Original Clinical Article

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Biomechanical considerations in slipped capital femoral epiphysis and insights into prophylactic fixation

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Abstract

Purpose Slipped capital femoral epiphysis (SCFE) is a deformity of the proximal femur secondary to widened and unstable physis. In stabilising the slip, gold standard treatments stop growth and involve premature physeal closure, which prevents the remodelling of the acquired deformity and creates a leg length discrepancy that may be significant in younger patients.

Methods We measured the impact of placing threaded screws across the proximal femoral physis by measuring the centre-trochanteric distance (CTD) and articulo-trochanteric distance (ATD) in participants with or without prophylactic fixation. We then compared the mechanical performance of static (stainless and titanium cannulated Synthes screws) and potentially growing implants (Synthes SCFE screw and Pega Medical Free Gliding screw) in a validated synthetic bone model.

Results In the review of 30 non-fixed and 60 fixated hips over a mean follow-up of 1.9 years, we have noted a significant difference in pre/post CTD and ATD, as well as the change in CTD and ATD over time. In the biomechanical study, the newer implants allowing growth (Synthes SCFE screw and Pega Medical Free Gliding screw) were both shown to be at least non-inferior.

Conclusions The primary deformity of a SCFE in itself alters hip mechanics. Also, as confirmed in this study, there is a secondary deformity that is created by static fixation and relative trochanteric overgrowth. To help remodel mild deformities and prevent secondary trochanteric overgrowth, growing implants seem to be non-inferior to the more standard means of fixation in static testing.

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Keywords: Slipped capital femoral epiphysis; SCFE; SUFE; fixation; growing

Introduction

Biomechanics

Where does a slipped capital femoral epiphysis (SCFE) biomechanically start? It is not known why the physis widens and starts to deform and an exploration of aetiology is beyond the scope of this paper. Various studies have looked at mechanical factors and obesity and are summarised below.[1-3] Widening of the physis in a functionally retroverted hip alters the loading in such a way as to slowly increase deformity. As the femoral head moves more posterior, the lower leg adopts a position of external rotation to avoid impingement. This in itself alters gait, and as lurching of the trunk becomes necessary to normalise the ground reaction force, further shear forces are placed on the physis. Further progression ensues until either an unstable slip occurs or the femoral head displaces to a point almost abutting the lesser trochanter and the metaphysis of the neck articulates with the acetabulum. The resultant pathoanatomy markedly distorts normal hip mechanics. The trochanter is displaced posteriorly and superiorly from the optimal point for insertion of the hip abductors, reducing offset and the normal lever arm the abductors need to maintain single limb stance.

Insights into the pathobiology and mechanics of SCFE help in directing treatment, but also in prophylactic treatment of hips at risk of future slip. In mild slips where the pathoanatomy has not severely altered hip biomechanics, arresting further progression is the main goal. Ascertaining whether the contralateral hip is retroverted and at risk of developing a SCFE is a secondary but important goal.[1-3]

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Posterior sloping angle (PSA) correlates well with the recommendation for prophylactic pinning of several clinical studies. Barrios recommended prophylactic pinning over 12° PSA, Zenios over 14.5° PSA and Phillips over 14° PSA.[4-6] Thus, at around 15° of retroversion, the hip is at risk of starting to slip. In a biomechanical saw-bone model, the energy to failure halved with every 5° increase of PSA from 15° to 30° and is virtually non-measurable over 50°.[7] This finding of decreased stability beyond 15° correlates nicely with the risk of developing a contralateral slip. However, there is still controversy regarding the best fixation technique for both mild slips and those where prophylactic fixation has been deemed to be indicated. There are a multitude of options of stabilising a SCFE; however, there are only two basic principles: stopping growth or allowing further growth.

Stopping growth versus guided growth

The current 'gold standard' of *in situ* fixation for SCFE is based on the concept that the growth plate is harming the patient in this disorder, and stopping growth with a fully or partially threaded cannulated screw is the safest option.[8] This method's reliability in stopping the progression of a slip has been shown in long-term studies;[9] however, one could hypothesise the risk of abductor weakness due to relative trochanter overgrowth. It may therefore be preferable to stabilise SCFEs with an implant that allows further growth. Unfortunately, not all implants designed to allow further growth after pinning a slip are available all over the world. The Hansson Hook Pin (Stryker) has been successfully used for decades in Scandinavia since the 1980s.[10,11] In the most recent studies, a mean of 7.1 mm further growth after stabilisation was noted, as compared with 10 mm in the contralateral hip. In Germany, a K-wire technique has also been proposed, using three or four wires to stabilise the affected hips as well as the prophylactic side.[12] This confers the potential advantages of maintenance of the articulo-trochanteric distance without relative trochanteric overgrowth, true remodelling of the head/neck junction to reduce impingement and reduced incidence of limb-length discrepancy. These advantages would be likely to be more realistically appreciated in younger patients. Potential disadvantages include the need to use a more complicated implant or multiple implants that have to be left proud at the insertion site and/or being exchanged once outgrown. In response, Pega Medical (Laval, QC, Canada) have manufactured a modular telescopic 'Free Gliding' Screw (FG Screw), which consists of a female component with proximal threads wholly within the epiphysis and a male component that telescopes within the female and engages the lateral cortex (Fig. 1a). Theoretically, with growth, telescoping should allow guided growth to occur, in the same principle as telescopic rods used in the long bones.[13] Another option is the Synthes SCFE Screw System that has a shank diameter which is the same diameter as the screw

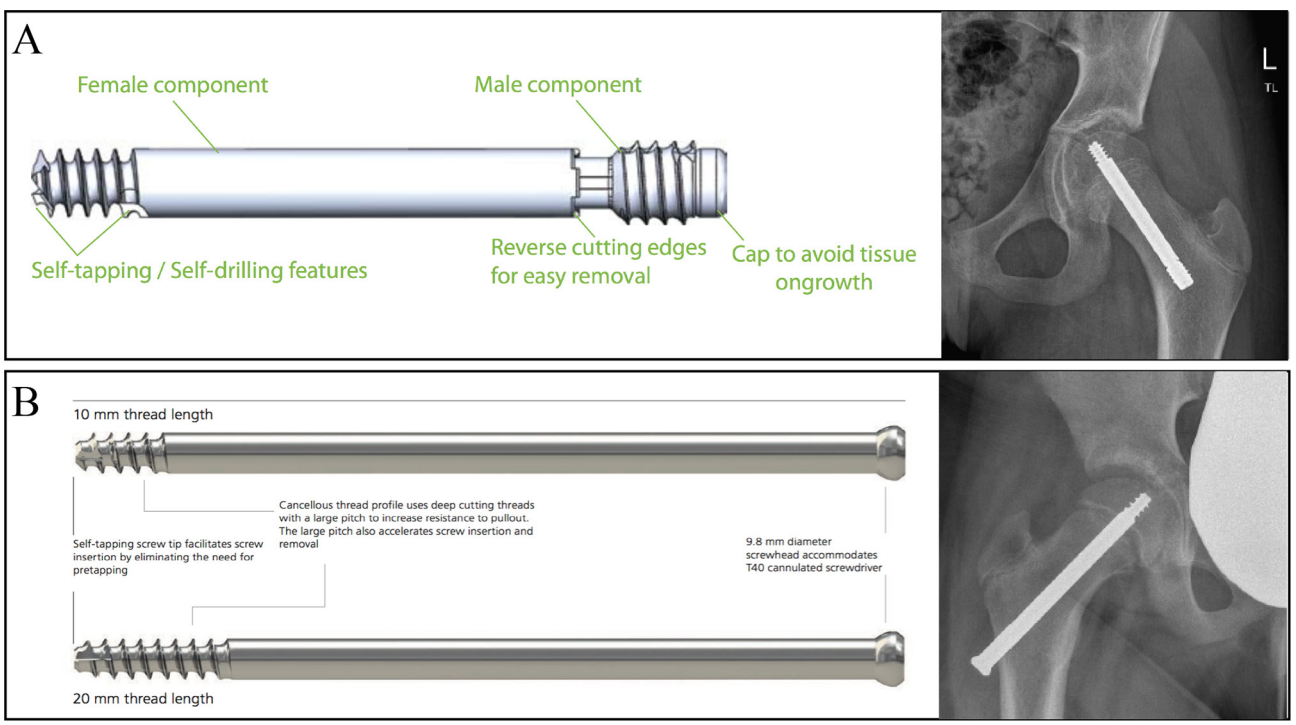


Fig. 1 Different available growing implants for SCFE fixation. (**a**) The Free Gliding SCFE Screw (Pega Medical); (**b**) the SCFE Screw System (Depuy-Synthes).

threads, to facilitate removal. Using the 10 mm thread version of this screw, it is possible to include the thread in the epiphysis of the head and leave the screw proud, and aim for guided growth as the thread stays within the head and drags the smooth shaft with it (Fig. 1b).

We studied the effect of fixation using fully threaded screws on the articulo-trochanteric distance (ATD) in our patient population and used our previously established SCFE model[7] to perform a biomechanical non-inferiority test of the recently developed FG Screw against standard Synthes implants and the newer Synthes SCFE screw design.

Patients and methods

Retrospective evaluation of trochanteric overgrowth

For the initial study, we retrospectively reviewed all patients treated for a unilateral SCFE between 2007 and 2013 at the Children's Hospital at Westmead. The inclusion criterion was a unilateral slip, regardless of method of treatment, with a focus on the study of the contralateral (non-affected) hip. We then divided the group into two: contralateral prophylactic percutaneous pinning *versus* non-pinning. We excluded all bilateral and subsequent slips and other treatments that could affect the trochanteric growth (e.g. use of a trochanteric entry nail). Both groups were compared for sex, age and time from pinning. Then, we measured the centre trochanteric distance (CTD)[14] and ATD[15-17] both initially and at their last follow-up (Fig. 2). The advantage of using both measurements is to be able to decrease the influence of the positioning in the measurement. We also evaluated the skeletal maturity of the cohort pre and post treatment using the modified Oxford hip score (OHS) (Fig. 3).[18] All measurements were made using the ruler tool on calibrated PACS images (Syngo Studio v36 Siemens, Germany).

Synthetic bone models, implants and biomechanical testing

Synthetic femora (Synbone; Neugutstrasse, Switzerland) were used to create a moderate SCFE (30° PSA) in a method previously established by the authors, which utilises silicon to model the epiphyseal plate.[7] A negative control group (n = 9) consisted of SCFE models that had no screw fixation. The other groups that were fixed had a guide-wire drilled into the centre of the femoral head with radiological confirmation and reamed up to the epiphyseal plate before drilling and screw insertion (Fig. 4). We tested five different cannulated screws (Depuy-Synthes; West Chester, PA, USA) and two positions of the Free Gliding screw (Pega Medical; Laval, QC, Canada) against the control group which had no fixation. Table 1 describes all screw types used. Testing was done on two different occasions. To ensure reproducibility, control and 6.5M 80/80 mm screws were retested (Table 1). Specimens were tested on a modified four-point bending apparatus, mounted to a 2 kN load cell on an Instron 5944 mechanical testing machine (Instron, Melbourne, Australia) as previously described.[7] They were then loaded in compression in displacement control at 0.5 mm/s, to the endpoint of catastrophic failure, with the strength, stiffness and energy to failure data recorded and collected.

Statistics

We used SPSS version 21.0.0.0 (IBM, Armonk, NY, USA) for data analysis. In the initial retrospective study, normality was tested for each variable using Kolmogorov-Smirnov. Normally distributed data were analysed using student's t-test and non-normally distributed data using a Mann-Whitney U test. The confidence interval was 95%. For the biomechanical study, normality was confirmed using D'Agostino and Pearson omnibus. To test the difference between groups, an ANOVA was done with a *post-hoc* Tukey to identify the difference between groups.

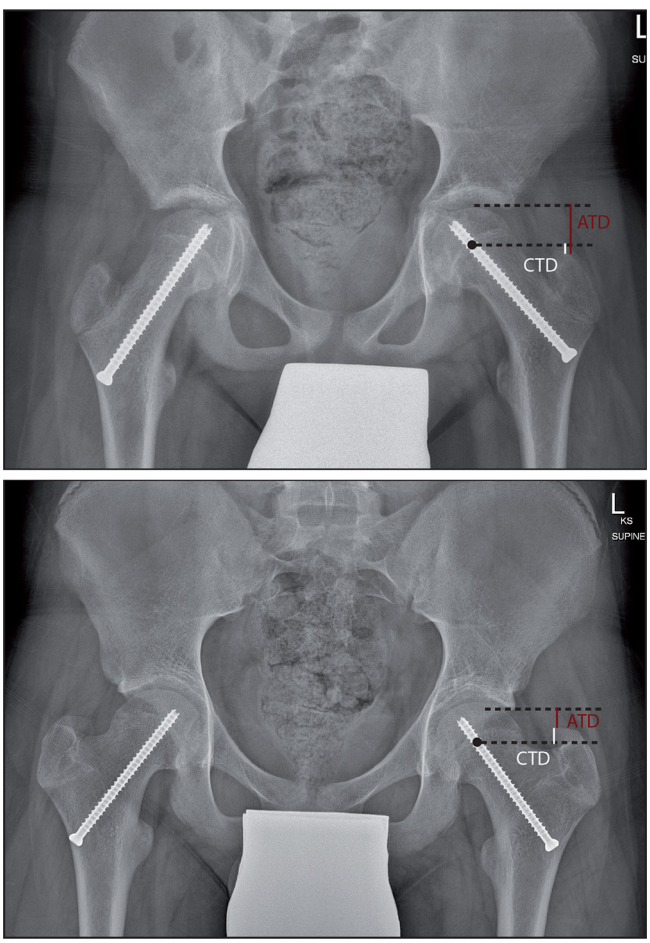
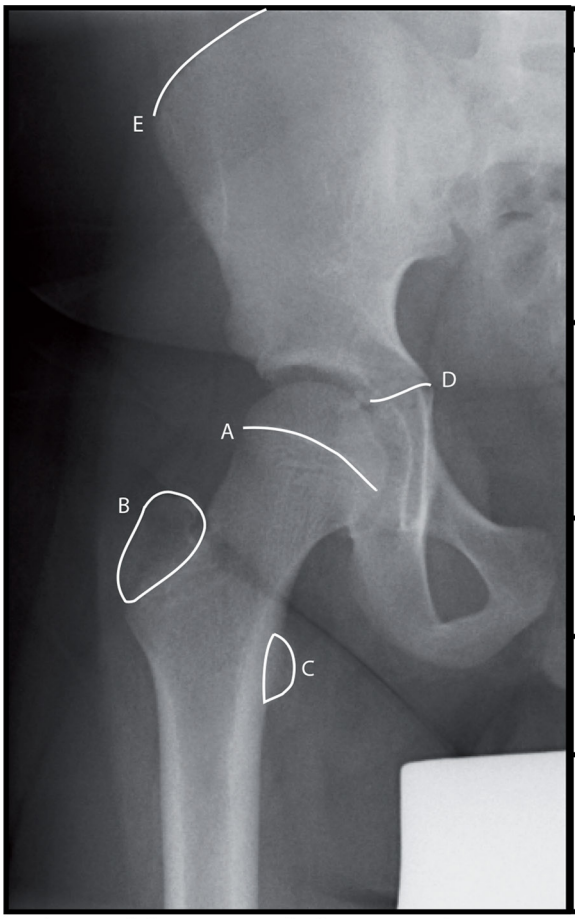


Fig. 2 Measurement technique for articulo-trochanteric (ATD) and centre-trochanteric (CTD) distances on initial and final radiographs.



	PHYSIS	POINTS	DESCRIPTION
A	Femoral Head	5	Straight neck, no fovea, medial beaking of epiphysis
		6	Epiphysis wider than neck, well defined fovea
		7	Physis starting to close
B	Greater trochanter	4	Simple ossified nodule
		5	Smooth connection between nodule and neck
		6	Physis starting to close
C	Lesser Trochanter	3	Physis clearly opened
		4	Physis partially closed
		5	Physis closed
D	Triradiate cartilage	1	Physis clearly opened
		2	Physis partially closed
		3	Physis closed
E	Ilium	3	Absence of ossified apophysis (Risser 0)
		4	Presence of ossified apophysis

Adapted from Stasikelis PJ et al. JBJS Am 1996; 78:1149-55

Fig. 3 The modified Oxford Hip Score (OHS) for skeletal maturity.

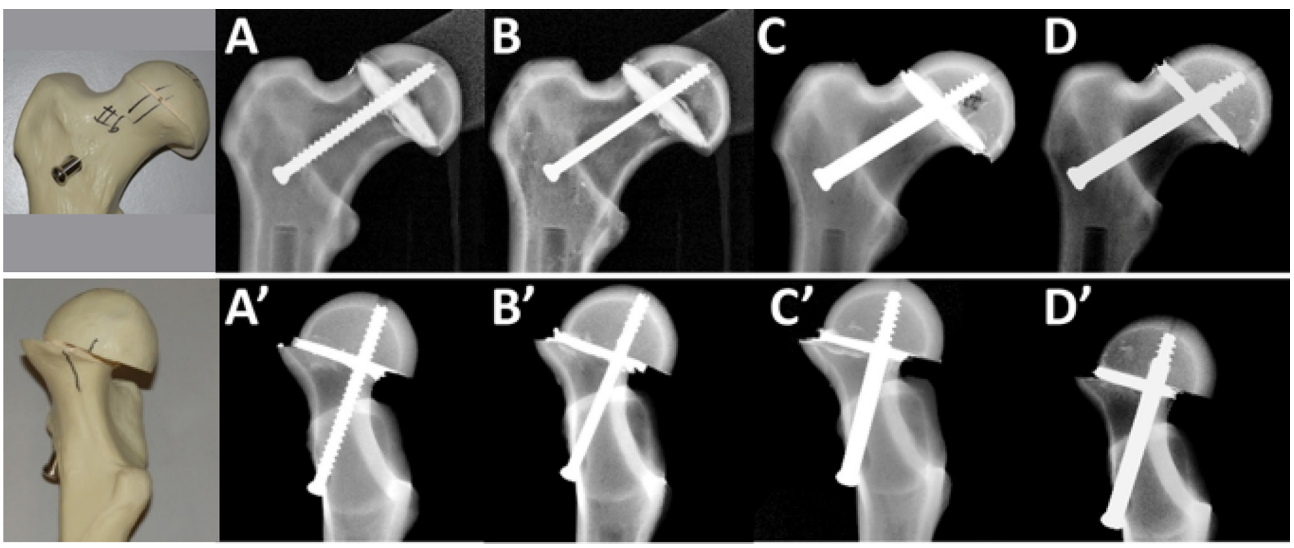


Fig. 4 Anteroposterior and lateral picture and radiographs of the saw-bone model with different types of fixation. (**a**) 6.5 Synthes cannulated screw fully threaded, (**b**) 6.5 Synthes cannulated screw partially threaded 16 mm, (**c**) 7.3 Synthes SCFE Screw System partially threaded 20 mm, (**d**) 7.3 Synthes SCFE Screw System partially threaded 10 mm.

Table 1. Screw characteristics.

Group	Abbreviated name	n
No fixation	Unfixed	14
6.5 Synthes cannulated screw fully threaded	6.5M - 80/80 mm	13
6.5 Synthes cannulated screw partially threaded 16 mm	6.5M - 80/16 mm	8
7.3 Synthes SCFE Screw System partially threaded 10 mm	7.3M - 80/20 mm	8
7.3 Synthes SCFE Screw System partially threaded 20 mm	7.3M - 80/10 mm	9
6.5 Synthes cannulated screw partially threaded 16 mm titanium	6.5M - 80/80 mm (Ti)	5
7.3 Pega Medical Free Gliding Screw 16 mm thread closed	FG 80 closed	5
7.3 Pega Medical Free Gliding Screw 16 mm thread opened 20 mm	FG 80 open	5

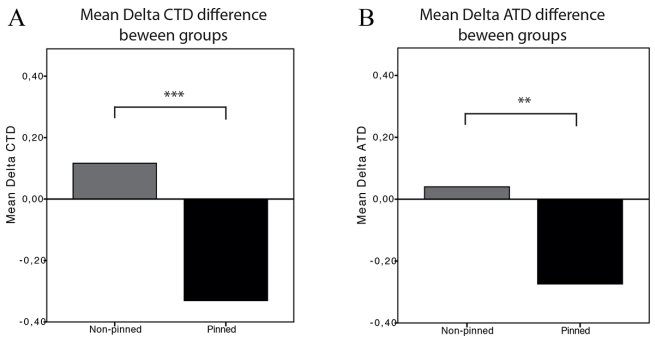


Fig. 5 Mean delta CDT and ATD in both groups. Note the significant difference in both measurements when the proximal femora are pinned with standard screws.

Results

Patient distribution

We included a total of 60 pinned hips in group P and 30 non-pinned hips in group NP. When comparing groups, the initial OHS was statistically different between groups (NP 21.13, P 20.12, p = 0.002), but was similar at the end of the follow-up. The Delta OHS was also significantly different (NP 2.9, P 3.95, p = 0.006), meaning that the pinned group started at a less mature stage to reach the same maturity stage as the other group at the end of the follow-up. The follow-up duration was the same in both groups (NP 1.93 years, P 1.88 years, p = 0.453), so was the age at surgery (NP 13.14 years, P 12.67 years, p = 0.190).

Trochanteric overgrowth measurement in pinned (P) versus non-pinned (NP) contralateral hips

In the NP group, there was no difference for the pre/post CTD and ATD measurements. However, in the P group, there was a significant difference in both pre/post CTD and pre/post ATD measurements (CTD pre/post -0.33 cm, p < 0.001, ATD pre/post -0.27cm p < 0.001). Also, when comparing both groups for delta CTD and delta ATD, there was a significant difference (Delta ATD P -0.27 cm *vs* NP 0.04, p = 0.01, Delta CTD P -0.33 cm *vs* NP 0.12, p < 0.001) (Fig. 5).

Because of the difference in maturity between groups, we repeated the analysis after excluding the immature patients (girls aged less than ten years and boys aged less than 12 years). The results obtained were very similar with again a significant decrease in CTD and ATD over time in the pinned group (data not shown).

Biomechanics

All of the groups with fixation were significantly stronger and stiffer than the unfixed control group. The Synthes SCFE screw and the Pega FG screw were both non-inferior in ultimate load, energy to failure and stiffness to a standard fully or partially threaded cannulated 6.5 AO screw (Synthes) when tested with this synthetic bone model (Fig. 6, Table 2). However, when comparing FG open and closed to the 7.3M 80/10 mm SCFE screw, there was a significant 41% and 43% decrease in energy to failure. In our own limited clinical short-term experience, the FG screw elongates and the 7.3 Synthes SCFE screw, if left long/proud at the insertion site, allows further growth similar to the Hansson hook pin (Fig. 7). Clinical longer-term outcome studies are needed to further investigate these newer SCFE implants.

Discussion

The use of an *in vitro* SCFE model in this study facilitated reproducible comparison of the biomechanics of new SCFE screw design to those screws used currently by the authors. Important considerations for screw selection include, but by no means are limited to, the number of screws used, the presence of threads across the physis, compression across the physis, the point of screw insertion in regards to acetabular impingement, ease of removal and the facilitation of proximal femoral growth with the screw *in situ*.

Prior to this study, the authors predominantly employed a single, centrally placed, fully threaded, cannulated screw when prophylactic fixation was deemed necessary. This technique has two advantages. The first is that fully threaded screws maintain a tapped path for the screw to follow on its removal at a later date if desired. Second, the presence of thread on both sides of the physis provides optimum strength, even without compression, as recently highlighted by Upasani et al.[19] However, our own data show a significant decrease in the articulo-trochanteric distance post pinning with a fully threaded cannulated screw. Örtegren et al recently reported significant continuation of growth after pinning slips with the non-threaded Hansson Hook Pin, which is an important consideration for those patients afflicted with SCFE years before skeletal maturity.[11] However, this device is not available in

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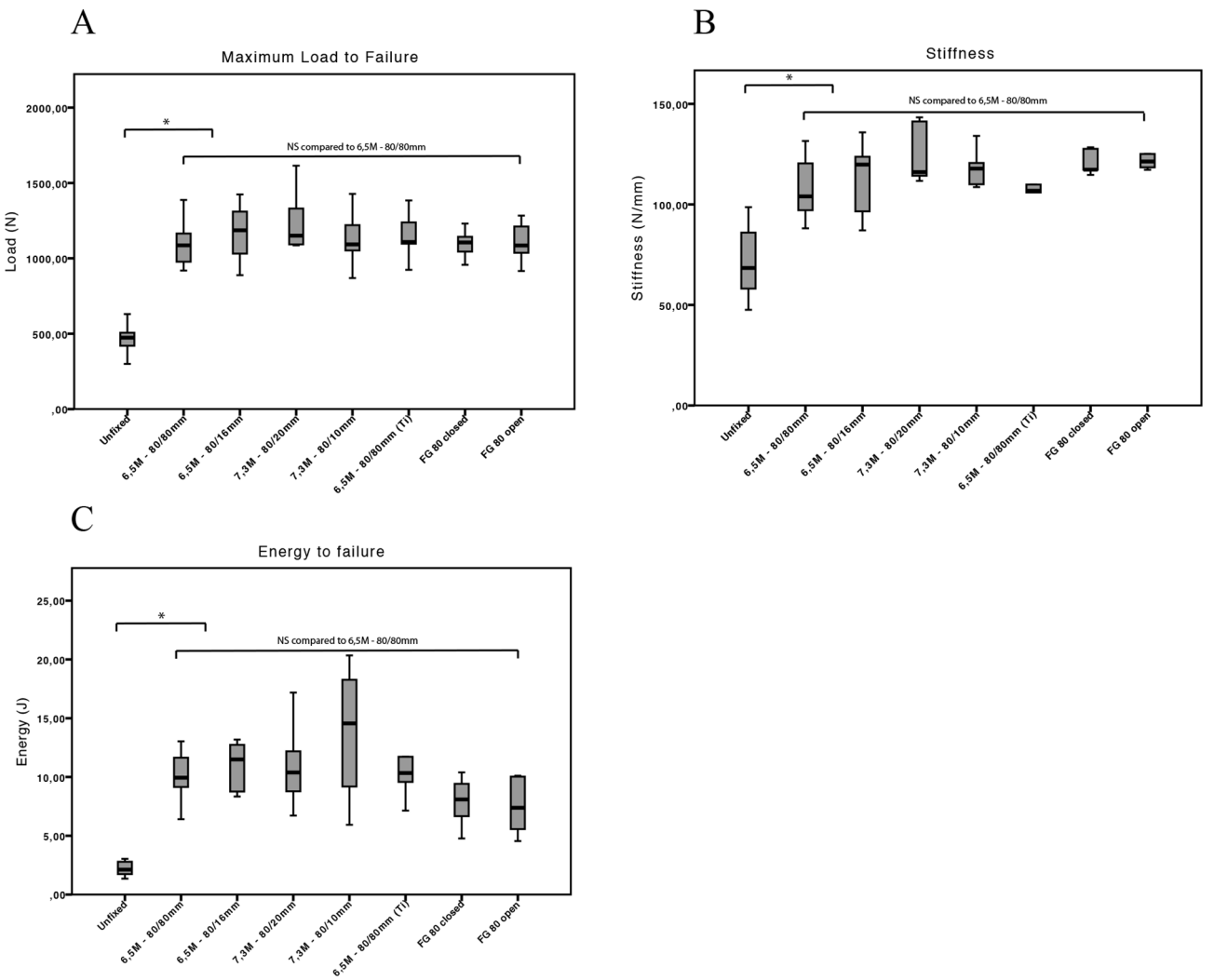

Fig. 6 Maximum load to failure, stiffness and energy to failure for all screws compared.

Table 2. Ultimate strength (N), energy to failure (J) and stiffness (N/mm) for fixed and unfixed groups against the 6.5M - 80/80 mm standard fixation group (*).

Group	n	Ultimate strength (N)	p	Energy to failure (J)	p	Stiffness (N/mm)	p
Unfixed	14	469 ± 77.48	0.00	2.29 ± 0.80	0.00	71.9 ± 16.1	0.00
6.5M - 80/80 mm*	13	1088 ±1 30.0	N/A	10.53 ± 3.03	N/A	108.0 ± 15.2	N/A
6.5M - 80/16 mm	8	1171 ± 186.6	0.92	10.94 ± 2.04	1.00	112.9 ± 17.6	1.00
7.3M - 80/20 mm	8	1231 ± 187.6	0.40	10.82 ± 3.23	1.00	124.8 ± 14.3	0.18
7.3M - 80/10 mm	9	1132 ± 191.6	1.00	13.39 ± 5.65	0.41	115.7 ± 14.9	0.92
6.5M - 80/80 mm (Ti)	5	1150 ± 171.9	0.99	11.05 ± 3.46	1.00	107.5 ± 7.05	1.00
FG 80 closed	5	1096 ± 102.9	1.00	7.87 ± 2.23	0.73	121.05 ± 6.5	0.67
FG 80 open	5	1107 ± 144.9	1.00	7.53 ± 2.53	0.60	123.7 ± 7.8	0.44

Australia or many other countries and therefore could not be included in our study. One alternative to this method is the use of screws with a partial thread occupying only the epiphysis, the smooth shank crossing the physis allowing further growth if the screw is left proud. Moreover, the Synthes SCFE Screw evaluated in this study (Screws C and D) also features a shaft width equal to that of the threads contained in the epiphysis. It has the advantage of easy removal without the need of reverse cutting, added to the cannulated screwdriver, enabling a threaded T-piece to be passed through and engaged with the head of the screw. In 2006, Seller et al published the clinical outcome of 29 unstable slips that were stabilised using a K-wire technique.[12] In their study, they underline the benefit of maintaining proximal femoral growth in regards to remodelling potential. The multiple K-wire technique

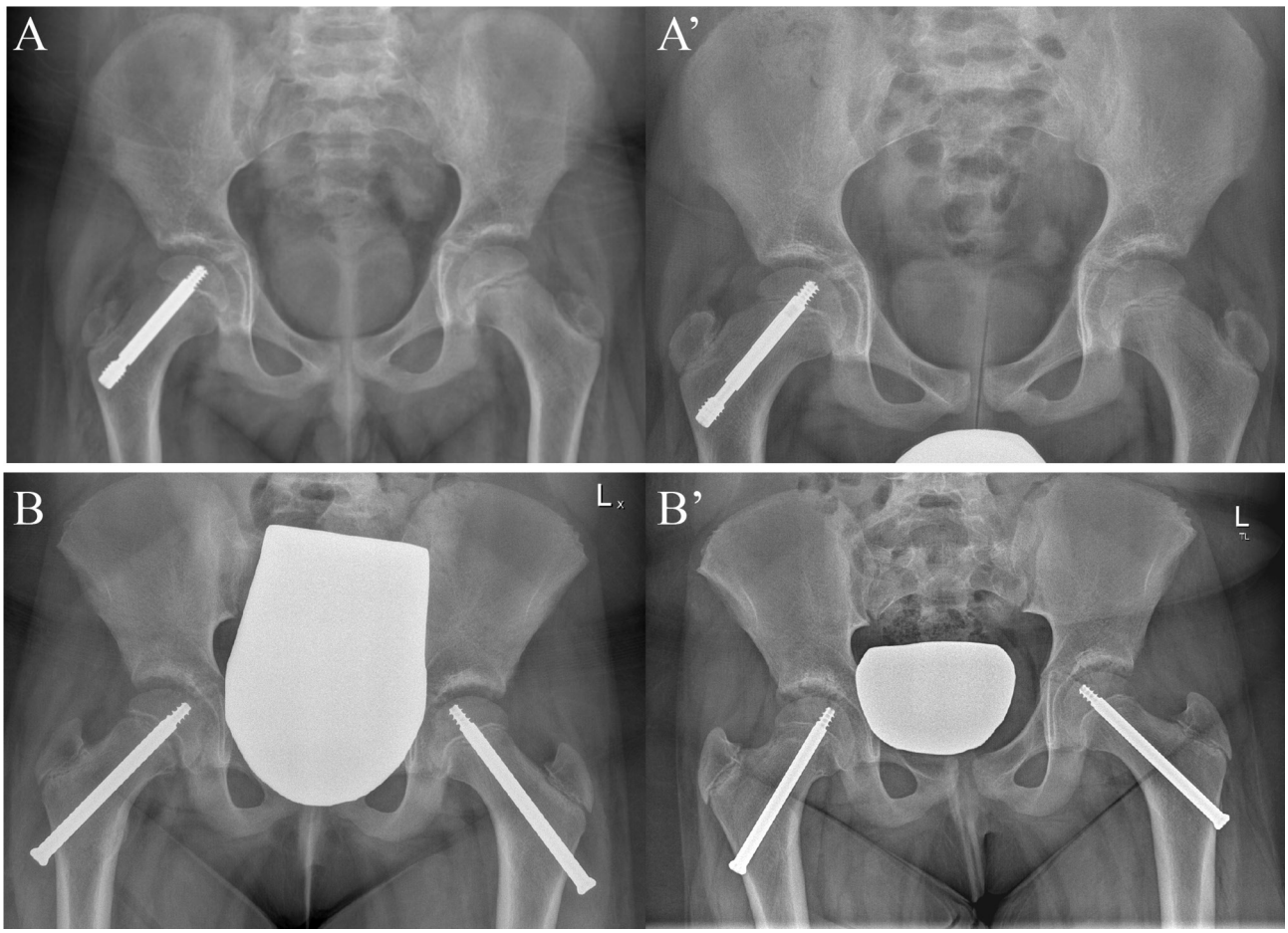

Fig. 7 A-A': Initial and last available radiograph of FG Screw (Pega Medical) fixation with 15-month interval. B-B': Initial and last available radiograph of Synthes SCFE Screw (Depuy-Synthes) with 19-month interval, after one screw exchange at 12 months.

seems to allow further femoral growth while protecting from recurrent slip. However, outgrown implants, like the Synthes SCFE screw, have to be replaced. Close monitoring has to be done in those patients because outgrown K-wires mean loss of epiphyseal fixation, which in turn are at risk of further slip in very young patients.[12] In this paper, biomechanical properties of multiple K-wires were not tested and for that reason cannot be compared.

One concern we had was that the screw threads may not provide sufficient grip in the epiphysis, which was the rationale for comparing the newer screws to those already in clinical use at the authors' institution. In the Synbone model system we used and the loading parameters chosen, these screws performed equally well to the current screws we are using clinically (Screw A). Based on these data, we now have limited clinical experience which suggests that the screw threads provide sufficient grip in the epiphysis to allow further growth, but more comprehensive clinical follow-up is required (Fig. 7).

Another alternative aimed at allowing further growth is the telescopic FG screw, which again demonstrated non-inferiority compared with standard screws both in closed mode, as it would be at introduction, and with a simulated 20 mm distraction. Unfortunately, the limited sample size permitted in this study limited the ability to demonstrate statistical significance from the trends observed; however, it was sufficient enough to demonstrate that the performance of the new SCFE screw design evaluated in this study was at least non-inferior to those being used by the authors currently. The fact that this is also an *in vitro* model of an acute SCFE should also be taken into consideration; it does not account for the bony bridging seen in adaptive remodelling in a chronic SCFE. In our early clinical experience, the FG screws telescope with further growth; however, the physeal widening seems to persist longer in some cases than in our experience with the standard fully threaded screws. This needs further study and to be accurately quantitated, but at present has not been associated with screw failure.

This study shows that a fully threaded screw used as fixation has an impact on proximal femoral growth, especially on the decrease of the ATD. Also, our biomechanical study

shows that the Synthes 7.3 SCFE screw and the Pega FG Screw perform in a simple Synbone model in a very similar fashion to standard fixation devices. The Synbone construct failed at the screw insertion site well before there was any real impact on fixation of the slip. It is hoped that this work will stimulate further research on the topic of SCFE fixation that allows further growth and that all implants allowing further growth are being made available more broadly in the future as we continue to evaluate best practice in the management of this increasingly common paediatric orthopaedic issue.

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COMPLIANCE WITH ETHICAL STANDARDS

FUNDING STATEMENT

The author or one or more of the authors have received or will receive benefits for personal or professional use from a commercial party related directly or indirectly to the subject of this article.

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ETHICAL STATEMENT

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Because of its non-nominal retrospective nature, the institutional ethics committee did not require informed consent from participants.

ICMJE CONFLICT OF INTEREST STATEMENT

JMB has received funding from Pega Medical for this study. For bias control, he has been blinded from the data collection and analysis. DGL reports that he is a consultant for OrthoPaediatrics; no direct biases were identified for this work. OB reports that he is a consultant for Orthofix; no direct biases were identified for this work.

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