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A LINEAR ACTUATED TORSIONAL DEVICE TO REPLICATE CLINICALLY RELEVANT SPIRAL FRACTURES IN LONG BONES

W. Brent Edwards^a and Karen L. Troy^{a,b}

^aDepartment of Kinesiology and Nutrition, University of Illinois at Chicago, Chicago, IL 60612, USA

^bDepartment of Bioengineering, University of Illinois at Chicago, Chicago, IL 60612, USA

Abstract

To better understand the mechanisms underlying spiral fracture we would like to carry out biomechanical tests of long bones loaded in torsion to failure. A device was fabricated to perform torsional tests of long bones using a single-axis linear actuator. The principal operation of the device was to transform the vertical displacement of a material testing machine's linear actuator into rotational movement using a spur gear and rack system. Accuracy and precision of the device were quantified using cast-acrylic rods with known torque-rotation behavior. Cadaveric experimentation was used to replicate a clinically relevant spiral fracture in eleven human proximal tibiae; strain gage data were recorded for a single specimen. The device had an experimental error less than 0.2 Nm and was repeatable to within 0.3%. Strain gage data were in line with those expected from pure torsion and the cadaveric tibiae illustrated spiral fractures at ultimate torque and rotation values of 130.6 ± 53.2 Nm and $8.3 \pm 1.5^\circ$, respectively. Ultimate torque was highly correlated with DXA assessed bone mineral density ($r = 0.87$; $p < 0.001$). The device presented is applicable to any torsional testing of long bone when only a single-axis linear actuator is available.

Keywords

torsion; mechanical testing; materials testing machine; structural properties; bone strength

INTRODUCTION

Bone fractures are biomechanical events that occur when the magnitude of the applied load exceeds the strength or failure tolerance of the bone tissue. Long bone fractures that are generated by torsional loads are often characterized by a spiral pattern [1–3]. These fractures may occur as a consequence of high- or low-energy trauma, wherein high-energy fractures are associated with loads sufficient to break a healthy bone and low-energy fractures are associated with a pathological bone state.

In an effort to better understand the etiology of low-energy spiral fracture, we would like to carry out biomechanical tests of long bones loaded in torsion to ultimate failure. Although, our laboratory is equipped with a materials testing machine (858 Mini Bionix II, MTS, Inc., Minneapolis, MN), this machine has only a single-axis linear actuator and due to budget

Corresponding Author: W. Brent Edwards, University of Illinois at Chicago, Department of Kinesiology and Nutrition, 1919 W. Taylor Street, 650 AHSB, M/C 517, Chicago, IL 60612, Phone: 312-996-1582, edwardsb@uic.edu.

DECLARATION OF CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

constraints we are unable to purchase the manufacturer's "Torsional Actuator Upgrade Kit". Here we develop, validate, and apply a linear actuated torsional device to replicate clinically relevant spiral fractures in long bones.

METHODS AND MATERIALS

A mechanical device was fabricated to load long bones in torsion (Figure 1). The principal operation of the device is to transform the vertical displacement of the material testing machine's linear actuator into rotational movement by way of a steel spur gear and rack system [4].

Development

The spur gear is mounted to, and housed within, a cast aluminum frame (15.88 mm thickness) using a steel tapered-roller bearing and roller assembly (for shaft diameter 31.75 mm, outer ring diameter 59.13 mm). The spur gear has a face width of 19.05 mm, 80 teeth, and a 127 mm pitch diameter. The cast aluminum frame is bolted to stock threaded holes in the material testing machine's working base. A 4140 chrome-moly rectangular bar (25.4 × 50.8 × 609.6 mm) is mounted orthogonal to the machine's linear actuator, and passes through the bottom of the cast aluminum frame, underneath the spur gear. The testing sample is attached to the system using two rectangular aluminum pots; the proximal pot is coupled to the spur gear and thus free to rotate, while the distal pot is attached to the rectangular bar and fixed in rotation. The position of the distal pot is adjustable along the length of the rectangular bar, thereby allowing testing samples of varying size. The rack is attached to the factory load cell placed in series with the linear actuator. A lateral support containing two needle bearings and mounted to the cast aluminum frame serves as a guide for the rack.

Depending on the direction of linear actuation (up or down), the spur gear can rotate either clockwise or counterclockwise so that long bones from both left and right limbs may be loaded in internal or external rotation. Measured values of axial force F and linear displacement d from the factory load cell and LVDT, respectively, are used to directly calculate torque T and angular rotation α during the test. This is accomplished using simple equations relating translational to rotation motion, wherein the relationship between F (N) and T (Nm) is:

$$T = (F - f)r$$

where r is the moment arm, or pitch radius of the spur gear (0.0635 m), and f is the friction required for mechanical operation of the device. For both clockwise and counterclockwise rotation we found f to be approximately 1.5 N, corresponding to 0.1 Nm of torque (Figure 2). This magnitude of friction was deemed negligible relative to our anticipated testing loads thereby simplifying the equation to:

$$T = 0.0635F$$

The relationship between linear displacement d (m) and angular rotation α (°) is:

$$\alpha = 180d/\pi r, \text{ or } \alpha = 0.9023d.$$

Validation

Accuracy and precision of the device was assessed using a cast acrylic rod (8528K33; McMaster-Carr, Chicago, IL) of known size (19.05 mm diameter) and material properties ($E = 3.1$ GPa, $\nu = 0.375$). Cast acrylic behaves linear-elastic until failure with a torque-rotation curve that can be solved analytically using the following equation:

$$\theta = TL/GJ \quad G = E/2(1+\nu) \quad J = \pi D^4/32$$

where θ is the angle of rotation, L is the “exposed” length of the rod, G is the shear modulus, and J is the polar moment of inertia. The cast acrylic rod was cut to 152.4 mm and the proximal and distal 25.4 mm were embedded within the proximal and distal pots using polymethyl methacrylate (PMMA). The rod was loaded experimentally at a fixed rotation rate of 9.023 °/s up to 30 Nm. The test was performed 5 times each in the clockwise and counterclockwise directions and experimental and analytical torque curves were compared using simple linear regression. The mean Pearson’s r coefficient and standard error of the estimate (SEE) were used as measures of experimental accuracy; the coefficient of variation in regression slopes provided information about experimental precision.

Application

People living with spinal cord injury (SCI) are particularly susceptible to low-energy spiral fractures. This population experiences marked bone loss at regions below the neurological lesion, such that within 2 to 3 years post SCI, approximately 50% of their bone mass has been lost at the knee [5, 6]. Consequently, the distal femur and proximal tibia are among the most common locations to fracture [7–10]. These fractures often occur during wheelchair transfers, falls from wheelchairs, and rolling over in bed (i.e., twisting or catching of the lower-extremity) [7–9], thereby implicating torsion as a primary mode of failure.

The device was used to replicate spiral fractures in proximal tibiae excised from eleven formalin-fixed cadavers (age 68.2 ± 15.8 yrs; 5 female; 3 left limbs). Osteotomy was performed 15 cm below the tibial plateau, and the proximal and distal most 2 cm of bone were potted using PMMA. Bone mineral density (BMD) of the potted specimens was acquired using a Hologic QCR-4500 (Hologic, Waltham, MA). A stacked rectangular strain gage rosette (WA-06-030WR-120; Micromeritics Group Inc, Raleigh, NC) was mounted to the anteriomedial surface of a single specimen. The gage was adhered with cyanoacrylate glue and covered with a polyurethane coating. Following ten conditioning cycles bones were loaded at a fixed rotation rate of 9.023 °/s until fracture (Figure 3). The fracture type and ultimate torque and rotation at failure were noted. Strain gage data were analyzed to ensure mechanical conditions were in line with those expected from pure torsion. Torque, rotation, and where applicable, strain gage data were collected at 1000 Hz. Pearson’s r was used to assess the correlation between BMD and ultimate torque.

RESULTS AND DISCUSSION

Accuracy of the device for both clockwise and counterclockwise rotation was excellent (Figure 4). The analytical and measured torque curves of the acrylic rod illustrated near perfect correlations, SEEs less than 0.2 Nm, and slopes of unity (Table 1). Precision was also excellent with the CV of the regression slopes being less than 0.3%.

All cadaveric tibiae illustrated spiral fracture patterns at mean ultimate torque and rotation values of 130.6 ± 53.2 Nm and $8.3 \pm 1.5^\circ$, respectively. BMD was highly correlated with ultimate torque ($r = 0.87$; $p < 0.001$; Figure 5), thus implicating its potential use as a fracture risk assessment tool in the SCI population. The strain environment of the gaged specimen mimicked that of an isotropic and homogeneous prismatic cylinder loaded in pure torsion (Figure 6). Principal strains were similar in magnitude and oriented near 45° relative to the bone’s longitudinal axis – the fracture plane coincided with the angle of maximum tensile strain. Likewise, the strain environment along the bone’s longitudinal and transverse axes was predominately shear with little normal strain. This small but finite normal strain can be explained by constrained warping of the specimen as well as the specimen’s complex geometry.

The device is currently limited to a maximum torque of ~318 Nm and an angular rotation of ~90° due to the 5 kN factory load cell and the 100 mm stroke of the linear actuator, respectively. Nonetheless, these limits are well above the ultimate values observed herein, as well as those observed for human femoral (mean torque 183 Nm, range 111 – 290.5 Nm; mean rotation 20.0°, range 9.4 – 30.7°) and tibial (mean torque 101, range 57–178 Nm; mean rotation 23.7°, range 14.1 – 37.4°) specimens loaded at high strain rates [2].

CONCLUSIONS

We developed, validated, and applied a linear actuated torsional device. The device is accurate, precise, and capable of replicating clinically relevant spiral fractures in long bones. Although the application of this paper dealt specifically with spiral fracture of the proximal tibia, the device presented is applicable to any torsional testing of long bone when only a linear actuator is available.

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Figure 1.
Front (left) and side (right) illustrations of the linear actuated torsional device.

Figure 2.

Friction required to operate the mechanical device (i.e., driven with no specimen) in the counterclockwise (CCW) and clockwise (CW) direction. Black and gray represent the group ensemble mean and standard deviation of five repeat trials.

Figure 3.
Photograph of the linear actuated torsional device with potted cadaveric specimen.

Figure 4.

Measured (solid) and analytical (dashed) torque-rotation curves for the acyclic rod loaded in the counterclockwise (CCW) and clockwise (CW) direction. The measured line represents the ensemble mean of 5 repeat trials. Standard deviation bands are plotted in gray, although these are difficult to see at the current resolution.

Figure 5. Bone mineral density (BMD) versus ultimate torque for the eleven cadaveric specimens.

Figure 6.

Torque and anteriomedial surface principal ($\epsilon_{\max}$, $\epsilon_{\min}$), normal (ϵ_1 , ϵ_2) and shear (γ_{12}) strains versus rotation for the cadaveric proximal tibia with strain gage rosette.

Table 1

Mean (SD) linear regression parameters comparing analytical and measured torque from five counterclockwise (CCW) and clockwise (CW) rotations of a cast acrylic rod.

	r	SEE (Nm)	slope	CV (%)
CCW	1.000 (0.000)	0.200 (0.013)	1.007 (0.003)	0.268
CW	1.000 (0.000)	0.161 (0.003)	1.022 (0.001)	0.085