

Vertically Oriented Femoral Neck Fractures: Mechanical Analysis of Four Fixation Techniques

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Objective: Femoral neck fractures in young individuals are typically high angled shear fractures. These injuries are difficult to stabilize due to a strong varus displacement force across the hip with weight bearing. The purpose of this study was to compare the biomechanical stability of four differing fixation techniques for stabilizing vertical shear femoral neck fractures.

Methods: Vertical femoral neck fracture stability was assessed using 4 surgical constructs in 32 cadaveric femurs: 7.3 mm cannulated screws placed in a triangular configuration (group 1), a 135-degree dynamic hip screw (group 2), a 95-degree dynamic condylar screw (group 3), and a locking proximal femoral plate (group 4). The 4 groups were matched for mean bone density and each specimen was tested under incremental loading, cyclical loading, and loading to failure. The modes of fixation failure were recorded for each specimen and the mean group stiffness, failure loads, and failure energies were calculated.

Results: All 8 specimens failed during incremental loading in group 1. Five of 8 constructs failed with incremental loading, and 3 failed with cyclical testing in group 2. The combined 16 specimens in groups 3 and 4 survived both incremental and cyclical loading. The differences in stiffness, failure loads, and failure energies between the 4 groups were statistically significant ($P < 0.001$). The strongest construct was the locking plate and the weakest construct was the 7.3-mm cannulated screw configuration. The cannulated screw configuration group failed as the screws backed out of the femoral head and by varus collapse of the osteotomy; the fixed angled devices all failed at the bone-implant interface.

Conclusions: The strongest construct for stabilizing a vertical shear femoral neck fracture is the proximal femoral locking plate, followed in descending order by the dynamic condylar screw, the dynamic hip screw, and the 3 cannulated screw configuration.

Key Words: femoral neck fracture, biomechanics, fracture fixation
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The incidence of femoral neck fractures in younger individuals is increasing secondary to a rising rate of high-energy trauma.¹ A common injury pattern in this population is a vertical shear fracture extending towards the lesser trochanter (Pauwels' III).¹ Surgical repair of this unstable fracture is indicated, but has been associated with exceptionally high complication rates, ranging from 30% to 60%.^{2–4} Strong varus displacement forces across the hip may lead to femoral neck fracture malunion, nonunion, and osteonecrosis.

There are several factors that contribute to fixation failure and revision surgery. Anatomic reduction and internal fixation has been shown to be important in preventing postoperative complications.^{5,6} Biomechanical studies have shown the importance of bone density in the holding strength of different fixation techniques. Also, an increased fracture angle has been shown to be a predictor of healing complications.^{7–11}

Previous investigators have evaluated fixation stability of vertically oriented femoral neck fractures using cannulated screw and sliding hip screw constructs in embalmed and/or osteoporotic bone specimens.^{12–15} The purpose of this study was to compare the biomechanical stability of 4 modern fracture fixation techniques using fresh frozen cadaveric hip specimens with normal bone density based on percent peak velocity.

MATERIALS AND METHODS

Specimens

A power analysis was performed from data obtained in a preliminary study on first generation composite bones (Sawbones Pacific Research Laboratories, Vashon, WA). Using a 10% difference between the implanted groups as significant and a calculated standard deviation of 5%, a minimum of 5 cadaveric specimens for each implant tested was deemed necessary to detect statistical significance.

Four surgical constructs were used to fix a simulated Pauwels' III femoral neck fracture: 7.3-mm cannulated screws (Synthes, Paoli, PA), a 135-degree dynamic hip screw (DHS; Synthes), a 95-degree dynamic condylar screw (DCS; Synthes), and a fixed-angle proximal femoral locking plate (PFLP; Synthes).

The Arthroscopy Association of North America provided 32 fresh human proximal femur specimens for the purpose of this study (age at time of death, 52–89 years). The bone mineral density of each specimen was measured by DEXA scanning and 8 specimens were allocated to each test group to account for the larger variation in mechanical properties in cadaveric

specimens. The average bone densities for the groups were between 0.862 ± 0.07 and 0.869 ± 0.15 g/cm³. The values between the four groups were not significantly different, with $P < 0.05$. These values fall within a normal range of percent peak velocity (percent peak velocity is a value assigned based on the bone mineral density (BMD) of the proximal femurs normalized to eliminate patient age and race) young adults based on calibration data for the HOLOGIC DEXA scanner at our institution.

Biomechanical Testing

The specimens were cleaned of soft tissue and stored at -20°C . Each specimen was thawed at room temperature for 6 hours prior to testing and sprayed intermittently with normal saline to keep the specimens hydrated.

A vertical osteotomy was created with a band saw, simulating a Pauwels' III femoral neck fracture. The osteotomy extended from the superior femoral neck to the basicervical region, and measured 90 degrees. The fracture was anatomically reduced and fluoroscopic guidance was used to implant the hardware and stabilize the osteotomy using one of 4 techniques. In all cases, the specimens were predrilled prior to the osteotomy to assist with anatomic reduction and implants were sized specifically for each specimen. Also to assist with compression across the osteotomy, a vice-grip was used to hold the specimens prior to implant placement.

In group 1, three 7.3-mm cannulated screws were inserted parallel into the femoral head in an inverted triangle configuration. The most inferior screw was positioned in the calcar region, above the lesser trochanter. The two cephalad screws were inserted superiorly, 5 mm from the anterior and posterior cortices of the femoral neck and 5 mm from subchondral bone.

In group 2, a 135-degree, 4-hole DHS plate was positioned with the central screw directed into the middle of the femoral head. The tip-to-apex distance of the central screw measured less than 25 mm in all 8 specimens. The side plate was fixed to the femoral shaft with four 4.5 mm cortical screws.

In group 3, a 95-degree, 6-hole DCS plate was fixed with the center screw positioned perpendicular to the fracture line. The tip of the screw was seated 5 to 10 mm from subchondral bone. The side plate was secured to the femoral shaft with four 4.5-mm cortical screws.

In group 4, a fixed angle PFLP was secured with 3 locking screws in the femoral head: two 7.3-mm screws at 130 degrees and 95 degrees, and one 5.0-mm screw at 135 degrees. The ends of all 3 screws were positioned 5 mm from subchondral bone. The side plate was affixed to the proximal femur using four 4.5-mm nonlocking screws. Figure 1 represents a sample radiograph of each implanted system.

The 32 specimens were tested in three modes: 1) incremental loading, 2) cyclical loading, and 3) loading to failure. The specimens were rigidly fixed in an aluminum cylinder in 25 degrees of adduction to simulate single leg stance.¹² The femoral shaft was secured in the apparatus with multiple screws, 15 cm distal to the greater trochanter. Each specimen was loaded vertically along the mechanical axis of the femur (center of the head to the center of the femoral condyl) by using an electric cylinder linear actuator (150-mm

stroke length and 7200-N loading capacity, EC3 series; Industrial Devices Corporation, Petaluma, CA), which was driven by a KollMorgen servomotor (Danaher Motion, Wood Dale, Illinois). A 10-mm thick flat aluminum plate was used to apply force over the center of the femoral head.

Nineteen points were marked around each specimen and digitized using an OPTOTRAK system with a digitizing probe (0.04-mm space resolution, OPTOTRAK 3020, Northern Digital Inc., Waterloo, Ontario, Canada). The digitized points were used to construct a local coordinate system in relation to the global coordinate system that is fixed in the camera (Fig. 2), thus allowing us to measure displacement of the femoral head with respect to the osteotomy in a 3-dimensional coordinate system.

Two triad markers were used to register the space orientation and position of the femoral head and shaft. The triads were firmly fixed to the bone using fine threaded screws. Two digitized points, labeled as 14 and 15, were used to register the relative displacement of the osteotomy in space. The triads defined two local coordinate systems fixed to the femoral head and shaft, respectively. The bones were assumed to be rigid bodies, so the relationship between the digitized points 14 and 15 and the corresponding local frame were fixed. By registering the space orientations and locations of each segment, the relative displacement between the two digitized points were calculated. In the pilot test, we also observed the relative rotation of the femoral head with respect to the shaft which occurred mainly in the sagittal plane. We observed no bending at the shaft. To quantify this, we also calculated the rotation angle of the femoral head with respect to the axis connecting points 11 and 13 of the base coordinate system.

A six-axis force/torque sensor (JR3 Inc., Woodland, CA) was used to measure the loading force perpendicular to the plate (the force along the z-axis in the sensor coordinate system). A linear potentiometer (maximum nonlinear $\pm 1\%$) built in the linear actuator was used to register the displacement along the loading direction. Data acquisition and motor control were implemented through a customized LabView program (National Instruments, Austin, TX) with 100-Hz sampling rate. The OPTOTRAK system was synchronized with the LabView program and both kinematic (markers, coordinates) and kinetic data (loading force) were collected. In all loading conditions the motor was set in velocity control mode and the linear actuator was driven by the motor continuously. Failure of fixation was defined as displacement of the osteotomy by more than 5 mm, hardware deformation, screw migration greater than 5 mm, and/or rotation of the femoral head by more than 5 degrees as reported in previous studies.^{12,16,17}

Incremental Load, Cyclical Load, and Load-to-Failure Test

Each specimen was incrementally loaded to 1400 N at a speed of 1 mm per minute. A 1400-N force is equivalent to two times the body weight of a 70-kg person, or the measured force on the hip in a 70-kg person standing on one leg.¹⁸ The constructs that survived incremental loading were tested under cyclical loading. A 1400-N force was applied at a frequency of 3 Hz for 10,000 cycles (3 Hz was selected to shorten the overall duration of testing). This number of cycles approximates the

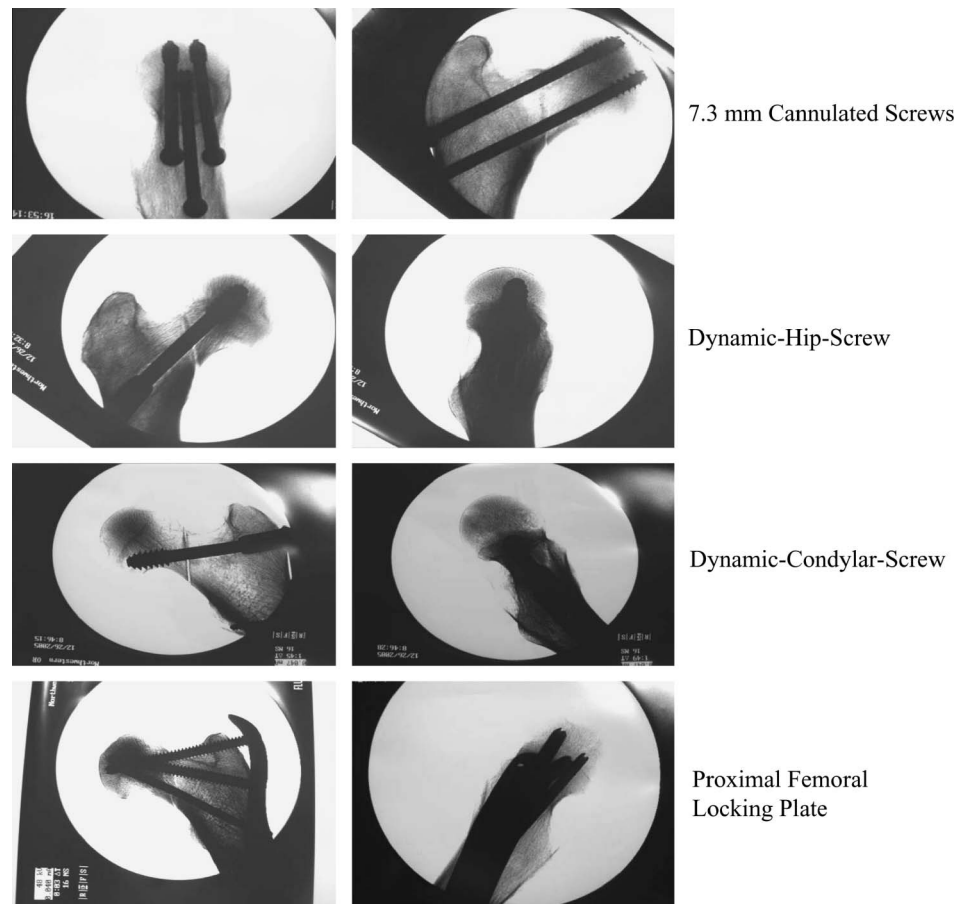


FIGURE 1. Radiographic sample of the 4 fixation techniques.

number of steps taken over a 4- to 6-week time period: the expected interval for fracture consolidation.^{12,19–21} A force feedback control using proportional-integral-derivative controller was implemented to maintain the loading force around the target level within a 10-N range. All specimens that remained intact after cyclical testing were loaded to failure. The modes of implant failure were recorded in each case.

Statistical Analysis

Data were digitally low-pass filtered with a 4th-order Butterworth filter at 5 Hz and analyzed with a customized MATLAB program (MathWorks Inc., Natick, MA). One-way analysis of variance and a Tukey-Kramer post-hoc test were performed for group comparison. Measurements including bone densities, relative stiffness (stiffness was calculated as the ratio of loading force to loading displacement using the linear portion ranging from 100 N to 1400 N of the load vs. displacement curves), failure strengths and failure energy were compared. All eight specimens in each group were analyzed at the failure point to calculate the biomechanical parameters for each group. A level of significance was determined for $P < 0.05$.

RESULTS

The biomechanical properties of the four fixation techniques are outlined in Table 1. In the cannulated screw

group, all 8 specimens failed during incremental loading. In the DHS group, 5 of 8 constructs failed with incremental loading, and 3 failed with cyclical testing. The 3 specimens that survived incremental loading had the highest group 2 bone density measurements. The three surviving specimens failed at cycle number 1087, 1822, and 7450. The combined 16 specimens in the DCS and PFLP groups survived both incremental and cyclical loading. The osteotomy displacement with cyclically loading was significantly greater in the DCS group when compared to the PFLP group (3.59 ± 1.18 mm vs. 1.71 ± 0.80 mm; $P < 0.002$).

With full weightbearing in the immediate postoperative period (corresponding to 1400 N loads) and using 6 weeks as the healing time for a femoral neck fracture (corresponding to 10,000 cycles), fractures fixed with 7.3-mm cannulated screws and a DHS plate fail prior to fracture union. The DCS construct and the locking plate construct provide improved fracture fixation by tolerating initial and cyclical loading prior to significant fracture displacement.

The PFLP construct demonstrated the greatest stiffness ($P < 0.05$). Stiffness values in the DCS and DHS groups were statistically equivalent, whereas the cannulated screw configuration was the weakest construct. The PFLP and the DCS constructs failed at higher loads than the DHS and cannulated screw constructs ($P < 0.05$). The failure energy in the PFLP group was the highest among the 4 constructs tested

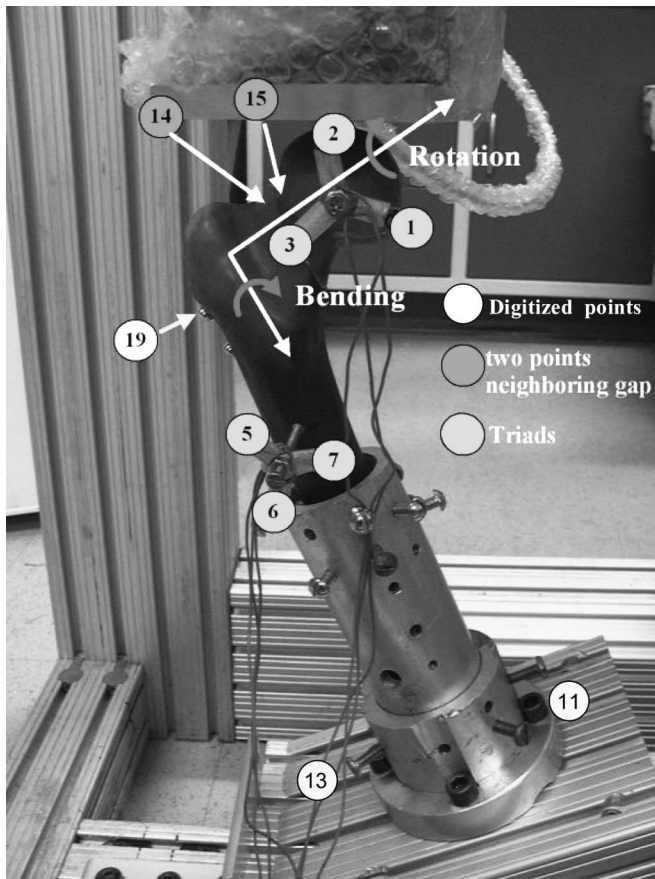


FIGURE 2. Digitalized points for constructing x-y-z coordinates.

($P < 0.05$), whereas there were no differences in failure energies between the other three groups ($P > 0.05$). The cannulated screws failed as the screws backed out of the femoral head. The DHS and DCS constructs failed by cutting out of the central screw superiorly. In the PFLP group, 5 cases failed with screws cutting through the femoral head, and 3 cases failed by screw bending. In all specimens, the femoral neck collapsed into varus alignment.

DISCUSSION

The ideal implant for fixation of a vertically oriented femoral neck fracture must withstand forces of weightbearing and restrict motion across the fracture site during bone healing. Secure fixation will conceivably reduce the high rates of

complications reported for treatment of this injury. Previous investigators have evaluated the use of cannulated screws and traditional fixed-angle devices in biomechanical models, but with mixed results.

Baitner et al used embalmed and osteoporotic bone specimens and showed that a DHS construct was significantly stronger than a 6.5-mm cannulated screw construct.¹² In contrast, Husby et al showed no significant differences between cannulated screws, a DHS plate, or Knowles pins when testing for bending failure.⁹ Swiontkowski et al assessed both torsional and bending stiffness using 6 different AO screw constructs and a DHS implant.¹⁰ They concluded that the DHS construct did not control torsional forces as well as 3 cannulated screws.

To our knowledge, there are no biomechanical studies comparing locking plate technology with traditional-fixed angle constructs or cannulated screws in the treatment of vertical femoral neck fractures. In a clinical report of 37 cases, Haidukewych et al found a trend toward fixed angle devices providing improved fracture stability, and decreased rates of nonunion and osteonecrosis when compared to cannulated screw fixation.²² The results of our study showed superior strength of the PFLP in comparison to the DHS, the DCS, and the 3 cannulated screw constructs in stabilizing a simulated Pauwels' III fracture.

The design of the PFLP allows for multiple points of angled fixation in the femoral head. Varus forces encountered during normal weight bearing are transmitted from the bone to the plate through rigid screw-plate interconnections, eliminating screw toggle.^{23,24} All 4 tested implants eventually failed by varus collapse and displacement of the femoral neck osteotomy. However, failure of the PFLP construct did not occur until 2 to 3 times the normal physiological loads at the hip were applied. In the cannulated screw group in 4 of the specimens, the screws failed by bending and the rest by loosening and migrating out of the bone. In the DHS, DCS, and PFLP groups the construct failed by screw cut out at the bone implant interface and not in the shafts. This can be affected by the bone density of the specimens. However, we tried to take this factor into account by matching the bone densities in all of the groups and by testing specimens that were not osteoporotic.

The advantages of our study included the large number of specimens tested in four different constructs, the use of fresh frozen cadaveric bone with normal bone mineral density, the utilization of a digital tracking system for measurements of osteotomy displacement and femoral head rotation with accuracy of 0.1 mm, and testing in static and cyclical loading phases. Also, we used a pilot study with a power analysis to determine the sample size in each group to make statistically significant conclusions.

However, there were several limitations of this study. We did not simulate all of the physiologic force components across the hip encountered during ambulation or with isolated muscle contraction. Varied directional vectors could have negatively impacted the stability of the PFLP fixation. Static loading in one direction does not simulate complex loads applied to the hip during walking. Torsion and the orientation of the axial load vectors change by flexing and extending the hip.

TABLE 1. Biomechanical Properties of the Four Fixation Techniques

Group	Construct	Stiffness (N/mm)	Failure Strength (N)	Failure Energy (J)
1	7.3-mm cannulated screws	166 ± 50	862 ± 366	2.9 ± 1.8
2	Dynamic hip screw	245 ± 51	1194 ± 213	2.5 ± 1.6
3	Dynamic condylar screw	320 ± 46	2156 ± 436	6.2 ± 2.4
4	Proximal femoral locking plate	618 ± 164	2431 ± 616	7.4 ± 4.1

Therefore loads are applied partly posteriorly, anteriorly, and inferiorly. In a prior biomechanical study by Deneka et al, these forces were studied comparing a cannulated screw construct to a DHS and derotation screw construct. They found that the DHS and derotation screw construct was a stronger construct.²⁵ Based on these results, we anticipate that the PFLP construct would be a stronger construct in torsion since the mechanism of failure in the PFLP, DHS, and the DCS construct were screw cut out.

In reference to implant design, the PFLP does not allow for fracture compression. This may adversely affect femoral neck healing given the importance of bone impaction and compression in fracture stability.³ The use of a torque screw driver results in a reliable way of assessing uniform compression; however, during the experiment we applied direct compression across the osteotomy site by using a vice-grip device prior to implant insertion. In an in-vivo setting, one can use a compression screw first through the locking plate and then exchange it for a locking screw at the end of the procedure. Also, in our study the osteotomy was created by a smooth saw cut; we did not take into account the effect of comminution and fracture irregularity on the stability of the implants. A prior cadaveric study by Kauffman et al has shown that posterior comminution adversely affects fracture stability to axial loads and anterior displacement.²⁶ This would affect in-vivo stability of fracture fixation. However, we feel that the PFLP would be the best construct in this situation because of the multiple fixed angled points of fixation in the femoral head making it a stronger load bearing implant compared to the cannulated screws, DHS, and DCS implants.

Of the 4 implants we tested for repair of a vertical shear femoral neck fracture, the PFLP was the stiffest construct. This implant tolerated high loads for extended cycles, simulating physiologic loads across the hip, and the time necessary for fracture union.^{12,19,20} Locking plate constructs may prove superior to traditional fixed angle devices and cannulated screw constructs in the treatment of this Pauwels' III fractures. However, in vivo animal studies and clinical outcome data are necessary to determine the stability of PFLP fixation and capacity for femoral neck fracture healing.

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