Torsional stability of a polished, collarless, tapered total replacement hip joint stem under vertical load: an *in vitro* investigation

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Abstract: The torsional stability of a polished, collarless, tapered total replacement hip joint stem has been investigated. It was believed that such a stem would show increasing torsional stability as the vertical component of load on the stem increased. The aim of the study was to examine this hypothesis by testing a number of specimens (including Exeter stems) with either a matt or polished finish, under increasing vertical load, measuring the torsional resistance of a specimen–cement construct within an outer constrained cement shell. It was concluded that stems with a polished, collarless, tapered shape showed increased torsional stability with increasing vertical load, while stems with a matt finish or a collar did not.

Keywords: polished, collarless, tapered hip joint stem, torsional stability, stem surface finish

1 INTRODUCTION

Total replacement hip joint stems with a collarless, polished, tapered shape that is designed to function with bone cement and to transmit load to the proximal femur, have been used for many years. This type of stem is typified by the Exeter stem which has a shape that can be divided into two parts: the proximal third that carries the head via a neck and a curved, wide tapered shape and a distal two thirds that comprise a straight taper, wide at the proximal end and narrow at the distal end (Fig. 1). It has been shown [**1**] that the proximal third transmits between 60 per cent and 70 per cent of the load, while the distal two thirds transmits between 30 per cent and 40 per cent of the load. The straight tapered distal two thirds of the stem has a further function: to act as a self-locking taper in the cement [**2**]. The action of self-locking makes the stem tighter in the cement as it subsides under load and can only be effective if the surface finish of the stem is highly polished (with an S_a or R_a of less than 0.1 μm). The current authors' hypothesis is that, when a collarless, polished, tapered hip joint stem such as the Exeter stem is subjected to loads *in vivo* which are completely defined by a combination of vertical, medial–lateral, and anterior–posterior force components, as the vertical load increases, so the ability to resist torsional loads also increases. The aim of the study was to examine this hypothesis by testing a number of specimens (including Exeter stems) with either a matt or polished finish, under increasing vertical load, measuring the torsional resistance of a specimen–cement construct within an outer constrained cement shell.

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2 MATERIALS AND METHODS

The torsional stability of seven different specimens was tested. The specimen details are listed in Table 1; the seven specimens comprised a cylinder, a tapered cone, and the distal two thirds of an Exeter stem, all with polished and matt surfaced versions, plus a polished tapered cone with a collar. Each specimen was implanted within a column of polymethylmetha-

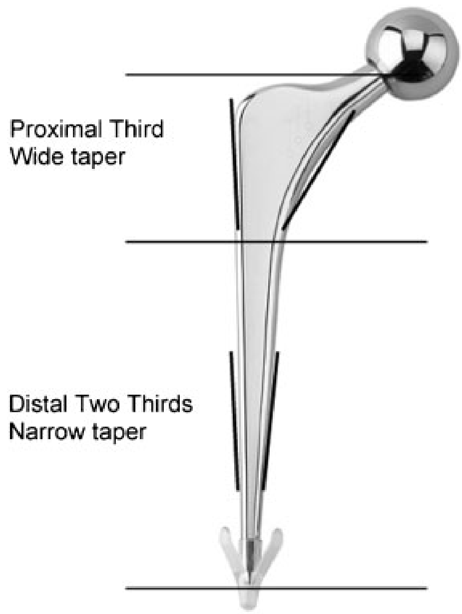

Fig. 1 Picture of Exeter stem with proximal and distal parts indicated

crylate (PMMA) cement such that its tip was level with the bottom of the column at the start of the test. The test specimen and its surrounding column of cement was then placed within a second, pre-polymerized, PMMA cement tube that was, itself, constrained within a metal shell (Fig. 2). It should be noted that the cement surrounding the specimen was not bonded in any way to the outer cement tube, but was manufactured to be a running fit in the outer tube. This ensured that no torsion could be transmitted from the specimen to the outer cement tube and its constraining metal shell until loads on the specimen caused the cement around the specimen to be forced outwards and provide frictional contact with the outer cement tube. No attempt was made to replicate the cortical bone that surrounds cement in the *in vivo* situation as the hypothesis was to be tested by the behaviour of the cement–cement interface and not by the amount of constraint provided by the cement–outer shell interface.

Using an outer shell made from, for example, a section of Sawbones femur, would have provided less constraint to the cement than the metal shell, but would not have altered the outcome of the various tests. The inner and outer cement shells and the metal outer constraint had a circular cross-section to ensure that any torque transmitted through the interface between the cement shells resulted from the behaviour of the various specimens under test; if a non-circular outer cross-section had been used (if, for example, a proximal section of Sawbones had been used) it would not have been possible to set a zero torque starting point as the non-circular shape of the outer constraint (Sawbone) would itself always allow transmission of torsion.

The overall construct was placed within a testing apparatus that could apply a pure torsional force to the stem in gradually increasing amounts by placing weights in a weight tray. This apparatus was placed within a testing machine (Lloyds EZ20 with a 10 kN load cell) that was able to put increasing amounts of vertical load on the specimen, from 1 to 7 kN (Fig. 3). The load range was chosen as it covers the range that most implanted hips may be placed under in day-to-day activity [**3**]. Thrust bearings were used at the top of the specimen loading rod and underneath the cement that surrounded the specimen to ensure that torsional frictional effects from the testing machine were minimized. It should be noted that the specimen was free to subside within its cement mantle through the central hole in the lower thrust bearing.

At each vertical load, increasing torque was gradually applied to the specimen and its torsional movement recorded until a 'yield point' was reached where the stem–cement construct moved significantly (i.e. more than 10°) within the outer tube. The measurements were repeated for vertical loads from 1 kN to 7 kN in 1 kN steps. The torque versus movement for each specimen at each vertical load was recorded. The

Table 1 Surface finish characteristics and test details of each test specimen (S_a: roughness over small area of surface, R_a: roughness over a line along the surface)

	Surface finish	Test details
Polished Exeter stem	$S_a = 0.163\ \mu m$	Tested over distal 100 mm
Matt Exeter stem	$S_a = 3.83\ \mu m$	Tested over distal 100 mm
Polished taper	$S_a = 0.186\ \mu m$	Test length = 100 mm, maximum dia. = 20 mm, minimum dia. = 6.0 mm cone angle = 7.9°
Matt taper	$S_a = 1.68\ \mu m$	Test length = 100 mm, maximum dia. = 20 mm, minimum dia. = 6.0 mm cone angle = 7.9°
Polished cylinder	$R_a = 0.166\ \mu m$	Diameter = 15 mm
Matt cylinder	$R_a = 1.41\ \mu m$	Diameter = 15 mm
Collared polished taper	$S_a = 0.163\ \mu m$	Test length = 100 mm, maximum dia. = 20 mm, cone angle = 7.9°

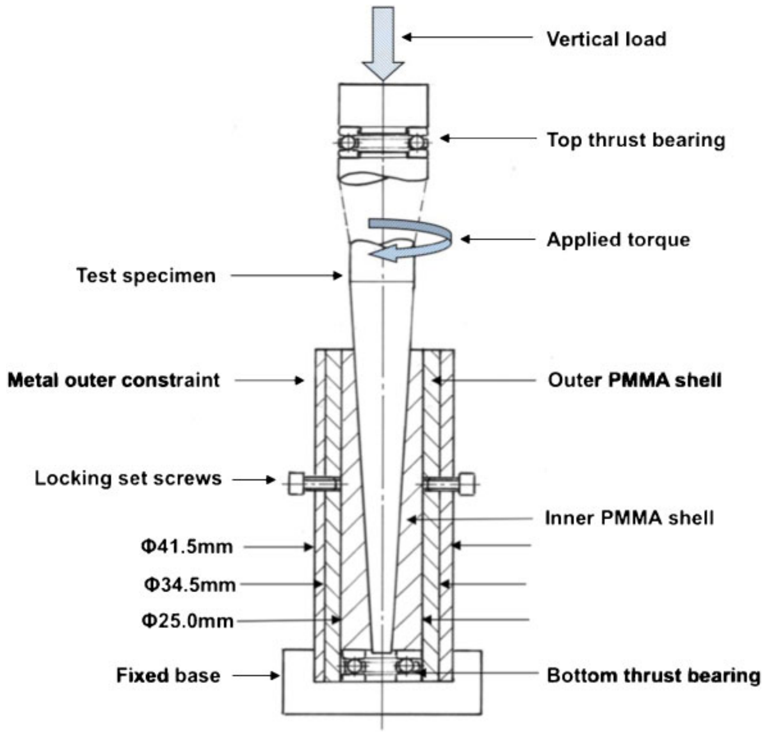

Fig. 2 Diagram of specimens in PMMA shells and outer constraint

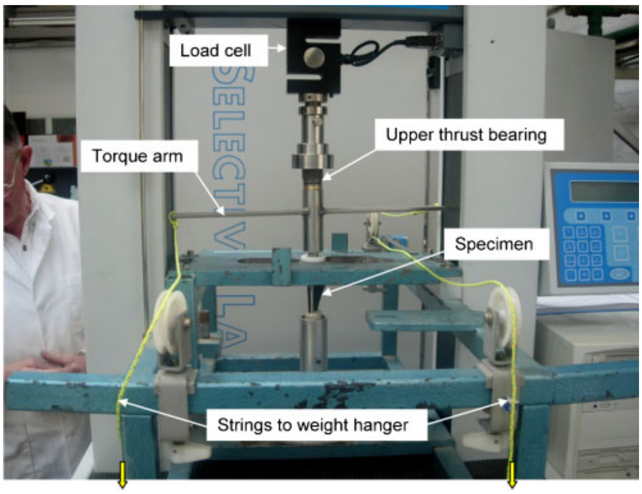

Fig. 3 Testing apparatus in loading machine

torsion transmitted by the bearings alone was assessed by putting a cylindrical loading rod between the top and bottom thrust bearings and a standard torque–twist test carried out.

3 RESULTS

Results are presented as a series of charts (Figs 4 to 10) showing the twist versus applied torque characteristic for each specimen as the vertical load on the specimen increased from 1 kN to 7 kN in 1 kN steps. A final test assessed the effect of the thrust bearings alone (see Fig. 11 later).

Tests on the distal two thirds (straight portion) of the polished Exeter stem (Fig. 4) show a gradual increase in the amount of torque required to produce twist and eventually, slip, with each increase in vertical load. The equivalent part of the matt Exeter stem (Fig. 5) shows only a small increase in torque producing twist for each increase in vertical load.

The polished circular taper (i.e. a polished conical taper) (Fig. 6) acts in very similar way to the polished stem with a large increase in the torque required to produce twist–slip with increasing vertical load. Similarly, the matt conical taper (Fig. 7) shows a much smaller increase in torque required to produce twist–slip compared with the polished cone.

The polished cylinder (Fig. 8) transmitted very small amounts of torsion before slipping took place, with the cylinder pushing through the outer tube without transmitting torsion when vertical forces larger than 2 kN were applied. The matt cylinder also pushed through the cement (Fig. 9) but not until 7 kN of vertical force was applied.

The polished cone with a collar (Fig. 10) had a similar torque–twist curve profile as the matt finished specimens. The test of the thrust bearings alone (Fig. 11) showed that they were not friction-free.

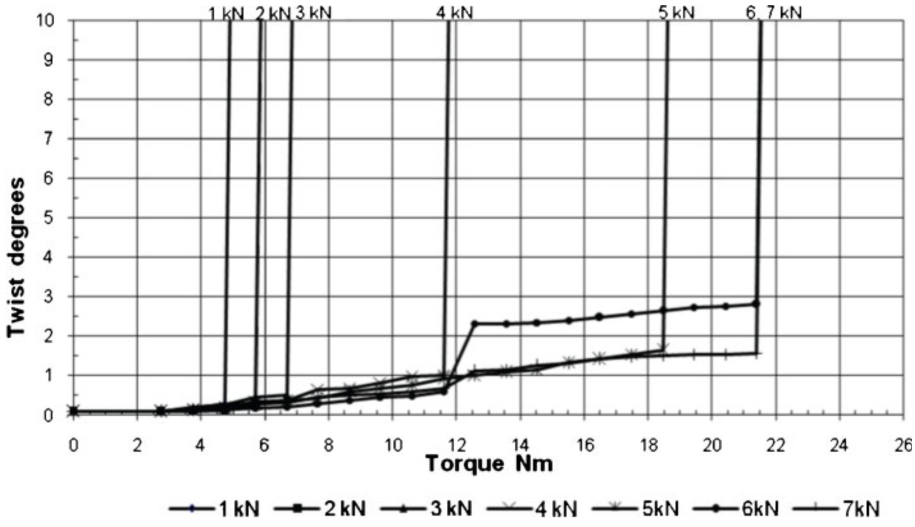

Fig. 4 Torque–twist chart for a polished stem

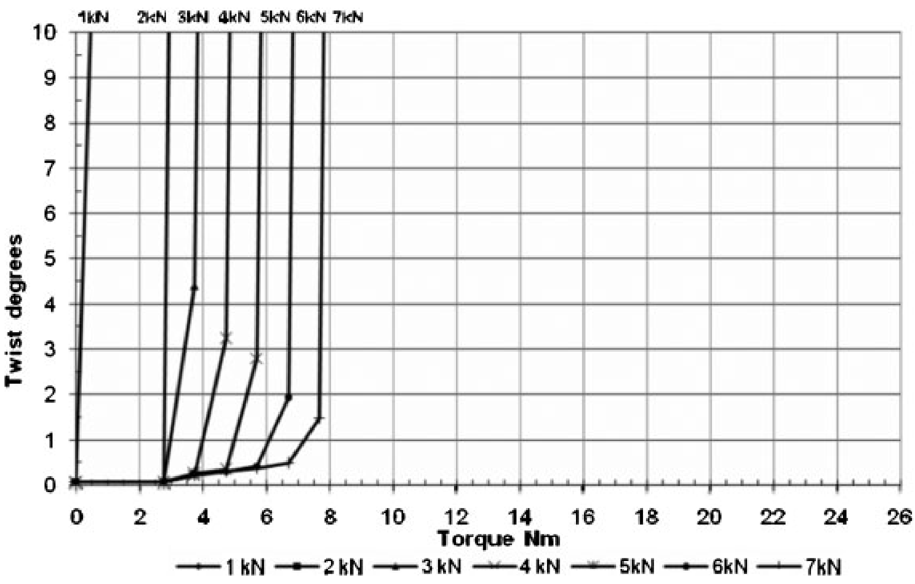

Fig. 5 Torque–twist chart for a matt stem

Each chart was reviewed and the torque to produce slip at the inner to outer cement interface calculated (Table 2). Figure 12, showing the torque to produce slip versus specimen type, was then drawn.

4 DISCUSSION

Figures 4 and 5 show tests on the polished and matt Exeter stems. Clearly, the torque needed to produce slip when the matt stem is loaded is much smaller than for the polished stem at all values of vertical load. It was observed at the time of testing that the polished stem subsided more in the cement than the matt stem. Larger amounts of stem subsidence, with slip at the stem–cement interface, produces a greater radial expansion of the cement around the stem and thus larger contact stresses between inner and outer cement components. The larger contact stresses at the cement–cement interface enables larger torques to be transmitted. Similar behaviour was observed with the and polished matt conical tapers (Figs 6 and 7).

The polished cylinder transmitted very small torques and was pushed through the cement surrounding it at low vertical load. The matt cylinder behaved in a generally similar way, except it took a much larger vertical force to push it through its surrounding cement. This was presumably attributable to the matt finish improving the bond between the stem and cement.

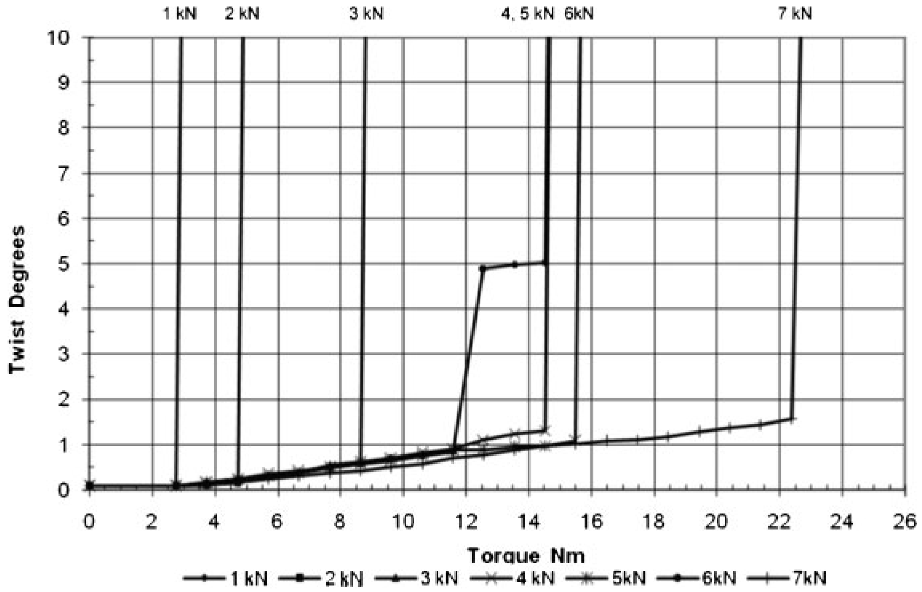

Fig. 6 Torque–twist chart for a polished circular taper

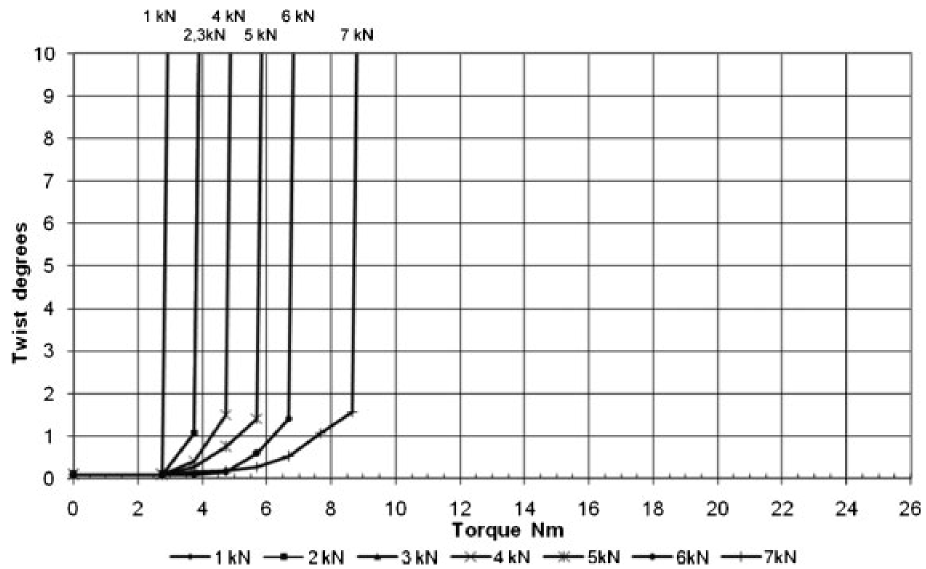

Fig. 7 Torque–twist chart for a matt circular taper

The polished cone with a collar, set in the cement that surrounds it so that the collar was in contact with the upper surface of the cement, had a similar torque–load curve profile (Fig. 10) to the matt surfaced specimens. The collar prevented the specimen subsiding within the inner column of cement and therefore the polished cone could not transmit forces to the outer column as it did when tested without a collar.

Each stem had a certain 'yield point' where the cement–cement interface completely gave way and the inner cement column moved freely within the outer tube (Fig. 12). There is an obvious difference between the polished specimens and the matt specimens, with the exception of the polished cone plus collar that performed in the same way as the matt specimens.

Tests set up so that vertical loads were applied directly to the thrust bearings showed that they were not friction free and were able to absorb some torsional force as the vertical force increased (Fig. 11). The effect of bearing friction on the torque–twist characteristics of both matt and polished specimens is significant. Looking at these specimens and the bearings alone results, Table 3 can be drawn up. Table 3 looks, as an example, at the torque to cause slip at an applied load of 7 kN, except for the matt cylinder that was pushed through the cement just before a vertical load of 7 kN was reached, for the matt cylinder behaviour at a

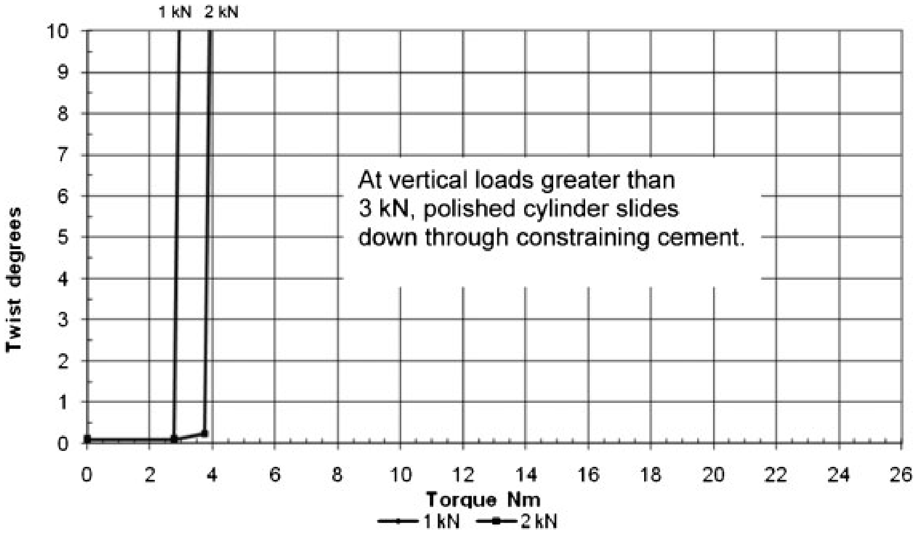

Fig. 8 Torque–twist chart for a polished cylinder

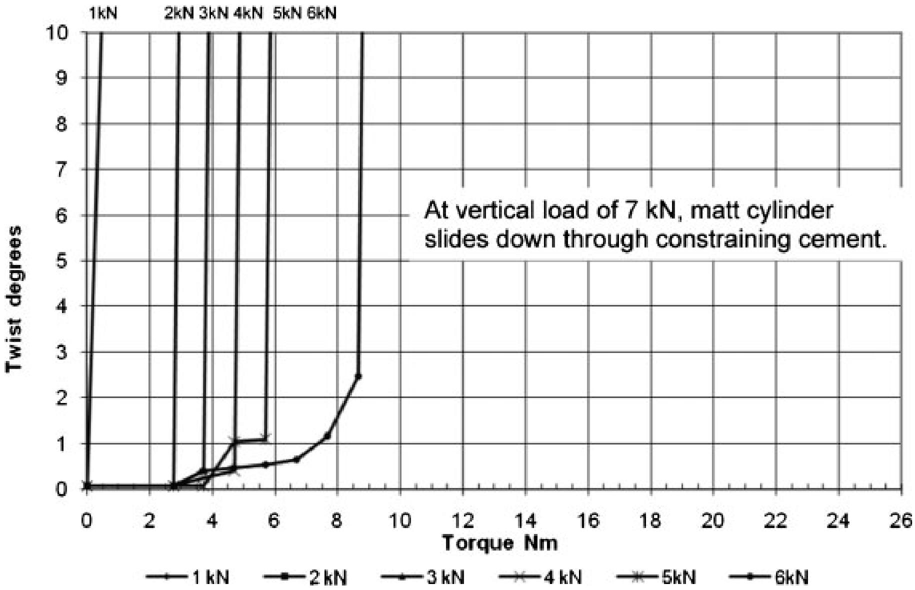

Fig. 9 Torque–twist chart for a matt cylinder

vertical load of 6 kN is recorded. It can be seen that the polished stem and the polished taper transmit substantial amounts of torsion when put under vertical load. The matt stem, matt taper and matt cylinder do not themselves transmit torsion even when put under vertical load. The polished cylinder simply pushes through the outer cement tube without transmitting torsion. The effect of putting a collar on the polished taper is important: the collar prevents the taper from subsiding in the cement cast around it and the collared taper transmits no torsion.

In this study the polished tapered stem and polished tapered cone acted in a very similar way. As increased vertical load was applied more torque was required to produce twisting of the inner cement column within the outer. When the effect of the thrust bearing was taken into account, the matt surfaced versions of the tapered stem, cone, and cylinder all showed no capacity to transmit torsion even with increased vertical load. The difference between the polished and matt groups of specimens is the ability of the polished specimens to subside within the inner PMMA shell. The matt surface improves the bond between the interface between the metal specimen and cement, hence resisting subsidence. The collared polished taper is prevented from subsiding within the cement owing to contact between the collar and the top of the cement column. Subsidence of a polished

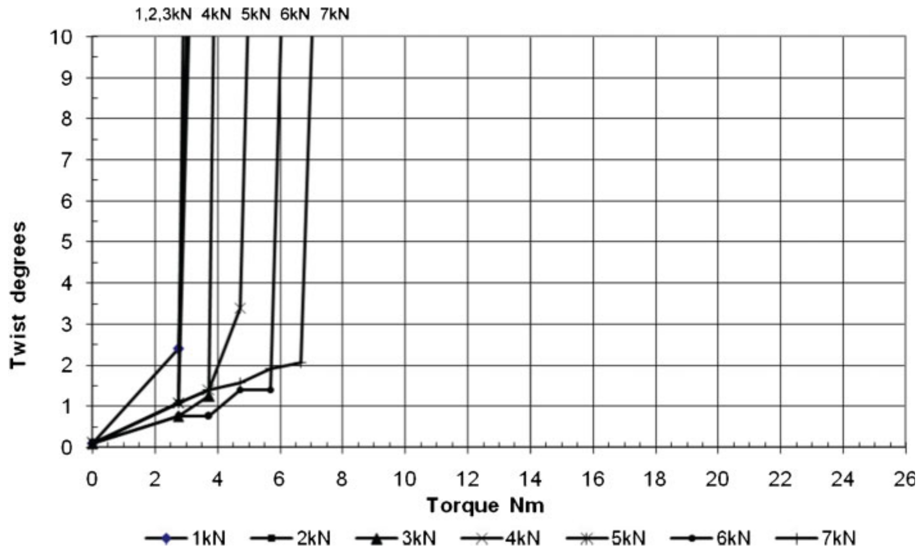

Fig. 10 Torque–twist chart for polished circular taper with a collar

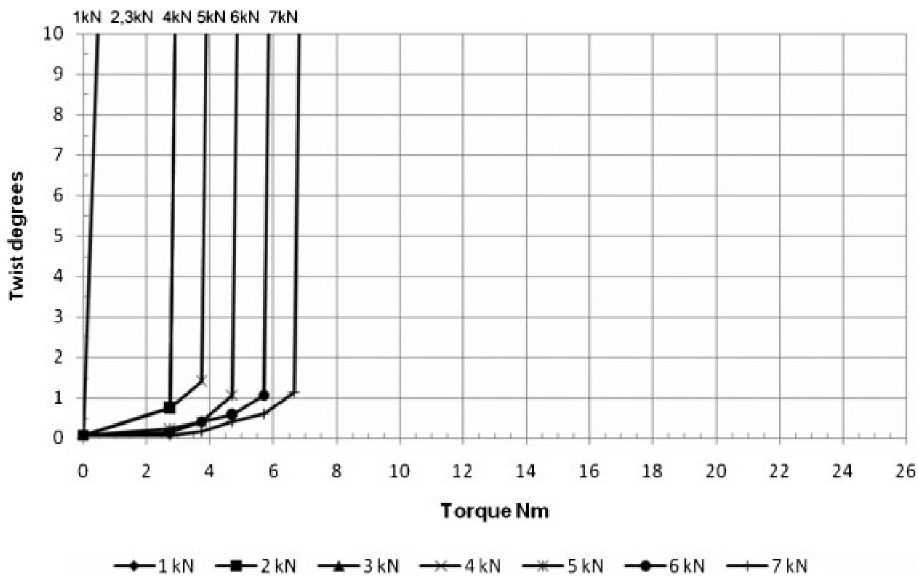

Fig. 11 Torque–twist chart for thrust bearings alone

Table 2 Torque to produce slip versus vertical load

Vertical load (kN)	Exeter polished stem	Exeter matt stem	Polished taper	Matt taper	Polished cylinder	Matt cylinder	Exeter collared stem	Thrust bearings alone
0	0	0	0	0	0	0	0	0
1	4.72	0	2.76	2.76	2.76	0	2.76	0
2	5.7	2.76	4.72	3.74	3.74	2.76	2.76	2.76
3	6.68	3.74	8.64	3.74		3.74	2.76	2.76
4	11.59	4.72	14.53	4.72		4.72	2.76	3.74
5	18.45	5.7	15.51	5.7		5.7	4.72	4.72
6	21.4	6.68	14.53	6.68		8.64	5.7	5.7
7	21.4	7.66	22.38	8.6			6.68	6.68

tapered shape within cement forces the cement outwards in a radial direction, increasing contact stresses between the inner cement mantle and the outer cement tube and allowing torsional forces to be transmitted through the cement. Any factor that prevents subsidence of an implant within cement (such as a matt surface or a collar) will prevent transmission of torsion.

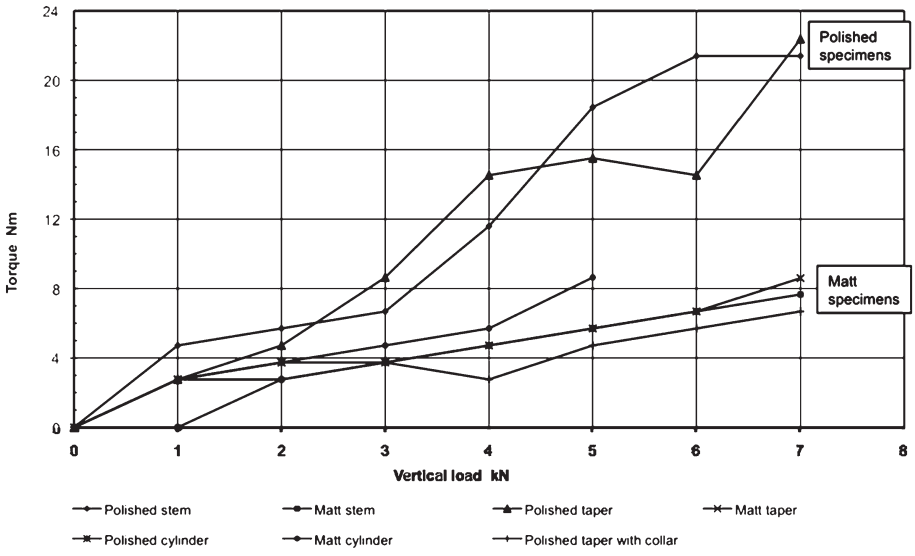

Fig. 12 Torque to produce slip versus vertical load

Table 3 Effect of the thrust bearings

Specimen	Vertical load: kN	Torque to cause slip: specimen as tested: Nm	Torque to cause slip: bearings alone: Nm	Torque to cause slip: specimen minus effect of bearings: Nm
Polished stem	7	21.40	6.68	14.72
Matt stem	7	7.66	6.68	0.98
Polished taper	7	22.38	6.68	15.70
Matt taper	7	8.64	6.68	1.96
Polished cylinder	–	–	–	–
Matt cylinder	6	6.68	5.70	0.98
Polished taper with collar	7	6.68	6.68	0.00

It has been reported that internal rotation of a cemented stem causing posterior head migration is a common and important mode of failure [**4**]. Forces directed posteriorly on the femoral head are common during activities of daily living such as stair climbing and rising from a chair [**5**, **6**]. Failure of a cemented implant may occur due to rotational stress causing disruption at the bone cement interface and subsequent loosening of the implant [**7**]. Movement at the bone–cement interface leads to the production of a membrane which when combined with particulate wear can lead to osteolysis and failure [**8**, **9**]. This initial movement is proportional to the magnitude of the stresses at the interface and inversely proportional to the ability of the interface to withstand it [**10**]. If the stem is able to resist the torsional shear force then migration and eventual loosening is less likely [**4**]. The geometry of the stem has been shown to be important in torsional stability. Stems which are of a generally rectangular shape, such as the Exeter, have the best cross-sectional shape to resist torsional load within the cement mantle [**11**]. When a stem of this shape is placed under such a load, shear and compressive stress will be transmitted to the bone-cement interface [**12**]. If a further radial compressive stress can be superimposed on the torsional shear stress, the interface between bone and cement will be better able to resist the applied loads.

The study was designed to examine the effect of surface finish on the ability of a cemented femoral stem to transmit torsion when put under load. To achieve this aim, a number of differently shaped specimens with a polished or matt surface finish were implanted in PMMA bone cement and placed in a specially designed test rig where they were put under vertical load. The effect of varying anterior–posterior or medial–lateral forces was not investigated. No attempt was made to replicate the biomechanical characteristics of cortical bone. Statistical significance between the various test results could not be determined as only single sets of tests were done for each specimen type.

5 CONCLUSION

The reported tests are the first to examine in the laboratory the effect of surface finish on the ability of a cemented stem under varying vertical load, to transmit torsional forces. The study demonstrates that a stem with a polished surface and tapered shape is able to subside within the cement mantle and will significantly increase the torsional stability of the bone–cement construct when placed under vertical load. The increase in torsional stability is attributable to the ability of the bone cement to move radially outwards by a combination of elastic and viscoelastic creep, producing radial compressive forces through the cement mantle and at the bone–cement interface. If the stem cannot subside and produce radial compression, such as when it has a cylindrical shape, or when it has a matt surface, or when it has a collar, then the compressive forces will not be induced in the same way and the torsional stability will not be improved under load. This finding has important implications to the clinical longevity of a femoral stem. A stem that is able to subside within a cement mantle and cause compression at the bone–cement interface will be more resistant to movement at this interface and therefore less likely to sustain osteolysis and eventual failure.

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