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ORIGINAL ARTICLE

Biomechanical comparison between standard and inclined screw orientation in dynamic hip screw side-plate fixation: The lift-off phenomenon

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Abstract *Background:* Common failure modes of dynamic hip screw are cut-out and lift-off. To minimize the latter, distal screws can be inserted in different orientations. However, the effectiveness remains controversial. The aim of this study was to biomechanically investigate the influence of distal screw orientation on construct stability.
Methods: Thirty artificial generic long bones were assigned to three groups ($n = 10$) and fixed with two-hole dynamic hip screw–plates, inserting distal cortical screws with neutral parallel screw orientation (A), divergent screw orientation (B) or convergent screw orientation (C). Starting at 60 N, cyclic loading was applied to the implant tip perpendicular to the lag screw axis with progressive peak load increase at a rate of 0.002 N/cycle until failure. Parameters of interest were construct stiffness and machine actuator displacement after 250, 1000 and 5000 cycles, as well as cycles to failure.
Results: Displacement after 250, 1000 and 5000 cycles was significantly higher in Group C than in Groups A and B, $p < 0.01$, whereas no significant differences were observed between Groups A and B, $p = 0.20$. Specimens in Group C failed after 11,584 [standard deviation (SD), 5924] cycles, significantly earlier than those in Groups A and B [A: 27,351 (SD, 12,509); B: 28,793 (SD, 14,764)], $p \leq 0.02$. Cycles to failure were not significantly different between Groups A and B, $p > 0.99$.

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The translational potential of this article: Parallel or divergent distal screw insertion provides similar construct stability in terms of resistance to plate lift-off. In contrast, converging screw insertion leads to inferior stability and is not advisable from a biomechanical point of view.

Introduction

Treatment of osteoporotic fractures remains one of the biggest challenges in trauma surgery [1]. New techniques and implants have been developed to improve stabilization at the bone–implant interface [2–4]. Osteoporosis-related low-energy hip fractures are the most frequent ones observed in elderly patients [5]. Among different surgical treatments of hip fractures, fixation with dynamic hip screw (DHS) has been established as the standard method of choice [6]. Good outcomes can be expected when treating stable fractures with DHS, whereas fixation of unstable fractures often can lead to unsatisfying results, especially in poor bone quality [7]. Apart from cut-out of the dynamic screw, the second most frequent failure type observed in the DHS is screw pull-out at the distal end of its side plate, leading to a plate lift-off from the femur shaft [8,9].

An elegant way to encounter plate lift-off in theory would be to improve screw fixation to bone by insertion in an inclined orientation. Several biomechanical tests have been performed to investigate the fixation strength of inclined locking screws [10,11] and the strength of nonlocking plate–screw constructs [12–15].

However, there is no consensus in the literature about the effect of screw orientation on the fixation strength. Dipaola et al [16] found higher pull-out forces in plates with screws oriented perpendicular to the plate versus screws placed at 12° inclination. Perren et al [11] investigated the biomechanical behaviour of locked parallel versus angulated plate–screw constructs. They found the highest pull-out force in constructs with 40° divergent angulated screws, whereas inclined screws did not improve the fixation strength when angulated up to 30°, regardless whether in diverging or converging fashion. Wähnert et al [10] compared different screw orientations in a model with locking plate–screw constructs under 0°, 10° and 20° diverging inclinations in terms of pull-out resistance. On the other hand, Robert et al [14] tested angulated screws in a range from 0° to 40° divergence in conventional plates using rigid polyurethane foam blocks. They reported significantly higher fixation strength with screws placed in divergent angles of 20° and 30°; however, when the screws were tested individually, the pull-out forces were higher for 0° screw orientation to the foam model than those of the constructs with angulated screws. Stoffel et al [12] investigated the fixation strength of conventional screw–plate constructs in polyurethane foam blocks under cantilever bending and concluded that placing a screw at the plate end in diverging inclination would increase the fixation strength.

To the best of our knowledge, there is no study comparing the fixation strength of differently inclined distal DHS nonlocking screws under dynamic cyclic loading. Therefore, the aim of the present study was to biomechanically compare the pull-out strength of distal two-hole DHS screws inserted neutrally applying the standard technique versus two alternative techniques with distal screw inclination in either convergent or divergent fashion in an artificial osteoporotic bone model. Focussing on a similar clinical question as in the study performed by Stoffel et al [12] and relying on their findings, this study tested the hypothesis that screw inclinations in both directions would significantly increase the pull-out strength compared to the standard technique.

Methods

Specimens and instrumentation

Thirty specimens, consisting of cylindrical polyurethane models (Generic Bone, Synbone AG, Zizers, Switzerland) with diameter and a length of 25 mm and 100 mm, respectively, and a density of 0.21 g/cm^3 [standard deviation (SD), 10%], were used as substitutes for osteoporotic femoral shafts. A two-hole 135° DHS steel side plate (DePuy Synthes, Zuchwil, Switzerland) was used to fix each specimen with two 32-mm-long 4.5-mm stainless-steel cortical screws. The specimens were assigned to three study groups with 10 specimens each (n = 10).

In Group A, the plate was fixed by inserting both screws parallel to each other and perpendicular to the plate surface, as shown in Figure 1A. In Group B, the proximal screw was inserted perpendicular to the plate, and the distal screw was inserted at a 30° inclination angle in diverging orientation, as shown in Figure 1B. For the fixation in Group C, the proximal screw was inserted again perpendicular to the plate, whereas the distal screw was inserted under an inclination angle of 30° in converging orientation, as shown in Figure 1C. The 30° inclination angle reflects approximately the maximum angle indicated for plates featuring holes for dynamic compression plating [17].

Each screw was inserted into a 3.2-mm pilot hole that was predrilled using a custom fixed-angle guide and subsequently tightened with 0.25 Nm using a dynamometric screw driver (#MT049, Mecmesin, Horsham, England). Finally, a DHS steel lag screw (DePuy Synthes, Zuchwil, Switzerland) was inserted through the barrel of the DHS plate, and a plastic ball of 35 mm diameter was screwed on it to resemble the femoral head. Sliding of the screw along

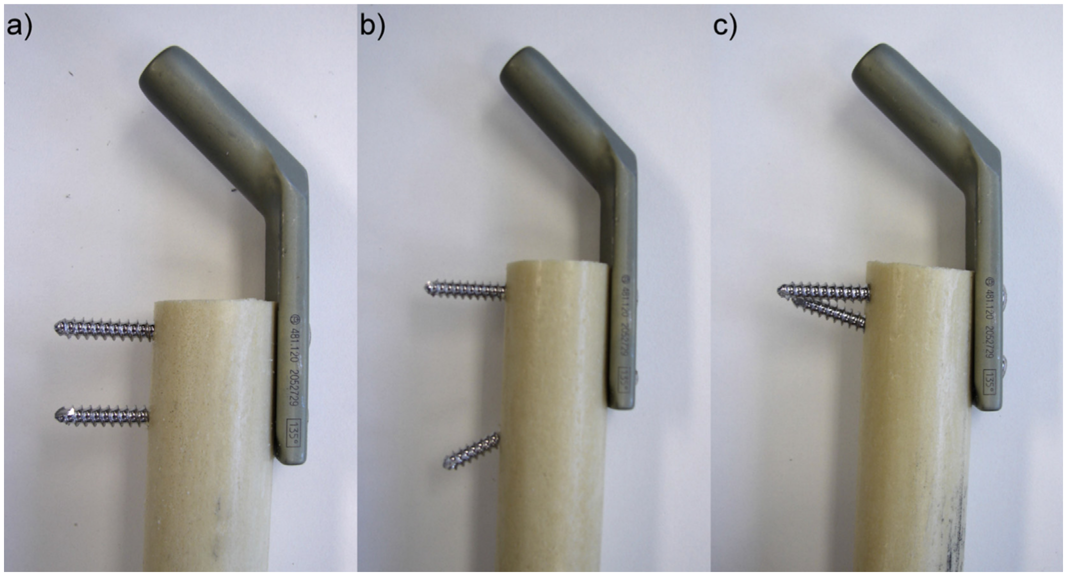

Figure 1 (A) Anteroposterior photographs of the DHS fixation in Group A; (B) anteroposterior photographs of the DHS fixation in Group B; (C) anteroposterior photographs of the DHS fixation in Group C.
DHS = dynamic hip screw.

the barrel was prevented in both directions by the ball and by a custom-made resistor that was fixed to the lateral side of the screw.

Mechanical testing

Mechanical testing was performed on a servohydraulic test system (Bionix 858.20; MTS Systems, Eden Prairie, MN, USA) equipped with a 4-kN/100-Nm load cell. The setup with a specimen mounted for testing is shown in Figure 2. A lever arm test setup was used to generate plate lift-off of the specimen constructs. The DHS was supported on a metal cylinder of 20-mm diameter at its junction between the barrel and the plate. In addition, the cylindrical polyurethane model was supported laterally at its distal end on a seesaw acting as a counter load. The DHS barrel of each specimen was aligned horizontally. The simulated femoral head was loaded in compression along the machine axis via a spherically shaped polymethylmethacrylate shell cup attached to the machine actuator.

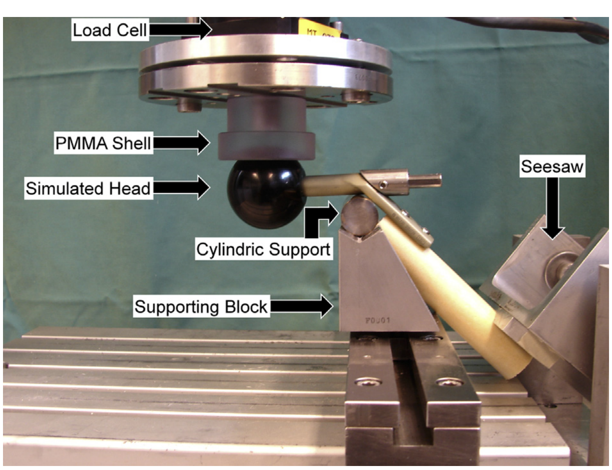

Figure 2 Test setup with a specimen mounted for mechanical testing.

Progressively increasing sinusoidal cyclic loading was applied at a rate of 5 Hz. Keeping the valley load of each cycle at a constant level of 20 N, the peak load, starting at 60 N, was increased at a rate of 0.002 N/cycle until the machine actuator reached a displacement of 10 mm, defined as a criterion for construct failure. The application of progressively increasing cyclic loading was found useful in previous studies [18,19].

Data acquisition and analysis

Machine data in terms of axial displacement (mm) and axial load (N) were acquired from the machine actuator and the load cell at a rate of 128 Hz. Construct stiffness (N/mm) was derived from the slope of the load–displacement curve of each specimen within a linear region at time points after 250, 1000 and 5000 cycles. In addition, machine actuator displacement was evaluated under peak loading at the same time points. The number of cycles until construct failure (cycles to failure) was computed together with the corresponding load at failure for each specimen separately. Finally, mode of failure was assessed via visual inspection of the specimens.

Statistical evaluation was performed using SPSS software package (IBM SPSS Statistics V21, IBM, Armonk, NY, USA). Descriptive statistics were run to calculate mean and SD of each parameter of interest in each group. Normal distribution and homogeneity of variance were screened and proved using Shapiro–Wilk and Levene tests, respectively. One-way analysis of variance with Bonferroni *post hoc tests* for multiple comparisons were conducted to assess statistical differences between the groups. A point biserial correlation was run to determine the relationship between the two parameters of interest, cycles to failure and mode of failure. The level of significance was set to 0.05 for all statistical tests.

Results

All parameters of interest were normally distributed within each group and with homogeneous variance among the three groups, $p \geq 0.081$.

Construct stiffness

The results for construct stiffness in each of the investigated time points are shown in Figure 3. The highest average values for construct stiffness after 250 cycles were observed in Group A with parallel inserted screws (64.1 N/mm; SD, 14.7), followed by Group B with diverging distal screws (61.4 N/mm; SD, 4.5) and Group C with converging distal screws (60.9 N/mm; SD, 13.7).

Construct stiffness after 1000 cycles was highest in Group B (61.7 N/mm; SD, 6.4), followed by Group A (58.5 N/mm; SD, 10.4) and Group C (57.4 N/mm; SD, 14.1).

After 5000 cycles, construct stiffness was with comparable values in Group C (66.2 N/mm; SD, 3.8) and Group B (66.1 N/mm; SD, 6.9), followed by Group A (60.7 N/mm; SD, 12.9).

No significant differences were registered among the groups for construct stiffness at each investigated time point, after 250, 1000 or 5000 cycles ($p \geq 0.45$).

Displacement

The results for actuator displacement at each of the three time points are shown in Figure 4. After 250 cycles, Group A was on average with the lowest displacement (0.84 mm; SD, 0.19), followed by Group B (1.07 mm; SD, 0.23) and Group C (1.57 mm; SD, 0.34). Groups A and B had significantly lower values than Group C ($p < 0.01$); however, no significant differences were detected between Groups A and B ($p = 0.20$).

The same tendency was observed for displacement after 1000 cycles, with Group A revealing the lowest values (0.99 mm; SD, 0.20), followed by Group B (1.21 mm; SD, 0.20) and Group C (2.07 mm; SD, 0.68). The displacement

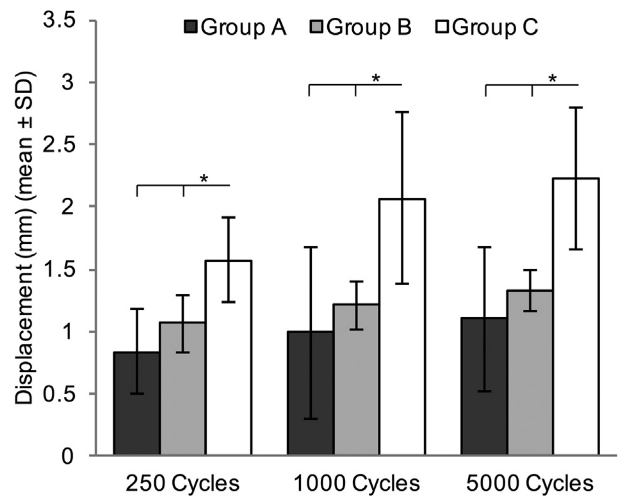

Figure 4 Diagram representing actuator displacement after 250 cycles, 1000 cycles and 5000 cycles in terms of mean and SD. Stars indicate significant difference.
SD = standard deviation.

values in Groups A and B were again significantly lower than that in Group C ($p < 0.01$), with no significant differences between these two groups ($p = 0.85$).

Similar results were observed for displacement after 5000 cycles, with the lowest values in Group A (1.10 mm; SD, 0.18), followed by Group B (1.33 mm; SD, 0.16) and Group C (2.22 mm; SD, 0.57). Displacements in Groups A and B differed significantly from those in Group C ($p < 0.01$). However, the differences between Groups A and B were not significant ($p = 0.55$).

Cycles to failure and corresponding load at failure

The number of cycles to failure and the corresponding load at failure were, respectively, 27,351 (SD, 12,509) and 87.4 N (SD, 12.5) for Group A, 28,793 (SD, 14,764) and 88.8 N (SD, 14.8) for Group B, and 11,584 (SD, 5924) and

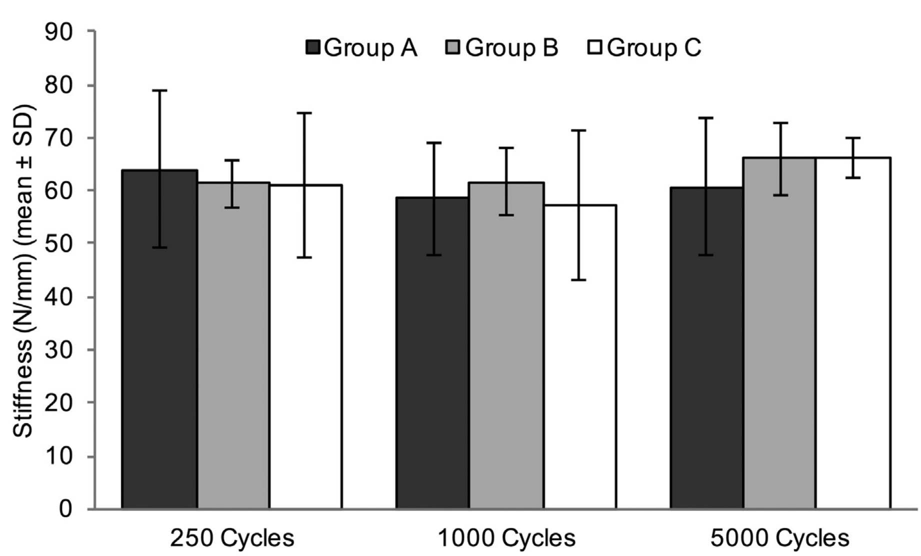

Figure 3 Diagram representing construct stiffness after 250 cycles, 1000 cycles and 5000 cycles in terms of mean and SD.
SD = standard deviation.

71.6 N (SD, 5.9) for Group C. The number of cycles to failure and the corresponding load at failure are shown in Table 1 for each specimen separately. Specimens in Groups A and B failed significantly later than the ones in Group C ($p < 0.02$). No significant differences were detected between Groups A and B ($p > 0.99$).

Mode of failure

Table 1 also indicates the failure mode of each specimen separately. Two exclusive construct failure modes were observed: pull-out of the distal screw and breakage of the bone model through the distal screw (Figure 5). The ratio pull-out to breakage in the groups was, respectively, 7:3 for Group A, 10:0 for Group B and 3:7 for Group C. The correlation between mode of failure and cycles to failure was weak and not significant for Group A (Pearson's $r = 0.030$, $p = 0.934$), but there was a strong positive correlation for Group C, which was significant (Pearson's $r = 0.665$, $p = 0.036$). For Group B, no statistics could be performed, considering pull-out as the exclusive failure mode.

Discussion

The aim of the present study was to investigate the holding strength of the DHS side plate in a simulated osteoporotic femoral shaft, considering three different insertion angles of its distal screw. The constructs with parallel and divergent inserted screws performed equally, revealed higher resistance in terms of displacement at different time points during the cyclic test and showed higher cycles to failure than the constructs with convergent screw insertion.

Bone mineral density is considered as the most important factor affecting the fixation strength of different bone—implant constructs [20]. Screw length, screw diameter and insertion torque have also been shown to influence construct stability [21]. The number of distal screws has also been addressed [22,23] in intertrochanteric fractures treated with a DHS, suggesting that more than four screws are not necessary to provide sufficient stability. Moreover, screws inserted at an inclined angle have shown to provide superior mechanical stability in multilevel anterior spinal instrumentation [24]. This approach could be transferred to prevent the DHS plate from lifting-off the lateral femur. It would be an elegant way to improve the fixation strength in the DHS plate—bone construct with the theoretical benefit of using shorter plates, allowing less invasive surgery [12,25].

However, the results of the present study could not confirm that diverging screws perform superiorly. The apparent advantage of screws inserted at an inclined angle is the longer bone-to-screw interface allowing to apply higher compression between bone and plate. This advantage is probably diminished by the asymmetrical stress the inclined screw is subjected to during pull-out loading, thereby losing the anchorage at the part of its thread facing the direction opposite to that of the applied load, as outlined by Perren et al [11]. The constructs with parallel and divergent screws resisted pulling forces equally. Surprisingly, converging screws showed inferior results. They displaced more and failed earlier. The stiffness, as a measure of the elastic response, remained on a similar level among all groups at each investigated time point; however, the plastic deformation, manifested by screw pull-out, was initiated at a lower peak load level in Group C than Groups A and B during cyclic loading. This comes along with the higher absolute level of displacement in Group C throughout the investigated time points. Therefore, construct stiffness is a less sensitive parameter than displacement, which is indicated in Figure A.1, showing 5-cycle load—displacement curves of each specimen at the time point after 5000 cycles. Although the ascending slopes of the curves indicate similar stiffness, the absolute displacement values are clearly distinguishable between the groups.

The mode of failure represented a further characteristic that distinguishes Group C from the other two groups. In this group, it correlated with the number of cycles to failure, showing that for its specimens, cut-out occurred after a rather lower number of cycles, in contrast to occurrence of fracture through the distal screw at a relatively later stage. Such a correlation was not evident for either of the other two groups. Generally, the constructs with parallel and divergent screw configurations tended to fail by screw pull-out, whereas those with convergent screw configuration favoured fracturing at the distal screw level. The high fracture rate in Group C may be ascribed to the proximity of the two screws at the trans-cortex side being a potential source of stress concentrations and therefore of earlier failure.

Our findings are supported by other studies only to a limited extent due to differences in used parameters. In

Table 1 Cycles to failure, corresponding load at failure and failure mode in the 3 groups, shown for each specimen separately.

Specimen	Group A			Group B			Group C		
	Cycles	Load	Failure	Cycles	Load	Failure	Cycles	Load	Failure
1	7610	67.6	Pull-out	10,728	70.7	Pull-out	13,627	73.6	Pull-out
2	19,850	79.9	Pull-out	34,764	94.8	Pull-out	17,291	77.3	Breakage
3	33,693	93.7	Pull-out	15,352	75.4	Pull-out	17,395	77.4	Breakage
4	22,947	82.9	Pull-out	1106	61.1	Pull-out	2283	62.3	Pull-out
5	20,964	81.0	Pull-out	35,382	95.4	Pull-out	1722	61.7	Pull-out
6	31,727	91.7	Breakage	33,830	93.8	Pull-out	14,667	74.7	Breakage
7	52,319	112.3	Pull-out	49,692	109.7	Pull-out	17,770	77.8	Breakage
8	35,717	95.7	Breakage	36,632	96.6	Pull-out	8893	68.9	Breakage
9	32,439	92.4	Pull-out	36,421	96.4	Pull-out	9350	69.4	Breakage
10	16,242	76.2	Breakage	34,025	94.0	Pull-out	12,842	72.8	Breakage

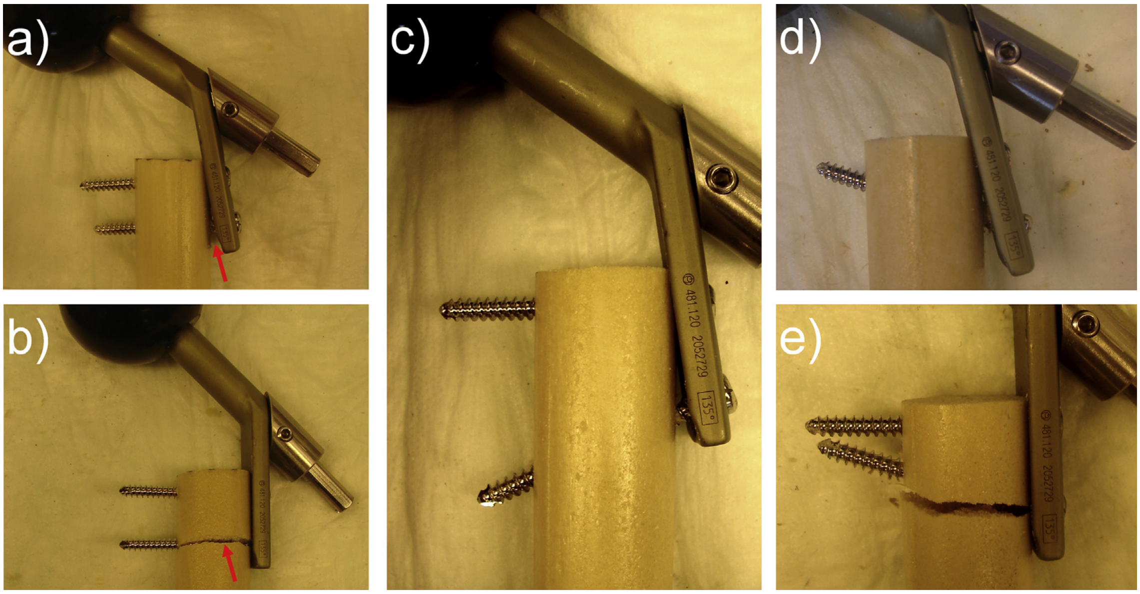

Figure 5 (A—B) Failure modes observed during mechanical testing in Group A; (C) failure mode observed during mechanical testing in Group B; (D—E) failure modes observed during mechanical testing in Group C. Screw pull-out, indicated by the red arrow in (A), was observed in 7 specimens of Group A (A), as exclusive failure mode in 10 specimens of Group B (C), and in 3 specimens of Group C (D). Breakage of the bone model through the distal screw, indicated by the red arrow in (B), was observed in 3 specimens of Group A (B) and in 7 specimens of Group C (E).

the biomechanical study of Amanatullah et al [26], the authors also reported lower construct stability with convergent screw configurations in malleolar fracture fixations. However, they investigated only bone-to-screw constructs without any plates. Other studies reported higher pull-out strength with converging or diverging screws [10—12,14,16], but all of them used other test parameters. Most of them were related to fixed-angle screws [10,11,16], whereas this study used standard cortical screws. Other authors [12,14] have tested screw—plate constructs using standard compression plates. However, they have applied quasi-static ramped loading, whereas our protocol included dynamic loading. We anticipate that dynamic loading gives more realistic feedback about the long-term behaviour of constructs and therefore better mimics the clinical situation. Moreover, information can be acquired about the fatigue resistance of a construct by application of such loading. Robert et al [14] tested constructs with screws inserted in neutral position against those in 10°, 20° and 30° divergent angulations under four-point bending, axial compression and axial torsion. The study probably most related to ours is published by Stoffel et al [12], who applied cantilever bending to screw—plate constructs in similar fashion to our setup.

One of the present study's limitations was the cantilever-like test setup designed to reproduce the lift-off phenomenon, thereby fostering screw pull-out while minimizing the risk of bone fracture. By applying compressive forces through the machine actuator, the DHS plate pivoted around the roller and initiated pulling forces on the screws directed perpendicularly to the axis of the cylindric bone model. We expect that plate lift-off underlies a similar mechanical principle of pivoting in clinical scenarios. Pilot tests have shown that it is practically impossible to reproduce screw pull-out in constructs loaded in a more physiologic manner under 20° lateral angulation of the simulated femoral axis with respect to the applied force. The setup in the present study was therefore inevitable and omitted compressive forces along the long bone axis, whereby they contribute clinically to additional shearing stresses on the screws.

However, bone fracturing could not be fully prevented. The underlying reason could have been the relatively weak bone model combined with a long distance between the distal screw and the lateral support, allowing excessive bending of the model and thus provoking damage around the distal screw. This low-density bone model was chosen to replicate the clinical scenario in which such plate lift-off failures occur and to express better the differences between the 3 groups. Synthetic bone material has the advantage of providing more homogeneous mechanical properties than cadaveric bone, the latter having higher variability and therefore being less suitable to compare the holding resistance of different screw configurations.

Finally, all specimens were tested at a rate of 5 Hz, which cannot be translated to physiologic conditions. Nevertheless, the machine actuator obeyed well the command signal for loading at this frequency (Figure B.1), and the parameters for the proportional—integral—derivative controller were held constant throughout all cyclic tests.

Conclusion

The present study showed more displacement and earlier failure when the distal screw is placed convergent into a DHS side plate and tested under presented loading parameters. This configuration should therefore be avoided from the biomechanical perspective. Moreover, no considerable differences were found between the fixation techniques with parallel and divergent placed screws regarding pull-out strength.

Conflict of interest

The authors have no conflicts of interest relevant to this article.

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Appendix

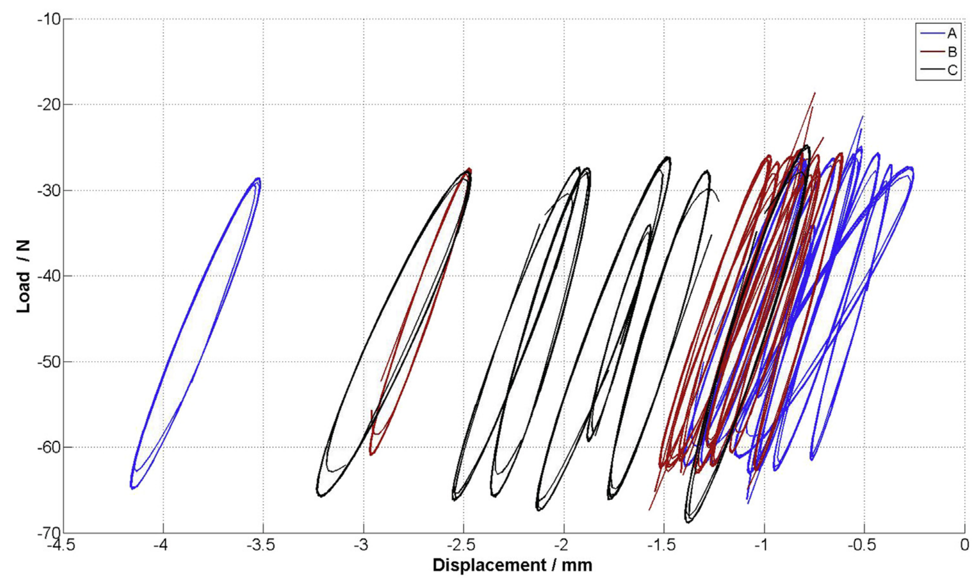

Figure A.1 Five-cycle load—displacement curves of all specimens in Group A (blue), Group B (red) and Group C (black) at the time point after 5000 cycles.

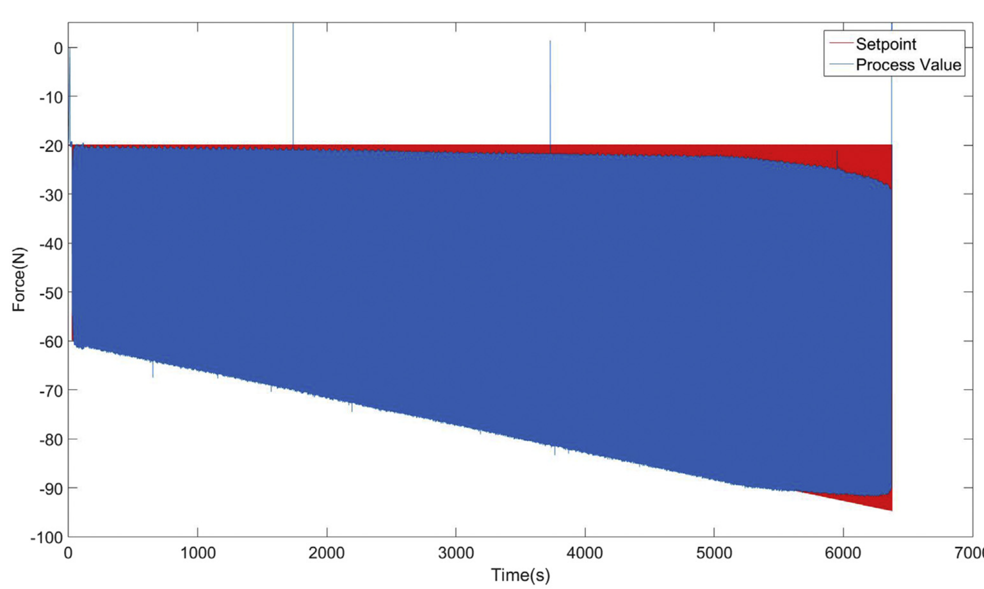

Figure B.1 Load—time curve of specimens that sustained more than 30,000 cycles, in terms of set point of the command signal (red) and processed value (blue), indicating a good match between them.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jot.2018.10.005.

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