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Interlocked Pins Increase Strength by a Lateral Spread of Load in Femoral Neck Fixation: a Cadaver Study

Zajištěné hřeby zvyšují tuhost fixace zlomenin krčku femuru vlivem laterálního rozložení zatížení: studie na kadáveru

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ABSTRACT

PURPOSE OF THE STUDY

To improve the important torsional, bending and compressive stability in femoral neck fixation, locking plates have been the latest contribution. However, increased strength by restricted fracture motion may come at expense of an altered load distribution and failure patterns. Within locking plate technology, the important intermediate fracture compression may principally be achieved by multiple sliding screws passing through a sideplate fixed to the femur or connected to an interlocking plate not fixed to the femur laterally, sliding “en bloc” with the plate. While biomechanical studies may deliver the short-time patient safety requirements in implant development, no adequate failure evaluation has been performed with interlocking devices ex vivo in this setting. In the present biomechanical study, we analysed if a novel femoral neck interlocking plate with pins could improve fixation performance by changing the parameters involved in the failure mechanism in terms of fixation strength, fracture motion, load distribution and failure pattern.

MATERIAL AND METHODS

Sixteen pairs of human femurs with stable subcapital osteotomies were fixated by 2 pins or 3 pins interlocked in a plate using a paired design. Femurs were loaded non-destructively to 10° torsion around the neck axis, 200 N anteroposterior bending and 500 N vertical compression in 7° adduction with 1 Hz in 20 000 cycles, and were subsequently subjected to destructive compression to evaluate failure patterns. Bending stiffness, compressive stiffness and displacement from compressive testing reflected fracture motion. Torque and compression to failure replicated known failure mechanisms and defined strength. To evaluate load distribution, associations between biomechanical parameters and measured local bone mineral measurements by quantitative CT were analysed.

RESULTS

Interlocked pins increased mean strength 73% in torsion and 39% in compression ($p = 0.038$). Strength was related to all 4 regional mineral masses from the femoral head to subtrochanterically with interlocking ($r = 0.64–0.83$, $p = 0.034$), while only to mineral masses in the femoral head in compression and to the head, neck and trochanterically in torsion with individual pins ($r = 0.67–0.78$, $p = 0.024$). No difference was detected in fracture motion or failure pattern.

DISCUSSION

Within the last decade, angular stable implants have expanded our therapeutic arsenal of femoral neck fractures. Increased stability at the expense of altered devastating failure patterns was not retrieved in our study. The broadened understanding of the effect of interlocking pins by an isolated plate as in the current study involved the feature to gain fixation strength. By permitting fracture compression, and through a significant change of correlations between mechanical parameters and local bone mineral factors, a lateral redistribution of load with interlocked pins from the fragile bone medially to the more solid lateral bone was demonstrated. Regarding the long-term patient safety of interlocked pins and healing complications of non-union and segmental collapse of the femoral head, a definite conclusion may be premature. However, the improved biomechanics of an interlocking plate must be considered a favourable development of the pin concept.

CONCLUSIONS

Interlocked pins may improve fixation performance by a better load distribution, not by restricting fracture motion with corresponding altered failure patterns. This is encouraging and a challenge to complete further studies of the interlocking plate technology in the struggle to find the optimal treatment of the femoral neck fracture.

Key words: femoral neck fracture, biomechanics, cadaver bone, bone mineral, internal fixation, locking plate, interlocked pins.

INTRODUCTION

Intracapsular femoral neck fractures comprise more than half of the common proximal femur fractures (13) with subcapital fractures as the most frequent type (12). The key complication with failure of the fracture to heal is determined by a pattern of torsional, bending and compressive instability (24, 27–28). High revision rates of 11–27% remain with internal fixation as the main treatment in non-displaced fractures and in middle-aged patients with displaced fractures (3, 14). No clear conclusion can be drawn between the traditional multiple screws, pins or a sliding hip screw (SHS) device on which implant is superior in this setting (12, 25).

To improve results, the use of locking plates has been the latest attempt. However, improved stability by locking plates restricting fracture motion with non-parallel screws, may change load distribution and come at cost of altered failure patterns of implant fatigue or cut-out both ex et in vivo (2, 7).

An advancement in the management of intracapsular fractures was suggested by the first published consecutive patient series using a locking plate with multiple telescoping screws permitting sliding with intermediate fracture compression (Targon Femoral Neck Plate, Aesculap, Tuttlingen, Germany) (20, 23, 26). Important comparative studies revealed lower rates of non-union and revision surgery with this implant in comparison with cannulated screws (1, 32), less subsidence of the head fragment and a lower rate of cut-out and conversion to hemiarthroplasty when compared to an SHS (11). So far, the question regarding the importance and real benefit for clinical practice is best answered by a meta-analysis of existing evidence documenting a reduced reoperation rate with this type of locking plate technology in comparison to the conventional fixation methods (35). The alternative to achieve intermediate fracture site compression as with parallel sliding screws locked in a sideplate fixed to the femur, is parallel screws interlocked in a plate not fixed to femur laterally, sliding en bloc with the plate. Currently, only improved stability from dynamic testing simulating partial or full weight-bearing has been reported by this novel fixation principle of interlocking screws by a plate not fixed to bone (4, 5).

Recently, the first interlocked pins have been developed from the original two Hansson pins (31). Enhanced torsional stability has been reported by the implant modification with a triangular pin configuration in synthetic bone blocks (10) (Fig. 1). A sufficient reduction to decrease reoperation rates was emphasized in the first patients (34). Concerns of increased stability at the expense of early devastating subtrochanteric fractures or later segmental collapse have been raised in the first randomised controlled trial (18). To our knowledge, there is a lack of biomechanical data to support these concerns.

The purpose of the current study was to perform an adequate failure evaluation of the interlocking fixation principle and evaluate if interlocked and traditional pins differ regarding strength, fracture motion, load distribution and failure pattern in intracapsular femoral neck fixation ex vivo. We hypothesised improved fixation stability without restricted fracture motion or altered fracture pattern by the novel implant as intended with the new implant design.

Fig. 1. The novel implant. The Hansson Pinloc® System with three pins in a top down triangular configuration interlocked in a plate laterally. The feature of a hook at the tip is unchanged from the original Hansson pin. The 4 commercially available plate sizes; 6, 8, 10 and 12 mm according to the length of the bridge between the proximal and distal pin hole from top.

MATERIAL AND METHODS

Specimen preparation

Following approval by the regional ethics committee, 16 pairs of fresh-frozen femurs from Caucasian donors without significant bone pathology were imported (Life Legacy Foundation, Tucson, AZ, USA); ten females and six males with a median age of 73 years (range, 60–78 years) and weight of 58 kg (37–91 kg). Before evaluation, the proximal femurs were thawed in room temperature overnight.

Guide-wire templates allowed a paired maximum distance between the parallel proximal and distal pins of 6, 8, 10 or 12 mm, in agreement with plate sizes and the stabilising impact by increased distance between pins (10). With three-pointed support, the first guide-wire was advanced in parallel with the neck along the femoral calcar until subchondrally, while the second was shifted posteriorly. With interlocked pins, a third guide-wire was shifted anteriorly to form a top-down isosceles triangle. Adequate positioning was controlled by fluoroscopy, guide-wires were over-drilled with a 6.7-mm drill bit and then removed.

Following pre-drilling, the femoral necks were osteotomised perpendicularly subcapitally with a hacksaw, according to AO/OTA 31-B1.2 (21).

The right femur of each pair was allocated at http://randomization.com. Individual pins were implanted with the original clinical configuration of two pins or three pins interlocked in the novel plate, resulting both in locking and an additional pin, with the same pin-lengths as the corresponding alternative in each pair (Fig. 2). To reduce variability, the same surgeon (JEB) performed all operations. To detect alterations by the

Fig. 2. The test models. Fluoroscopic images of one pair of fixated cadaveric proximal femurs with a subcapital osteotomy perpendicular to the central femoral neck axis. To the left the novel femoral neck plate interlocking three pins, the original fixation configuration by two individual pins to the right.

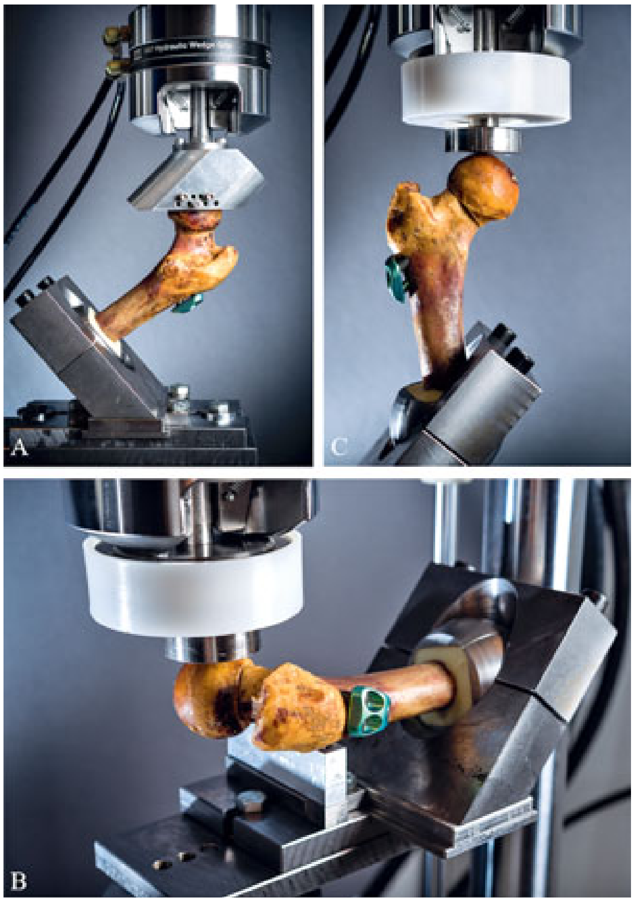

Fig. 3. The test directions.
A – testing in torsion around the femoral neck length axis,
B – anteroposterior bending test in simulated sitting position,
C – axial compression test in simulated standing position.

implant modification, the optimal configuration of three interlocked pins has already been reported (10). The predecessor represented the natural control group, supported by two Hansson pins being the most frequently evaluated pin design within randomised clinical trials and the lack of superiority between traditional implants (25).

The Hansson Pinloc® System (Swemac Innovations, Linköping, Sweden) was applied with pins of titanium alloy grade 5 with 6.5 mm shaft diameter. The four plate sizes were applied in four pairs each. The reinforced, threaded pin-base allowed interlocking into the aluminium plate at 125° before the inner tongue was introduced in the head.

Mechanical testing

The 150 mm long proximal femurs were cemented distally (Biomet Orthopaedics GmbH, Dietkon, Switzerland) and mounted in a testing machine (MiniBionix 858 MTS Systems, Eden Prairie, MN, USA) with a load cell with respective axial and torsional characteristics; capacity 10 kN and 100 Nm, resolution 1 N and 5 Nmm, displacement 0.001 mm and 0.1º, accuracy < 0.5% and sampling 0.01 s. The piston´s load and displacement were recorded by a computer (MTS FlexTest 40 with Station Manager, Eden Prairie, MN, USA).

Firstly, three quasi-static non-destructive tests were performed three times each with a 30 N vertical preload (Fig. 3). In a steel-cup simulating acetabulum, the head was superficially screw-fixated and subjected to a torsional testing rate of 1º/s both ways around the neck´s length axis with 10º as the maximum value. This was done to keep results within the elastic range by almost perfect correlation to initial stiffness (10) and still reflect displacement associated with an increased risk of nonunion (27). To avoid shear accumulation, a low-friction piston applied load on the femoral head in the following tests (rate 200 N/s, maximum bending 200 N, maximum compression 500 N). In anteroposterior bending, horizontally-oriented specimens were loaded vertically to simulate the load direction when sitting down (6), while a support beneath the minor trochanter isolated displacement to the fracture region, i.e. as in fracture motion. In compressive tests, vertical specimens with 7º adduction simulated the load direction during one-leg stance (6).

Subsequent dynamic compression with a sinusoidal loading pattern (rate 1 Hz, cycles 20 000, preload 60 N) was applied to simulate a relevant number of steps until consolidation with partial weight-bearing of one-time median bodyweight of donors in our study (2, 6, 19).

Finally, to simulate subtrochanteric fracturing, a quasi-static compressive load-to-failure (LTF) was tested (rate 250 N/s, maximum load 10 kN, preload 60 N), as hip joint reaction force may exceed eight times bodyweight during stumbling (6). After testing, the failure patterns were inspected.

Regarding the choice of outcomes, the best line fit of the slope of the load-deformation curve's linear elastic portion defined stiffness in bending and compression, while displacement was measured after cycling. These parameters were chosen to reflect fracture motion at a low loading level, while in overloading this was reflected by displacement at failure. Torque at risk of failure (10º) (TAF) (10) and LTF exposed respective torsional and compressive strength. The compressive failure was defined by abrupt increment or 10 mm distal displacement, as in fractures that subsequently did not heal (28). The term "pro-interlocking" refers to the proportion how often the interlocked specimens outperformed the paired individual pins.

Bone mineral assessment

Before specimen preparation, a quantitative CT (QCT) with bone scan parameters (100 mA, 120 kV, 3 mm slices) was performed in a Siemens Somatom Definition Edge (Siemens Healthcare GmbH, Erlangen, Germany). QCT allows presenting cortical and cancellous bone densities as volumetric density per unit of area (CT-density/cm^2) without considering slice thickness, presumed infinitely thin. In densities above -100 HU (threshold value representing fat), mineral density estimation with excellent reproducibility and accuracy is possible (15).

The bone mineral assessment was modelled after previous work by our laboratory and intended to reflect load distribution, as local femoral mineral mass may predict fixation strength by variable cancellous density in mainly spongy bone and cortical area in compact bone (33).

Syngo.via imaging software (Siemens Healthcare GmbH, Erlangen, Germany) was used to measure bone mineral by the same instructed operator. The levels of three-pointed pin support and the subtrochanteric level possibly involved in its failure were analysed in four slices; the cross-sectional slice in the mid-head, -neck, -trochanter (halfway between the greater trochanter´s tip and the minor's lower border) and 20 mm distal to the minor (Fig. 4). A region of interest (ROI) was drawn around the external cortex to obtain bone area, around the internal cortex to derive the medullary/cancellous area, with cortical area as the difference between these regions. To assess mean cancellous density, the medullary area was analysed, while with cortical density, a 5 mm^2 ROI was placed exclusively within the homogenous cortex. The regional bone mineral mass was calculated as the summarised product of cancellous and cortical area and density in each slice. No difference in regional bone mineral mass was detected between the groups of individual and interlocked pins, neither in the femoral head, neck, trochanterically nor subtrochanterically ($p = 0.217$).

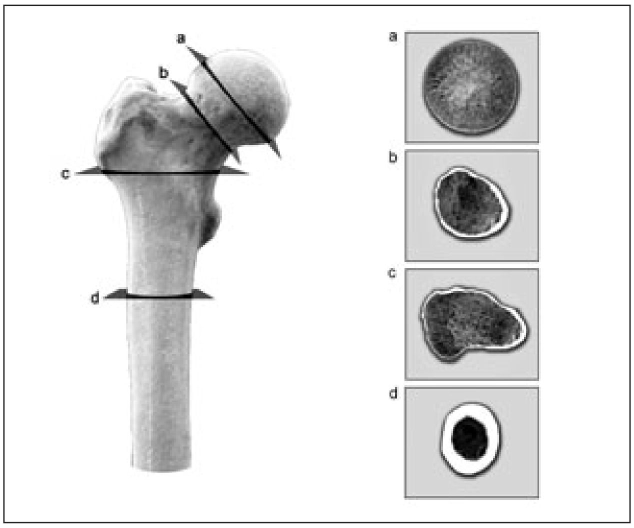

Fig. 4. The bone mineral parameters. To the left a proximal femur with marked levels for CT-slices for quantitative bone mineral analysis. To the right the corresponding cross-sectional CT images.
A – perpendicular to the central femoral neck axis in the mid-head,
B – the mid-neck,
C – the shaft halfway between the greater trochanter´s top and the lower border of the minor,
D – the subtrochanteric area 2 cm below the trochanter minor.

Statistics

As powering for failure rate was not considered feasible, a sample-size calculation with a minimal important difference of 2 mm fracture displacement and 1.5 mm standard deviation, revealed that 8 pairs were needed to complete testing and achieve 90% power (STATA, StataCorp, College Station, TX, US).

Data were processed by MATLAB (MathWorks Inc, Natick, MA, USA), tested for normality (Shapiro-Wilk) and homoscedasticity (Levene's test) and further analysed by IBM SPSS Statistics (SPSS Inc. Chicago, IL, USA). Beside descriptive statistics, paired t-tests, one-way analyses of variance and post-hoc tests with Bonferroni correction were computed with continuous parameters and McNemar´s test with categorical variables. Results were expressed as mean or median with range or standard deviation. A Pearson correlation analysis was performed between bone mineral and biomechanical parameters. All tests were two-tailed and assessed at the 5% significance level.

RESULTS

The biomechanical parameters with comparisons are presented (Table 1). A technical error caused failures of three pairs during bending and further two pairs failed by displacement in cyclic compression and were excluded from further analysis. The remaining 11 pairs showed linear elastic load-displacement curves prior to LTF.

Considering strength (TAF and LTF), interlocked pins outperformed individual pins in all pairs. TAF was 6.2 Nm (SD 3.8 Nm) in individual pins and 10.7 Nm (SD 4.9 Nm) in interlocked pins with a mean increase of 73% ($p < 0.001$). LTF was 2034 N (SD 793 N) in individual pins and 2827 N (SD 1405 N) in interlocked pins with a mean increase of 39% ($p = 0.038$).

No significant difference was found regarding fracture motion. Pro-interlocking ratio in bending stiffness was 10/13 ($p = 0.09$), compressive stiffness 4/13 and displacement 7/11. No difference was detected in displacement at failure ($p = 0.477$).

In LTF, the failure pattern affected all points of three-pointed fixation in both groups. Femoral head compression and a transverse subtrochanteric fracture developed in all specimens and a medial fissure along the calcar in five individual and two interlocked specimens ($p = 0.371$). No other failure signs were identified.

Table 1. Biomechanical comparison of fixations in three load directions

Fixation method	Torque at failure (Nm)	Bending stiffness (N/mm)	Compressive stiffness (N/mm)	Displacement (mm)	Load to failure (N)	Displacement at failure (mm)
Interlocked pins	10.7 (4.9)	201 (64)	631 (186)	1.6 (0.8)	2827 (1405)	5.2 (3.0)
Individual pins	6.2(3.8)	193 (73)	658 (178)	1.9 (1.0)	2034 (793)	6.2 (3.5)
Interlocked/individual pins	1.73*	1.04	0.96	0.84	1.39*	1.20
"Pro-interlocking"	16/16*	10/13	4/13	7/11	11/11*	4/11

Mean values with standard deviation (SD) in parentheses.
*Indicate statistical significant difference ($p < 0.05$).
"Pro-interlocking" refers to the proportion of how often the interlocked pins outperformed the paired individual pins.

Table 2. Bone mineral parameters from 16 pairs of proximal femurs with comparisons

Bone mineral parameter/ CT level	Cancellous area (cm^2)	Cancellous density (HU/cm^2)	Cortical area (cm^2)	Cortical density (HU/cm^2)	Cancellous mineral mass (HU)	Cortical mineral mass (HU)	Bone mineral mass (HU)
Femoral mid-head	15.2 (2.7) a	255 (69)a	2.1 (0.4) b	789 (193) b	3897 (1267) a	1650 (501) b	5544 (1442) b
Cervical mid-neck	5.9 (1.2) b	52 (61) b	1.7 (0.3) b	1690 (198) a	298 (366) c	2933 (629) c	3231 (727) c
Mid-trochanter	13.8 (2.9) a	77 (48) b	3.8 (0.6) a	1701 (124) a	1071 (646) b	6396 (1269) a	7466 (1718) a
Sub-trochanter	2.9 (0.7) c	-46* (57) c	4.0 (1.0) a	1598 (306) a	-123 (121) c	6307 (1900) a	6184 (1909) b

Mean values with standard deviation (SD) in parentheses.
A mean proximal femur value for each pair with SD was calculated based on the analysed CT-slices.
Different small letters within the same column indicate different parameter values in comparisons between the CT levels for each parameter, ($a \neq b \neq c$, $p < 0.05$).
*Negative value represents fat without calcium

Table 3a. Correlations of biomechanical versus mineral parameters in the proximal femur

Fixation	Bone mineral mass/ Biomechanical parameter	Caput	Collum	Trochanter	Subtrochanter
Interlocked pins	Torque at risk of failure (TAF)	0.69**	0.83**	0.74**	0.70**
	Bending stiffness	0.28	0.18	-0.06	0.12
	Compressive stiffness	0.33	0.13	-0.06	0.08
	Compressive deformation	-0.57	-0.58	-0.28	-0.53
	Compressive load to failure (LTF)	0.64*	0.80**	0.72*	0.73*
	Compressive displacement at failure	0.38	0.22	0.33	0.42
Individual pins	Torque at risk of failure (TAF)	0.78**	0.74**	0.78**	0.46
	Bending stiffness	0.29	0.17	0.33	-0.12
	Compressive stiffness	0.64*	0.63*	0.49	0.01
	Compressive deformation	-0.63*	-0.54	-0.51	-0.17
	Compressive load to failure (LTF)	0.67*	0.50	0.46	0.47
	Compressive displacement at failure	0.41	0.38	0.39	0.40

* Correlation significant at the 0.05 level.
** Correlation significant at the 0.01 level.

The proximal femur's mineral parameters with statistics are presented (Table 2). The femoral head exposed the highest cancellous mineral density and mass, while the trochantanteric and subtrochanteric level revealed the highest cortical mineral area and mass and the proximal femur´s lowest regional bone mineral mass in the femoral neck ($p < 0.001$).

The significant correlations between biomechanical and bone mineral parameters in both groups (Table 3a) were confined to between the proximal femur's regional mineral mass and strength. Interlocked pin strength was related to all regional mineral masses from the femoral head to subtrochanterically ($r = 0.64$–0.83, $p = 0.034$). In difference, individual pins were only significantly correlated to the femoral head mineral mass in LTF ($r = 0.67$, $p = 0.024$) and not to the subtrochanteric mineral mass with TAF ($r = 0.46$, $p = 0.085$) (Fig. 5). In subgroups (Table 3b), the significant correlations were

Table 3b. Correlations of biomechanical versus mineral parameters in the proximal femur subgroups

Fixation	Biomechanical parameter	Bone mineral parameter	Location:	Caput	Collum	Trochanter	Subtrochanter
Interlocked pins	TAF	Cancellous density		0.46	0.47	0.66**	-0.04
		Cancellous area		0.58*	0.35	0.24	-0.52*
		Cortical density		-0.13	0.32	0.19	-0.12
		Cortical area		0.48	0.67**	0.65**	0.67**
	LTF	Cancellous density		0.54	0.43	0.53	-0.29
		Cancellous area		0.57	0.49	0.42	-0.67*
		Cortical density		-0.39	0.31	0.28	-0.10
		Cortical area		0.15	0.64*	0.59	0.69*
Individual pins	TAF	Cancellous density		0.59*	0.61*	0.70**	0.16
		Cancellous area		0.53*	0.34	0.28	-0.44
		Cortical density		-0.09	0.18	0.33	-0.05
		Cortical area		0.64*	0.50	0.61*	0.69*
	LTF	Cancellous density		0.72*	0.81**	0.43	0.38
		Cancellous area		0.19	0.23	0.23	-0.26
		Cortical density		0.09	0.00	0.40	0.18
		Cortical area		0.31	0.22	0.38	0.38

* Correlation significant at the 0.05 level.
** Correlation significant at the 0.01 level.

limited to density of spongy bone and area of compact bone (r = 0.59–0.81, p = 0.017), with the cancellous area in the femoral head (r = 0.53–0.58, p = 0.036) and its absence subtrochanterically as the only contradictions (r = -0.67– -0.52, p = 0.039). In the pin group, 6/9 significant correlations were to medial parameters; 5 to cancellous density and 3 to cortical area. With interlocked pins, 6/9 significant correlations were to lateral parameters; 1 to cancellous density and 5 to cortical area.

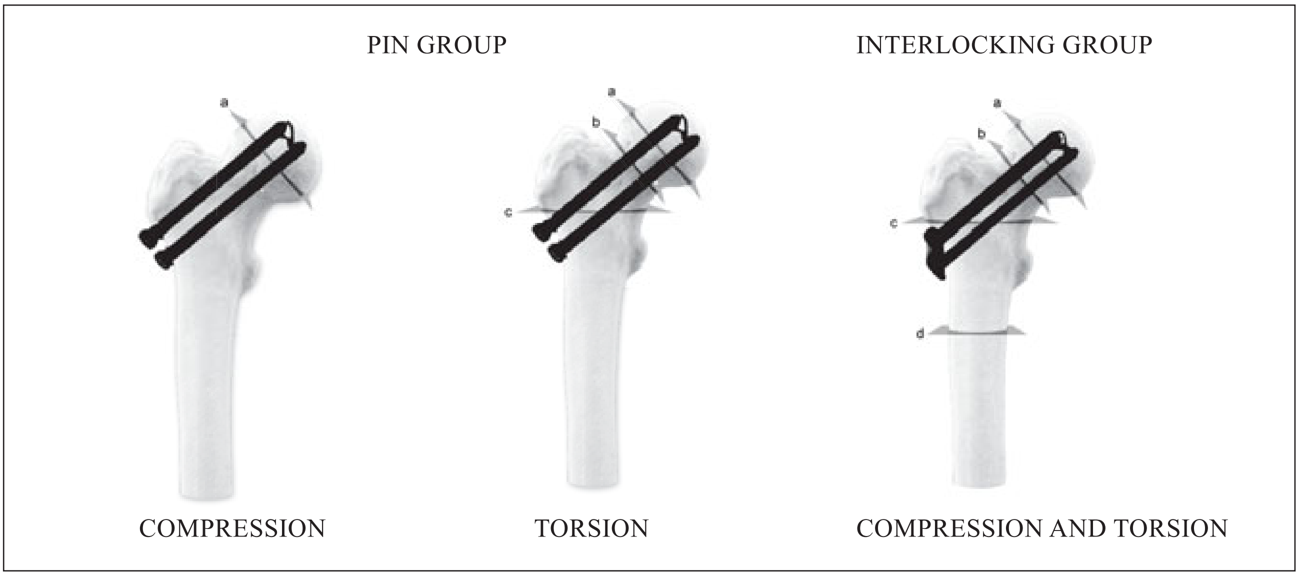

Fig. 5. The proximal femur´s load distribution with comparison of implants. The set of significant correlations between regional mineral masses and strength in compression and torsion are illustrated by the actual cross-sectional slices both within pin and interlocking group. In theory, with application of load on the femoral head as in the current study, load is transferred through the implant and absorbed by bone mineral along the pins in the regions involved in 3-pointed support and subtrochantericallly, which is potentially involved in the failure pattern initiation (A–D; for definitions, please see Fig. 4). By improved load distribution, overloading of the weakest point medially within pin group may be prevented within the interlocking group, while the hold in more solid and stiff bone laterally is utilized to increase fixation strength.

DISCUSSION

In the current study of intracapsular femoral neck fixation ex vivo, interlocked pins increased strength with a lateral shift of bone mineral parameters predicting strength, while no change in fracture motion or failure pattern were detected when compared to individual pins.

The locking plate design combines the medial hold in the femoral head with multiple screws and the lateral hold by an SHS to enhance fixation strength (26). While active screw compression may increase stability and an SHS compresses passively, the locking plates differ regarding the amount of interfragmentary compression permitted and handling them as a group may not be right.

The genuine locking plates do not only restrict motion between screws and plates, but also at the fracture site. This may be accomplished by non-parallel locking screws, which have been reported to increase stability, but the increased load-sharing by implants may result in a change of failure patterns with implant fatigue and cut-out ex vivo (2). In addition, the alternative design to prevent fracture motion by fully-threaded parallel locking screws may come at cost of an induced failure at an earlier time interval during testing (16).

The locking plates with sliding screws permitting intermediate compression may increase torsional and compressive stability in comparison with cannulated screws and an SHS (9). No change in failure pattern has been found in comparison to other fixed-angle fixations ex vivo (30), but concerns of an underestimated cut-out rate in reported case series have been explained by increased load-sharing with such an implant in unstable fractures (8).

The interlocking plate is designed to achieve intermediate compression safely and has been reported to moderately reduce, yet preserve micro-motions and translations (4, 5). This complies with the lack of difference regarding fracture motion in the current study, which indicates that femoral neck compression is permitted as the plate leaves the trochanteric wall.

Increased torsional stability by the Hansson Pinloc® System was previously reported in comparison to the original pin configuration; both by the interlocking plate per se, its size and triangular shape allowing a third pin (10). This complies with the enhanced torsional stability in the current study. Regarding comparison to other ex vivo studies with a similar implant design, interlocking 3 screws reduced torsional micromotions, while no difference in other rotations, translations or load distribution was found (4). However, the reduced compressive displacement and no impact on torsional displacement by interlocking screws in another report make a clear conclusion challenging (5). The added torsional and compressive strength in the present study elaborate further on the stabilising potential of such devices.

While the advantage of a good medial anchorage in the femoral head with multiple screws or pins may provide some rotational stability, the poor hold of the fracture laterally with such implants may be a limiting factor (26). The apparently more pronounced impact on torsional stability by interlocked pins in the current study may be attributed an enhanced lateral fixation by the plate, i.e. an ability to better neutralise torque around the femoral neck axis by interlocking pins. Contrarily, the permitted fracture compression and apparently less improved compressive stability may reflect the inability to neutralize vertical compression with a sideplate not fixated to the femur laterally.

The significant correlations between mechanical performance and bone mineral density measured by dual-energy X-ray absorptiometry (DEXA) have already been reported with locking plates with sliding screws, cannulated screws and an SHS (9). Correspondingly, femoral head bone mineral density measured by high-resolution peripheral quantitative computed tomography has been reported to influence performance with such fixations (30). In difference, no association between performance and osteoporosis and no impact on load distribution were reported by interlocking screws during physiological loading levels (4). We found a lateral shift in the set of local bone mineral parameters associated with fixation strength – apparently from the medial hold in fragile bone with pins to the lateral hold in solid compact bone with interlocked pins. The increased compressive and torsional strength indicated an improved load distribution by spreading femoral head loadings along the three-pointed support of each pin in a lateral direction with the interlocking device (Fig. 5). Principally, the interlocking plate ensures equally distributed load amongst and along pins and underlay the interpretation of the mechanism of action as a lateral spread of load.

An increased load at the proximal femur's lateral aspects, where tensile forces are substantial, is suggestive of a subtrochanteric failure initiation. A different fracture pattern originating from the lateral screw-holes with interlocking has already been suggested (5). In agreement with our results no such failure pattern has been reported clinically so far (18, 34).

To the best of our knowledge, this is the first study to evaluate the failure of a femoral neck fracture interlocking fixation device involving both load to failure and failure pattern recognition. We did not only attempt to explain the mechanism of action of increased fixation stability despite permitting fracture motion, but also identified the risk of an altered point of failure initiation by a possible change in load distribution, which was indirectly evaluated by QCT.

The angular stable implants have expanded our therapeutic arsenal of femoral neck fractures. The increased stability at the expense of altered devastating failure patterns was not retrieved in our study. The broadened understanding of interlocking pins by a plate as in our study involved the feature to gain fixation strength by permitting fracture compression and a lateral spread of load from local bone mineral factors in the fragile bone medially with pins to the more solid lateral bone with interlocked pins. Considering the long-term patient safety with healing complications of non-union and segmental collapse of the femoral head of interlocked pins, a definite conclusion may be premature. Regarding the clinical relevance of our findings, the safe biomechanical impact may be too low to gain long-term clinical importance by interlocking pins. Consistently, similar union rates have been reported by comparing the new device to the predecessor (18), but possible biases of a learning curve and multi-centre trial may apply. Hence, a definite conclusion may be premature. However, the improved biomechanics must be considered a favourable development of the pin concept.

Limitations are noted. To correct for material properties only titanium pins were used, but results should also be transferable to the original hook-pins in steel. To simulate a non-displaced or an anatomically reduced fracture, a representative stable subcapital osteotomy was chosen. These results nuance the profound torsional impact by interlocked pins in an unstable mid-cervical osteotomy (10) and may also differ from results with a genuine fracture. While a paired study in human bone is considered beneficial, this approach only permitted evaluating the implant as a unit. A stepwise impact by the implant modification has previously been reported mainly by the plate, but also by the third pin in torsion (10) and both these changes underlay our findings. The obvious limitation by specimens without soft tissue and the responses of bone healing in the long-term complete the limitations of the test model.

We tested relevant strengths and weaknesses of the fixations by provoking failure as with the subtrochanteric fracture by axial load reported previously (22), but it is unclear which load combination that causes fracture clinically. However, the failure mechanism may have been better distinguished by a high-speed digital camera with strain measurements by digital image correlation, which was not in the amenities of our lab. In correspondence with our findings, an increased load to an unaltered transverse or oblique subtrochanteric fracture preceded the recommendation of the top-down triangular implant orientations (22), as the benefit of ex vivo failure evaluations is to deliver the short-time patient safety (29).

Regarding choice of set-up, point-based strain measurements did not reveal any difference by interlocking screws within physiological loading (4), while the current correlation analysis of implant performance and hold reflected load-dependent measurements related to local bone mineral parameters when simulating clinical interesting failure mechanisms. This justified interpreting the relationship as stress in different regions or as load distribution. We did not measure strain directly, but argue that the interpretations on load distribution provide additional info in comparison to isolated measurements of strain.

While no normative femoral mineral data exists by QCT, the measured densities with variation were within the normal ranges and known associations between strength and local bone mineral parameters were retrieved (33). As bone mineral density measured by DEXA and CT are correlated (17) our findings may be extrapolated to the setting of low bone mineral content.

Regarding the choice of statistics, a correlation does not imply causality. Although, the reasonable system of correlations suggests a causal relationship, a larger sample-size is necessary to perform a multiple regression and reveal the factors´ relative importance.

CONCLUSIONS

In agreement with our hypothesis, femoral neck fixation by multiple interlocked pins may increase fixation stability by a possibly change in load distribution. By allowing fracture motion, the failure pattern appears to be without alterations, which is encouraging of the introduction and further studies of the interlocking plate technology.

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