four different osteosynthesis constructs for SPD, including SPF of L5 versus L4 and L5 along with or without TTS in both cases. Our operating hypothesis is that the combination of TTS with SPF of L4 and L5 would be the construct model that would withstand more loading cycles before failure.

Material and methods

By means of a formerly described method [21], an unstable standardized H-type sacral fracture in twenty synthetic replicas of a male pelvis articulated to the lumbar spine, L1 to sacrum, (Model: 1300, SawbonesTM; Pacific Research Laboratories, Vashon, WA, USA), instrumented with four different techniques, were mechanically tested. Twenty models were tested, corresponding to 4 different constructs with 5 samples in each group [21].

- Group 1. Instrumentation of the L5-Iliac bones with TTS.
- Group 2. Instrumentation of the L4-L5-Iliac bones with TTS.
- Group 3. Instrumentation of L5-Iliac bones without TTS.
- Group 4: Instrumentation of L4-L5-Iliac bones without TTS.

Specimen preparation

For better handling, the L1-L4 segment in groups 1 and 3 and the L1-L3 segment in groups 2 and 4 were removed from the specimens.

For reproducibility purposes, to prepare the fracture models, the osteosynthesis was placed first and then the fracture was produced. In all cases, the pedicular screws for the L4 and L5 fixation (Xia 3, Stryker, Allendale, USA) were 50 mm long and 6,5 mm wide and were introduced by means of a conventional technique [22,23].

For the placement of the iliac screws (Xia 3, Stryker, Allendale, USA) −90 mm in length and 8,5 mm in diameter- and the TTS (Asnis 3, Stryker, Selzach, Switzerland) [24] a plastic and copper guide, developed from the solid model of each iliac crest obtained from the CT of a

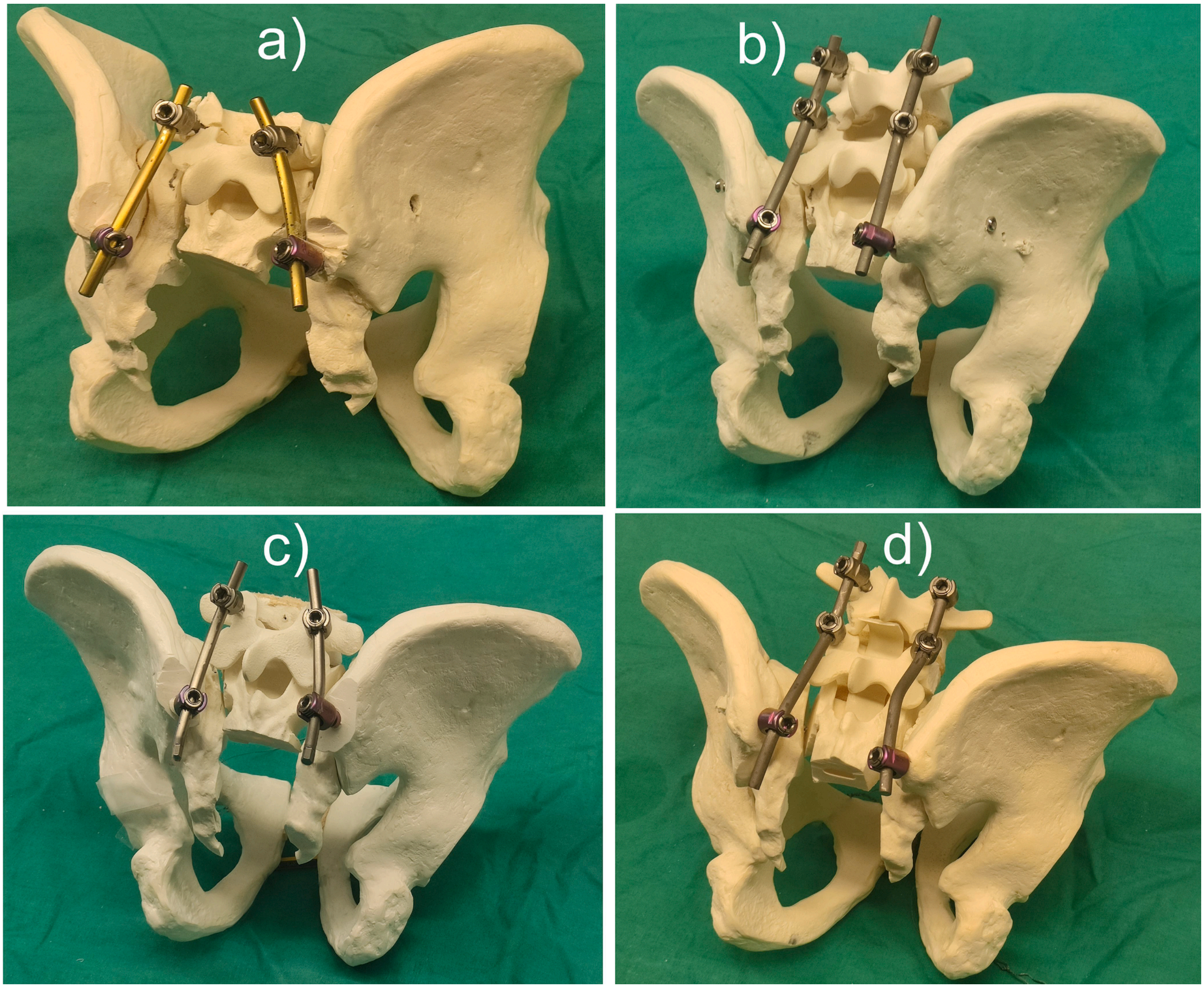

Fig. 1. The four models of SPF. Group 1: Instrumentation of the L5-Iliac bone with TTS. Group 2: Instrumentation of the L4-L5-Iliac bone with TTS. Group 3: Instrumentation of the L5-Iliac bone without TTS. Group 4: Instrumentation of the L4-L5-Iliac bone without TTS.

specimen, was used. [21]. The pedicle screws were connected with 5,5 mm rods on both sides [25].

Subsequently, the fracture was made with an oscillating saw, with the vertical lines through the sacral foramina and sacral ala and the horizontal part through the middle of the S2 vertebral body with a 1 cm fracture gap. The purpose of this separation was to obtain a comminuted completely unstable fracture model, only stabilized by the osteosynthesis material (Fig. 1). All the preparations were performed by the same orthopedic surgeon.

Twelve physical markers were attached to the specimen to be used during the tests, together with 6 virtual markers created by software (Fig. 2):

- On each hemipelvis, 3 reflective markers were attached far enough from the fractures so that they were not hidden in any frames during the test (LP-1, LP-2 and LP-3 on the left hemipelvis; RP-1, RP-2 and RP-3 on the right hemipelvis).
- On the sacrum, 2 markers were fixed along the posterior line of each fracture plane (LS-2 and LS-3 for the fracture on the left; RS-2 and RS-3 for the fracture on the right) along with a third marker that defined with the previous ones a plane perpendicular to each fracture (LS-1 and RS-1 respectively).On the sacrum, 4 virtual markers were created at the proximal and distal end of each fracture plane (LS-P and RS-D at the left fracture; RS-P and RS-D at the right fracture).
- On each hemipelvis, 2 virtual markers were created facing the corresponding virtual markers on the sacrum in direction perpendicular to the respective fracture planes (LP-P and LP-D; RP-P and RP-D respectively).

Biomechanical testing

The instrumented lumbopelvic complex was tested in a universal testing machine according to a previously described set-up [21,26] (Fig. 3). The test reproduced loads in the bipodal standing position, simulating the forces generated by the primary muscle groups involved in walking. Antero-posterior tilting, depression elevation and ipsilateral-contralateral rotation of the pelvis when an external load was applied was allowed.

The load applied to the specimen was measured using a 2kN-rated Class 1 load cell (HBM, Darmstadt, Germany). Simultaneously, the 3D positions of the physical markers were recorded using a videogrammetry system [21].

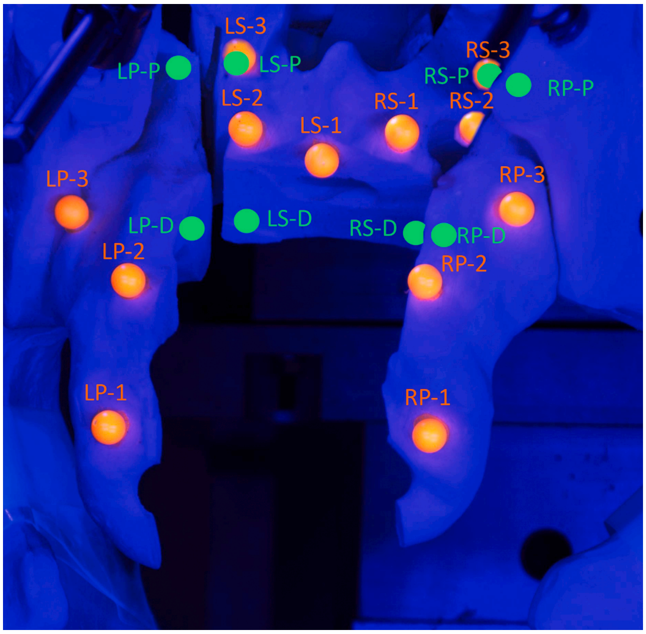

Fig. 2. Physical markers (orange) and virtual markers (green).

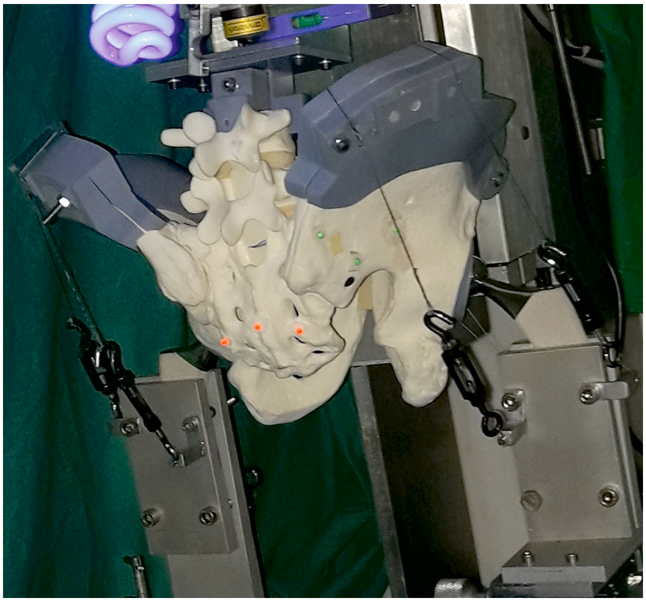

Fig. 3. Specimen in the testing machine.

The specimen was subjected to the following compression test, the load being applied on the center of the metal plate attached to the most proximal vertebra of the lumbo-pelvic complex:

- Phase 1, preconditioning: The specimen was subjected to 150 N of compression and positioned to mimic an upright static posture [21, 27–30] by tensioning the braids that simulated the muscle groups. Once stabilized, the displacement of the right femoral stem on the base table was blocked to simulate stable foot contact without slippage, and the load was maintained for 45 s. Then, the positions of the markers were recorded to calculate the specimen's position at the initiation of the test.
- Phase 2, cyclic load: Cyclic loads of 50 N to 400 N at 1 Hz were applied for 10,000 cycles to simulate the gait pattern of a 75 kg male walking twice a day for 10 min at a natural cadence during the first three postoperative weeks [21]. The positions of the markers were recorded for 10 cycles of every 100-cycle period, and the compression load was continuously monitored.
- Phase 3, intermediate stabilization: If the specimen survived the cyclic test, it was loaded at 150 N of compression for 45 s.
- Phase 4: A compression load-to-failure test was carried out at 0.25 mm/s. The positions of the markers and the compression load were continuously recorded.

Data analysis

a) Resistance: The resistance of each specimen was studied by analyzing the evolution of the compression load in phase 4 of the biomechanical test, where two parameters were computed:
   - Ultimate load: It is the maximum compression borne by the specimen in the test.
   - First peak load: The failure of mechanical systems subjected to displacement-controlled tensile or compression tests is manifested as a local maximum followed by a clear decrease in load. The first local maximum on the load curve preceding the ultimate load, if existed, was registered as the first peak load, and was associated to the initiation of mechanical failure of the fixation.

Obviously, if there was no local maximum prior to the ultimate load, the same value was assigned to both parameters.

a) Proximal and distal absolute displacement at the fracture planes: The absolute proximal and distal displacements in the left and right fracture planes were calculated as the difference between the distance in every frame for each pair of virtual markers (green markers in Fig. 2) and their distance at the initiation of the test (specifically, the left proximal was from LP-P to LP-S, the left distal from LP-D to LS-D, the right proximal from RP-P to RS-P, and the right distal from RP-D to RS-D).

To mitigate the influence of the different supports of the two femoral stems, the proximal and distal displacements resulting from pooling displacements at both fracture planes were also calculated.

a) Tangential and perpendicular displacement at the fracture planes: The proximal and distal absolute displacements were divided into two components by projecting the absolute displacement onto each fracture plane and onto the direction normal to it.

Statistical analysis

The group size was selected based on the maximum compression load borne by the first three samples tested. As described in the results section, the groups without TTS (groups 3 and 4) did not even survive the first load of phase 2, so they could not be statistically compared with the groups with TTS (groups 1 and 2). Therefore, two comparative statistical studies were performed, on one hand, between the two groups without TTS and, on the other hand, between the two groups with TTS.

For the groups without TTS, calculations using G*Power 3.1.9.7 software [31] yielded a minimum group size of $n = 4$ with the Wilcoxon-Mann-Whitney test for a computed difference in the mean load of 75 N with SD = 34.9 for group 4 and SD = 9.6 for group 3 at $\alpha = 0.05$ with a power of 0.8. For the groups with TTS, $n = 4$ was calculated for a computed difference in the mean load of 150 N with SD = 60.1 for group 2 and SD = 42.3 for group 1 with the same parameters. Thus, a conservative sample size of $n = 5$ was chosen, which is equal to or greater than the sample size in previous studies on pelvic fracture fixation evaluation [32–37].

To assess for possible differences between groups with fixation up to L4 or up to L5, a 2-tailed Student's t-test for unpaired samples with unequal variance was applied. The Excel 2019 software package (Microsoft Corp, Washington, USA) was used for all analyses; $p \leq 0.05$ was considered statistically significant.

Results

a) Resistance: Regarding the repairs with TTS (groups 1 and 2), Fig. 4 shows the progression of the compression load in the load-to-failure tests at phase 4 of the experimental test. All samples showed a clear first peak load, characteristic of the initiation of mechanical failure in displacement-controlled tests, which was highlighted with empty square markers. The ultimate load, maximum load borne by the sample, is also flagged with a filled circular marker in Fig. 4. The mean value and standard deviation (SD) of the first peak load (Table 1) was 922.1 N (94.7 N) for group 1 and 802.0 N (20.5 N) for group 2, being significantly higher for group 1 by 13.0 % ($p = 0.046$). The ultimate load (Fig. 5) showed a mean value of 1138.2 N (SD 155.3 N) for group 1 and 880.6 N (SD 58.4 N) for group 2, also being significantly higher for group 1 by 22.6 % ($p = 0.017$).

Regarding the groups without TTS (groups 3 and 4), none of the specimens survived the first load cycle in phase 2 of the biomechanical test, i.e., fixation failure always occurred below 400 N. To make the comparative analysis of the resistance between both

Table 1
Mean and SD (in parenthesis) of the first peak load and ultimate load for the four studied groups expressed in N.

	Group 1	Group 2	Group 3	Group 4
First peak load	922.1 (94.7)	802.0 (20.5)	170.9 (64.9)	230.5 (114.0)
Ultimate load	1138.2 (155.3)	880.6 (58.4)	283.2 (24.2)	327.3 (62.1)

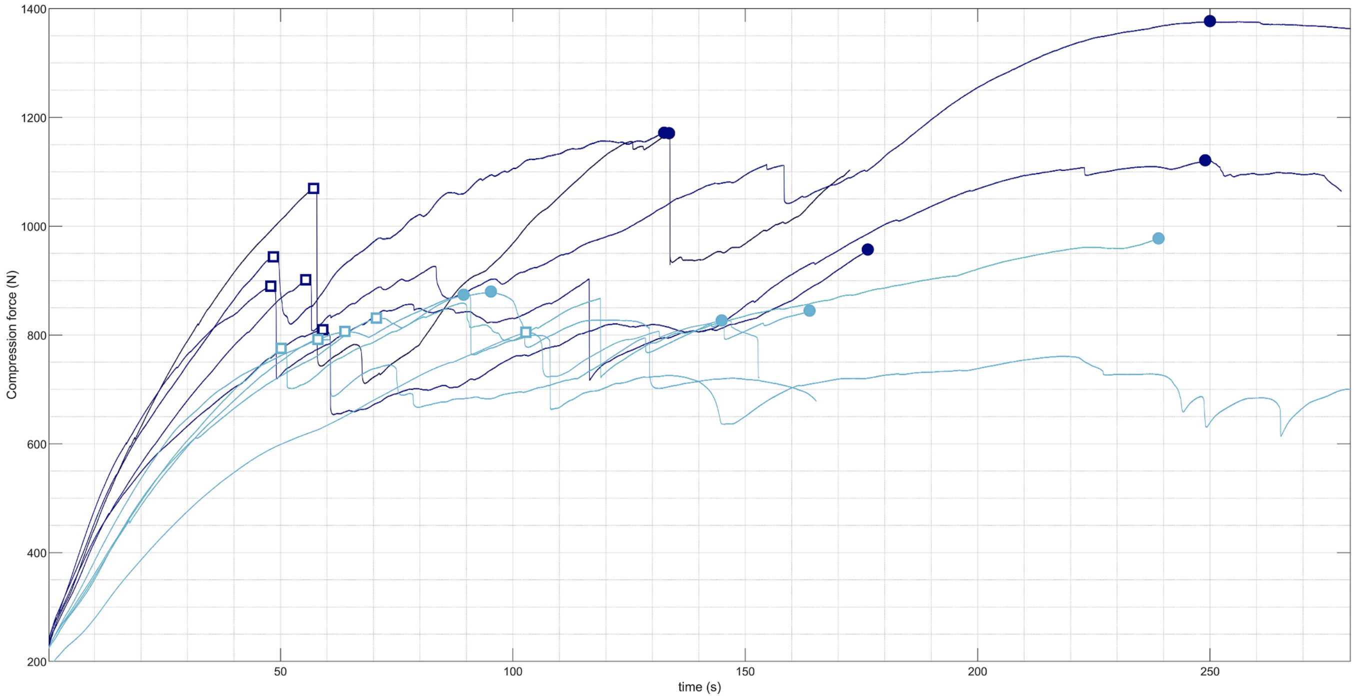

Fig. 4. Compression force in displacement-controlled load-to-failure test for repairs with TTS. Light blue: group 1. Dark blue: group 2. Empty square marker: first peak load. Filled circular marker: ultimate load.

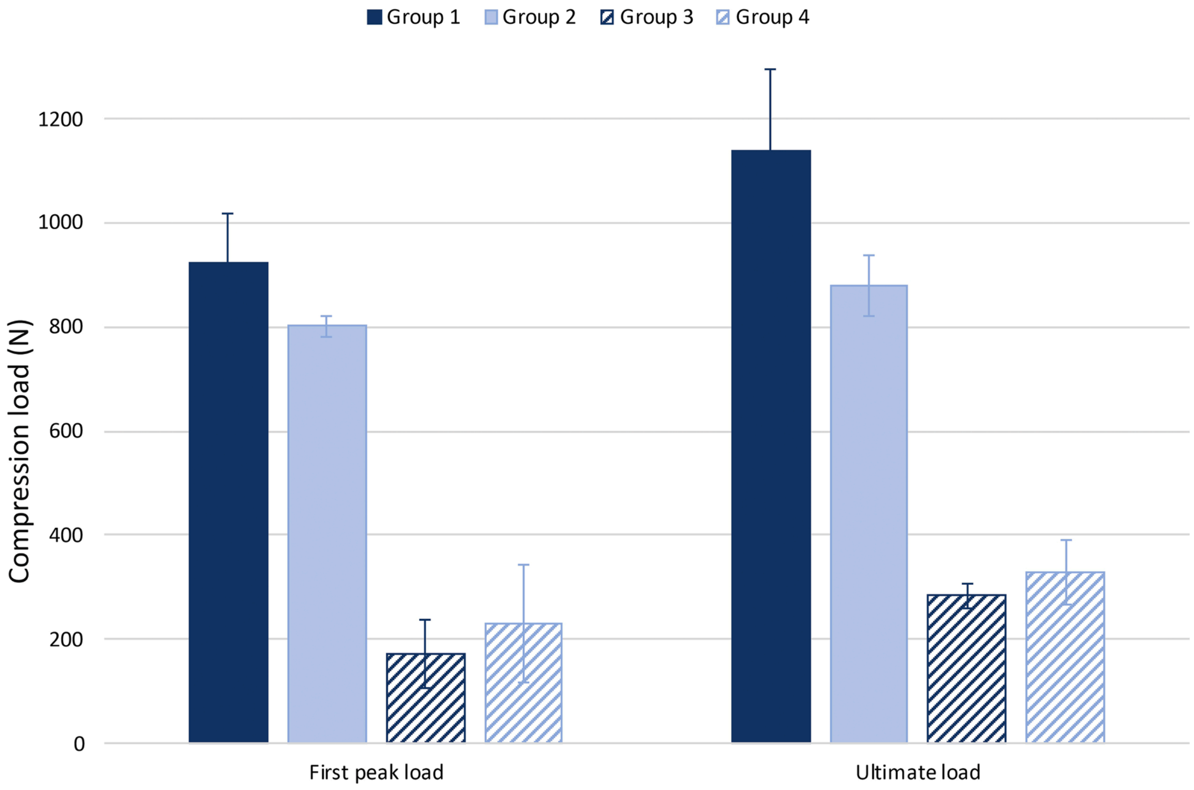

Fig. 5. Mean and SD compression load(N) at the first peak load and at the ultimate load for groups 1 (solid dark blue), 2 (solid light blue), 3 (dark blue with pattern) and 4 (light blue with pattern) computed at the load-to-failure test for groups 1 and 2 and at the loading phase of the first cycle for groups 3 and 4.

fixations possible, the first peak load and the ultimate load were calculated as detailed in section 2 of this document but on the curve corresponding to the loading phase of the first cycle in phase 2 of the test, since the failure occurred in this period, and it was not possible to execute phases 3 and 4 or even complete phase 2. Fig. 5 displays mean and SD values computed for the aforementioned parameters,

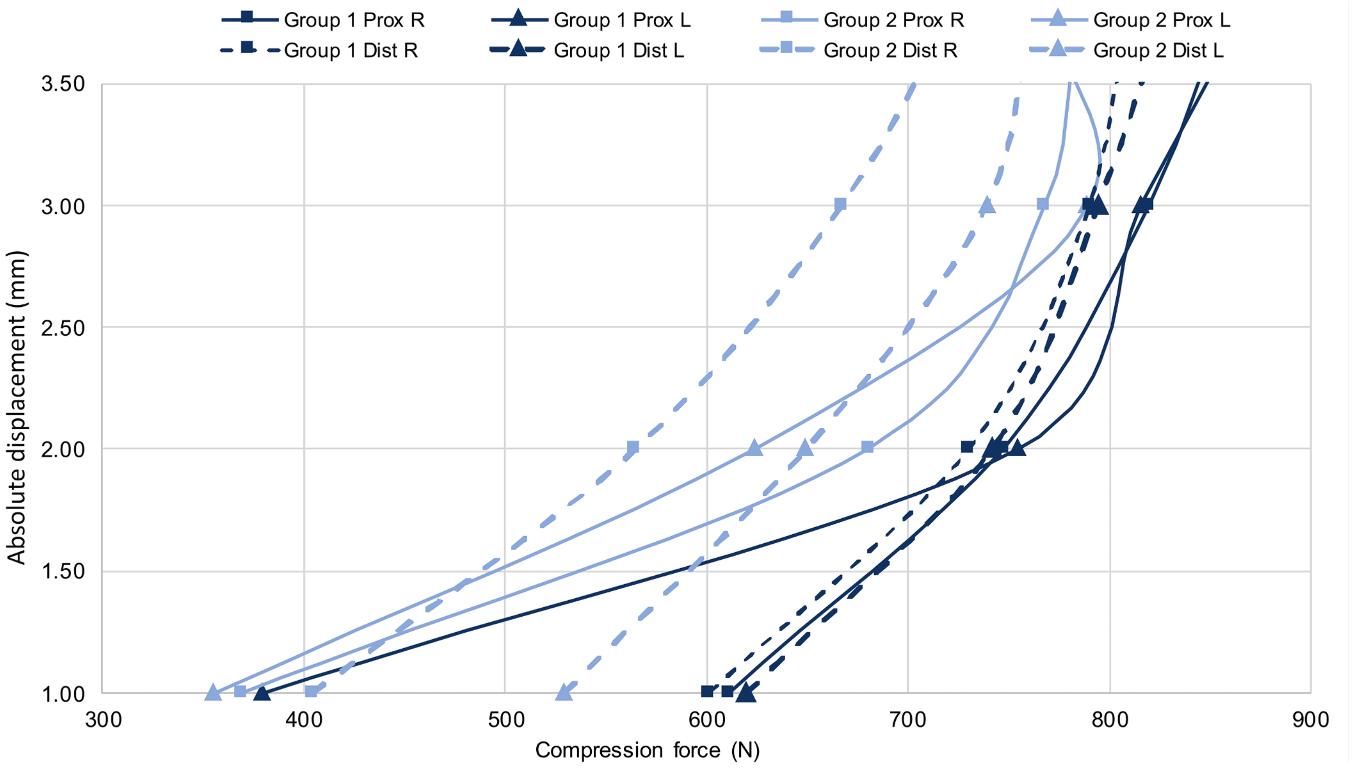

Fig. 6. Mean displacements between the 4 pairs of markers placed along the two fracture planes as a function of the applied compression load in the load-to-failure test.

which are also detailed in Table 1. No differences were detected between the groups for any resistance parameter.

The compression resistance could not be statistically compared between groups with and without TTS, since the former failed in a load-to-failure test performed after 10,000 load cycles that did not exist for the latter. Nevertheless, the results clearly demonstrated a much lower compression resistance for the fixations without TTS (Fig. 5).

a) <u>Proximal and distal absolute displacements at the fracture planes</u>: As aforementioned, no specimen without TTS survived phase 2 of the loading test, consequently no fracture plane displacement data are available for these groups. Fig. 6 shows the mean absolute displacements between the 4 pairs of markers placed along the two fracture planes as a function of the applied compression load in the load-to-failure test (data for the 5 tested specimens are provided as supplementary material). Displacements lower than 1 mm have not been included, as they involved a high measurement error and are not clinically relevant. Displacements higher than 3.5 mm have not been included in the study either as very uneven behavior was observed among the samples above this value, because in most of the trials it was reached after the initiation of mechanical failure of the fixation as identified by the first peak load (55 % of group 1 samples; 45 % of group 2 samples). Moreover, fracture displacements greater than 2 mm can be considered clinical failure of the repair [38–41]. For the entire compression range, the absolute mean displacements are smaller in group 1 (dark blue lines) than in group 2 (light blue lines). For group 1, higher mean displacements were found for the distal markers (dashed lines) than for the proximal markers (solid lines) at both fracture sides, the difference becoming clearer the greater the load was. The mean and SD of the load generating a displacement of 1, 2 and 3 mm are detailed in Table 2.

Fig. 7 shows the absolute displacements resulting from pooling displacements at both fracture planes, the mean and SD values of the compression loads that generate characteristic displacements are also listed in Table 2 (data for the 5 tested specimens are provided as supplementary material). Higher mean displacements are observed in group 2 than in group 1. The difference was more pronounced for distal markers, where higher displacements were observed except in the lowest load interval for group 1 repairs (displacements lower than 1.8 mm). For the distal markers, the load needed to yield displacements of 1 mm and 2 mm was significantly higher for group 1 ($p = 0.018$ and $p = 0.020$ respectively) and showed a tendency to significance at 3 mm ($p = 0.059$), although this situation would already be considered clinical failure. No significant differences between groups could be detected for the proximal markers at 1, 2 or 3 mm.

Table 2

Mean and SD (in parenthesis) of compression load generating absolute displacements of 1, 2 and 3 mm in each fracture plane and pooled in both fracture planes for Group1 and Group 2, expressed in N.

		Between proximal markers		Between distal markers	
	Displac.	Group 1	Group 2	Group 1	Group 2
Right fracture	1	610.9 (236.6)	369.1 (173.6)	601.2 (145.1)	404.5 (87.6)
	2	747.3 (147.2)^{1}	680.5 (128.7)	730.1 (133.5)^{1}	564.5 (94.0)
	3	819.5 (91.8)^{2}	767.6 (100.0)^{2}	790.0 (105.2)^{2}	667.2 (103.1) ^{2}
Left fracture	1	379.3 (180.2)	355.1 (177.5)	619.7 (121.7)	528.7 (124.9)
	2	754.5 (101.8)	623.8 (112.4)	741.8 (114.1)^{1}	648.8 (117.3)
	3	815.4 (100.1)^{1}	789.1 (113.4)^{2}	794.5 (82.0)^{3}	738.9 (110.3) ^{2}
Pooled	1	495.1 (192.9)	483.0 (180.8)	610.4 (125.4)	466.6 (100.3)
	2	750.9 (119.8)^{1}	685.5 (82.3)	735.9 (122.1)^{1}	606.6 (105.9)
	3	817.7 (208.2)^{3}	804.3 (63.4) ^{2}	792.3 (91.3)^{2}	703.0 (106.2)^{2}

The superscript, when displayed, indicates the number of specimens that reached the corresponding displacement after the first peak load.

a) <u>Tangential and normal displacement at the fracture planes</u>: For a more detailed analysis of the fracture motion, the displacements between markers have been divided into two components: tangential to the fracture planes, reflecting sliding between bone sections, and perpendicular to these planes, reflecting fracture opening. Fig. 8 plots the displacements tangential to the fracture planes pooling both fracture sides in the load-to-failure test, showing greater mean slippage for the repairs of group 2 for all the studied intervals, although no significant differences between groups could be detected. Additionally, mean and SD of the compression loads that generate displacements of 0.5, 1, 1.5, 2, 2.5 and 3 mm in the direction tangential to the fracture planes are shown in Table 3 (data for the 5 tested specimens are provided as supplementary material).

As the loading direction was nearly parallel to the fracture planes, the displacements in the direction perpendicular to them were very minor, which greatly diminished the importance of the representation of its mean evolution. For all the samples in group 2 an opening of both fractures was observed in proximal and distal markers while in group 1 three of the specimens showed fracture opening at the distal level but closure at the proximal level.

Discussion

Osteosynthesis using only TTS for vertical sacral fractures usually fails due to its inability to neutralize vertical shearing forces. To this aim, lumbopelvic fixation increases stability in this type of injury [42,43]; although articles regarding patient treatment do not usually specify the immediate postsurgical treatment and, therefore, the validity of the fixation [44–48]. In other case series, patients are only allowed to bear weight several weeks after surgery [49]. There are few publications in which immediate foot loading is authorized, whether partial [50,51] or complete [19,52,53]. In addition, since authors use several combinations of osteosynthesis, it has become very difficult to know the performance of every type of fixation for each fracture pattern.

The introduction of the concept of triangular osteosynthesis [13,54] was based on combining bilateral fixation of the L4 and L5 levels with two screws in each iliac bone connected vertically with a bar -the so-called SPF- and horizontally with cross-link devices together with 2 TTS [2,20].

In the design of our study, based on previous biomechanical models [21], the applied loads were intended to generate vertical shearing forces on the fractures in the most unfavorable conditions due to the absence of stability by the soft tissues and contact between the fracture lines. This way, all stability lay on the osteosynthesis. The biomechanical performance of four lumbopelvic fixations for sacral H-type fractures was evaluated by testing replicas of a synthetic male pelvis articulated to the lumbar spine, from L1 to the sacrum. Specifically, we studied a spinopelvic L4 and L5 pedicle to iliac fixation and only from L5 to iliac; in two of the four groups constructs were combined with TTS. Two main findings were observed in our study. On the one hand, TTS are needed to provide sufficient fixation, otherwise simple spinopelvic constructs fail. On the other hand, in the case of bilateral triangular osteosynthesis -combination with TTS, greater stability is obtained when the fixation is limited to L5 and the iliac bone, without fixing L4 (alternative hypothesis).

Analysis of the results of compression tests showed that specimens stabilized with bilateral triangular osteosynthesis survived a cyclic test simulating ambulation for 10 min twice a day at a cadence of 1 Hz for 21

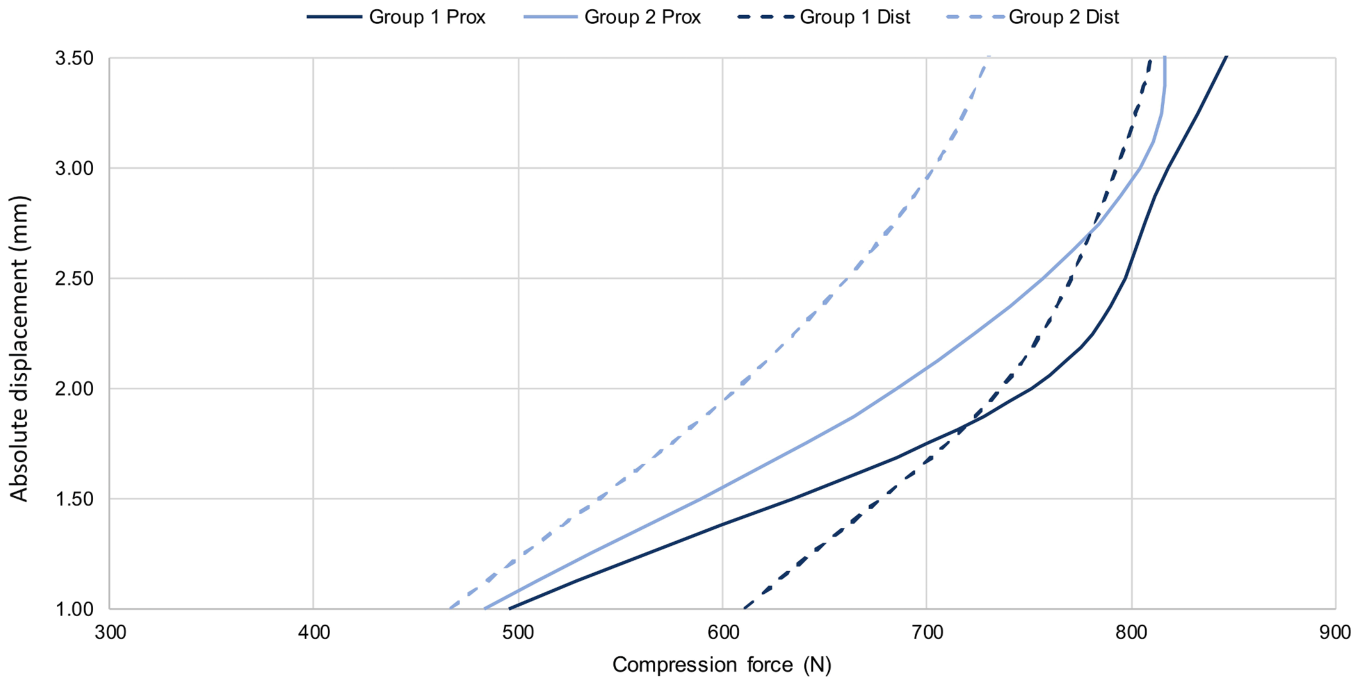

Fig. 7. Absolute displacements resulting from pooling displacements at both fracture planes. Solid lines: proximal markers. Dotted lines: distal markers.

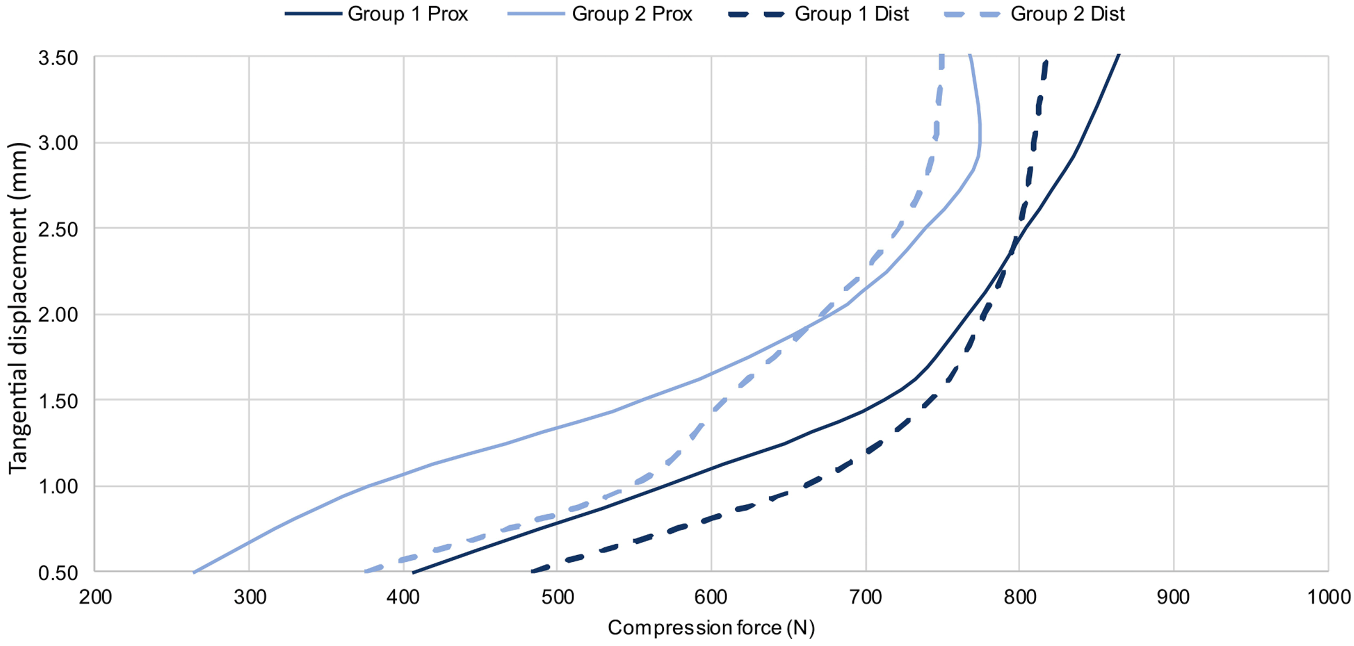

Fig. 8. Displacements tangential to the fracture planes pooling both fracture sides in the load-to-failure test.

days, representative of weight bearing in the first three weeks after surgery [54]. In contrast, fixations that did not incorporate TTS did not provide sufficient stabilization as all specimens in these groups failed at loads of less than 400 N, representative of the maximum axial load during walking of a 75 kg man.

Likewise, in terms of resistance in the load- to-failure test, both the first peak load and the last load were significantly greater in group 1, that is, fixation in the spine only up to L5 combined with TTS. The first peak load indicates the compressive forces that initiates mechanical failure of the system in a displacement-controlled compression test, while the ultimate load is the maximum force supported by the construct [55,56]. It was found that the necessary compression loads to produce displacements of 1 mm and 2 mm in the distal area of the fracture had to be significantly higher for group 1 as well.

Following our previous studies [21] and literature [38–41], we used a 2 mm fracture line displacement as the limit criterion for considering fixation failure. Probably because displacements occurred under compression loads after the onset of mechanical failure in most of the samples, identified by the first load peak, resulting in a high dispersion of values, the differences regarding loads that produced displacements of 1 or 2 mm between the proximal markers were not significant either for group 1 or 2. Anyway, the mean load was greater for group 1.

In the samples without TTS, no significant differences were found between groups 3 and 4 in the parameters related to fixation strength.

Table 3

Mean and SD (in parenthesis) of compression load generating tangential displacements to the fracture of 0.5, 1, 1.5, and 2 mm in each fracture plane and pooled in both fracture planes for Group1 and Group 2, expressed in N.

		Between proximal markers		Between distal markers	
	Displ.	Group 1	Group 2	Group 1	Group 2
Right fracture	0.5	524.6 (179.7)	292.6 (138.0)	514.5 (133.5)	296.3 (127.1)
	1	646.9 (246.4)	398.4 (164.0)	633.0 (132.0)	513.7 (160.3)^{1}
	1.5	698.4 (174)^{1}	631.2 (136.7)	718.6 (138.7)^{1}	574.2 (141.3)^{1}
	2	776.0 (132.7)^{2}	704.5 (136.5)^{2}	753.7 (109.2)^{1}	643.6 (144.7)^{1}
	2.5	832 (122.4)^{2}	746.3 (116.8)^{3}	770.1 (93.5)^{2}	691.4 (139.0)^{1}
	3	855.5 (115.0) ^{3}	754.7 (97.6)^{3}	811.5 (89.1)^{2}	738.9 (137.2)^{1}
Left fracture	0.5	285.5 (122.0)	234.4 (13.9)	687.1 (147.2)	455.5 (132.1)
	1	490.0 (192.4)	357.2 (178.4)^{1}	765.6 (151.8)	581.8 (148.7)^{1}
	1.5	725.6 (130.8)^{2}	480.9 (206.4)^{2}	800.2 (148.3)	642.0 (124.3)^{1}
	2	757.8 (100.1)^{3}	649.6 (117.1)^{2}	829.5 (137.7)^{2}	698.8 (118.6)^{1}
	2.5	776.4 (73.4)^{3}	730.3 (119.3)^{2}	805.7 (81.4)^{2}	750.0 (120.3)^{2}
	3	819.8 (95.6)^{4}	792.8 (114.0)^{2}	810.9 (77.5)^{4}	750.2 (90.6)^{3}
Pooled	0.5	405.1 (136.4)	263.5 (67.0)	483.8 (114.7)	375.9 (100.3)
	1	568.5 (204.6)	377.8 (106.2)^{1}	660.1 (123.5)	547.8 (150.5)^{1}
	1.5	712.0 (150.3)^{1}	556.1 (152.3)^{2}	742.1 (137.0)^{1}	608.1 (128.0)^{1}
	2	766.9 (112.5)^{2}	677.1 (124.4)^{2}	777.0 (123.3)^{2}	671.2 (128.6)^{1}
	2.5	804.2 (93.6)^{3}	738.3 (113.7)^{3}	799.8 (97.7)^{2}	720.7 (127.5)^{2}
	3	839.6 (102.0)^{4}	732.5 (102.9)^{3}	811.4 (74.4)^{4}	744.5 (101.0)^{3}

The superscript, when displayed, indicates the number of specimens that reached the corresponding displacement after the first peak load.

However, it should be noted that both the first and the last peak loads were not calculated in a displacement-controlled load-to-failure test, but in the loading phase of a force-controlled loading cycle.

Regarding the displacements in the fracture planes, they could not be calculated due to premature failures of the specimens, not foreseen in the study design. The test was designed by synchronizing the videogrammetry system in the load-to-failure phase, but without recording any data in the previous phases. Also, due to that, it was not possible to statistically compare the resistance between the groups without and with TTS, since the former could only be analyzed in the loading phase of the first cycle of the test, which they did not survive, and the latter were analyzed after having been subjected to 10,000 loading cycles, since they did not present mechanical weakness in the cyclic phase. The greater compression load that the specimens with triangular osteosynthesis were able to withstand was evident, with much higher average values of the resistance parameters.

Despite what is proposed in many studies on the treatment of traumatic SPD [8,45,48,50,51,57–59], in our experiment, as stated, it was not found advantageous to extend lumbar osteosynthesis to L4 (groups 2 and 4). Although with our test configuration the displacements in the direction perpendicular to the fracture plane were much smaller and although no statistical differences were found between the groups for this variable, it was observed that all the samples in group 2 exhibited opening of the fractures both proximally and distally, while in group 1three of the specimens showed fracture with distal opening, but proximal closure. This behavior suggests that the instantaneous axes of rotation of the relative motion of the hemipelvises with respect to the sacrum are closer to the fracture planes in group 1 than in group 2. In other words, extending the fixation up to L4 generates a mechanical configuration with an instantaneous axis of rotation further from the sacrum than if the fixation is restricted to L5. This scenario, on one hand, would justify the smaller displacements between markers observed for group 1 and, on the other hand, the smaller displacements could imply a lower tension in the interaction between the fixation elements and the bone, resulting in greater resistance of the construction. New studies on failure kinematics with greater statistical power or setups that cause greater perpendicular displacements to the fracture planes could confirm the hypothesis.

In our study, the instability problems observed in the absence of TTS could have been solved using cross-link type devices [8,57]. However, during the design it was decided not to use them, as well as posterior plating, because it is known that they may cause several negative clinical consequences; also, it would be enlarging the research. Their use increases the duration of surgery, especially if they are added at several levels. They produce an increase in the volume of osteosynthesis material in the surgical field in an area where the skin is usually thin and may be traumatized in cases of SPD. They can lead to a decrease in the bone surface available for bone consolidation, which can favor the appearance of pseudo-arthrosis as well as facilitate the appearance of dead spaces, since they make it difficult for the muscles onto apply to the vertebral bone plane, favoring the formation of hematomas that, in turn, can become infected. Cross-link devices also increase the total cost of surgery [60–62]. In a recent meta-analysis, it has been concluded that cross-link devices are only suggested in C1-C2 fixations while in other situations more studies are needed to obtain evidence to establish recommendations [63].

Our study may have some limitations. One of them arises from the use of synthetic bone specimens, previously used in comparative studies on fixations in the pelvis and spine [30,35,64–66]. Nevertheless, we think that synthetic bone has the advantage of having homogeneous mechanical properties [67,68], which reduces sample-related bias, and they are functionally closer to young adult human samples than to normally available elderly human cadavers. Hence, recommendations about osteoporotic bones cannot be made. So far, no evidence exists about that [7]. Osteoporosis is not only a qualitative disease, but also a quantitative one; Therefore, it is very difficult to make individualized recommendations.

Another possible limitation of our study consists of not having stabilized the symphysis pubis. In the bone models used, the pubic symphysis is joined by means of foam rubber. Stabilization of the symphysis pubis by plate osteosynthesis in patients with a comminuted fracture of the sacrum increases stability in axial rotation at the level of the sacral fracture focus [8]. On the other hand, studies that also used a synthetic bone pelvis where the pubic symphysis had not been fixed either, found that the displacement of the symphysis was negative in the horizontal plane, with closure in the event of vertical displacements of 9–11 mm [35], also seen clinically [27]. Moreover, when different sacral fracture patterns are associated with other fractures in the anterior part of the pelvic ring, the combinations of both can be so numerous that it is not feasible to systematize them in a biomechanical or a clinical study. Some other particular cases such as TTS placement in sacral dysmorphism cannot be studied in this research. Nevertheless, we can assume that, in those cases, screw placement at the level of the S2 vertebra instead of S1 should be considered. The combination of many variables, apart from the ones considered in this research, such as osteoporosis, fixation of anterior elements, sacral dysmorphism with TTS in S2, also TTS in S1, posterior plating, and some others, would require so many groups and specimens that the research would be infeasible.

Conclusion

According to our results, it can be concluded that, in SPD, better stability is obtained when proximal fixation is only up to L5 without including L4 (alternative hypothesis), the addition of TTS being essential.

CRediT authorship contribution statement

Enrique Sevillano-Perez: Investigation. **Maria Prado-Novoa:** Conceptualization, Formal analysis, Investigation, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing, Validation, Visualization. **Sergio Postigo-Pozo:** Conceptualization, Formal analysis, Investigation, Visualization. **Alejandro Peña-Trabalon:** Investigation, Software, Visualization. **Enrique Guerado:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing, Visualization.

Declaration of competing interest

None of the authors have financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work. This disclosure Includes employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/registrations, and grants or other funding.

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Supplementary materials

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